Chapter 1

Introduction

The south Asian summer monsoon (ASM) is part of the seasonal reversal of the wind system and it has profound impact on the millions of people across the south and Southeast Asia, through their dependence on the associated changes of rainfall. The changes in the rainfall associated with this seasonal reversal of the wind system has immense impact on the agricultural production and, hence the economic stability of the countries across the south and Southeast Asia. Previous studies have shown the existence of a low level westerly wind during the boreal summer season (June-September) over the peninsular India, known as the Low Level Jet stream (Findlater, 1969a,b; Joseph and Raman, 1966) and it is characterized by a cross-equatorial flow in the equatorial Indian Ocean and a southwesterly flow in the Arabian Sea, Bay of Bengal and the Indian subcontinent (Figure 1.1a). This large-scale pattern of wind reverses during the boreal winter season (November-February) and becomes northeasterly (Figure 1.1b). The seasonal migration of the Inter Tropical Convergence Zone (ITCZ) is responsible for this wind reversal (Gadgil, 2003).

1.1 Monsoon Intraseasonal Oscillation (MISO)

The summer monsoon rainfall over the south Asia is not homogeneous, it is interrupted by periods of abundant and scanty rainfall, that are manifestations of MISO. The subseasonal (intraseasonal) variability of the ASM typically has a broad timescales between 10 to 100 days. Within this broad range of periodicity, two dominant scales of intraseasonal
Figure 1.1: Climatological mean wind (ms\(^{-1}\)) at 850 hPa based on NCEP/NCAR reanalysis during (a) boreal summer (June-September) and (b) boreal winter (November-February).

variability, 30-60 days and 10-20 days are observed during the boreal summer monsoon period (Figure 1.2). Both these dominant modes contribute significantly to the total intraseasonal variability of the ASM (Goswami, 2005). The 30-60 day mode explains 2/3 of the total intraseasonal variability, whereas the 10-20 day mode explains only 1/4 of the total intraseasonal variability (Annamalai and Slingo, 2001). The high frequency mode with a period between 10 and 20 day propagate westward (Chatterjee and Goswami, 2004; Chen and Chen, 1993; Krishnamurti and Bhalme, 1976) and the low frequency mode with a period between 30 and 60 day propagate northeastward from equator to Indian land mass (Goswami, 2005; Sikka and Gadgil, 1980; Yasunari, 1979). The active and break phases of the ASM are closely connected to these fluctuations in the tropical atmosphere (Gadgil and Asha, 1992; Goswami and Shukla, 1984; Lawrence and Webster, 2002; Yasunari, 1980) and thus has received wide attention during the earlier decades. A prolonged break of monsoon lead to large-scale droughts (Joseph et al., 2009) and it is shown that the prolonged break during the growth periods can have severe impact on the crop development and, hence yields (Lal et al., 1999). Therefore, the information on how the rainfall is distributed within the season is more important for the agricultural community. Besides the low frequency fluctuations, a high frequency synoptic scale system with time scales of 5-7 days (lows and depressions) is also a common feature of the summer monsoon rainfall over the south Asia (Figure 1.2).

The strength of the Intraseasonal Oscillation (ISO) during the boreal summer season is typically weak and it is more complex in structure compared to the boreal winter ISO
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Figure 1.2: Composite of the power spectra of GPCP gridded daily rainfall anomalies for 11 (1997-2007) boreal summer seasons (June-September) averaged over the region 10°N-25°N, 80°E-100°E. The red line indicate the Markov Red Noise spectrum and the lower and upper dotted lines indicate the lower (5% confidence level) and upper confidence bound (90% confidence level) for Markov respectively.

(Madden, 1986), which is also known as Madden Julian Oscillation (MJO). While the MJO propagate eastward along the global equator (Madden and Julian, 1971, 1972), the boreal summer ISO (MISO) shows a more complex propagating behavior, including its northeastward propagation over the ASM domain and the westward propagation over the the western north Pacific (Annamalai and Slingo, 2001; Wang and Xie, 1997). The dominant mode of the MISO with a 30-60 day period has a large spatial scale and shows a quadrapole structure (Annamalai and Slingo, 2001). That means, during the active phase of the MISO, the convection strengthens over the Indian continent and it extends towards the equatorial western Pacific through the Maritime continent. Meanwhile the suppressed convection is evident over the equatorial Indian Ocean and the northwestern Pacific and the opposite happens during the break phase.

The westward propagating 10-20 day mode (quasi-biweekly mode) has a smaller spatial scale compared to the northeastward propagating 30-60 day mode (Goswami, 2005). During the boreal summer, this mode is most prominent over the western Pacific warm pool.
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and the Indian Ocean region. Krishnamurti and Bhalme (1976) proposed a cloud-radiation-convection feedback mechanism to explain this high frequency mode. According to them, an enhanced surface temperature due to the radiation makes the atmosphere unstable and leading to the generation of moist convection. Once the convection established, the clouds inhibit the incoming solar radiation and the resultant surface cooling suppress the convection, increase the incoming radiation, and makes the atmosphere again unstable. However, they could not establish the scale selection of this mode quantitatively. Later, Chen and Chen (1993) investigated the structure and propagation characteristics of this mode and found that this mode has a zonal wavelength of about 6000 km and the westward propagating phase speed around 4-5 m/s. However, they also failed to explain the scale selection of this mode. According to Goswami and Mathew (1994), the 10-20 day quasi-biweekly mode is an unstable mode in the tropical atmosphere forced by the wind-evaporation feedback mechanism in the presence of background westerlies. However, this unstable mode in the tropical atmosphere does not capture the observed zonal wavelength (Goswami, 2005). Chatterjee and Goswami (2004) proposed a mechanism to explain the scale selection of the quasi-biweekly mode. Using a two layer atmospheric model with a steady boundary layer, they showed that convective feedback in the presence of frictional boundary layer force $n=1$ Rossby mode and its space and time scale is identical to the observed quasi-biweekly mode (10-20 day mode).

1.2 Relationship between MISO and Monsoon Variability

Reliable prediction of seasonal mean Indian summer monsoon rainfall is of critical importance because of millions of people across large parts of India depends upon the the rain-fed agriculture for sustenance. Earlier studies have shown that the dominant mode of MISO has a large spatial structure similar to that of the seasonal mean and its interannual variability (Goswami and Ajaya Mohan, 2001; Sperber et al., 2000) and therefore, the MISOs have a crucial role in influencing the seasonal mean and its predictability (Gadgil, 2003; Goswami and Ajaya Mohan, 2001; Sperber et al., 2000). A significant change in the character of the MISO would therefore, result in a change in the seasonal mean and its predictability. Some studies have argued that the MISOs do not contribute significantly to the seasonal monsoon
strength (Krishnamurthy and Shukla, 2007; Singh et al., 1992). In contrast, to these studies, Lawrence and Webster (2001) showed an inverse relationship between the MISO and the seasonal monsoon strength. Clearly, more efforts are needed to understand the differences in these studies.

1.3 Large-scale dynamics, and northward propagation of MISO

Several studies have found a link between the intraseasonal variations in the convection and the large-scale dynamics (Goswami and Ajaya Mohan, 2001; Goswami and Shukla, 1984; Sperber et al., 2000). It is found that the dominant MISOs with 30-60 day periodicity have been found to arise from the interaction between the organized moist convection and large-scale dynamics (Goswami and Shukla, 1984). They found that an initial large-scale convective activity in the unstable atmosphere will increase the tropospheric heat source and the static stability of the atmosphere and thereby suppress the convection itself. Meanwhile, the radiation and weakening of the dynamic process will bring the atmosphere to a new unstable state and the whole process will take around 30-60 day time. A strong coupling between the intra-seasonal variation of rainfall and circulation has also been reported (Goswami and Ajaya Mohan, 2001; Sperber et al., 2000). Wang and Xie (1997) showed the importance of large-scale mean monsoon flows and moisture distribution in the structure, development, and maintenance of MISO.

The propagation characteristics of the MISO are more complex than the propagation characteristics of winter MJO. One of the most striking features of the 30-60 day mode (MISO) is its northward (poleward) propagation over the Indian monsoon region from the equator to about 25°N (Murakami et al., 1984; Sikka and Gadgil, 1980; Webster et al., 1998; Yasunari, 1979, 1980). The phase speed of the poleward propagation is about 1° degree latitude per day (Goswami, 2005). It also exhibits a northwestward propagating mode in the western Pacific region. This northward and northwestward propagation of the MISO coexist with an eastward propagating convection along the equator that is weaker in boreal
summer than in boreal winter (Hendon and Salby, 1994; Julian and Madden, 1981). These three propagating modes interact with one another and make the MISO more complex. Besides the northward propagation, the MISO also shows the southward propagation from the equator to about $10^\circ S$ (Goswami, 2005). The MISO starts in the western equatorial Indian Ocean, propagates eastward towards the eastern equatorial Indian Ocean, and amplifies over the central/eastern equatorial Indian Ocean. From there it split into two branches, one branch propagates towards the northern latitude, and another branch propagates towards the southern latitude. Meanwhile a small fraction of the ISO convection moves eastward over the Maritime continent (Ajayamohan et al., 2011; Ajayamohan and Goswami, 2007; Annamalai and Slingo, 2001; Lau and Chan, 1986; Wang and Rui, 1990). Although, the southward movement is not strong, the pronounced northward propagation is seen in the ASM region.

The similarity of the temporal scale of the MISO and winter MJO has led some authors (Lau and Chan, 1986; Yasunari, 1979) to suggest that the northward propagating convective mode over the ASM domain is associated with the eastward propagating convection band along the equator. Previous studies (Jones et al., 2004; Lawrence and Webster, 2001; Wang and Rui, 1990) found some independent northward propagating ISO event over the ASM region. Wang and Rui (1990) have shown that almost half of the northward propagating convection bands over the Indian monsoon region are independent ISO events. However, Lawrence and Webster (2001) found that about 78% of the northward propagating ISO events during boreal summer are associated with eastward propagating convective band along the equator.

### 1.4 Theories for northward propagation

As discussed in the above section, an important characteristic of the MISO is its northward propagation over the ASM region. Several different theories have been proposed to identify the processes responsible for the northward propagation of the MISO (Annamalai and Slingo, 2001; Gadgil and Srinivasan, 1990; Goswami and Shukla, 1984; Jiang et al., 2004; Kemball-Cook and Wang, 2001; Kemball-Cook et al., 2002; Krishnan and Venkatesan, 1997; Lawrence and Webster, 2002; Wang and Xie, 1997; Webster, 1983). Using an idealized two-dimensional coupled ocean-atmospheric model, Webster (1983) suggested that the meridional
Figure 1.3: Schematic diagram which describe the evolution of the northward propagating mode in the meridional plane. The thick vertical arrow represent the center of boundary layer moisture convergence and horizontal arrow represent the poleward propagation of the cloud band. The thin dotted (solid) lines represent the phase of the divergence at 925 hPa (relative vorticity at 850 hPa) with the positive phase above the base line and negative phase below the base line. The sun like symbol represent the clear sky condition. The closed arrows represent the anomalous Hadley circulation (Courtesy: Goswami, 2005)

gradient of land surface heat flux destabilizes the atmosphere ahead of the convection and aids the northward propagation of the convection. However, this study failed to explain propagation in the northern Indian Ocean and failed to simulate the observed periodicity. Goswami and Shukla (1984) showed that the convection-thermal relaxation feedback might be responsible for a standing oscillation between the equator and the monsoon trough. According to their theory, an initial convection increases the tropospheric heat source, as a result stabilizes the atmosphere and weakens the convection, and the resultant increase in radiation and weakening of the Hadley cell destabilize the atmosphere again. However, this study did not explore a clear physical mechanism responsible for the poleward propagation of the MISO. Using a zonally symmetric model, Gadgil and Srinivasan (1990) reported that the northward gradient
of convective instability is responsible for the northward propagation of the MISO. However, the zonally symmetric dynamics fails to explain the observed zonal (eastward/westward) propagation associated with the MISO. It would appear that wave dynamics are crucial to explain fully the MISO propagation. Krishnan and Venkatesan (1997) proposed a mobile wave-CISK mechanism to explain the northward propagation of MISO. Several observational and modelling studies showed that Rossby wave emanation from the eastward propagating equatorial ISO convection is instrumental for the poleward propagation of MISO (Annamalai and Slingo, 2001; Kemball-Cook and Wang, 2001; Kemball-Cook et al., 2002; Lawrence and Webster, 2002; Wang and Xie, 1997). Using the reanalysis data, Kemball-Cook and Wang (2001) showed the importance of air-sea interaction as a cause of northward propagation of the MISO. Later, Hsu et al. (2004) suggested that the deep moisture convergence to the north of the convection contributes to the northward propagation of the MISO.

Using a two and half layer model, Jiang et al. (2004) introduced a conceptual picture for the northward propagation of the MISO. They proposed that the 30-60 day northward propagating mode as an unstable mode of summer mean flow and introduced two physical mechanisms for the northward propagation of this unstable mode, a vertical shear mechanism and a moisture convection feedback mechanism. The vertical shear mechanism explains the northward propagation away from the equator and the moisture-convection feedback mechanism explains the propagation close to the equator. It is shown that the strong easterly vertical wind shear over Asian monsoon region couples the baroclinic and barotropic modes in the free atmosphere and creates the barotropic vorticity to the north of maximum convection and as a result, a divergence in the free atmosphere is established to the north of the maximum convection. This leads the northward shift of boundary layer moisture convergence and thus the ISO convection and facilitates the northward propagation of the MISO away from the equator (Jiang et al., 2004). The moisture advection by the mean flow and the mean boundary layer humidity during summer season also makes the convergence to be maximized to the north of convection center (Jiang et al., 2004). However, close to the equator, the northward propagation of the MISO is mainly controlled by the the low-level moisture gradient in the north-south direction (Jiang et al., 2004). Therefore, both easterly wind shear of zonal wind and north-south
moisture gradient contribute to the northward propagation of MISO. Recently, Kang et al. (2010) showed the importance of convective momentum transport by cumulus convection in the northward propagation of the MISO. They found that the large-scale momentum mixing by the cumulus convection in the presence of mean vertical shear produces convergence to the north of the convection and facilitate the northward propagation.

Although a single mechanism has not emerged to explain fully the northward propagation of the MISO, all these aforementioned studies identified processes which may play important roles in the northward propagation characteristics of the MISO and may not be mutually exclusive. Based on the previous modelling and theoretical studies as discussed above, Goswami (2005) described in detail the evolution of the northward propagating mode by using a schematic diagram as shown in Figure 1.3.

1.5 Role of the Indian Ocean in MISO

Importance of the Indian Ocean Sea Surface Temperatures (SSTs) for the MISO characteristics has been explored using observations and General Circulation Models (GCMs) (Achuthavarier and Krishnamurthy, 2011; Fu et al., 2003; Klingaman et al., 2008; Krishnamurthy and Kirtman, 2009; Sengupta et al., 2001; Vecchi and Harrison, 2002). All these studies pointed out that the MISO over the ASM region is strongly coupled to the underlying SST in the Indian Ocean region. Using the TMI SST, Sengupta et al. (2001) showed an intraseasonal variability in the SST. They found that the large spatial structure of the intraseasonal variability of the SST is similar to that of the atmospheric counterparts and it shows the coherent northward propagation from the equatorial Indian Ocean.

A consistent relationship between convection, SST, and surface heat fluxes in the Indian Ocean have been established at ISO time scales during the boreal summer (Fu et al., 2003; Sengupta et al., 2001). During the northward propagation of the MISO, warm (cold) SSTs lead (lag) the maximum convection by about 10 days in the Indian ocean. When convection reaches its maximum (wet phase), the incoming solar radiation decreases, followed by an increase in the latent heat release due to enhanced evaporation associated with enhanced westerly wind. This leads to cold SST anomalies about 10 days after peak convection. Similarly,
during the suppressed phase of the convection, the incoming solar radiation increases followed by a decrease in the latent heat release associated with decreased westerly wind and finally leads to warm SST anomalies about 10 days before the maximum convection. Although, the basic properties of MISO emerge from the internal atmospheric variability, the air-sea coupling modifies its amplitude and meridional propagation speed (Ajayamohan et al., 2008; Fu and Wang, 2004; Fu et al., 2003; Goswami, 2005; Rajendran and Kitoh, 2006; Waliser et al., 2003).

1.6 Unique warming trend in the Indian Ocean

The Indian Ocean is continuously warming for the last three decades, displaying a strong linear trend in the SST (Ajayamohan and Rao, 2008; Rao et al., 2010, 2012), and the warming trend is most pronounced in the tropical Indian Ocean compared to the other tropical ocean basin. It is found that the ongoing warming of the tropical Indian Ocean in the recent decades has strengthened the convection over the west central equatorial Indian Ocean and led to anomalous easterlies along the equator (Rao et al., 2012), consequently favoring frequent positive Indian Ocean Dipole (IOD) events. In another study, Rao et al. (2010) showed that the combined influence of linear warming trend in the tropical Indian Ocean and the warming associated with the positive IOD created a strong anomalous warming in the Southern Tropical Indian Ocean (STIO) region in 2008 summer monsoon period, and caused the abnormal drought in the central Indian region.

The ongoing Indian Ocean warming will significantly enhance the moisture content in the atmosphere and thereby the convection. It also may enhance the air-sea coupling and the large-scale atmospheric circulation. Therefore, a significant change in the MISO is expected in the recent warming period. Hence, the study on the modulation of the MISO in the recent warming period is highly significant.
1.7 The Onset, withdrawal, and length of the rainy season of the Indian summer monsoon

One of the notable annual features of the south Asian summer monsoon system is the remarkable regularity in the sudden onset and the gradual withdrawal of rainfall over the Indian subcontinent indicating the beginning and the end of the rainy season. The south Asian summer (June-September) monsoon precipitation shows no long-term trend over the last several decades (Goswami et al., 2006a) despite the rise in global mean surface temperature. However, few recent studies highlight the importance of the timing and the variability of the onset and withdrawal phase of the monsoon as it is intrinsically linked with the length of the summer monsoon season. The seasonal mean rainfall can be influenced by changes in the length of the rainy season (LRS). The phase of MISO affects the timing of the onset, withdrawal and, hence the LRS of the ASM (Murakami et al., 1986). It is shown that the year-to-year variations of the onset and withdrawal of the ASM is primarily determined by the phase changes of the low frequency ISO (Murakami et al., 1986). Almost in all years, the onset of the Indian summer monsoon is triggered by the northward propagation of the wet phase of the MISO with considerable interannual variations (Ajayamohan and Rao, 2008; Goswami, 2005). Hence, the study on the modulation of the onset, withdrawal, and the associated teleconnection patterns assume significance in the recent warming environment.

1.7.1 The onset

The onset of the Indian summer monsoon occurs suddenly, and it has been considered as the beginning of the rainy season over the Indian subcontinent. Large-scale changes in the circulation features occur in association with the onset of the Indian summer monsoon (Ananthakrishnan and Soman, 1988; Joseph et al., 1994, 2006). The low-level southwesterly winds in the Arabian Sea becomes strong and the deep convection oriented in east-west direction passing through the southern tip of Indian during the onset phase of the Indian summer monsoon (Joseph et al., 1994). During the onset of the Indian summer monsoon, a rapid increase in the precipitation rate, vertically integrated humidity, kinetic energy in the low-level
winds, exist in the Indian summer monsoon region (Krishnamurti, 1985). The Tibetan plateau as an elevated heat source plays a crucial role in triggering the monsoon onset (Yanai et al., 1992).

1.7.2 The withdrawal

The withdrawal of the Indian summer monsoon is characterized by the southward movement of the monsoon trough, the displacement of the moist marine air by a dry continental air mass and the development of an anticyclonic flow over north and central India. The upper level anticyclone at 200mb centered over northern India in JJAS shifts to Southeast Asia. It is also characterized by the reduction of rainfall over India, the decay of anticyclonic circulation seen over the Tibetan Plateau during the monsoon season, a weakening and the disappearance of the easterly jet stream from south of the Himalayas to be replaced by the reappearance of the subtropical westerly jet stream (Dey, 1977). The withdrawal phase faithfully begins over northern India in September with a gradual equatorward movement and a deceleration of the low-level westerly flow.

1.7.3 The length of the rainy season

The LRS has crucial role in determining the seasonal mean rainfall of the Indian summer monsoon, which is the difference between the withdrawal and onset dates (Goswami and Xavier, 2005). Therefore, a change in the timing of the withdrawal or the onset dates may also influence the LRS.

1.8 Different criteria to define the onset and withdrawal

Several criteria have been formalized to define the onset and withdrawal of the Indian summer monsoon (India Meteorological Department (IMD., http://www.imd.gov.in); Fasullo and Webster (2003); Goswami and Xavier (2005); Syroka and Toumi (2002, 2004); Wang and Lin (2002)). Based on the increase in the rainfall, the strength of the westerlies in the northern Indian Ocean and the reduction in the OLR field, the IMD defines the onset of
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the Indian summer monsoon, which marks the beginning of the boreal summer rainy season over the Indian subcontinent. The conventional definition of the Indian monsoon withdrawal date defined by the IMD is based on a reduction in rainfall totals and the establishment of lower tropospheric anticyclonic circulation over certain regional subdivisions. Dynamically, a complete reversal of lower tropospheric flow patterns is used to define the withdrawal date. Syroka and Toumi (2002, 2004) defined a low-level (850 hPa) circulation index as the difference between a southern region (5\degree N-15\degree N; 50\degree E-80\degree E) and a northern region (20\degree N-30\degree N; 60\degree E-90\degree E) to represent the withdrawal phase of monsoon. The withdrawal of the monsoon is strongly correlated with El Niño Southern Oscillation (ENSO) when the above mentioned circulation index is used (Syroka and Toumi, 2004). Wang and Lin (2002) defined the onset and withdrawal of the monsoon based on the relative climatological pentad mean rainfall, which is the difference between the climatological pentad mean rainfall for May-September and that for January. They defined the withdrawal of the monsoon as the transitional pentad in which the relative climatological pentad mean rainfall falls below 5 mm day\(^{-1}\). Based on the hydrological cycle, Fasullo and Webster (2003) used the vertically integrated moisture transport as a proxy for defining the monsoon onset and withdrawal dates. Their index has a significant relation with the monsoon onset and ENSO, but the relationship with the monsoon withdrawal and ENSO is not significant. Later, Goswami and Xavier (2005) and Xavier et al. (2007) used the meridional gradient of the tropospheric temperature averaged between 200 hPa and 700 hPa as a proxy to define the onset and withdrawal dates. The onset, withdrawal, and the length of the Indian summer monsoon calculated using such a thermodynamic index exhibit significant relationship with ENSO (Goswami and Xavier, 2005).

1.9 Change in the background SSTs of the world oceans after 1976/1977

It should be noted that the tropical Pacific underwent a major climate shift around 1976/1977 (Graham, 1994). The 1976/1977 shift in both the eastern and central North Pacific Ocean was caused by unique atmospheric anomalies, which acted several months before
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the 1976/1977 winters (Miller et al., 1994). It is hypothesized that the Pacific shift is also associated with a tropical Atlantic shift (Murtugudde et al., 2001).

Previous studies have reported an increase in SST and convective activity over the eastern and central Pacific since 1976/1977 (Kachi and Nitta, 1997; Nitta and Yamada, 1989; Wang, 1995) and at the same time a cooling in the extra-tropical North Pacific and South Pacific is reported to have occurred (Wang, 1995). Due to the changes in the Pacific background state since 1976/1977, the characteristic of ENSO evolution is hypothesized to be different across the 1976/1977 climate shift (Wang, 1995). The SST anomalies associated with the PRE76 ENSOs appear first in the eastern Pacific and extend to the central Pacific and conversely, during POST76 ENSOs, the SST anomalies evolve first in the central Pacific and spread to the east (Wang, 1995). The period of ENSO is also shown to increase during the POST76 period (An and Wang, 2000). Terray and Dominiak (2005) showed a remarkable change in the lead-lag relationship between Indian Ocean SSTs and ENSO evolution after the 1976/1977 climate shifts. They pointed out that, the southern Indian Ocean SSTs during late boreal winter are a highly significant precursor to ENSO evolution after 1976/1977 while a surface warming is also noted over the Indian Ocean since 1976/1977 (Aoki et al., 2003; Nitta and Yamada, 1989).

Before the 1976/1977 climate shift, SST anomalies in the tropical Indian Ocean consisted of a basin wide warming during most of the developing phases of ENSO whereas after this shift, SST anomalies have displayed an east-west gradient (Annamalai et al., 2005). They found that the formation (absence) of the South China Sea anticyclone during PRE76 (POST76) is the prime reason for the difference in Indian Ocean SST anomalies. The changes in the convective activities over the tropical central, the eastern Pacific and the Indian Ocean and the associated circulation patterns after the 1976 climate shift (Nitta and Yamada, 1989; Wang, 1995) can influence the timing of the onset, and withdrawal of the Indian summer monsoon and it is discussed in Chapter 4.

1.10 Outline of the thesis

The goal of this thesis is to examine in detail the modulation of the MISO and the characteristics of the Indian summer monsoon features, such as the onset, withdrawal, and
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the LRS in the recent warming period. To date, no detailed study has been carried out to understand the modulation of MISO in the recent warming period. The detailed objectives are to:

- investigate the modulation of the MISO characteristics such as amplitude, propagation and space-time structure in the recent decade and try to understand the factors responsible for the MISO change in the recent period,

- investigate the mechanism for the MISO change using the Atmospheric General Circulation Model (AGCM) sensitivity experiments,

- investigate in detail the modulation of the Indian summer monsoon onset, withdrawal, and the LRS in the recent decades.

- investigate the simulation of MISO in the latest Coupled Model Intercomparison Project phase5 (CMIP5) coupled GCMs and to understand how the MISO has changed under the global warming scenario,

- understand the future projections of the onset, withdrawal and the LRS using the CMIP5 models,

The thesis is divided into six chapters. The Chapter 2 describes the datasets, the AGCM used, and the statistical and other diagnostic methods explored in this thesis. It also describes the limitations of Outgoing Longwave Radiation (OLR) data and issues of reanalysis data in the climate variability study. The Chapter 3 discusses the change in the characteristics of the MISO in the recent decade (2001-2010) compared to a former decade (1979-1988). It is found that the MISO variance over the Indian summer monsoon has increased in the recent warming decade compared to a former decade. Using AGCM sensitivity experiments, this Chapter also explain the mechanism for the modulation of MISO in the context of the Indian Ocean warming. Model experiments suggest that increased Indian Ocean SST and the associated changes in the air-sea interaction, the mean moisture convergence, and the large-scale circulations are responsible for the modulation of the MISO.
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It is shown that the year-to-year variability of the Indian summer monsoon onset and withdrawal is primarily determined by the phase changes of the MISO. A change in the phase of MISO during the early (late) monsoon season will make a change in the monsoon onset (withdrawal) dates. Therefore, it is interesting to look at how the monsoon onset, withdrawal, and the associated teleconnection have changed in the recent decades. The Chapter 4 discusses the modulation of the monsoon onset dates, the withdrawal dates, and the LRS in the recent decades.

The Chapter 5 presents the simulation of MISO in the latest CMIP5 coupled models and its modulations under global warming scenarios. By analyzing the multiple aspects of MISO, it is found that the model MPI-ESM-LR is the best model to represent the reasonable MISO characteristics. Therefore, this model is used to assess the future change in the MISO characteristics under the global warming scenario. The result of this chapter is consistent with the observational finding presented in Chapter 3. Using the CMIP5 models, this chapter also discusses the future projections of the onset, withdrawal and LRS in the global warming scenario. The final Chapter offers a summary of the thesis and the future works to be carried out.