Abstract

Droughts are ranked among the foremost of natural hazards to mankind, given that the impacts of prolonged rainfall deficiencies cut across various sectors of the society – viz., agriculture, food-production, irrigation, power-generation, water-management, hygiene, industries, socio-economic development, individual household communities and a host of other activities. Over the years significant knowledge has been gained about the incidence of droughts over different parts of the world, based on the available rainfall and other climatic records. Furthermore, the advances in climate modelling and the advent of high-power super-computers over the last couple of decades, have led to better understanding of the various feedback mechanisms associated with the occurrence of droughts (eg., Albedo-biosphere feedback; SST boundary forcing from ocean-atmosphere coupled phenomena like El Nino / Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) etc; orographic effects; Monsoon-Desert mechanism; effect of persistent mid-latitude circulation anomalies, prolonged breaks in the monsoon rainfall activity, radiative effects of dust and aerosols, etc). The mechanisms contributing to the generation and maintenance of droughts vary from region-to-region; and various aspects relating to the dynamics of monsoon-droughts over India are still not fully understood. By conducting numerical simulation experiments using atmospheric general circulation models (GCM) along with extensive diagnostics of multi-source climate data-sets, we have investigated some of unresolved issues pertaining to occurrence of monsoon droughts over India. A chapter-wise description of the Ph.D. thesis work is briefly summarized below.

Chapter-I begins with a general introduction about the climatology of the arid regions of the world. A fairly detailed discussion on the causes of large-
scale aridity over different regions (e.g., Sahel region, the Gobi Desert, the Maritime continent of Indonesia, Mediterranean region, the Far East and so on) is included in this chapter, in order to provide a broader perspective of the aridity inducing mechanisms and their relevance in the context of monsoon droughts over India. This chapter also discusses about the classification of droughts; examples of major monsoon droughts over India during the last century; the linkages between droughts and anomalous atmosphere-land-ocean conditions on the regional and global scale. The last section of this chapter provides the plan and scope of the present research work and the scientific issues that have been examined in this thesis.

**Chapter-II:** One of the inadequately understood aspects of monsoon droughts pertains to interactions between the extra-tropical circulation and the monsoon rainfall variations. Although, past studies have reported that weak phases of the Indian monsoon generally tend to be associated with anomalous southward intrusion of cold westerlies from the extra-tropics, the cause and effect relationship between the monsoon rainfall variations and the extra-tropical circulation anomalies has not been adequately resolved. In particular, the dynamical link between the anomalous mid-latitude circulation and the monsoon convection anomalies in sustaining the drought conditions over the subcontinent is not yet understood. Understanding this problem is crucial in order to gain insight about the atmospheric internal dynamics during monsoon droughts. In this chapter, we have conducted a 20-year simulation of a high-resolution atmospheric general circulation model (GCM) forced with climatological mean SST as boundary condition. The GCM shows a fairly realistic simulation of the mean monsoon rainfall and the large-scale circulation features. In addition, the GCM simulation exhibits remarkable interannual variations of monsoon precipitation over the sub-continent – with the 20-year
run showing incidence of 4 monsoon-droughts. The question that is addressed here is the likely cause of the monsoon-droughts in the 20-year model simulation – in which the SST boundary condition has been fixed to climatology.

Detailed analysis of the GCM simulations and additional analyses based on simplified model experiments reveal that the internally-forced droughts in the GCM emanate largely from prolonged monsoon-breaks which occur on sub-seasonal time-scales; and involve dynamical feedbacks between the monsoon convection anomalies and circulation changes over the sub-tropics and mid-latitudes. In this feedback, the suppressed monsoon convection allows generation of an anomalous quasi-stationary circulation pattern extending across continental Eurasia; which in turn induces anomalous cooling in the middle and upper-troposphere through cold-air advection – leading to decrease in the meridional thermal contrast over the sub-continent and thereby allowing the monsoon to weaken further. It is shown that the anchoring of anomalous troughs over west-central Asia and Indo-Pak; as well as the down-stream ridge over East Asia during weak-monsoon phases involve dispersion of Rossby waves, generated through interactions between the sub-tropical westerlies and the monsoon convection anomalies, in the summer-time sub-tropical westerly flow. The results of our study convincingly demonstrate that such an internal feedback between the mid-latitude circulation and monsoon convection can lead to prolonged breaks in the monsoon rainfall; thereby resulting in drought-like conditions over the sub-continent.

**Chapter-III:** One of the important and interesting aspects of the interannual variability in the tropics is the association between the Indian summer monsoon circulation and the convective activity over west Pacific.
Observations indicate that many monsoon droughts in the past were associated with enhancement of convection and cyclonic activity over the Northwest (NW) Pacific. In Chapter-III, we have carried out a detailed analysis of observations of atmospheric circulation over a 56-year period (1948-2003) in order to gain insight about the teleconnection between monsoon droughts and the NW Pacific convective activity. The results indicate that the year-to-year variations in the large-scale summer monsoon circulation exert influence on the tropical Pacific cyclone activity. The cyclogenesis over NW and tropical west-central Pacific is found to be 33% higher during weak monsoon years as compared to the strong ones. Also, there is greater tendency for the Pacific cyclones to move northward and re-curve (to the north of 20°N) during weak monsoon years. The patterns of large-scale circulation anomalies that influence the cyclogenesis and movement of cyclonic systems over NW Pacific during strong and weak monsoons are discussed in detail in this chapter. Given that the interannual variability of the large-scale circulation over the Indo-Pacific sector is linked to El Nino / Southern Oscillation (ENSO), the present analyses raise several questions. Based on the overall analyses, it is suggested that improved understanding of the interactions among the large-scale monsoon circulation, tropical convection and the Pacific cyclonic disturbances is crucial in order to unravel the details of the ENSO-monsoon dynamical link.

Chapter-IV is a sequel to the previous chapter and the focus here is on GCM simulations in order to understand the dynamical links among monsoon droughts, ENSO and convection changes over NW Pacific. Despite significant advances in our knowledge about the ENSO and monsoon systems, aspects relating to the ENSO-Monsoon dynamical link still remain unclear. For example, it is generally regarded that the ENSO-monsoon connection primarily operates through anomalous displacements of the Walker circulation in the
equatorial region. However, this classical description of the ENSO-monsoon teleconnection, based on the simple equatorial Walker cell argument, is not adequate to explain the large-scale pattern of rainfall anomalies associated with some of the monsoon droughts such as those witnessed during 2004, 2002, 1991, 1986 etc. Although these monsoon drought periods occurred during El Nino conditions in the Pacific, the precipitation patterns in the Pacific were mostly enhanced in the off-equatorial regions of the sub-tropical NW Pacific. This raises the question concerning the sustenance of the off-equatorial rainfall anomalies over NW Pacific and their interaction with the Indian monsoon.

In order to address this problem, an ensemble of GCM simulation experiments and a detailed diagnostic analysis of observations were performed. Based on the results of our study, a new pathway for the ENSO-monsoon connection has been identified. It is shown that this pathway, which occurs through the NW Pacific, is much different from the classical teleconnection via. the equatorial Walker-cell. The results of this study show that warm SST anomalies in the equatorial central Pacific generate anomalous circulation and convection patterns not only over the equatorial west Pacific; but also over the sub-tropical NW Pacific. The dynamics of the anomalous circulation pattern over NW Pacific is discussed in detail in this Chapter. It is shown that the ENSO-induced pattern of large-scale circulation anomalies and the associated intensification of convective activity over NW Pacific is a key factor that forces descent and rainfall suppression over the Indian subcontinent through anomalous east-west circulation in the 10°N-20°N latitude belt.

Chapter-V presents an analysis of monsoon simulations from the state-of-art climate models, with the aim of understanding the current level of skills in simulating the observed inter-annual variability (IAV) of monsoon rainfall
and drought occurrences over the subcontinent. For this purpose, hindcast simulations of both atmospheric general circulation models (AGCMs) and ocean-atmospheric coupled models were examined. The AGCM hindcasts examined in this study were based on 5-member ensemble simulations of the Center for Ocean-Land-Atmosphere (COLA) model, over a 20-year period (1985-2004), conducted under the Seasonal Prediction of the Indian Monsoon (SPIM) project. For the coupled model analysis, we have examined ensemble hindcasts from 7 coupled models over a 22-year period (1980-2001) from the DEMETER multi-model prediction system. The analysis reveals that accurate modeling of the IAV of the Indian monsoon rainfall still remains a major challenge. The limitations in modeling the monsoon rainfall variability and possible ways to address this problem are discussed in this chapter.

In **Chapter-VI**, the high-lights of the thesis work are presented. The outlook for future research is briefly summarized at the end.

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