Abstract

The relatively weak synoptic-scale tropical storms, known as low-pressure systems (LPSs), contribute as much as 60% of the summer monsoon precipitation over the hugely populated central India. Although LPSs form over all monsoonal regions, they are more prominent over the Indian Summer Monsoon (ISM) domain with 12±2 sys- tems every June – September period. These rain-bearing systems originating in the Bay of Bengal (BoB) help the South Asian region to meet their irrigation needs, and also, these storms have the potential to cause floods in the Indo-Gangetic regions. De- spite its importance in the hydrological cycle of South Asia, the genesis mechanisms of LPSs are not fully known, and these vortices are not properly represented in the cur- rent generation climate models either. Therefore, a better understanding of the genesis mechanisms of LPSs helps in representing the LPS-related dynamics in coupled mod- els well, which further minimises the uncertainty in ISM rainfall simulated by these models. The genesis of LPSs is broadly classified into two mechanisms: in situ (LPS_i) and downstream amplification (LPS_d). About a third of total LPSs are formed by the downstream amplification of the westward propagating atmospheric disturbances from the Pacific, and the remaining due to the in situ mechanisms over the BoB.

In chapter 3, Initially, a simple objective-based automated tracking algorithm is de- veloped to classify LPSs into “downstream" and “in situ" LPS based on the propagation of anomaly of relative vorticity at 850 hPa (ζ_{850}) from the West North Pacific (WNP). This algorithm is applied to the models from the fifth and sixth phases of the coupled model intercomparison project (CMIP5/6), and bulk statistics are presented. Besides the two broader genesis mechanisms (downstream and in situ), a third category named “uncertain cases" is also defined, where both the signals from BoB (for in situ) and WNP (for LPS_d) are present at the same time. Irrespective of their skill in simulat- ing the LPSs, all models have a predominantly in situ genesis mechanism, in line with the observations, with an average of 56% systems falling under this category. Also, in CMIP5, the average downstream genesis in the models is 32%, closer to the ob- served 30%. Whereas the ensemble mean of CMIP6 shows 29% LPS_d genesis, which is comparable with the observations. Although the bulk statistics of the in situ and LPS_d genesis across the models in boreal summer is comparable to that of observations, sub- stantial inter-model variability is observed in both CMIP 5 and 6. Also, it is observed that there are significant differences in the temporal distribution of downstream LPS genesis in models. Although the models realistically capture the fraction of LPS_d for the whole monsoon season, they tend to simulate a higher number of genesis in the early phase of monsoon as opposed to the observed peak in August and September, which is linked to a stronger Rossby wave activity in the models in June.

The relationship between LPS_d and WNP tropical cyclones (TCs) was investigated in the 1970s and 1980s, but a strong causality has not been established, chapter 4 of the thesis discusses the establishment of causality. In this study, TCs over WNP are grouped into six different

clusters on the basis of their genesis location as well as the length and recurvature of the trajectories. This clustering is done using a polynomial mixture regression model. It is observed that the LPS_d genesis is associated with the TCs over WNP. The top four clusters of TCs over WNP, which made landfall over the South China Sea and adjoining land regions and have the least angle of recurvature, contribute to about 83% of the downstream LPS genesis. The diabatic heating from the TCs over the WNP is a major source for the genesis of Rossby waves. Therefore, causality has been established between the fluctuations of the mean sea level pressure (MSLP) over the BoB prior to the initiation of LPSs and the Rossby wave activity over WNP through a transfer entropy analysis. To examine the previously observed link between WNP TCs and LPSs further, sensitivity experiments have been performed using an atmospheric general circulation model (AGCM) by imposing sea surface temper- ature (SST) warming over two patches over the WNP (one patch is over the genesis locations of TCs in cluster B alone and another patch is over the genesis locations of TCs in cluster A to D) so that the model simulates TCs in desired clusters. In each experiment, the model simulated TCs in clusters, with the size of the clusters proportional to the area of SST warming patches. The LPS genesis frequency over the BoB responded strongly to the SST warming imposed over the WNP, with more sensitivity to the landfalling TC cluster in the South China Sea. It is observed with the simulation of the increased number of TCs that the diabatic heating is enhanced and results in generating/amplifying westward propagating Rossby waves. These sensitivity experiments support the observed hypothesis that the Rossby wave propagation from the WNP TCs triggers the downstream LPSs over BoB.

The ISM rainfall undergoes a cycle of enhancement and weakening, known as active and break spells. This cycle is associated with the large-scale Monsoon Intra-seasonal Oscillation (MISO), which is the dominant mode of sub-seasonal monsoon variabil- ity. The LPSs are observed to cluster in the active phase of the MISO. However, the LPS-MISO interaction in the climate models has not yet been investigated. In Chapter 5 of the thesis, the relationship between MISO and LPSs is examined in the historical simulations of 20 coupled models from the CMIP6. It is observed that, as in the

observations, the LPSs tend to cluster during the active phase of ISM in the model simulations. The observations show that the frequency of LPS genesis during the active phase of ISM is 2.6 times more than that during the break phase. In the model simulations, the LPS genesis distribution is also skewed towards the positive phase of MISO, albeit with considerable inter-model variability. Irrespective of the genesis types, the LPSs are clustered in the active phase in observations and model simulations. A strong negative meridional shear of zonal wind at 850 hPa ($\frac{dU850}{d\phi}$)is observed over the head BoB, the core LPS genesis region, in both observations and CMIP6 models during the active phase of ISM. The vertical shear simulated by the models differs from the ob- servations. The vertical shear simulated by the CMIP6 models does not vary much between active and break phases. The analyses suggest that part of the uncertainty in simulating the LPSs might be linked to the skill of models in simulating the ⇣850 pattern over the WNP, which is a key factor in triggering the downstream genesis of LPS.

Finally, considering the importance of LPS in causing floods, the prediction of these storms is important irrespective of their genesis type. Understanding both downstream and in situ LPS genesis mechanisms could lead to a substantial advancement in climate modeling in the long run. However, with the recent advancement in machine learning techniques, this could be easily achieved for immediate action. In Chapter 7 of the dissertation, a framework is developed using the LPS neural operator with a newly in- troduced Fourier layer (FConvLSTM) to predict the spatial structure of MSLP anomaly over the BoB at a resolution of 1x1. In the next step, we reconstructed the MSLP using the predicted anomaly and the climatology, which is then used to track the LPSs using a Lagrangian tracking algorithm. The median pattern correlation between the predicted and actual mean sea level pressure anomalies over the BoB is about 88%, 60%, and 50% for 24, 48, 72-hour forecasts. The proposed model improves the accuracy of predictions compared with the earlier ConvLSTM models. The pattern correlation between the observed and predicted synoptic activity index is 0.94, 0.9, and 0.87 for 1, 2, and 3-day ahead predictions, respectively. A well-trained model of FConvLSTM takes only $\sim$3.2 s to generate a one-day forecast on a one GPU node of Nvidia V100 in the PADUM supercomputer at IIT Delhi, which is computationally extremely cheap compared to the conventional numerical weather prediction models. The proposed LPS Neural Operator can advance the current operational weather forecasting substantially.