Chapter 1

Introduction

1.1 Large scale circulations in the tropical atmosphere

In this chapter an overview of the large scale characteristics of the tropical atmospheric circulations has been presented. In order to gain a good appreciation of this subject, we first elucidate the main features such as: the structure of the time averaged heating in the tropical troposphere, the dynamics of the time-mean tropical Walker and Hadley circulations and the variability associated with tropical atmospheric motions on different time scales. Although the above discussions are quite general, the emphasis is mainly on the aspects that are directly relevant to the thesis. After presenting a general outline, we have summarized the various theoretical problems that were examined along with the important results.

Much of the large-scale circulations in the tropics are directly driven by convective heating. Considerable insight into the dynamics follows from a study of the response of the atmosphere to tropical heat sources and heat sinks. The diabatic heating is a foremost component of the tropical atmospheric system. The dominant contribution to the diabatic heating in the tropics comes from latent heat release by
cumulus clouds. A broad sketch of the observed time-mean heating in the tropical atmosphere is given below. Observations by Ramage (1968), Krueger and Winston (1974), Liebmann and Hartmann (1982) and many others, indicate that the tropical atmosphere possesses strong longitudinal variations in the distribution of cloudiness and precipitation. The zonally asymmetric distribution of tropical convective activity arises primarily because of the heating associated with the warm sea surface temperature (SST) and equatorial land areas. The regions of intense equatorial convection are located mostly over Indonesia and western Pacific, continental Africa and South America. There are also cloud free zones (e.g. eastern Pacific, the deserts of Iran and Saudi Arabia), which are associated with radiative cooling. This longitudinal variation in the heating distribution drives the planetary scale circulations in the tropics. A schematic view of the prominent east-west circulations in the tropical atmosphere is shown in Fig. 1.1. The major divergent circulations associated with the convective heat sources over equatorial Africa, western Pacific and South America are well depicted in Fig. 1.1. The most striking feature is the east-west circulation in the equatorial Pacific, which is forced by the deep convective heating over Indonesia and western Pacific. The eastward branch of the divergent circulation descends in the eastern Pacific and the westward branch descends near Saudi Arabia. In addition to the east-west circulations, there are large overturnings in the meridional plane caused by north-south heating contrasts. The well known example is the Indian summer monsoon circulation, which results from strong diabatic heating over the elevated Tibetan plateau, the Bay of Bengal and north east India.

The planetary scale features in the tropical atmosphere exhibit variability on various time scales. On the interannual time-scale, the Walker circulation in the equatorial Pacific undergoes significant changes. The phenomenon of changes in the Walker circulation over the equatorial Pacific, caused because of SST anomalies, is called Southern Oscillation. It should be noted that the interannual variations in the
Fig. 1.1. Schematic view of the major east-west circulations in the tropical atmosphere. (Adapted from review article of P.J. Webster. Reference: Page 242, Large scale dynamical processes in the atmosphere. Hoskins and Pearce, Academic Press (1983)).
tropical atmosphere are strongly coupled to fluctuations in the tropical SST. For example, during El Niño, a warm SST occurs in the eastern Pacific ocean. The response of the tropical atmosphere to this warm SST anomaly results in a modification of the Walker circulation in the equatorial Pacific. It is found that the zone of maximum convective activity shifts to the central Pacific. Consequently, the rainfall pattern gets displaced to the east of Indonesia resulting in drought over Australia and Indonesia. The structure of the tropical diabatic heating also exhibits distinct seasonal variations. During the northern hemispheric winter, the active zones of convection are located, along the ITCZ, over the equatorial western Pacific and the continents of Africa and South America. The winter Asian monsoon circulation, the Walker circulation in the equatorial Pacific and the east-west circulations associated with the heating over Africa and South America are the outstanding features during the winter months. When a transition from the northern winter to the northern summer occurs, the monsoon rainfall belt (convective heating) shifts from the Indonesian region to the foothills of Himalayas (Krishnamurti (1985)). The prominent circulations during summer are the mean meridional (Hadley) as well as the east-west (Krishnamurti (1971)) circulations associated with the Indian summer monsoon and the circulations induced by the heating over the Mexican highlands. Coming to the subseasonal time-scale, the predominant variability in the tropics has a period of about 30-50 days. The 30-50 day oscillation manifests itself as a slow eastward propagation of equatorial convective activity. Previous studies have shown that this eastward propagation of convective activity arises because of interactions between the planetary scale motions and tropical cumulus convection. During the northern summer, the 30-50 day wave interacts with the Indian summer monsoon circulation thereby producing a slow northward progression of convective activity over India. Observations indicate that as a result of this interaction the rainfall activity over India vacillates between active and break periods.
1.2 Plan and scope of the thesis

In this section, we shall present a gist of the topics covered in the thesis and a brief summary of the main results. A concise review of some of previous studies has been provided, wherever necessary, for the sake of maintaining the continuity of the description.

1.2.1 The time-mean Walker circulation in the Pacific

Observations suggest that large convective heating, which is most prominent during the northern winter, occurs over Indonesia and equatorial western Pacific (Ramage (1968), Krueger and Winston (1974) and Liebmann and Hartmann (1982)). In addition there is a dry zone over the eastern Pacific where the longwave cooling is substantial. This zone is cloud free and is characterized by widespread subsidence and strong surface easterly trades. Gill (1980) theoretically explained the steady state Walker circulation in the equatorial Pacific, by studying the stationary waves forced by an isolated heat source, using a system of shallow water equations on an equatorial $\beta$-plane. He showed that a heat source symmetric w.r.t the equator triggered Kelvin waves to its east and Rossby waves to its west. Gill's model offered an elegant explanation for the Walker circulation in the equatorial Pacific in terms of the stationary Kelvin wave response. But the main drawback in Gill's model was the use of large values of the dissipation parameters (Rayleigh friction and Newtonian cooling). Gill (1980) used a very strong dissipation which had an e-folding time-scale of about 2 days. The physical processes which can produce such strong dissipation effects are still not fully understood, although some studies (eg. Holton and Colton (1972).
Stone et al. (1974) speculate that vertical transport of horizontal momentum by deep cumulus convection can act as a damping mechanism. Nevertheless, the use of a strong damping (e-folding time ~ 2 days) by the linear model of Gill (1980) may not be justifiable. However, there are studies based on GCM simulations (e.g. Manabe et al. (1974), Kasahara et al. (1973)), that have realistically modelled the time-mean flow patterns, without incorporating such strong dissipation terms in the model.

One of the motivations behind our study is to understand, what parameters control the longitudinal scale and intensity of the time-mean Walker circulation. Phillips and Gill (1987) proposed that it was the damping term (Rayleigh friction) that accounted for the zonal scale of stationary Kelvin waves. They argued that a strong damping term would localize the stationary waves near the forcing region, while a weak damping term would allow the response to have a greater zonal extent. Phillips and Gill (1987), however could not account for the short time-scales associated with the strong values of dissipation. In our study, we have examined the nature of east-west circulations in the equatorial Pacific, induced by the heating over Indonesia and the radiative cooling in the eastern Pacific. We have studied the influence of the radiative cooling over the eastern Pacific in controlling the scale and intensity of the Walker circulation. We have used weak dissipation (Rayleigh friction) in our studies. Idealized forcing experiments were carried using a 2-level linear equatorial β-plane model as well as a 5-level global spectral model. Since idealized studies are also amenable to analytical treatment, we have supplemented the model results with analytical calculations. The steady state equations in the 2-level model reduce to a system of linear algebraic equations. The stationary response to a given forcing is determined by solving this system of equations numerically. In the case of the 5-level global spectral model the prediction equations are integrated, with the forcing kept constant for the entire period of integration and the steady state response is calculated. Our studies indicate that the strength and zonal extent of the Walker
cell, is controlled by the positions and intensities of the heat source over Indonesia and also the heat sink in the eastern Pacific. We have shown that the radiative cooling in the eastern Pacific, which is quite substantial, determines the region of the subsiding branch of the Walker circulation. It is found that the time-mean response forced by the combination of a heat source and a heat sink, results in a superposition of stationary Kelvin waves emanating from the heat source and stationary Rossby waves emanating from the heat sink. The Walker circulation in the equatorial Pacific exhibits variability on the subseasonal, seasonal and interannual time-scales. In our idealized forcing experiments, we varied the relative distances between the diabatic heating and longwave cooling regions and calculated the impact on the east-west circulations. It was found that the intensity of the time-mean Walker circulation exhibited significant variations, as the distance between the heat source and the sink was changed. The circulation pattern was most intense, when the separation between the heating and cooling regions was minimum.

Another aspect that has been investigated pertains to the impact of nonlinearities on the stationary Kelvin and Rossby waves. This was essentially based on a comparison of the stationary wave response in the linear and nonlinear versions of a 5-level global spectral model. It was found that the influence of nonlinear terms was strongly felt in the vicinity of an intense convective heat source. Due to this impact, the structures of the stationary Kelvin and Rossby waves, near the forcing region, were considerably modified. It was also seen, mainly on the western side of the forcing region, that the nonlinear advection terms produced an eastward displacement of the upper level highs. In Gill-type of linear models, one has to employ a very strong damping, in order to obtain an eastward shift of the upper level anticyclones, which may not be realistic. We find that, even in the presence of weak dissipation it is still possible to explain the eastward shift by including nonlinear advection terms in the model. Due to the eastward shift of the highs at the upper levels, there is an
enhancement of the upper level divergence and the anticyclonic circulation over the region of forcing. It is also found that the effects of nonlinear terms become smaller when the intensity of the heat source is reduced. In the case of an antisymmetric heat source, it is found that the stationary Rossby wave pattern to the west of the forcing region shows distinct eastward shift in the NLM. The vertical profiles of the time-mean zonal wind, for the case of the symmetric forcing, reveal that the linear and nonlinear solutions exhibit distinct changes in the mid tropospheric levels. It is found that nonlinear terms favour the generation of westerlies in the equatorial region. Further, it is found that nonlinearities account for an increase in the vertical shear at around 400 mb. The role of nonlinear terms in aiding the generation of westerlies and also modifying the vertical shear of the basic flow, might be useful in understanding the phenomenon of midlatitude teleconnections (see. Lim and Chang (1983), Zhang and Webster (1989), Lim and Chang (1986) and Kasahara and Silva Dias (1986)). The significance of nonlinear dynamics with regard to time-mean circulations in the tropical atmosphere has been again stressed in Chapter IV.

1.2.2 The winter and summer time-mean circulations during 1979

Having so far described the stationary wave response of the tropical atmosphere induced by idealized heating distributions, let us now examine the case of more realistic time-mean circulations in the tropics. We have studied the time-mean circulations during winter (1978-79) and summer (1979), which are described in Chapter III. We have basically examined the equilibrium response, using a 2-level linear equatorial β-plane model as well as a 5-level nonlinear global spectral model, induced by the observed time-mean diabatic heating during winter (1978-79) and summer (1979). We have made use of the observed time averaged diabatic heating computed by Schaack
et.al (1990), during winter (1978-79) and summer (1979), in our forcing experiments. In the case of the 2-level linear equatorial β-plane model, the observed diabatic heating is prescribed at the 500 mb level only. The steady state equations in the 2-level model reduce to a system of linear algebraic equations. The steady state response to a given forcing was determined by solving this system of equations numerically. But in the case of the 5-level nonlinear global spectral model, the observed diabatic heating was prescribed at all the five vertical levels in the model. The 5-level global spectral model was integrated, with the forcing kept constant throughout the period of integration, and the steady state response was calculated.

The gross features of the time-averaged heating field during winter (1978-79) were the active zones of convection located along the ITCZ that extended from South America across the Atlantic, Africa, the Indian ocean and into the western Pacific. The most prominent heat source, associated with the winter Asian monsoon, occurred over the equatorial western Pacific. A well defined cooling maximum exceeding 1.0°K per day, was seen in the oceanic region to the west of South America. We found that both the 2-level linear model and the 5-level nonlinear global spectral model, reproduced most of the gross structural features of the mean circulation during winter (1978-79) reasonably well. The stationary Kelvin and Rossby waves forced by the Indonesian heating were seen in the time-mean flow patterns. The divergent circulations forced by the convective heating over the western Pacific, continental South America and Africa were seen in both the models. However, it was found that the circulation in the 2-level linear model was generally weaker as compared to the response in the 5-level global spectral model. Features such as the Walker circulation in the Pacific and the Hadley-type of circulation in the western Pacific were relatively stronger in the 5-level global spectral model. Further, the circulation features were more close to the observed flow patterns, in the case of the 5-level global spectral model. This is mainly due to the fact that in the 2-level model the prescription of
the forcing was at the 500 mb level alone, thereby restricting the vertical variation of heating to the first baroclinic mode only. Further nonlinear advection terms were absent in the 2-level linear model. On the other hand, the 5-level nonlinear global spectral model has been forced using the heating fields at all the 5 model levels. The more accurate vertical representation of the forcing and also the inclusion of nonlinearities in the 5-level global spectral model, resulted in more realistic flows in the case of the 5-level model. Using the maps of velocity potential distribution at 300 mb, we have calculated the intensities of the Walker and Hadley circulations. It was found the Walker circulation was most intense in the regions of central and eastern Pacific. The Hadley-type of circulation over the western Pacific was strongest in the equatorial region. These results match well with observed circulation patterns during winter (1978-79).

The major heating zones during summer (1979) were located over the Tibetan plateau, the Bay of Bengal and northeast India and the highlands of Mexico. Regions of radiative cooling were located over the oceans of north Pacific and Atlantic. The India summer monsoon region was characterized by a reverse Hadley circulation comprising of low-level south westerly flow and upper level easterlies. In addition to the mean meridional circulation, the strong zonal asymmetry in the distribution of the diabatic heating resulted in major tropical east-west circulations. The gross circulation features at the upper levels, such as the Tibetan anticyclone, the easterlies over the Indian subcontinent and the major east-west circulations were seen in the 2-level linear model response. However, the speeds of the upper level easterlies over the Indian monsoon region were relatively smaller than the observed flows. The 5-level nonlinear global spectral model reproduced the structure of both the upper and lower level circulations quite well. The intensity of the Tibetan anticyclone and the speed of the upper level easterlies in the 5-level model were more realistic. Similarly, the low-level southwesterly flow over the Indian subcontinent, matched well with the
observations. The more realistic upper and lower level circulation features in the 5-level model can be mainly attributed to the accurate representation of the vertical structure of diabatic heating and also the inclusion of nonlinear terms in the model. The major east-west circulations, forced by the heating over the Indian monsoon region, were distinctly seen from the velocity potential maps. Fairly strong subsidence was observed close to Pakistan and Rajastan which explains the poor rainfall over northwest India during summer 1979. The intensity of the Hadley circulation, computed from the velocity potential distribution at 300 mb, showed that the meridional circulation was quite intense over the Tibetan plateau. The velocity potential maps also displayed prominent east-west circulations at the 300 mb level associated with the heating over the Indian monsoon region and Mexico.

1.2.3 The vorticity balance in the tropical upper troposphere

The vorticity equation is an extremely useful tool for understanding the dynamics of the tropical atmospheric motions. By performing a scale analysis in the tropics, one finds that the divergence equation can be approximated by a balance condition. Similarly, the thermodynamic equation simplifies to a balance between the diabatic heating (cooling) term and the adiabatic cooling (heating) due to ascent (descent). Therefore, the vorticity equation being a prognostic relation is best suited for understanding the dynamics of tropical large scale motions. In the past, there have been quite a few theoretical calculations of the nature of vorticity balance in the tropics (eg. Holton and Colton (1972), Sardeshmukh and Held (1984) and Sardeshmukh and Hoskins (1985)). Holton and Colton (1972) used a barotropic vorticity equation linearized about a zonal mean, to study the observed vorticity balance at 200 mb during summer 1967. They used the observed winds and divergence at 200 mb.
and calculated the vorticity distribution from the linear barotropic vorticity equation. They found that, a large vorticity damping (e-folding time < 1 day) had to be included in the equation, so that the calculated vorticity field matched with the observed vorticity distribution. They speculated that such a large vorticity damping can appear because of vertical transport of momentum, from the surface to the top of the atmosphere, by deep cumulus clouds. The use of such a rapid vorticity decay term at the upper troposphere, which may not be realistic, is the main drawback of the linear model of Holton and Colton (1972). Studies based on nonlinear models (GCMs) present a different view of the vorticity balance in the tropics. For instance, Sardeshmukh and Held (1984) simulated the July mean circulation using the GCM at GFDL. Inspite of the fact that the vertical transport of momentum by cumulus convection was not included, the model produced a realistic simulation of the large-scale upper tropospheric circulations. They suggested that the nonlinear advection terms were important in determining the vorticity balance in the tropical upper troposphere. They showed that the linear models had to compensate for the neglected nonlinearities by employing a strong vorticity dissipation term.

We have already demonstrated in Chapter II, the significance of nonlinear dynamical effects on the stationary Kelvin and Rossby waves in the tropics. One can also estimate the impact of nonlinearities on the time-mean vorticity balance in the tropical troposphere by means of diagnostic calculations. In Chapter IV, we have performed budget studies of the vorticity balance in the tropical upper troposphere using the fields generated by three different forcing experiments in a 5-level global spectral model. In the first experiment, the model was forced using an idealized heat source in the western Pacific and a heat sink in the eastern Pacific. The dissipation terms in the model are very weak (e-folding time ~ 15 days). The 5-level global spectral model was integrated, with the forcing kept constant, till a steady state was attained. Similar forcing experiments were performed by forcing the model using the
time-averaged diabatic heating for winter (1978-79) and summer (1979) respectively. Based on the model generated fields, vorticity budget studies at 300 mb, were performed for all the 3 cases. We have explicitly calculated all the terms in the vorticity equation, including the vertical advection and twisting terms. In addition, we have computed area averages for the various terms in the vorticity equation over different regions. For the case of the idealized forcing, the region between the heat source and the sink was chosen for calculating the area averages. In the case of winter 1978-79, the area averages were calculated in the region of the Walker circulation over the equatorial Pacific. In the case of summer 1979, the averages were calculated for the region covering the northern summer monsoon area. We find that the primary vorticity balance at 300 mb, in all the 3 cases, is between the nonlinear terms involving the time-mean vorticity stretching and the horizontal advection of absolute vorticity. This suggests that nonlinear effects are important for the vorticity balance in the tropical upper troposphere. Our result conforms with the findings of Sardeshmukh and Hoskins (1985). The contribution from the vertical advection and twisting terms was found to be small. The terms involving the transients were found to be generally small in the low latitudes.

1.2.4 Linear and nonlinear studies of the tropical Hadley cell

As mentioned earlier, the observed atmospheric general circulation in the tropics owes its existence to the strong longitudinal variation in the distribution of diabatic heating. However, by suppressing the zonally asymmetric components and retaining only the symmetric part, it is possible to study the meridional or Hadley circulations. Zonally symmetric circulations offer a simpler perspective of the more complicated
atmospheric general circulation. Zonally symmetric studies provide valuable information about the transport of momentum, heat and water vapour between the tropics and the midlatitudes. Zonally symmetric flows also serve the role of basic state in instability studies. In Chapter V, we have carried out linear and nonlinear studies of the time-mean tropical Hadley circulation, forced by idealized diabatic heating. By comparing the response in the two models, we have examined the role of nonlinearities in modifying the time-mean meridional circulation in the tropics. In the past, there have been a few interesting linear and nonlinear calculations of the tropical Hadley cell. Schneider and Lindzen (1977) used a linearized axially symmetric model to study the steady-state response induced by the annual mean cumulus convection. They found that the mean meridional circulation driven by the zonally symmetric latent heat distribution, matched with the annual mean observed circulation only when 'cumulus friction' was included. They associated cumulus friction, with the vertical transport of horizontal momentum by cumulus convection. Quite contrary to the linear calculations, the GCM simulations by Manabe et al. (1970) and Kasahara et al. (1973) and the nonlinear calculations by Held and Hou (1980) showed that cumulus friction was not important in determining the steady-state tropical Hadley circulation. Further it should be noted that there are still uncertainties in the actual estimates of cumulus friction in the tropics. The GCM simulations of Manabe et al. (1970) and Kasahara et al. (1973) could realistically reproduce the Hadley circulation without specifying cumulus friction. Held and Hou (1980) have pointed out that nonlinear dynamical effects are important in maintaining the tropical Hadley cell.

In Chapter V, we have investigated the impact of nonlinear terms on the time-mean tropical Hadley circulation. The model used for our study is an axisymmetric 5-level global spectral model. We have studied the time-mean zonally symmetric response induced by idealized heating, using both linear (LM) and nonlinear (NLM) versions of this model. By comparing the response of the LM and NLM, we have
isolated the effects of nonlinearities on the time-mean tropical meridional circulation. We have considered two cases of forcing: a strong heat source (max heating 5° K per day) and a weak heat source (max heating 2° K per day). The Rayleigh friction and Newtonian cooling terms were quite weak (decay time ~ 15 days). It was found that the nonlinear vertical advection terms transport considerable flux of easterly momentum upwards in the region of the forcing. The transport of horizontal momentum from the surface to the top of the atmosphere results in the slowing down of the tropical trade winds in the NLM. We have carried out an explicit calculation of the angular momentum transport terms, which also indicates that a significant fraction of the easterly momentum is being transported upwards in the region of the forcing. In addition, it was noted that the nonlinear meridional advection terms displaced the core of the upper level westerly jets, poleward by about 6° latitude. It was found that the term involving the nonlinear vertical advection of temperature produces considerable adiabatic cooling, over the region of forcing. Consequently, the neglect of this nonlinear term in the thermodynamic energy equation, resulted in a large warming in the L.M. Thus there was an additional kinetic energy generation in the L.M. Infact, it was found that the global mean kinetic energy (GMKE) was significantly damped in the case of the NLM as compared to the LM. The dissipation of GMKE in the NLM is because of the two major nonlinear effects: (a) the large adiabatic cooling produced by the nonlinear vertical advection of temperature (b) the large vertical transport of easterly momentum from the surface to the upper levels. In the case of the weak forcing, it was found that the effects of nonlinear vertical advection (upward transport of easterly momentum and adiabatic cooling effect) were smaller. The poleward shift of the upper level westerly jets was also smaller (3° latitude) in this case. It was noticed that the damping of the GMKE, by nonlinear interactions, was quite small as compared to the strong forcing case.
1.2.5 Northward propagation of the 30-50 day oscillation

Till now our discussions were centered mostly on time-mean circulations in the tropics. However the final chapter of the thesis has been devoted to a theoretical study of the most popular intraseasonal transient in the tropical atmosphere, i.e, the 30-50 day oscillation. On the subseasonal time-scale, the tropical atmosphere is characterized by a slow eastward propagation of equatorial convective activity. This equatorial mode, which takes about 30 to 50 days to go around the globe, was first detected by Madden and Julian (1971). Numerous observations (eg. Lau and Chan (1983), Lorenc (1984), Lau and Phillips (1986), Knutson and Weickmann (1987) and many others) indicate that the intraseasonal fluctuations of convective activity are strongest over the Indian ocean and the western Pacific ocean. Many theoretical studies (eg. Davey (1984), Lau and Peng (1987), Yamagata (1987), Lau and Shen (1988) and others) explain the eastward propagation by a mutual interaction of the equatorial dynamics and convective activity. It is found that the oscillation propagates slowly over regions of warm SST, because the higher saturation moist content lowers the static stability of the atmosphere. Due to this reduced static stability, the Kelvin waves propagate with a slower phase speed (Davey (1984), Miyahara (1987) and Lau and Shen (1988)). But one of the most interesting aspects of the 30-50 day oscillation is its interaction with the Indian summer monsoon. Many observations in the past (eg. Yasunari (1979,1980), Sikka and Gadgil (1980), Krishnamurti and Subrahmanyam (1982), Krishnamurti et.al (1985) and others) have shown that the arrival of the equatorial low-frequency 30-50 day mode over the Indian summer monsoon region is characterized by a northward movement of convective anomalies over the Indian subcontinent. The northward progression rate is roughly about 1° latitude per day. The interaction of the Indian summer monsoon and the 30-50 day oscillation produces a low frequency variability in the monsoon rainfall over India, resulting in active and break phases in the monsoon (eg. Yasunari (1981), Hartmann and Michelson (1989)).
An understanding of the physical mechanism responsible for the northward movement of convective anomalies over the Indian summer monsoon region will go a long way in predicting the monsoon variability.

In Chapter VI, we have performed a theoretical study using an axisymmetric 5-level global spectral model, to understand the interaction of the Indian summer monsoonal circulation and the equatorial 30-50 day oscillation. The treatment of the problem is as follows. A basic flow which closely resembles the time-mean Hadley circulation over the Indian monsoon region, was first generated in the model by forcing it with an appropriate heating distribution. The next step was to produce near-equatorial perturbations in the model, thereby mimicking the arrival of the planetary scale 30-50 day mode over the Indian longitudes. The perturbations were actually generated in the model, by temporarily switching on an equatorial heat source. Later, we investigated the impact of cumulus heating (CISK) on the perturbations. The cumulus heating based on CISK was interactively determined from the low-level circulation. The assumption in CISK is that, the latent heat release by cumulus clouds is enhanced by the low-level frictional convergence of the large scale flow field and the latent heat in turn drives the large scale circulation. It should be noted that over the Indian summer monsoon region, there is a large cyclonic vorticity associated with the low level southwesterly flow. Therefore, Charney’s CISK for cumulus heating works in an utmost efficient manner, in this region. Our main interest was to examine the interactions between the time-mean basic flow and the cumulus convection. The model was integrated in the presence of cumulus heating. It was observed that the perturbations moved northward at the rate of about 0.5° latitude per day. It was also found that the low-level zonal wind field lagged meridionally behind the cumulus heating distribution. This meridional phase difference, induced by the CISK mechanism, resulted in the northward movement of the low-frequency intraseasonal convection. Our study suggests that the interaction between the cumulus heating
and the Indian summer monsoon circulation, plays a vital role in establishing the
northward propagation of intraseasonal convective activity.