Chapter 6

Conclusions and Future Scope

6.1 Conclusions

The MISO and its modulations under the warming world is the focus of this thesis. The change in the characteristics of the MISO in the recent decade and the mechanism responsible for this change is discussed. The simulation of the MISO in the latest CMIP5 models and its modulations under the global warming scenario is also one of the focuses of this study. The phases of MISO affect the timing of the onset and the withdrawal of the Indian summer monsoon. Therefore, a change in the onset and withdrawal of the Indian summer monsoon and its possible tele-connections are also discussed in the context of the recent warming. The main results and the scope of the future research is summarized below.

6.1.1 Modulation of MISOs in the recent decade

The Indian Ocean SST during the boreal summer has shown a significant warming of 0.3°C in the recent decade (2001-2010) compared to a former decade (1979-1988) and it is most pronounced in the central tropical Indian Ocean. By using the reanalysis and satellite-derived datasets, the Chapter 3 investigated how the MISO over the ASM region has been modulated by the recent warming in the Indian Ocean. It is found that the MISO variance has increased over the ASM region in the recent period compared with the earlier decade. It is also noted that the speed of northward propagation of the MISO has slowed down in 2001-
2010, resembling more of a standing oscillation in the equatorial belt. The decreased easterly zonal wind shear in the ASM region and the reduced equatorial moisture gradient over the Indian Ocean might be responsible for the observed changes in the propagation characteristics of the MISO in the recent decade. The mechanism for the modulation of MISO is tested by conducting several model sensitivity experiments with an AGCM. The model experiments suggest that due to the pronounced warming over the tropical Indian Ocean, an anomalous moisture convergence occurs over the oceanic region and an anomalous divergence occur over the Indian land mass. As a result, the upper tropospheric temperature gradient reduces and thereby weakens the monsoon wind and finally reduces the vertical wind shear. The decreased mean monsoon wind also weakens the moisture gradient across the equator. Both these factors contribute to the decreasing phase speed of the northward propagating MISO. The increased SST over the Indian ocean and the associated changes in the air-sea interaction also increases the moisture content of the atmosphere and thereby enhances the amplitude of the MISO. This is significant in the context of the rapid and monotonic warming that is unique to the Indian Ocean in recent decades and the consequences of such changes in MISO must be understood fully since they determine the seasonal amount of rainfall over the Indian subcontinent.

6.1.2 Modulation of monsoon onset and withdrawal in recent decades

A clear shift in the withdrawal dates of the Indian Summer Monsoon is observed in the long-term time series. Prior (posterior) to the 1976/1977 climate shift most of the withdrawal dates are associated with a late (an early) withdrawal. As a result, the LRS over the Indian land mass has also undergone similar changes (i.e., longer (shorter) LRS prior (posterior) to the climate shift). In this study, probable reasons for this significant shift in the withdrawal dates and the LRS are investigated using reanalysis/observed datasets and also with the help of an AGCM. Reanalysis/observational datasets indicate that prior to the climate shift the SST anomalies in the eastern equatorial Pacific Ocean and the Arabian Sea exerted a strong influence on both the withdrawal and the LRS. After the climate shift, the influence of the eastern equatorial Pacific Ocean SST has decreased and surprisingly, the influence of the Arabian Sea SST is almost non-existent. On the other hand, the influence of the southeastern equatorial
Indian Ocean has increased significantly. It is observed that the upper tropospheric temperature gradient over the dominant monsoon region has decreased and the relative influence of the Indian Ocean SST variability on the withdrawal of the Indian Summer Monsoon has increased in the post-climate shift period. Sensitivity experiments with the contrasting SST patterns on withdrawal dates and the LRS in the pre- and post-climate shift scenarios, confirm the observational evidences presented above.

### 6.1.3 MISOs in CMIP5 coupled GCMs and its modulations under global warming scenario

The simulation of the MISO has been analyzed in the historical run of the 32 models, which participated in the CMIP5, and it is shown that the current state-of-the-art GCMs still have difficulties to properly simulate the MISO. Compared to CMIP3 models, more CMIP5 models simulated the northward propagation of MISO. This is achieved by improving the eastward propagation of convection beyond 100°E and thereby the tilted rain band in CMIP5 models. The majority of the models could not simulate the spatial pattern of MISO variance over the ASM region and many of them failed to capture all the three peak centers of MISO variance over the Indian summer monsoon region. Many of the models underestimated the MISO variance over the equatorial Indian Ocean, and it is associated with the seasonal mean dry biases over this region. A reasonable representation of the intraseasonal SST and its coupling to the convection over the equatorial Indian Ocean and an equatorial eastward propagation of convective anomalies beyond 100°E assure realistic simulation of MISO over the ASM domain. It is found that the models MIROC5, IPSL-CM5A-LR, GFDL-CM3, CMCC-CM, and MPI-ESM-LR are able to represent reasonable MISO characteristics and can be used to unravel the MISO characteristics. However, considering the multiple aspects of the MISO, it is found that the model MPI-ESM-LR is the best to represent the MISO.

The MPI-ESM-LR has been used to study the modulation of the MISO characteristics under the future global warming scenario. It is found that the MISO variance has increased over the Indian summer monsoon domain and the northward propagating mode has strengthened under the future warming scenario. The lag latitude diagram showed that the
phase speed of the northward propagation of the MISO has slowed down under the warming scenario (RCP4.5). The weakening of easterly wind shear over the ASM domain is responsible for the slow propagation speed. The projected changes in the MISO characteristics under the global warming scenario is consistent to the observational findings shown in Chapter 3. The projected increase in the SST over the Indian summer monsoon domain and the associated changes in the air-sea interaction, moisture convergence, and the large-scale circulation are responsible for the changes in the MISO characteristics.

Using the CMIP5 models, this Chapter also discussed how the onset, withdrawal, and the LRS of the Indian summer monsoon are changed under the global warming scenario. The majority of the models showed an early withdrawal and delayed onset dates under the global warming scenario. In response to these changes in the monsoon withdrawal and onset dates, the length of the rainy season also shortened under the global warming scenario. It is found that the pronounced increase in the SST over the Indian Ocean and the associated changes in the convection due to the global warming enhanced the TT over the Oceanic region (south of 10°N) and as a result, weakened the TT gradient and thereby changed the timing of onset and withdrawal dates. The role of the Indian Ocean SST warming in modulating the TT is confirmed by using couple of AGCM experiments.

### 6.2 Future Scope

Clearly, the tropical Indian Ocean is the location for the genesis of Madden Julian Oscillations (MJOs) and its interactions with MISO have been a focus on numerous studies. The focus of this thesis is solely on the impact of warming on MISO even though they may be intricately interconnected with MJO. Hence, a separate study can be carried out to explore the MJO-MISO response to warming. While discussing the simulation of MISOs in the CMIP5 models, it is noted that the use of dynamic vegetation in the model improves the amplitude of the MISO when compared to the model with prescribed vegetation. Even though it is tempting to conclude that the use of dynamical vegetation map in the model is important to simulate the MISO characteristics reasonably; it is, however, not clear how and why it modulates the amplitude of the MISO. The changes in the surface temperature and moisture availability by the dynamic
vegetation may affect the amplitude of MISO, this requires further investigation. In Chapter 4 we have found that monsoon onset is correlated with Pacific SSTs and Arabian Sea SSTs, which became stronger in recent decades. Is it suggesting that the monsoon monsoon onset is more predictable in recent decades? Clearly, more efforts are needed to understand the underlying mechanism behind this association.