CHAPTER 1

Introduction

Chapter 1: Introduction

1.1 Introduction

The Himalaya, called “the abode of snow” from Sanskrit, is the youngest and highest mountain chain in the world, stretching ~2400 km in length from east to west and ~150-250 km in width from north to south, having an average elevation of 3,500 meters above mean sea level (amsl). It is widely believed that the Himalayan mountain system was originated by the ‘continent-continent’ collision of the Indian plate and Eurasian Plate (Wadia, 1966; Powell and Conaghan 1973; Yin and Harrison, 2000). The Himalaya also known as ‘Third pole of the world’ or ‘Water tower of Asia’ has maximum snow/ice deposition outside the North and South poles. Several perennial rivers originate from the snowy peaks of the Himalaya such as the Ganga, Brahmaputra and Indus Rivers, supplying water for drinking and agriculture purposes in densely populated regions of south Asia. Availability of water in these rivers in turn is determined by the precipitation (rain/snow) over the Himalayan terrain. Moderate changes in precipitation intensity or onset/withdrawal timing in the past are known to have incurred heavy losses of life and resources due to severe floods and draughts (Shewale and Kumar, 2005; Cook et al., 2010; Sinha et al., 2011).

The Himalayan mountain system is marked by varied climatic conditions spatially as Himalayan orography plays an important role in the regional precipitation pattern both spatially and temporally. From east to west, the climate of the Himalaya varies from tropical to subtropical, moist temperate to wet temperate and semi-arid to arid. The Himalayan region receives precipitation from two major moisture sources, the Indian Summer Monsoon (ISM) in summers and the Mid-Latitude Westerlies (MLW) in winters. The influence of ISM winds decreases towards northwest. In the northeast (NE) Himalaya, precipitation is mainly contributed by the ISM while in central and northwest (NW) Himalaya, the MLW also contribute a significant amount of precipitation. Since, the ISM plays a major role in supplying moisture to the Himalaya except some regions of the NW Himalaya, I have mainly focused on ISM variability in the NE and NW Himalaya as my Ph.D. thesis work.

1.2 The Indian monsoon at a glance

The word 'Monsoon' is coined from the Arabic word "*Mausim*" meaning season. The 'Monsoon' is an interhemispheric land-atmosphere-ocean coupled mechanism showing seasonal reversal in wind direction, generally associated with precipitation in warmer hemisphere (Halley, 1686; Gadgil, 2003). Monsoon may be associated with the wet (southwest Indian or summer monsoon) or dry winds (northeast Indian or winter monsoon). During the boreal summers, a strong pressure gradient develops between the Indian Ocean and south Asia due to differential heating of oceanic and continental regions (Fein and Stephens, 1987; Quade et al., 1995). As a result, low atmospheric winds blow from the Indian Ocean towards the Indian landmass. After crossing the equator, these winds get deflected in right direction due to influence of Earth's "Coriolis effect" and enter the Indian subcontinent from the southwest direction, hence called the southwest Indian monsoon (SWIM) or Indian summer monsoon (ISM) (Figure 1.1; Webster et al., 1998; Gadgil, 2003).

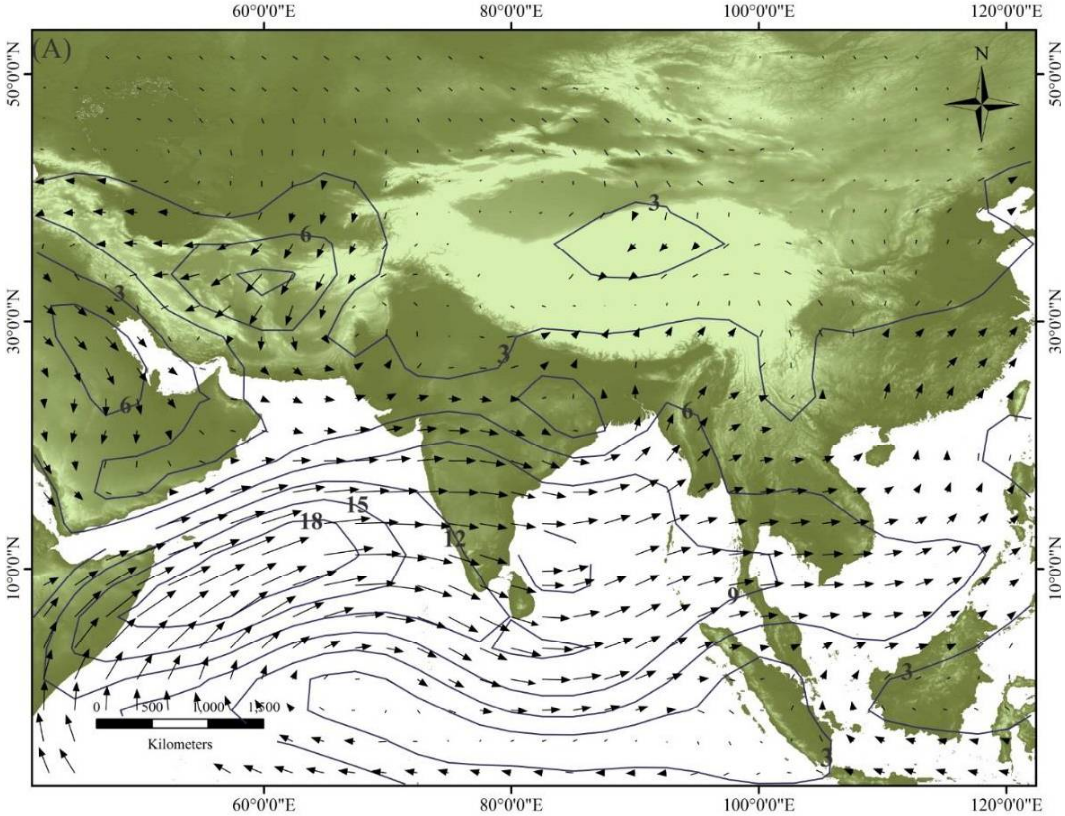

Figure 1.1 July mean 850mb pressure level using the 1981-2010 climatological base period based on International Research Institute for Climate and Society, Earth Institute, Columbia University. The arrows indicate the wind vectors, along with contours indicating the resultant wind speed (m/s). Vector orientation indicates the direction of the resultant wind, and the vector length indicates the wind speed *http://iridl.ldeo.columbia.edu/maproom/Global/Climatologies/Vector_Winds.html) (After Dutt et al., 2015).*

Due to shape of the Indian subcontinent, ISM winds bifurcate into two branches, the Arabian Sea branch and the Bay of Bengal (BoB) branch. The Arabian Sea branch first strikes the Western Ghats and then move further towards the low pressure areas of the Indian peninsula and Ganga plain. The BoB branch of the ISM first strikes NE India and then moves towards the Ganga plain following the low pressure areas from the Bay of Bengal to northwestern India (Gadgil, 2003). The ISM supplies around 80 % of the precipitation throughout the Indian subcontinent except few regions of southern and western India (Parthasarathy, 1986; Gadgil, 2003). During winters, the winds blow from the Indian landmass to the Indian Ocean from the northeast direction, hence called the northeast Indian Monsoon (NEIM) (Figure 1.2). NEIM winds are relatively dry and variable but supply moisture to some parts of southern India, e.g. the state of Tamil Nadu (Parthasarathy, 1986; Gadgil, 2003). Some parts of the northern and northwestern India also receive some precipitation by the MLW which bring moisture from the Atlantic Ocean and the Mediterranean Sea in winters (Tian et al., 2007; Kotlia et al., 2015). Upon reaching Asia, the MLW bifurcate into two branches due to orographic barrier of the Himalaya and Tibetan Plateau. During summers, the MLW weakens over northern India and slowly disintegrate, causing the main MLW flow north of the Himalaya into Central Asia. However during winters, the southern branches of the MLW reform over the northern part of India bringing the winter precipitation (Lockwood, 1974; Pant and Kumar, 1997).

The ISM precipitation largely controls the socio-economic growth of 1/3rd of the world population residing in the Indian subcontinent. The agriculture contributed ~14 percent of Gross Domestic Product (GDP) in India, which is directly affected by the ISM intensity and timing (Gadgil, 2003; Shewale and Kumar, 2005). The extreme events of last few years like 2013 Kedarnath floods, 2014 Kashmir floods, 2015 Chennai floods and 2016 Assam floods as well as repeated droughts in Maharashtra, Haryana and Bihar etc. demonstrate the importance of ISM precipitation and its intensity. The palaeoclimatic records also indicate the huge losses of life and migration of large population during these extreme precipitation events in the history (Cook et al., 2010; Giosan et al., 2012; Dixit et al., 2014).

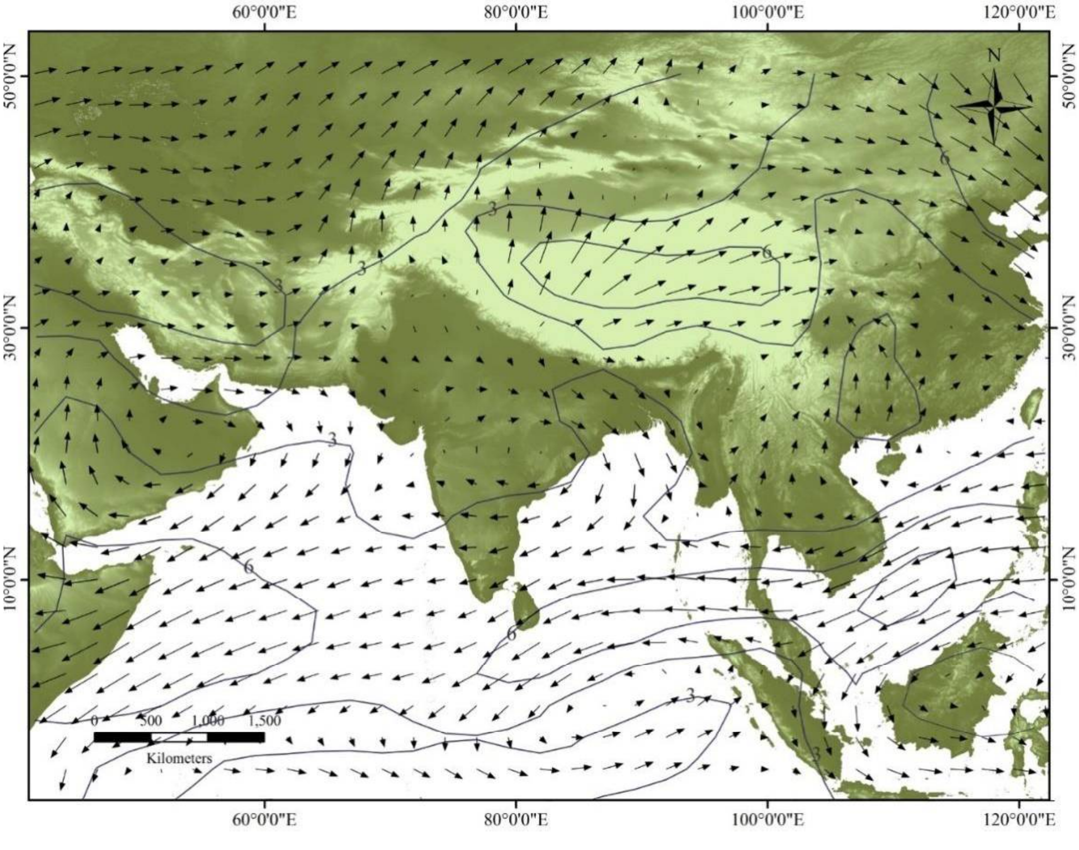

Figure 1.2 January mean 850mb pressure level using the 1981-2010 climatological base period based on International Research Institute for Climate and Society,

Earth Institute, Columbia University. The arrows indicate the wind vectors, along with contours indicating the resultant wind speed (m/s). Vector orientation indicates the direction of the resultant wind, and the vector length indicates the wind speed http://iridl.ldeo.columbia.edu/maproom/Global/Climatologies/Vector_Winds.html) *(After Dutt et al., 2015).*

Numerous studies put the initiation of ISM circulation ~11 Ma (Quade et al., 1989; Prell et al., 1992; Rea et al., 1998; Gupta et al., 2004; Sanyal et al. 2010). However, recent study from the Oman Margin puts the onset of the Indian monsoon at 12.9 Ma (Gupta et al., 2015). The intensification of the Indian monsoon on tectonic time scales has often been linked with the phased uplifts of the Himalaya-Tibetan Plateau (Kroon et al., 1991; Prell et al., 1992). However, Boos and Kuang (2013) recently suggested that the Himalaya influenced the ISM by acting as a barrier to the MLW. The heating of the low elevated areas was more effective in deriving the Indian monsoon than the heating of the Himalaya-Tibetan plateau (Boos and Kuang, 2013).

During the past three centuries, the solar insolation and associated differential heating of land and ocean have been suggested as the primary forcing factors for deriving monsoonal circulation (Halley, 1686; Charney, 1969). But this hypothesis has been criticized by some workers recently because there is no direct correlation between land-sea thermal contrast and ISM precipitation, as ISM is strongest during July and not in the hottest month of June, and the hottest regions of NW India get little monsoonal rainfall (Gadgil, 2003). An alternative hypothesis has been proposed that the latitudinal movement of the Inter Tropical Convergence Zone (ITCZ) (a narrow latitudinal belt of clouds) is major forcing factor in controlling the strength of the ISM (Reihl, 1954; Charney, 1969; Gadgil, 2003). The seasonal latitudinal migration of the ITCZ determines the onset, withdrawal period, frequency and intensity of rainy season in the tropics (Reihl, 1954; Charney, 1969; Gadgil, 2003). During summers, the maximum solar insolation lies at 23.5°N (Tropic of Cancer), hence the ITCZ moves towards the low pressure areas of the northern hemisphere, resulting in pulling of moisture rich winds from the Indian Ocean towards the Indian subcontinent. While during winter, the maximum insolation lies at 10°N and ITCZ move towards the low pressure areas in South resulting in retreat of the monsoon from NE direction (Gadgil, 2007).

The strength of the ISM is known to be influenced by several external and internal factors on interannual to millennial time scales. The external factors include the changes in Earth's movement around the Sun (eccentricity) and its own axis (precession and obliquity), and changes in solar irradiance. All these effects cause the changes in hemispheric distribution of insolation affecting the global climate (Neff et al., 2001; Clemens and Prell, 2003; Laskar et al., 2004; Yuan et al., 2004). The palaeoclimatic datasets for ISM variability indicate that the solar insolation has critical influence on ISM variability (Agnihotri et al., 2002; Fleitmann et al., 2003; Gupta et al., 2005; Wang et al., 2005; Dutt e al., 2015). The internal factors include changes in snow cover in the Himalaya and central Asia, sea surface temperatures, atmospheric circulation and volcanic activity. Numerous models and palaeoclimatic studies suggested an inverse relationship between ISM intensity and the Eurasian snow cover (Shukla 1987; Bamzai and Shukla, 1999). The increase in the Eurasian snow cover leads to the colder temperature on land due to consumption of some of solar energy in melting the snow. The El Niño Southern Oscillation (ENSO) is another important factor that affects the ISM intensity. Stronger is the ENSO, lesser will be the summer monsoon precipitation (Kumar et al., 2006; Gupta, 2010; Gadgil, 2014). However, this correlation is not constant and several normal monsoon years have been reported in the presence of strong ENSO (Ashok et al., 2001; Krishnaswamy et al., 2014). Another important factor is the Indian Ocean Dipole (IOD) which is the east-west temperature gradient in the Indian Ocean (Saji et al., 1999; Ashok et al., 2001; Krishnaswamy et al., 2014). A positive IOD is characterized by higher precipitation over southern Asia, whereas a negative IOD is linked to the weaker monsoonal precipitation (Krishnan et al., 2011). The cooling of the North Atlantic Ocean also influences the intensity of ISM through the MLW mechanism (Fleitmann et al., 2003; Gupta et al., 2003; Dutt et al., 2015). Several workers have reported that the millennial-scale ISM variability is well correlated with North Atlantic warming/cooling oscillations (Fleitmann et al., 2003; Gupta et al., 2003; Menzel et al., 2014).

1.3 ISM variability during the Holocene

Recent studies indicate that the Holocene climate had experienced repeated occurrences of abrupt centennial to millennial scale shifts in the Indian monsoon.

Changes in the ISM strength during the Holocene have been reconstructed by a large number of palaeoclimatic archives including marine sediments from the Arabian Sea (Overpack et al., 1996; Sarkar et al., 2000; Gupta et al., 2003; Staubwasser et al., 2003) and BoB (Chauhan 2004; Govil and Naidu 2011; Rashid et al., 2011), and continental records of lake sediments (Enzel et al., 1999; Demske et al., 2009; Wünnemann et al., 2010, Leipe et al., 2014, Mishra et al., 2015; Prasad et al., 2014; Hou et al., 2016), peat bogs (Phadtare et al., 2000; Rawat et al., 2015), speleothems (Fleitmann et al., 2003; Yadav and Ramesh 2005; Sinha et al., 2011; Berkelhammer et al., 2012; Dutt et al., 2015), tree rings (Singh and Yadav 2005; Cook et al., 2010; Yadav 2011; Yadav et al., 2017), sand dunes (Singhvi et al., 1994; Juyal et al., 2006) and fluvial deposits (Burbank et al., 1996; Bookhagen et al., 2005; Srivastava et al., 2017). These records indicate the wetter and warmer climatic conditions in the Indian subcontinent during the early Holocene when the ISM was strong (Gupta et al., 2003; Fleitmann et al., 2003; Berkelhammer et al., 2012; Dutt et al., 2015). This strengthening of the ISM is attributed to increased solar insolation and northward shifting of the ITCZ (Fleitmann et al., 2003; Dutt et al., 2015). The monsoonal strength gradually declined during the middle Holocene. In the late Holocene, an abrupt cold-arid phase occurred throughout the globe that reduced the precipitation in monsoon affected regions including the ISM in the Indian subcontinent (Berkelhammer et al., 2012; Dixit et al., 2014; Leipe et al., 2014). But these records are not always correlatable which may be due to different response of two branches of the ISM (the Bay of Bengal branch and the Arabian Sea branch), changes in moisture source (effects of westerlies), limitations in the responses of proxies and position of the ITCZ (Prasad and Enzel, 2006; Fleitmann et al., 2007; Wang et al., 2010; Sinha et al., 2011; Dutt et al., 2015). Some studies also indicate an intense ISM during the Medieval Warm Period (MWP) and Current Warm Period (CWP) while the cold phase of the Little Ice Age (LIA) witnessed a weak ISM phase in the region (Thompson et al., 2000; Agnihotri et al., 2002; Anderson et al., 2002; Gupta et al., 2003; Singh et al., 2015). Nevertheless, the high resolution studies of precipitation variability in the Himalayan regions are lacking. Studies in Himalayan regions are very important as the Himalaya is the major source of water for most of the perennial rivers in the Indian subcontinent.

1.4 Definition of the Problem

The Himalayan ecosystem is very fragile due to rapid changes in the temperature with altitude. These erratic climatic conditions make the region quite vulnerable and unpredictable. Therefore, the signatures of past climate documented by various natural archives in the Himalayan regions (via lake sediments, ice cores, peat deposits, speleothems) are very useful in understanding the sensitivity of monsoonal system.

The changes in the intensity of the ISM behavior have been documented in a number of natural archives. The marine records from the Arabian Sea and Bay of Bengal present ISM variability on longer time scales (Overpack et al., 1996; Sarkar et al., 2000; Gupta et al., 2003; Staubwasser et al., 2003; Chauhan 2004; Govil and Naidu 2011; Rashid et al., 2011). But these records are not always synchronous with the continental records. The terrestrial archives (lake, speleothems and tree rings) can provide the high resolution changes of the monsoonal variability, but most of the available records are of low resolution and not from the Himalayan regions. Also the instrumental records are very sparse from the Himalayan regions. Therefore, in the present work, we have selected two limestone caves, the Wah Shikar and Mawmluh cave from NE Himalaya and the Tso Moriri Lake from NW Himalaya to understand the high resolution variability of the ISM across the Himalayan region.

1.5 Objectives

The major objectives of this research work are:

1. To reconstruct history of the Indian Summer Monsoon in the Himalayan region with an emphasis on extreme monsoon events (droughts and floods) during the last 1000 years
2. To understand a relationship between Indian summer monsoon and mid latitude westerlies
3. To understand forcing factors that drove changes in the Indian summer monsoon on short time scale
4. To investigate the role of climate in driving major socio-economic changes in south Asia

To achieve these objectives, I selected the Wah Shikar and Mawmluh caves from NE Himalaya and the Tso Moriri Lake from NW Himalaya. The caves lie in the region of maximum rainfall in the world and cave deposits of this region are well established proxies for reconstructing the variability of ISM precipitation (Parthasarthy, 1986; Gadgil, 2003; Sinha et al., 2011; Berkelhammer et al., 2012; Dutt et al., 2015). On the other hand, the Tso Moriri Lake lies in the cold desertic region of Ladakh in the NW Himalaya, receives very little of annual precipitation. But, this region is situated on the northern margin of Inter Tropical Convergence zone (ITCZ) and reflects the modest change in the regional climate (Wünnemann et al., 2010; Leipe et al., 2014; Mishra et al., 2015).

The regional precipitation and climatic variability in the NE and NW Himalaya have been reconstructed based on multiple proxies analysis of the cave and lake deposits, respectively. The intercomparison of theses records with earlier established palaeoclimatic time series have been done to understand the probable forcing mechanisms on different time scales.

1.6 Organization of the Thesis

The organization of my thesis is based on the stable isotopic investigations ($\delta^{18}O$ and $\delta^{13}C$) on speleothem samples from the Wah Shikar and Mawmluh caves, Shillong Plateau, NE Himalaya and multiple proxies (grain size, elemental abundances, stable isotopes) from the Tso Moriri Lake, Ladakh, NW Himalaya.

Chapter 1: Introduction chapter gives an introductory account of precipitation pattern in the Himalaya, the Indian summer monsoon and its variability during Holocene. The objectives and significance of this study have also been discussed in this chapter.

Chapter 2: Study area and Modern climatic conditions discusses about the geology and modern climatic conditions in the study areas: the Wah Shikar cave and Mawmluh cave, Shillong Plateau, NE Himalaya and the Tso Moriri Lake, Ladakh, NW Himalaya.

Chapter 3: Materials and Methods describes in detail the field sampling, chronology and analytical procedures adopted for various analyses of the speleothem sample from the Wah Shikar and Mawmluh cave, NE Himalaya and sediment samples from the Tso Moriri Lake, NW Himalaya.

Chapter 4: Variability in Indian summer monsoon strength in the northeast Himalaya during the last millennium with major emphasis on extreme events describes ISM variability in the NE Himalaya over the past millennium using stable isotopic ($\delta^{18}O$ and $\delta^{13}C$) investigations of stalagmite (cave) carbonate from the Wah Shikar cave (WSS-3), Shillong Plateau, NE Himalaya. The impacts of ISM changes on the Indian society and controlling mechanisms of ISM variability in this time span are also discussed.

Chapter 5: Abrupt changes in Indian summer monsoon strength between 33,800 to 5,500 yrs BP discusses the changes in ISM strength in NE Himalaya during 33,800 to 5,500 yrs BP with emphasis on abrupt climate events, using the stable isotopic ($\delta^{18}O$ and $\delta^{13}C$) investigations of stalagmite MWS-1 from the Mawmluh cave, NE Himalaya. The changes in Indian summer monsoon have been compared with the global climate pattern. The forcing factors and global teleconnections to the ISM during this time span are also investigated.

Chapter 6: Abrupt weakening of the Indian summer monsoon ~4.3 kyr BP:

collapse of the Indus Valley civilization describes the precipitation variability in the NW Himalaya during the last 4,500 years based on study of multiple proxies including $\delta^{18}O$ and $\delta^{13}C$ ratios in bulk carbonate, elemental abundances, $\delta^{13}C$ ratio in bulk organic carbon, total organic carbon (TOC) percentage and grain size variations from the Tso Moriri Lake, Ladakh Himalaya. The ISM weakening around 4.3 kyr BP coinciding with the collapse of the Indus Valley civilization have been discussed in detail.

Chapter 7: Conclusions chapter discusses the conclusions of my research work in reference to the proposed objectives.

Chapter 8: References lists the references of the literature referred in this work.

1.7 Significance of this study

The present study focuses on the reconstruction of abrupt precipitation events in the Himalayan region using proxy records from the NE and NW Himalaya. The knowledge about the occurrence of abrupt and extreme precipitation events in the past, will help to understand their frequency and intensity in near future in changing global climatic conditions and making the strategies to minimize the effect of such events. The role of ISM precipitation in shaping the history of south Asia can also be investigated using these high resolution records. This data will fill the data gap of ISM variability in the Himalayan region which can also be used in making/improving climatic models.