Chapter 4

Indian monsoon droughts and their linkage with convective activity over northwest Pacific

4.1 Introduction

In the recent past, the Indian subcontinent experienced a severe monsoon drought during 2002. Much of the rainfall decrease occurred in the core rainy month of July 2002, when the rainfall distribution over the country was nearly 50% below the long-term normal (Figure 4.1a) and was the lowest in the historical records in the last 130+ years [Gadgil et al., 2002, 2004; Sikka, 2003; Kalsi et al., 2004; Fasullo, 2005]. The spatial pattern of the rainfall anomaly during July 2002 (Figure 4.1b) shows wide-spread negative anomalies over the Indian subcontinent, the adjoining Arabian Sea, Bay of Bengal, and the Indonesian region. The anomalies of vertical velocity at 500 hPa show positive values over these regions indicative of large-scale subsidence (Figure 4.1c).
Inter-annual Variations of July Rainfall over India

Figure 4.1: (a) Year-to-year variation of July rainfall over India (All-India rainfall) for the period (1871-2002) expressed as percentage departure from its long-term mean (273 mm). Note that the rainfall departure for July 2002 was nearly -50%. The all Indian rainfall data are from http://www.tropmet.res.in. (b) Spatial distribution of July 2002 rainfall anomalies (mm day$^{-1}$) using gridded rainfall data from Climate Prediction Center Merged Analysis of Precipitation (CMAP). The contour interval is 2 units. (c) Anomaly of 500 hPa vertical velocity (hPa s$^{-1}$) from NCEP reanalysis for July 2002. The values are scaled by a factor of 1,000.
In contrast to the deficit rainfall over the subcontinent, the precipitation anomalies over the equatorial eastern Indian Ocean were significantly enhanced (Figure 4.1b) and strong upward motions occurred over the region (Figure 4.1c). Fasullo [2005] showed that the near-equatorial convective anomalies during 2002 influenced the Hadley and Walker circulation over the Indian Ocean and African region in a manner as to decrease the moisture transport over India. More recently, Krishnan et al., [2006] have reported a dynamical coupling between the Indian Ocean circulation and the southwest monsoon winds that can force drought conditions over the subcontinent.

The point, which is of concern to this study, is the belt of increased precipitation and anomalous ascending motion between 10°N - 20°N over northwest (NW) Pacific during July 2002, which extended eastward from the Philippines and Taiwan region towards the date line; along with a southeastward extension east of New Guinea (Figures 4.1b-c). It is important to point out that the rainfall intensification over NW Pacific was accompanied by enhanced typhoon activity over the region [Vinay Kumar and Krishnan, 2005]. Tracks of observed typhoons (Figure 4.2a) indicate that as many as seven tropical storms formed over the west-central Pacific during July 2002 and most of them moved northward causing heavy rainfall over the Philippines-Taiwan region. Similar instances of northward moving cyclonic disturbances over west Pacific associated with weak monsoon situations have been reported by earlier studies [e.g. Raman, 1955; Rajeevan, 1993; Vinay Kumar and Krishnan, 2005].

A majority of monsoon droughts in the past have occurred in conjunction with El Niño events in the Pacific [Sikka, 1999]; and the relationship between El Niño-Southern Oscillation (ENSO) and the Indian summer monsoon rainfall has
Figure 4.2: (a) Observed typhoon tracks over tropical Pacific for July 2002 from Joint Typhoon Warning Center, USA. (b) The observed SST (°C) in July 2002; contour interval is 2 units. (c) SST anomalies (°C) for July 2002; contour interval is 0.5 units.
been well-documented [e.g., Pant and Parthasarthy, 1981; Rasmusson and Carpenter, 1983; Shukla and Paolino, 1983 and others]. Ocean temperature observations during 2002 revealed the development of a moderate El Nino in the summer season, when anomalous westerly winds excited equatorial Kelvin waves that depressed the thermocline and elevated the sea-level as they propagated eastward [McPhaden, 2004]. The observed SST during July 2002 was warmer than 30°C in the equatorial central Pacific Ocean and the warm SST anomalies extended east of 150°E with a maximum of about 1.5°C around the dateline (Figures 4.2b-c). It can also be noticed in Figure 4.2c that the tropical central and eastern Indian Ocean was characterized by warm SST anomalies of about 1°C. Observations of sub-surface temperature in the Indian Ocean indicate that the anomalous warming of the equatorial eastern Indian Ocean during the summer of 2002 was maintained by anomalous equatorial westerlies which caused deepening of the oceanic mixed-layer and depression of thermocline in the region [Krishnan et al., 2006].

It is recognized that the ENSO-monsoon dynamical linkage involves anomalous changes in the equatorial Walker cell associated with the eastward displacement of convection to the central-eastern Pacific [Kanamitsu and Krishnamurti, 1978; Keshavamurty, 1982; Palmer et al., 1992; Ju and Slingo, 1995; and others]. Fasullo and Webster [2002] have argued that this classical description of ENSO-monsoon teleconnection, based on the simple equatorial Walker cell argument, is not adequate to explain the observed variations in the monsoon hydrological budget. In fact, the observed rainfall anomalies over the tropical Pacific during July 2002 show that the belt of enhanced rainfall was displaced significantly north of the equator with the maxima located over the NW Pacific between 10°N - 20°N (Figure 4.1b). The question is whether the ENSO
conditions during 2002 contributed to the anomalous intensification of off-equatorial convection over NW Pacific? Another related issue is about the enhanced cyclogenesis of Pacific typhoons observed over the region. Studies have shown that ENSO induced circulation changes can affect the frequency of tropical storms over the Pacific basin [Chan, 1985; Chen et. al., 1998; Wang and Chan, 2002]. While warm SSTs (> 27°C) are known to be conducive for the formation of tropical cyclones [Gray, 1968], it is not clear if the ENSO related large-scale circulation response during 2002 affected the tropical cyclone activity over NW Pacific. In this chapter, we have carried out GCM simulation experiments and diagnostic analysis of observed data products to understand the interactions among the ENSO induced large-scale circulation anomalies, the west Pacific tropical cyclonic systems and the NW Pacific convective anomalies and their dynamical link with the drought conditions over India. The details of the GCM experiments are given below. It must also be mentioned that this chapter is not merely restricted to the case study of the 2002 monsoon drought. As it will be seen later, the study also includes additional supporting analysis and GCM experiments, which were performed in respect of other analogue cases that resembled the 2002 summer monsoon.

4.2 Data and methods

4.2.1 Datasets used

Datasets from multiple sources have been employed in the present study. They include gridded rainfall data from Climate Prediction Center Merged Analysis of Precipitation (CMAP), which is a product of merging rain gauge observations and precipitation estimates from satellites [Xie and Arkin, 1997]. The data of All
India summer monsoon rainfall is from the Indian Institute of Tropical Meteorology (http://www.tropmet.res.in). Atmospheric circulation parameters are based on the National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis dataset [see Kistler et al., 2001]. The outgoing long wave radiation (OLR) observations from NOAA satellite (http://www.cdc.noaa.gov) are used to infer the tropical convective activity. The SST data used in our study is based on the Optimum Interpolated SST (OISST), which utilizes in situ and satellite-derived SSTs plus SSTs simulated by sea ice cover [Reynolds and Smith, 1994]. The observed cyclone tracks over tropical Pacific (best track data) are from the Joint Typhoon Warning Center (JTWC), USA.

4.2.2 Model and design of experiments

We have performed 4-sets of 10-member ensemble simulation experiments using an atmospheric GCM from Center for Ocean-Land-Atmosphere (COLA). This is a global spectral model with horizontal resolution truncated at wave number 30 (triangular truncation T30) and consists of 18 unevenly spaced sigma levels in the vertical. The complete documentation of the model framework and the physical parameterization schemes used in the GCM are provided by Kinter et al., [1997]. This GCM has been extensively used for monsoon studies [e.g., Fennessy et al., 1994; Krishnan et al., 1998; Krishnan et al., 2003]. The observed global atmospheric conditions from NCEP reanalysis for 10 consecutive days (22-31 May 2002) were processed in order to obtain the multiple initial conditions necessary for performing the ensemble runs. All the model experiments, starting from different initial conditions, go through 30 September 2002. Initial conditions (ICs) for the land surface (soil moisture, snow cover, etc.) are
Experiment | SST boundary condition | Atmospheric Initial condition |
--- | --- | --- |
CLIMSST | Observed climatological SST | Ten ensemble members initiated from (22, 23, ... 31) May 2002 |
Ten ensemble members CLIMSST (01, 02, ..., 10) | | |
GLB2K2 | Observed climatological SST + anomalies of 2002 for global oceans | Ten ensemble members initiated from (22, 23, ... 31) May 2002 |
Ten ensemble members GLB2K2 (01, 02, ..., 10) | | |
PAC2K2 | Observed climatological SST + anomalies of 2002 for Pacific Ocean only | Ten ensemble members initiated from (22, 23, ... 31) May 2002 |
Ten ensemble members PAC2K2 (01, 02, 03.....10) | | |
NOPAC2K2 | Observed climatological SST + anomalies of 2002 everywhere except Pacific Ocean | Ten ensemble members initiated from (22, 23, ... 31) May 2002 |
Ten ensemble members NOPAC2K2 (01, 02, ..., 10) | | |

Table 4.1: Design of GCM simulation experiments.

set to climatological values. Linear time-interpolation of these parameters from the monthly climatologies provides the land surface initial conditions on a given date for starting the model integration. After, commencement of the integration, these land surface parameters are predicted by the model. The SST used for prescribing the boundary conditions in the GCM is based on the observed OISST [Reynolds and Smith, 1994].

The four sets of experiments differ from each other with regard to the specification of the SST boundary forcing. Each of these four sets in turn comprises 10 realizations, for which the GCM was integrated starting from 10 different initial conditions (Table 4.1). The first experiment labeled as CLIMSST
uses observed monthly climatological SST as bottom boundary condition. In the second experiment (GLB2K2), the monthly SST anomalies of 2002 were superimposed on the monthly climatological SST. In the third experiment (PAC2K2), SST anomalies of 2002 were superimposed on observed climatological SST only in the Pacific Ocean (105°E - 80°W) and climatological SST was used elsewhere. In the fourth experiment (NOPAC2K2), climatological SST is specified only in the Pacific Ocean and observed SST of 2002 is specified in all other oceans. The NOPAC2K2 experiment is intended to evaluate the GCM simulated response in the absence of the forcing from the Pacific SST anomalies of 2002. The SST boundary forcing and initial conditions used in the four experiments are summarized in Table 4.1.

4.3 Results

4.3.1 Observed convection and large-scale circulation features

The observed mean OLR and low-level winds for July climatology are shown in Figure 4.3a. The low-level wind field shows the summer monsoon cross-equatorial flow and southwesterly winds from the Arabian Sea into the Indian subcontinent and extend eastward beyond the Bay of Bengal into Burma and Indo-China. The climatological low-level monsoon westerlies converge with the easterly trade winds from the Pacific over the region of South China Sea and Philippines. Convection during the boreal summer is active over a wide region extending from the west coast of India up to the Philippines as seen from the low OLR values; with the convection maximum located over the head Bay of Bengal and northeast India where the magnitude of OLR is about 180 W m$^{-2}$ (Figure 4.3a). A zone of secondary convection can be noticed over the equatorial Indian
Figure 4.3: (a) The July climatology of OLR (W m\(^{-2}\)) from NOAA satellite (source: http://www.cdc.noaa.gov) and 850 hPa wind (m s\(^{-1}\)) from NCEP reanalysis dataset. Deep convection in the tropics is characterized by low cloud-top temperatures and small OLR values; while high OLR values indicate scarcity or absence of cloud cover (b) The July climatological walker cell shown by the longitude-pressure cross-section of zonal wind (m s\(^{-1}\)) and vertical wind (hPa s\(^{-1}\)) components averaged meridionally between 10\(^\circ\)N-20\(^\circ\)N; the vertical velocity is taken with negative sign. (c) The climatological winds (m s\(^{-1}\)) at 200 hPa for the month of July. (d) Same as in (a) except for July 2002 anomalies; zero contour is suppressed. (e) Same as in (b) except for July 2002 anomalies. (f) Same as in (c) except for July 2002 anomalies.
Ocean with OLR values less than 210 W m\(^{-2}\). The climatological summer monsoon convection is associated with strong upward velocities over the Indian (75°E - 95°E) and East Asian (100°E - 130°E) longitudes as can be seen from the longitude-pressure (x-p) section of the east-west circulation averaged over the (10°N - 20°N) latitude belt (Figure 4.3b). The climatological upper-tropospheric wind field reveals strong easterlies to the west of 125°E and an anticyclonic circulation over the Tibetan region (Figure 4.3c).

The anomalies of 850 hPa winds and OLR for July 2002 are shown in Figure 4.3d. The positive OLR anomalies over north-central India and the Arabian Sea region, which are as large as +40 W m\(^{-2}\), indicate strong suppression of convection over the region. The low-level wind anomalies over India show an anomalous anticyclonic circulation co-located with the region of suppressed convection. Notice that the suppressed convective anomalies extended south-eastward from the Indian region into equatorial west Pacific and the maritime continent of Indonesia. An anomalous enhancement of convection and an intensified shear zone can be seen over the equatorial eastern Indian Ocean in Figure 4.3d, which are typical of weak monsoon conditions [e.g., Krishnan et al., 2000; Annamalai and Slingo, 2001]. Another conspicuous feature in Figure 4.3d is the enhanced convective anomalies over NW and north-central Pacific in the 10°N - 20°N latitude belt, which extends eastward from around 100°E beyond the dateline. This belt of increased convection is associated with westerly wind anomalies and an anomalous cyclonic circulation over NW Pacific. In the equatorial west-central Pacific, the westerly wind anomalies correspond to a weakening of the easterly trade winds (Figure 4.3d).
Figure 4.3e shows the (x-p) section of east-west circulation anomalies over the 10°N - 20°N latitude belt during July 2002. The anomalous ascending motion between 110°E - 145°E corroborates the increased convective activity over the NW Pacific; while the anomalous subsidence between 75°E - 90°E is consistent with the decreased convection over the Indian landmass. The subsiding branch of the anomalous east-west circulation over the Indian region during July 2002 was also noted by Fasullo [2005]. The upper tropospheric circulation anomalies (Figure 4.3f) show anomalous westerlies over the Indian region corresponding to a weakening of the tropical easterly jet during July 2002. A cyclonic anomaly can be seen over west-central Asia and the Indo-Pak region in Figure 4.3f. Earlier studies have reported that such extra-tropical troughs are associated with cold air advection, which intrude southward and tend to weaken the monsoonal circulation through decrease of the meridional temperature gradient [e.g., Ramaswamy, 1962; Keshavamurty and Awade, 1974; Raman and Rao, 1981; Krishnan et al., 1998]. The off-equatorial anticyclonic anomaly at 200 hPa over NW Pacific corresponds to the upper tropospheric outflow associated with the enhanced convection over the region.

4.3.2 Analysis of GCM simulations

The results from the four sets of GCM simulation experiments are presented in this section. The ensemble mean of the July precipitation simulated by the CLIMSST experiment is shown in Figure 4.4a. The simulation shows rainfall over the Indian landmass with maxima located over the Bay of Bengal and the eastern Arabian Sea. Over the equatorial eastern Indian Ocean, the west Pacific and South China Sea the simulated rainfall is about 6-9 mm day\(^{-1}\). The low-level winds in the CLIMSST simulation show the summer monsoon cross-equatorial
July Rainfall (mm/day) and 850 hPa Winds (m/s)

Figure 4.4: (a) The GCM simulated July rainfall (with contour interval of 3 mm day$^{-1}$) and 850 hPa wind (m s$^{-1}$) for the CLIMSST experiment. The fields shown are averages of the 10 ensemble realizations. (b) Same as in (a) except for the GLB2K2 anomalies. (c) Same as in (a) except for the PAC2K2 anomalies. (d) Same as in (a) except for the NOPAC2K2 anomalies. Anomalies in (b)-(d) are obtained by taking averages of the member-to-member differences for GLB2K2 and CLIMSST, PAC2K2 and CLIMSST, and NOPAC2K2 and CLIMSST, respectively.

flow over the Indian region; as well as the easterly trades and the subtropical high over the Pacific. The overall simulation of rainfall and large-scale circulation features in Figure 4.4a is consistent with observations. However, some of the
finer details of the monsoon rainfall are not as well simulated - partly because of the coarse model resolution and partly due to deficiencies in the treatment of physical processes in the GCM. For instance, the west coast rainfall maximum over India is weak and is shifted more westward as compared to the observed precipitation. Also the rainfall maximum over the Bay of Bengal shows a southward shift relative to the observed position. While noting such discrepancies, it must be pointed out that accurate simulation of the monsoon rainfall and its variability still remains a challenging issue [Gadgil et al., 2002]. Moreover, the purpose of this study is not to critically focus on the accuracy of the monsoon simulated rainfall; instead, the experiments are aimed at understanding the anomalous character of the monsoon large-scale response during 2002.

The precipitation and low-level circulation anomalies simulated by the GLB2K2 experiment for July 2002 are shown in Figure 4.4b. The anomalies are computed by taking the mean of the member-to-member differences between the GLB2K2 and CLIMSST experiments. The negative rainfall anomaly and the anomalous anticyclone over north-central India and northern Arabian Sea and Bay of Bengal in Figure 4.4b indicate suppression of monsoon rainfall activity in the GLB2K2 experiment relative to CLIMSST run. The near-equatorial positive rainfall anomalies are shifted more northward over southern India in the GLB2K2 simulation as compared to the observed anomalies, indicating the bias in the model simulation - which may be related to the coarse resolution and strong sensitivity of the model to warm SST anomalies in the equatorial region [Krishnan et. al., 2003]. An interesting aspect of the GLB2K2 simulation is the enhanced precipitation and anomalous cyclonic circulation over the NW Pacific region, extending eastward of Philippines and Taiwan. The precipitation decrease
over the Indonesian region and increase over the equatorial central Pacific; and
the westerly wind anomalies over the equatorial Pacific in Figure 4.4b clearly
bring out the ENSO response in the GLB2K2 simulation. Also it must be pointed
out that most of the ensemble members of the GLB2K2 experiments showed an
anomalous decrease of rainfall over India and increase over NW Pacific,
indicating the robustness and consistency of the simulated response.

The rainfall anomaly in the PAC2K2 simulation shows enhanced
precipitation over NW and equatorial central Pacific, Indo-China and Bay of
Bengal; and decreased precipitation over the Indian landmass (Figure 4.4c). The
low-level circulation response shows anomalous westerlies corresponding to
weakening of the easterly trades over the equatorial Pacific; an intensified
cyclonic circulation anomaly over NW Pacific and an anomalous ridge over the
Indian region (Figure 4.4c). The increased precipitation over NW and equatorial
central Pacific, in the GLB2K2 and the PAC2K2 simulations, is suggestive of the
commonality in response to the anomalous Pacific SST forcing during 2002.

The NOPAC2K2 experiment shows an anomalous rainfall decrease over
Bay of Bengal and a low-level anticyclonic anomaly over the Indian region
(Figure 4.4d). Further, it can be noticed that the precipitation is enhanced over the
equatorial Indian Ocean and south-eastern Arabian Sea in the NOPAC2K2
simulation; as in the GLB2K2 run (Figure 4.4b). Our understanding suggests that
the simulated rainfall increase over the equatorial Indian Ocean is related to the
warm SST anomalies in the region. In fact, earlier studies have pointed out the
role of the Indian Ocean SST boundary forcing in affecting the precipitation
anomalies over the near-equatorial region and the Indian landmass [e.g.,
Chandrasekar and Kitoh, 1998; Krishnan et al., 2003]. While, it is recognized
that the interactions between the monsoonal circulation and the Indian Ocean
dynamics are important in determining the variability of the monsoon rainfall
[Krishnan et al., 2006], it must be mentioned that the focus of this study is to
clarify the out-of-phase rainfall variability between the NW Pacific and the
Indian region observed during 2002. It can be seen from Figure 4.4d that the
simulated precipitation anomalies over the NW and equatorial central Pacific are
very small in the NOPACK2 experiment. The above results from the GCM
experiments suggest that the intensified precipitation anomalies over NW Pacific
were largely forced by the ENSO conditions.

The main features of the upper tropospheric circulation at 200 hPa – viz.,
the Tibetan anticyclone, the Tropical Easterly Jet and the mid-Pacific trough are
seen in the CLIMSST simulation (Figure 4.5a). The 200 hPa wind anomalies in
the GLB2K2 and PAC2K2 simulations show anomalous westerlies over the
Arabian Sea and the Indian Ocean which correspond to weakening of the upper-
level easterly flow; and an eastward shift of the upper-level anticyclone over NW
Pacific (Figures 4.5b-c). The strong anticyclonic anomaly over NW Pacific in
Figure 4.5c is consistent with the intensification of rainfall over this region in the
PAC2K2 experiment. Nevertheless, it must be mentioned that the differences in
the upper-level circulation response over the tropical and southern Indian Ocean
between GLB2K2 and PAC2K2 are related to the differences in convection
anomalies over the Indian Ocean between the two experiments. In the
NOPAC2K2 experiment, the upper tropospheric circulation response shows
anomalous westerlies over India and the equatorial Indo-Pacific region (Figure
4.5d); while the anticyclonic anomaly over NW Pacific is not discernible.
July 2002 Winds at 200 hPa (m/s)

Figure 4.5: GCM simulated 200 hPa winds (m s$^{-1}$); (a) July mean from CLIMSST experiment, (b) July 2002 anomaly from GLB2K2, (c) same as (b) except for PAC2K2, (d) same as (b) except for NOPAC2K2.

We now examine the simulated vertical velocity field ($\omega$) at 500 hPa in the four model experiments. The CLIMSST simulation shows ascending motions over the Indian and Asian monsoon regions and the tropical Indo-Pacific sector as evidenced from the negative vertical velocities; while subsidence ($\omega > 0$) can be noticed over the subtropical southern Indian Ocean and the region over Arabia and west Asia (Figure 4.6a). The anomalies of vertical velocity at 500 hPa from the GLB2K2, PAC2K2 and NOPAC2K2 simulations are shown in Figures 4.6(b-d). It can be noted from Figure 4.6b that the positive anomalies over the Indian
July Vertical Velocity at 500 hPa (x 1000) hPa/s

**Figure 4.6:** Same as Figure 4.5 except for 500 hPa vertical wind (hPa s$^{-1}$). 

region correspond to anomalous subsidence; while the negative anomalies over the equatorial Indian Ocean and the NW Pacific are associated with anomalous upward motion in the GLB2K2 simulation. In order to quantify the changes in the vertical velocities over different regions, we have computed the area-averaged values of $\omega$ anomalies ($\omega_{\text{IND}}$, $\omega_{\text{EOC}}$, $\omega_{\text{NWP}}$) over the Indian region (70°E - 90°E; 10°N - 25°N); the equatorial Indian Ocean (65°E - 95°E; 10°S - 5°N) and the NW Pacific (110°E - 145°E; 10°N - 20°N), respectively.
The area-averaged \( \omega \)-anomalies at 500 hPa for July 2002 computed from NCEP reanalysis (Figure 4.1c) are found to be \( \omega_{\text{IND}} = +0.03 \) hPa s\(^{-1} \); \( \omega_{\text{EIO}} = -0.008 \) hPa s\(^{-1} \) and \( \omega_{\text{NWP}} = -0.019 \) hPa s\(^{-1} \), respectively. For the GLB2K2 experiment, the corresponding values are \( \omega_{\text{IND}} = +0.023 \) hPa s\(^{-1} \); \( \omega_{\text{EIO}} = -0.011 \) hPa s\(^{-1} \) and \( \omega_{\text{NWP}} = -0.020 \) hPa s\(^{-1} \), respectively. Thus, the GLB2K2 experiment is consistent with NCEP reanalysis in showing the anomalous subsidence over the Indian region and anomalous upward velocities over the equatorial Indian Ocean and NW Pacific. In the case of the PAC2K2 simulation (Figure 4.6c) anomalous descent can be seen over the Indian landmass (\( \omega_{\text{IND}} = +0.018 \) hPa s\(^{-1} \)) and ascent over the NW Pacific (\( \omega_{\text{NWP}} = -0.048 \) hPa s\(^{-1} \)). Over the equatorial Indian Ocean, the PAC2K2 simulation mostly showed anomalous descending motions (\( \omega_{\text{EIO}} = +0.01 \) hPa s\(^{-1} \)). The NOPAC2K2 simulation (Figure 4.6d) showed anomalous subsidence over the Bay of Bengal and northeast India; and ascending motions over the south-eastern Arabian Sea and the equatorial Indian Ocean. The area-averaged values of the \( \omega \) anomalies in the NOPAC2K2 simulation are (\( \omega_{\text{IND}} = +0.009 \) hPa s\(^{-1} \), \( \omega_{\text{EIO}} = -0.011 \) hPa s\(^{-1} \), \( \omega_{\text{NWP}} = +0.014 \) hPa s\(^{-1} \)). The anomalous ascending motions over NW Pacific in the GLB2K2 and PAC2K2 simulations suggest that the convective activity and vertical velocity over this region were determined by the ENSO induced large-scale circulation response during 2002.

4.3.3 Tropical cyclone activity in the GCM simulation

GCM simulations can be used to investigate the climatology and physical characteristics of tropical storms in the model [eg. Manabe et al., 1970; Bengtsson et al., 1996; Vitart and Anderson, 2001; Wu and Wang, 2004]. The genesis and movement of tropical cyclone is intimately linked to the mean large-
scale circulation. The level of steering flow for the NW Pacific cyclonic systems is known to be located in the lower and middle troposphere \cite{Holland et al., 1993; Wu and Wang, 2004}. Using daily GCM outputs from the four experiments (CLIMSST, GLB2K2, PAC2K2 and NOPAC2K2), we have examined the simulated tropical cyclone activity over NW Pacific. Following the criteria similar to Bengtsson et al., [1996], we first determine the initial location of a tropical cyclone center from the GCM output as given below.

1) Wind speed at 1,000 hPa > 10 m s$^{-1}$
2) Relative vorticity at 850 hPa > 2.0x10$^{-5}$ s$^{-1}$
3) The mean wind speed at 850 hPa > mean wind speed at 300 hPa
4) The sum of the temperature anomalies (deviation from the mean, consisting of 3 x 3 grid points) for the levels 700, 500 and 300 hPa > 2°C
5) Minimum duration of the event is at least 2 days

After identifying the cyclone centers, 10-day forward trajectories are calculated over the tropical west-central Pacific domain (110°E – 180; 5°N - 25°N) using the model simulated steering flow. It must be mentioned that an initial point along a track may be newly generated low-pressure point or may be a point along an existing cyclone. The forward trajectory computation is based on the technique of Krishnamurti et al., [1996]. Following an approach similar to Wu and Wang [2004], we make use of the pressure-weighted mean flow from 850 hPa to 200 hPa as the steering flow. It must be mentioned that an initial point along a track may be newly generated low-pressure point or may be a point along an existing cyclone. Before proceeding further, examples of cyclone tracks for a single realization in each of the 4 simulation experiments (CLIMSST,
Figure 4.7: Example illustrating the cyclone trajectories for the July month obtained from a single realization of the GCM simulation for (a) CLIMSST, (b) GLB2K2, (c) PAC2K2 and (d) NOPAC2K2.

GLB2K2, PAC2K2 and NOPAC2K2) are illustrated in Figures 4.7(a-d) respectively. Inspection of Figure 4.7 suggests that the cyclone tracks in the GLB2K2 and PAC2K2 experiments extend meridionally beyond 30°N; while those in CLIMSST and NOPAC2K2 experiments are mostly confined to the south of 30°N. Further, it can be noticed that the northward extending cyclone tracks in GLB2K2 and PAC2K2 shows significant recurvature around 30°N. The tracks of tropical cyclones shown in Figure 4.7 motivated us to further understand the tropical cyclone activity over northwest Pacific from all the ensemble members in the four experiments.
Figure 4.8: Map of cyclone density values computed on 1.8° x 1.8° grid boxes by counting the number of cyclones passing through a grid-box from the GCM experiments, (a) CLIMSST, (b) GLB2K2, (c) PAC2K2, (d) NOPAC2K2. The density values in each experiment are calculated separately for every ensemble member and then averaged over the 10-cases.

Figure 4.8 shows the cyclone density values computed for the four experiments. The cyclone density values are determined by counting the number of cyclones passing through every 1.8° x 1.8° grid box during the summer monsoon season. The cyclone density is basically a measure of how frequently a specific grid box is affected by storms [Wu and Wang, 2004; Vinay Kumar and 153]
Krishnan, 2005]. The cyclone density maps shown in Figures 4.8(a-d) are averages determined from the 10-member ensembles for CLIMSST, GLB2K2, PAC2K2 and NOPAC2K2 experiments, respectively. An inter-comparison of cyclone density values in Figures 4.8(a-d) is useful in inferring the activity of tropical Pacific cyclonic systems in each of the four experiments relative to one another. The cyclone density in the CLIMSST simulation (Figure 4.8a) shows cyclonic activity over the region of China Sea extending northeastward towards central Pacific. Further, it can be seen that the cyclone density values over NW Pacific in the GLB2K2 and PAC2K2 (Figures 4.8b-c) are significantly enhanced as compared to the CLIMSST and NOPAC2K2 simulations (Figures 4.8a-d). While noting the high cyclone density values in the PAC2K2 simulation, it must be mentioned that our intention here is to basically use the GCM simulations as a guiding tool to understand the cyclonic activity over NW Pacific in terms of the large-scale circulation anomalies. In this context, it can be seen from Figure 4.4 that the increased cyclonic activity in the GLB2K2 and PAC2K2 experiments, relative to the CLIMSST and NOPAC2K2, is consistent with the enrichment of low-level cyclonic vorticity over the NW Pacific region in the GLB2K2 and PAC2K2 experiments (Figures 4.4b-c). In other words, the GCM simulations bring out the point that the enhanced tropical cyclonic activity over NW Pacific was essentially determined by the large-scale circulation response to ENSO conditions during 2002.

### 4.4 Extended analysis of analogue cases

Encouraged by the above results, we have further investigated other analogue cases that were similar to July 2002 in terms of the out-of-phase convection variability between the Indian subcontinent and the NW Pacific. Following the
lines similar to Fasullo [2005], we have identified the analogues cases. Using monthly data of all India rainfall [Parthasarathy et al., 1995], OLR data from NOAA satellite (1979-2004) and OISST dataset (1981-2004), we have applied the following objective criteria for identifying the analogues.

- Monthly anomaly of all India rainfall should be below 10% of the climatological normal.
- Enhanced periods of convection over NW Pacific are identified based on the criterion that the area averaged OLR anomalies over (10°N - 20°N; 130°E - 180°E) should be less than -15 W m⁻².
- The Nino3.4 SST anomaly (170°W - 120°W; 5°S - 5°N) should exceed 0.5°C.

### 4.4.1 Observed anomaly patterns

Based on the above criteria, we have identified three other instances viz., (August 1986, August 1991, August 2004) that resemble July 2002 in terms of the out-of-phase convective anomalies over the Indian subcontinent and NW Pacific as seen from the OLR anomaly composite (Figure 4.9a). Note that the enhanced convective anomalies over the subtropical NW Pacific in Figure 4.8a extend eastward well beyond the dateline; while the convection over equatorial west Pacific is suppressed. The Indian Ocean convective anomalies show a dipole pattern, consisting of enhanced convection over the eastern equatorial Indian Ocean and suppressed convection over the west, which is similar to that noted by Gadgil et al., [2004]. Tropical cyclone tracks during these weak-monsoon cases revealed west Pacific storms that mostly moved northward and recurved.
Figure 4.9: (a) Composite of OLR anomalies (W m\(^{-2}\)) base on three different weak cases of Indian summer monsoon (August 1986, August 1991 and August 2004). Notice the enhanced convection over NW Pacific and suppressed convection over the Indian sub-continent. (b) Typhoon tracks over tropical Pacific Ocean during these week monsoon cases reveal the pre-dominance of northward moving cyclonic systems associated with re-curvature around 25°N. The northerly and westerly tracks are shown in red and blue colors respectively. (c) Composite of SST anomalies (°C) based on the three week monsoon cases show the anomalous El Nino warning in the equatorial central pacific.
Figure 4.10: Anomaly composite of geopotential height (m) and streamlines based on the three analogue events (i.e., August 1986, August 1991 and August 2004) (a) 850 hPa (b) 700 hPa, (c) 250 hPa. The anomalous lows and highs are indicated as "L" and "H" respectively. The meridional pattern of alternating highs and lows extending from the equatorial west Pacific into the sub-tropical and mid-latitude Pacific can be clearly noticed.
around 25°N between Taiwan and Japan (Figure 4.9b). It is also important to mention that these four weak-monsoon cases coincided with El Nino events as seen from the warm SST anomaly in the central-eastern equatorial Pacific (Figure 4.9c).

Composite maps of large-scale circulation anomalies for the analogue cases, based on NCEP reanalysis, show an anomalous circulation pattern extending meridionally from the equatorial Pacific into the subtropics and mid-latitudes (Figure 4.10). In the lower troposphere (Figures 4.10a-b) a well defined cyclonic anomaly can be noticed over east of China, Taiwan and the Philippines region; followed by an anomalous high over Japan and further northeastward. In addition, a weak ridge can be seen co-located with the suppressed convection over the Indonesian and equatorial west Pacific region in Figures 4.10(a-b). The upper tropospheric circulation anomalies reveal an anomalous anticyclone over NW Pacific (Figure 4.10c). In other words, the vertical variation of the circulation anomalies over the NW Pacific was associated with a baroclinic structure indicative of the deep dynamical response to enhanced convection over the region.

4.4.2 GCM simulated response for analogue cases

On the lines of the 2002 simulation experiments, we have repeated the CLIM, GLB, PAC and NOPAC simulations for the past analogues (i.e., August 1986, August 1991 and August 2004). The specification of the SST boundary forcing in the 4-sets of experiments (CLIM, GLB, PAC and NOPAC) is similar to the 2002 experiments (see Table 4.1). For each of the 3-analogue cases, 5-member ensemble runs were carried out thereby yielding a total of 15 simulations for
Anomaly Composites
Rainfall (mm/day) & 850 hPa Winds (m/s)

Figure 4.11: The GCM simulated rainfall (mm day$^{-1}$) and 850 hPa wind (m s$^{-1}$) anomalies; (a) GLB (b) PAC, (c) NOPAC experiments. For each of the 3 analogue cases (August 1986, August 1991 and August 2004), we have performed 5-member ensemble runs. The GLB, PAC and NOPAC anomalies are relative to the CLIM experiments.
each of the 4 sets (CLIM, GLB, PAC and NOPAC) of experiments. The ensemble runs were started from 5 different initial conditions during end of July of the respective year. The initial conditions were obtained from NCEP reanalysis. Since the 3-analogue cases happen to coincide with the August month, we have basically examined the simulated response for August 1986, August 1991 and August 2004 in the 4-sets of experiments. Figures 4.11 (a-c) show the composite of precipitation and low-level wind anomalies from the GLB, PAC and NOPAC simulations respectively. The GLB, PAC and NOPAC anomalies were computed relative to the CLIM experiment.

All the three experiments show decreased monsoon rainfall and low-level anticyclonic anomalies over the Indian region - with the negative rainfall anomalies being more prominent in the GLB simulation. On the other hand, the increase of rainfall and intensification of the cyclonic anomaly over NW Pacific are seen mainly in the GLB and PAC experiments. Over the equatorial Indian Ocean and south-eastern Arabian Sea, strong increases in rainfall can be noted in the GLB and NOPAC simulations. The PAC simulation also shows positive precipitation anomalies over the equatorial Indian Ocean with accompanying westerly wind anomalies and an intensified near-equatorial trough that are typically observed during weak monsoon conditions [Krishnan et al., 2006]. There are two important points emerging from the above results. The first pertains to the influence of the equatorial Indian Ocean precipitation anomalies on the rainfall decrease over India through weakening of the monsoon Hadley circulation. This point has been documented by several studies [e.g. Chandrasekar and Kitoh, 1998; Krishnan et al., 2003; Fasullo, 2005; Krishnan et. al., 2006]. The second point, which is of primary interest to this study, is the enhancement of convection over NW Pacific in response to the warm Pacific
SST anomalies and its role in affecting the monsoon rainfall over India. In the following section, we shall discuss the dynamics of the out-of-phase rainfall variability between NW Pacific and the Indian region.

4.5 Dynamical linkage between northwest Pacific convection and Indian monsoon

Based on the results discussed above, it is possible to deduce the dynamics associated with the enhancement of convective anomalies over NW Pacific during ENSO conditions. A key aspect to be recognized is the anomalous suppression of convection over the equatorial west Pacific during the warm phase of ENSO. Studies have shown that interactions between the tropical convective anomalies and the wind anomalies can generate and maintain large-scale anomaly patterns of alternating highs and lows which extend meridionally from the equatorial region into the sub-tropics and mid-latitudes through Rossby wave dispersion [e.g. Hoskins and Karoly, 1981; Nitta, 1987]. Furthermore, the meridional dispersion of Rossby waves is known to be strongly enhanced in a belt of westerlies located over the region of anomalous convection [Hoskins and Karoly, 1981; Lau and Lim, 1984; Chang and Webster, 1990].

Upon examination of the wind data from NCEP reanalysis, we have noticed that low-level westerly winds prevailed over the tropical west Pacific, extending eastward up to nearly 150°E and northward up to about 15°N, during July 2002 as well as the other analogue cases of August 1986, August 1991 and August 2004. Therefore, a possible explanation for the anomalous circulation pattern of alternating high and lows over the Pacific can be attributed to meridional dispersion of Rossby waves due to interactions between the
Figure 4.12: Schematic shows the linkage between the Indian summer monsoon rainfall and the convective activity over NW Pacific during ENSO events. The ENSO induced circulation response is characterized by an anomalous meridional circulation pattern of alternating highs and lows, extending from the equatorial west Pacific into the sub-tropics and mid-latitude regions, which is associated with Rossby wave dispersion due to interactions between the west Pacific convective anomalies and westerly winds over the region. Anticyclonic anomalies are labeled “A” and cyclonic anomalies as “C”. The meridional circulation pattern is associated with enrichment of low-level cyclonic vorticity over NW Pacific, which favors enhanced cyclonic activity and intensified precipitation over the region. The strong ascending motions over NW Pacific force subsidence and rainfall reduction over the Indian subcontinent through anomalous east–west circulation in the 10–20°N latitude belt.
suppressed convection over equatorial west Pacific and the anomalous westerly winds over the region. The same is illustrated in the schematic in Figure 4.12. Note that the meridional circulation pattern is characterized by an intensified cyclonic anomaly over the NW Pacific region. In fact, both observations as well as GCM simulations provide support indicating that the enrichment of low-level cyclonic vorticity over NW Pacific favored enhanced cyclogenesis in the region (Figures 4.7, 4.8, 4.9). The above results when juxtaposed together indicate that the enhanced precipitation over NW Pacific was sustained by the intensified low and increased cyclonic activity over the region. In turn, the strong ascending motions over NW Pacific forced subsidence and rainfall reduction over the Indian subcontinent through anomalous east-west circulation around the 10°N - 20°N latitude belt (Figure 4.11). Thus, the convection variability over NW Pacific can serve as an important component that mediates the ENSO-monsoon teleconnection dynamics.

If indeed the reduced warm pool convection provides a mechanism for intensifying the off-equatorial convective anomalies over NW Pacific as in (July 2002, August 1986, August 1991 and August 2004), we might inquire about the possible occurrence of ENSO events in which the warm pool convection was not greatly reduced and therefore the convective anomalies over NW Pacific were not affected? In fact, Fasullo (2005) noted that not all ENSO cases are associated with major reduction in the warm pool convection (eg., 1963, 1976). It can be seen from his study that the precipitation anomalies over NW Pacific and the Indian monsoon region were not significant during such cases – thus suggesting the role of the equatorial west Pacific precipitation anomalies in determining the off-equatorial convective anomalies over NW Pacific. Further studies will be required to address this issue in greater detail.
4.6 Concluding remarks

The monsoon drought condition over India during July 2002 was one in which the rainfall distribution over the country was the lowest in the historical records during the last 130+ years. A number of studies have documented the role of the tropical Indian Ocean convective anomalies in affecting the monsoon precipitation over India during 2002 through anomalous changes in the monsoon Hadley cell. However, a poorly understood aspect of this drought period pertains to the anomalous intensification of convective activity over a wide region of the NW Pacific. Such intensified convective anomalies over NW Pacific have also been observed during other instances of weak Indian monsoons in the past. In this chapter, we have carried out GCM simulation experiments and supplementary diagnostic analysis of observed datasets in order to understand the dynamical linkage between the monsoon rainfall deficiency over India and the anomalous intensification of convective activity over NW Pacific.

The results point to the role of ENSO conditions in forcing large-scale circulation anomalies favorable for the intensification of convection over the NW Pacific region. The circulation anomalies in the lower troposphere manifested in the form of a meridional pattern comprising of an anomalous anticyclone over the equatorial west Pacific; a cyclonic anomaly over the subtropical NW Pacific and an anticyclone further northward. It is inferred that this meridional pattern of alternating highs and lows is associated with Rossby wave dispersion arising due to interactions between the near-equatorial convective anomalies and the anomalous westerly winds over the tropical west-central Pacific. The generation of the meridional circulation pattern enriches the low-level cyclonic vorticity over NW Pacific and thereby favors enhanced cyclogenesis and intensified...
precipitation over the region. In turn, the strong ascending motions over NW Pacific force subsidence and rainfall reduction over the Indian subcontinent through east-west circulation anomalies around the $10^\circ$N - $20^\circ$N latitude belt. The nature of linkage between ENSO and the Indian summer monsoon, which emerges from the present analysis, is mediated by convection changes over NW Pacific and appears to be rather different from the classical picture of teleconnection which involves anomalous changes in the equatorial Walker cell.