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PRECIPITATION FLUCTUATIONS IN THE NEPAL HIMALAYA AND ITS VICINITY AND RELATIONSHIP WITH SOME LARGE SCALE CLIMATOLOGICAL PARAMETERS

ARUN B. SHRESTHA[a,b,]*, CAMERON P. WAKE[a,c], JACK E. DIBB[a,c] and PAUL A. MAYEWSKI[a,c]

[a] *Climate Change Research Center, University of New Hampshire, Durham, NH, USA*
[b] *Department of Hydrology and Meteorology, Kathmandu, Nepal*
[c] *Department of Earth Sciences, University of New Hampshire, Durham, NH, USA*

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ABSTRACT

Precipitation records from 78 stations distributed across Nepal were analysed and all-Nepal (1948–1994) and subregional records (1959–1994) were developed. The all-Nepal and regional precipitation series showed significant variability on annual and decadal time scales. Distinct long-term trends were not found in these precipitation records. The all-Nepal record agrees well with the precipitation records from northern India, while it does not compare well with the all-India precipitation record.

The all-Nepal monsoon record is highly correlated with the Southern Oscillation Index (SOI) series. The exceptionally dry year of 1992 recorded in Nepal coincides with the elongated El Niño of 1992–1993 and the Mount Pinatubo eruption. A remarkable cooling in the region covering the Tibetan Plateau also occurred in 1992, suggesting that Pinatubo aerosol played a major role in the drought of that particular year in Nepal. In other years, the correlation between the precipitation record from Nepal and the temperature of the Tibetan Plateau is not significant, while a stronger correlation with temperature over the Indian Ocean and southern India exists. This provides further support for the strong relationship between the El Niño–Southern Oscillation (ENSO) and precipitation fluctuation in Nepal. The correlation is stronger between all-Nepal monsoon precipitation and SOI averaged over seasons following the monsoon compared with seasons preceding the monsoon. Copyright © 2000 Royal Meteorological Society.

KEY WORDS: Nepal; Himalaya; south Asia; spectral analysis; El Niño

1. INTRODUCTION

Surface air temperature is commonly used to study the state of climate systems and numerous studies have investigated trends in global, hemispheric and zonal mean temperatures (e.g. Angell and Korshover, 1978; Jones *et al.*, 1986a,b,c; Hansen and Lebedeff, 1987, 1988; Hansen *et al.*, 1996). In addition, several modelling studies have attempted to calculate the changes in temperature caused by increases in greenhouse gases (GHG) (e.g. Mitchell *et al.*, 1990; IPCC, 1996). However, while temperature is a good indicator of climate change, precipitation may be of equal or greater importance in terms of monitoring global change in low and mid-latitude regions because of their vulnerability to both water shortages and quality (Farmer and Kelly, 1989; Mirza and Dixit, 1997). Analyses of global precipitation variations reveal marked trends in recent decades. For example, rain and snowfall amounts over the middle and high latitudes rose steadily over the past decades, whereas a pronounced decreasing trend occurred in the subtropics (Bradley *et al.*, 1987; Diaz *et al.*, 1989). This trend observed in the subtropics is largely accounted for by droughts occurring in parts of sub-Saharan and Sahelian Africa (Bradley *et al.*, 1987; Follard *et al.*, 1990).

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* Correspondence to: Department of Hydrology and Meteorology, PO Box 406, Babar Mahal, Kathmandu, Nepal; e-mail: dhm@wlink.com.np

South Asia is a region influenced by the summer monsoon and the agricultural subsistence of the region's population depends greatly on monsoon rains. While several studies on monsoon and annual precipitation in India do not identify any long-term trends (Parthasarthy and Mooley, 1978; Hakkarinen and Landsberg, 1981; Mooley and Parthasarthy, 1983; Parthasarthy *et al.*, 1992), Kothyari and Singh (1996), based on non-parametric analyses, suggest a slight decrease in precipitation after the 1960s.

The climate of South Asia is dominated by the monsoon circulation system. The summer monsoon dominates the climate from May to September and westerly circulation dominates from November to March. The influence of these two circulation systems is not evenly distributed over the Himalaya, with summer rainfall greater in the southeast and westerly-derived winter precipitation greatest in the northwest (Nayava, 1980; Mani, 1981).

While abundant work has been carried out on monsoon and annual precipitation in India, there exists only limited knowledge concerning precipitation variations in the foothills and mountains of Central Asia. Recently, Shrestha *et al.* (1999) studied temperature trends over Nepal and found broad agreement with temperature trends in the Northern Hemisphere (NH) and the Tibetan Plateau, while the Nepal temperature trends differ from those found in the Indian plains.

In this paper, the precipitation records from stations distributed across Nepal for the longest possible period (1948–1994) are analysed. Based on these records, for the first time an all-Nepal (1948–1994) and within-Nepal regional (1959–1994) precipitation series is developed to study annual and seasonal precipitation changes. These records are compared and contrasted with precipitation records from India, temperature records from neighbouring regions to the north and the south of the Himalaya, in addition to other records of large scale climatological parameters.

2. DATA AND METHODS

Precipitation data were obtained from the Department of Hydrology and Meteorology (1966–1997), Nepal. Precipitation records from 89 stations were examined, with data dating from prior to 1976 and continuing until the present. In 1948, only 14 precipitation stations existed in Nepal but by 1959 this had increased to 83. The earliest year to provide adequate record length (~ 40 years; World Meteorological Organization, 1966a) and to include enough stations for a fairly widespread geographic coverage is 1959. These 83 stations have relatively few missing data (less than 3% of the total number of annual values). As a result of great changes in elevation within a relatively short distance, there are great differences in precipitation within relatively small distances. Hence, it is not possible to fill missing data solely by spatial interpolation (Hormann, 1994). Therefore, major portions of missing data sets were filled using temporal interpolation (monthly value as an average of the same month for a period between ± 2 years; World Meteorological Organization, 1966a).

The 83 stations selected were tested for homogeneity, normality and the presence of persistence using rigorous statistical examinations. The homogeneity of the series was tested using Swed and Eisenhart's run test (run above and below median) (World Meteorological Organization, 1966a,b). Only two stations failed the test, as their numbers of runs were above the limit at the 5% significance level. The chi-square test was performed to test the normality of each station record (Crow *et al.*, 1960). Only four stations showed frequency distributions other than Gaussian. To examine the presence of Markov type persistence in the time series, autocorrelation up to 10 lags (10 years) was examined. Just three stations showed significant autocorrelation. Altogether, five station records were discarded following these statistical tests, reducing the number of stations used for further investigations to 78 (Figure 1).

The precipitation data used in this study are published as monthly precipitation values (Department of Hydrology and Meteorology, 1966–1997). From the monthly precipitation values, annual precipitation values were calculated as the sum of January–December precipitation. Furthermore, seasonal precipitation values were derived as follows: Winter (December of previous year to February); pre-monsoon (March–May); monsoon (June–September); and post-monsoon (October and November).

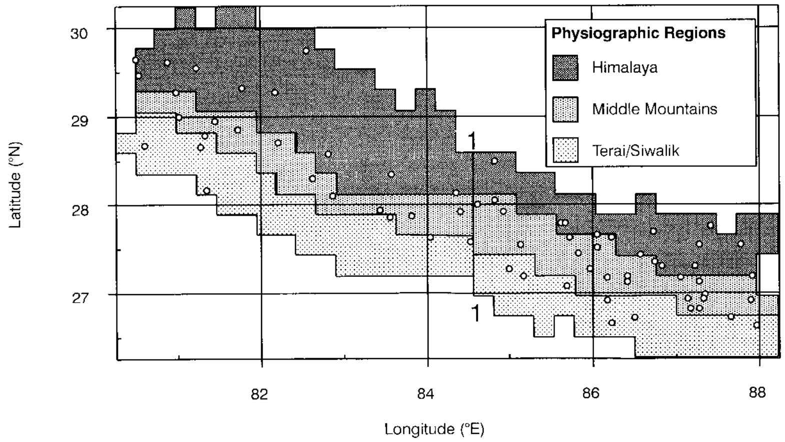

Figure 1. Station location map and delineation of six subregions. The vertical line 1–1 separates eastern and western subregions. Open circles identify the station locations for precipitation records used in this study

All-Nepal precipitation series was developed using the method described in Hansen and Lebedeff (1988). The advantage of this method over simple area weighted averaging is the possibility of using a variable number of stations for different time periods. In this method, a relatively long record is initially chosen. The second record (generally shorter) is linearly shifted by a value equal to the difference between the averages of the two records, for the overlapping period (subperiod). For that subperiod, the annual precipitation values of the first record are substituted by averages of the original first record and the transformed record for respective years. This process is repeated with the transformed first record and remaining records. The time series developed by this method can be used to analyse trends and variability; however, absolute precipitation values cannot be obtained.

The regional precipitation series were only derived for the period following 1959, when all 78 stations were operational. In this analysis, the country was divided into three regions: Terai and Siwalik; Middle Mountain; and Himalaya. These divisions are based primarily on the representation of each region by the maximum possible and uniformly distributed number of stations. It is fairly common to combine Terai and Siwalik regions as one climatic region (Chalise, 1986). Because of the narrow elongated nature of these three regions, and the uneven zonal dominance of the summer monsoon and westerly circulation over them, they were further divided into western and eastern parts (Figure 1). For the six regions, precipitation series were developed by arithmetically averaging the station records. To remove the interannual variability, and to investigate if trends are present in the record, the all-Nepal and six regional precipitation series were smoothed using a robust spline with 65% smoothing (Meeker *et al.*, 1995). All precipitation series are standardized by subtracting the mean and dividing by the S.D.s.

To investigate whether the all-Nepal record had periodicities common to large scale climatological phenomena, the all-Nepal precipitation series was subjected to spectral analysis. The spectral analysis was performed by fast Fourier transform (FFT), using a split cosine window with 25% tapers on both sides but without any padding (Meeker *et al.*, 1995).

3. RESULTS

3.1. All-Nepal precipitation series

The standardized all-Nepal monsoon precipitation series shows great interannual variability in the amount of precipitation (Figure 2(a)). The spline curve shows that there is also a significant decadal scale variability with distinct peaks in 1962, 1973 and 1984.

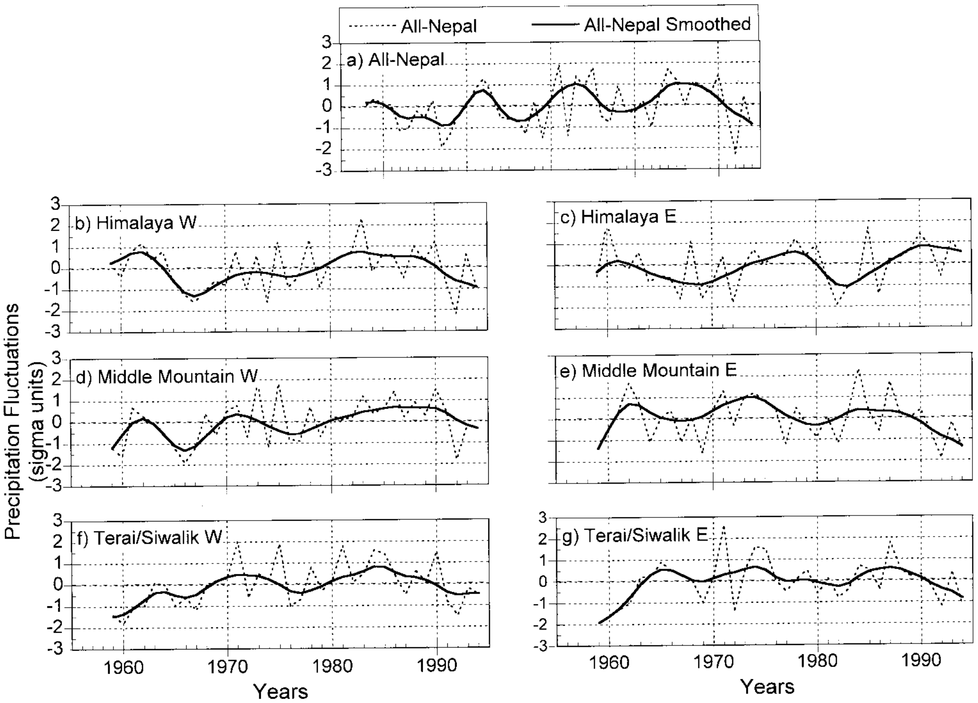

Figure 2. Standardized monsoon precipitation series in sigma units (dotted lines) and their spline curves (solid lines) for: (a) all-Nepal; (b) Himalaya West; (c) Himalaya-East; (d) Middle Mountain West; (e) Middle Mountain East; (f) Terai/Siwalik West; and (g) Terai/Siwalik East subregions. Note time scale difference between (a) and (b–g)

Oscillatory characteristics, visible in the series, are supported by spectral analyses which show significant peaks (at 95% confidence level) at periods close to 2.5 and 11 years in both the all-Nepal annual and the monsoon precipitation series (Figure 3(a, b)). Similarly, the winter, pre-monsoon and post-monsoon series also contain significant peaks at periods close to 2.5 years, although the 11-year peak is not present (figures not shown).

After 1990 the all-Nepal series shows a downward trend, the timing of which is consistent with the near 11-year periodicity, although the duration of the drop is longer than would be expected from the 11-year cycle alone. This is possibly because of end effects inherent in the smoothing technique. It should be noted that 1992 is the driest year in the entire record (more than 2 S.D.s below normal).

3.2. Regional precipitation series

The 2–5 year oscillatory characteristics in the all-Nepal series are also visible in regional series (Figure 2(b–g)). Furthermore, the majority of the regional series display oscillations similar to the 11-year oscillation in the all-Nepal series, although the phasing and amplitudes of these oscillations differ by region.

As in the spline of the all-Nepal record, all of the smoothed regional series show a drop in precipitation in the early-1990s and 1992 is markedly dry in all of the regional series.

4. DISCUSSION

Model studies suggest an increase (5–15%) in monsoon precipitation with greenhouse-induced global temperature increases (e.g. Follard *et al.*, 1990; Meehl and Washington, 1993; Meehl *et al.*, 1996). This is consistent with the basic principle of the monsoon—increase in land–ocean thermal contrast as a result

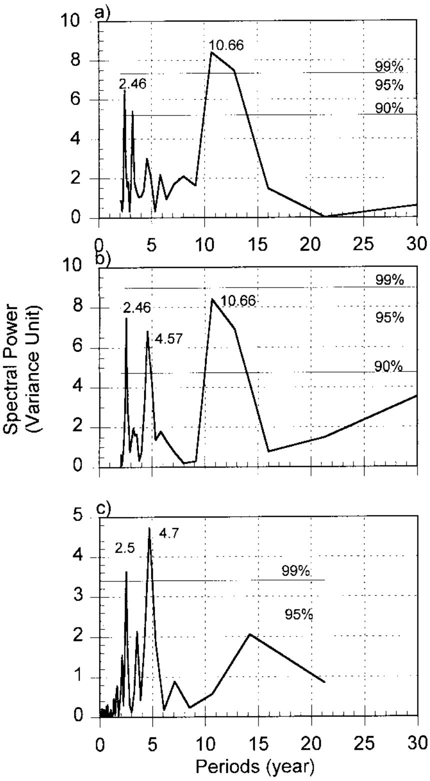

Figure 3. Power spectra of all-Nepal precipitation series for the (a) annual, (b) monsoon season and (c) SOI series

of global warming, resulting in intensification of monsoon circulation (e.g. Meehl, 1994). Preliminary model results on changes in precipitation in Nepal due to an increase in atmospheric GHG also predict precipitation increases, especially in the western part of the country (personal communication Dr M.L. Shrestha, DHM), although model studies that include sulphate aerosol forcing predict monsoon precipitation to decrease (Lal *et al.*, 1994, 1995; Mudur, 1995). However, there is no indication of an overall trend in precipitation in Nepal. An increasing trend is apparent between 1967 and 1990 in the all-Nepal and the three western regions' records, although the magnitude is low compared with the annual and decadal variability. The lack of a distinct long-term trend in precipitation in Nepal may be the result of Nepal's location between two large emission sources in Asia, i.e. China and India (Foell *et al.*, 1995; Arndt *et al.*, 1998). Recent studies show that the sulphate aerosol burden in the atmosphere in Nepal is largely of Indian origin (Arndt *et al.*, 1998). It is likely that the increase in atmospheric sulphate aerosol has already begun to affect the monsoon in the Himalaya, offsetting the increasing trend in monsoon precipitation that would have been caused by the increase in atmospheric GHG alone.

Despite the lack of long-term trends, the presence of characteristics common to all-Nepal and regional precipitation series indicates homogeneity in precipitation on annual and seasonal time scales, despite great orographic disparity. The presence of 2.5 and 11-year periodicities in the all-Nepal annual and seasonal series suggests that the records could be related to large scale climatological parameters, such as the quasi-biennial oscillation (QBO) and sunspot cycles, respectively. A direct comparison between the all-Nepal precipitation record and the QBO record (equatorial wind speed at 50 mb; NOAA, Climate Prediction Center; http://nic.fb4.noaa.gov/data/cddb/) shows that the relationship is not consistent as the two records are in-phase during some periods while out of phase in others, suggesting that the QBO is not responsible for the 2.5-year periodicity in the all-Nepal records (figure not shown). The all-Nepal precipitation record was also compared with the Zurich sunspot number dataset (NOAA. National Geophysical Data Center; http://www.ngdc.noaa.gov/stp/SOLAR/SSN/SSN.html). Again, a statistical relationship between two series was not found.

Several studies on monsoon precipitation in India have discovered a close relationship between the monsoon and El Niño–Southern Oscillation (ENSO) (e.g. Mooley and Parthasarthy, 1983; Khandekar and Neralla, 1984; Khandekar, 1991; Barnett *et al.*, 1991). El Niño warm phases are associated with warmer sea surface temperature (SST) in the equatorial Pacific as well as in the Indian Ocean, resulting in a decreased land–ocean thermal contrast, thus reducing the strength of the monsoon. A spectral analysis of the monthly SOI record (NOAA, National Geophysical Data Center) for the period 1967–1994 (overlapping the length of the all-Nepal record) shows the presence of significant peaks at 2.5 and 4.7 years (Figure 3(c)). Furthermore, direct comparison between the all-Nepal precipitation series and the SOI shows strong agreement between these records, i.e. low all-Nepal precipitation during El Niño warm phase periods (low SOI) (Figure 4(a)). The all-Nepal monsoon precipitation also contains a periodicity close to the 4.7-year periodicity in SOI (i.e. 4.6 years), although significant only at 90% (Figure 3(b)), suggesting that the 2.5-year periodicity in the ENSO has a strong relationship with the all-Nepal monsoon record. The relationship between the all-Nepal record and SOI is much better than that observed between the all-India precipitation and SOI, especially for the period after 1970. The correlation coefficient between the all-Nepal monsoon record and annual averaged SOI for the period 1970–1994 is 0.64 ($n = 94$, $p < 0.05$; Table I).

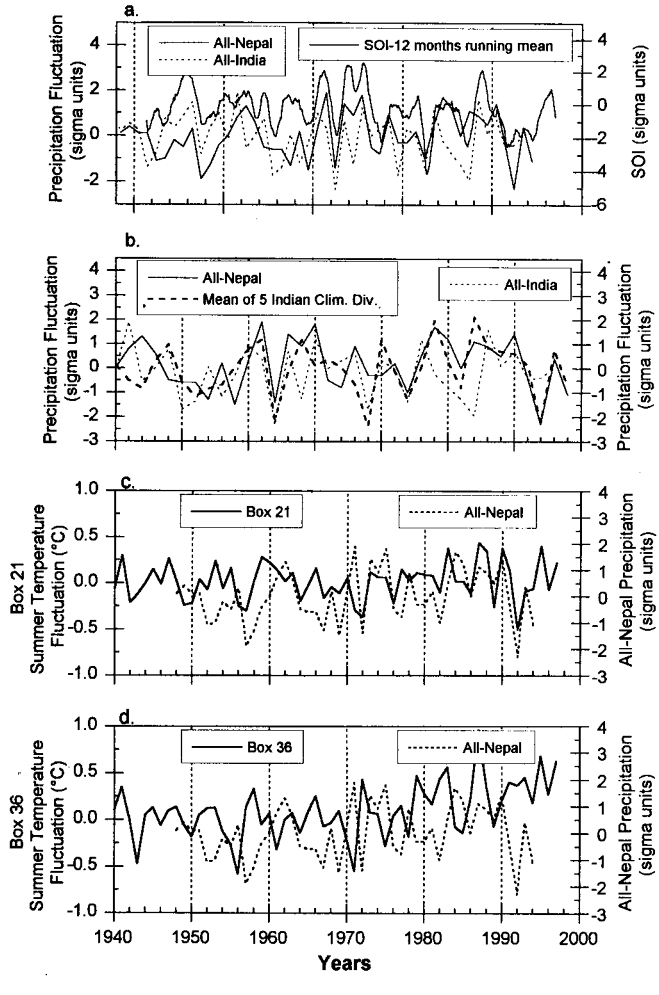

Figure 4. Comparison between: (a) all-Nepal precipitation, all-India precipitation, and SOI; (b) all-Nepal precipitation, all-India precipitation, and weighted mean precipitation series of five northern Indian climatological divisions; (c) all-Nepal monsoon precipitation and Box 21 (Tibetan Plateau) temperature; and (d) Box 36 (India/Indian Ocean) temperatures

Table I. Correlation between all-Nepal monsoon precipitation and SOI

Period	Average SOI							
	Annual	Antecedent season (January–May)	Succeeding season (October–December)	Antecedent winter (December–February)	Antecedent pre-monsoon (March–May)	Concurrent monsoon (June–September)	Succeeding post-monsoon (October–November)	Succeeding winter (December–February)
1951–1994	0.49	0.28	0.50	0.12	0.40	0.43	0.49	0.51
1961–1994	0.56	0.27	0.60	0.09	0.45	0.52	0.59	0.54
1971–1994	0.64	0.30	0.70	0.04	0.53	0.63	0.69	0.65

A comparison between precipitation fluctuations over Nepal and over India does not show good agreement. Although a dry (wet) year in the all-India record (Sontakke *et al.*, 1993) is generally a dry (wet) year in the all-Nepal record, the magnitudes are considerably different (Figure 4(b)). The year 1992 was the driest in the all-Nepal records, as well as in most of the regional records (about 2 S.D.s below normal). In the same year, the all-India record precipitation was also below normal, but not as low as in Nepal (Figure 4(b)). On the other hand, the weighted mean precipitation from five northern Indian climatological divisions exhibit a comparable drop in precipitation from 1990 to 1992 (Figure 4(b)). Variations thereafter are also comparable with those in the all-Nepal record. This result asserts that the unique climate episode of 1991–1992 prevailed in the northern part of the subcontinent, but was absent in the southern regions. It is suggested that the precipitation climatology in the northern part of the subcontinent (including the Himalayan region) is different from the rest of the subcontinent, and that the precipitation record from India as a whole (and generally excluding the Himalayan region) is not always a suitable representation for the region.

The exceptionally dry year of 1992 coincides with two climatologically prominent incidents: an elongated warm phase El Niño of 1991–1993 and the Mount Pinatubo eruption of June 1991. Both events could have negative impacts on monsoon precipitation (Nicholls, 1983; Handler, 1986; Barnett *et al.*, 1991; Meehl, 1994). Widespread cooling resulting from the Mount Pinatubo eruption has been recorded (World Meteorological Organization/United Nations Environmental Program, 1995; Hansen *et al.*, 1996), although such cooling was not observed in Nepal (Shrestha *et al.*, 1999). However, a considerable drop in temperature occurred in the region to the north of the Himalaya (Box 21 mean temperature record developed by Hansen and Lebedeff (1988) and Hansen *et al.* (1996)), including the Tibetan Plateau (Figure 4(c)). For the entire length of the record, there is a significant positive correlation between the all-Nepal precipitation and the Tibetan Plateau temperature records ($r^2 = 0.40$; $p = 0.05$), whereas the correlation is not significant if the 1992 data is not included ($r^2 = 0.30$; $p > 0.05$). A similar comparison with Box 36 (including India and the Indian Ocean) shows a better negative correlation ($r^2 = 0.45$; $p = 0.01$; analysis includes 1992 data) (Figure 4(d)). It is suggested that the anti-correlation between India/Indian Ocean temperature and the all-Nepal precipitation is the manifestation of the link between El Niño events and the monsoon precipitation over the Himalaya. The year 1992 is unique in the sense that there are synchronous drops in the Tibetan Plateau temperature and all-Nepal precipitation records, while there is no reciprocal rise in the India/Indian Ocean temperature (Figure 4(c, d)). The decrease in Tibetan Plateau temperature for the year 1992 cannot be associated with the El Niño event as a decrease in land temperature (in Central Asia) resulting from El Niño events has yet to be observed. This result asserts that the Pinatubo aerosol is responsible for the temperature decrease over the Tibetan Plateau, which in turn resulted in the decrease in monsoon precipitation in Nepal in that particular year. We also investigated the potential influence of two other major volcanic eruptions within the period of precipitation records from Nepal: Agung (March 1963) and El Chichon (April 1982). The precipitation record from Nepal and the Tibetan Plateau temperature record do not show a drop in 1963 similar to that observed in 1992. This is most likely a result of significantly lower aerosol loading from the Agung eruption (McCormick *et al.*, 1995), combined with the fact that the aerosol loading was concentrated more in the southern hemisphere (Sato *et al.*, 1993). While the eruption of El Chichon coincides with a significant drop in precipitation in Nepal (and in India) and a slight drop in the Tibetan Plateau temperature record, 1982 also experienced a strong El Niño. Furthermore, the amount of stratospheric aerosol produced by the El Chichon eruption was much smaller than that produced by Pinatubo (McCormick *et al.*, 1995).

To investigate the cause and effect relationship between the all-Nepal monsoon precipitation and ENSO, correlation coefficients between all-Nepal monsoon series and SOI averaged over different seasons were computed (Table I). The correlation coefficients between the all-Nepal monsoon series and SOI averaged over seasons following the monsoon are higher compared with those with seasons preceding the monsoon.

Furthermore, the relationship improves in the later part of the record. This result supports the findings of studies suggesting the role of the monsoon in triggering El Niño (e.g. Khandekar, 1991; Barnett *et al.*, 1991, etc.). These studies, however, emphasize the role of Eurasian snow cover (ESC) on the monsoon, which in turn is suggested to influence ENSO. We also investigated the influence of ESC (NOAA, Climate Prediction Center: http://nic.fb4.noaa.gov/data/cddb/) on monsoon precipitation in Nepal. Previous work identified an inverse relationship between all-Indian monsoon precipitation and ESC (Dey and Bhanu Kumar, 1982; Khandekar, 1991), although this relationship has recently been questioned (personal communication, C. Duncan, University of Massachusetts). A comparison of ESC and the all-Nepal precipitation record showed only a weak correlation ($r = -0.01$). The statistical relationship between all-Nepal monsoon and ENSO found in this study is possibly a product of complex atmosphere–ocean dynamics and requires further investigation.

5. SUMMARY AND CONCLUSION

Precipitation data from Nepal over the past three decades show large interannual and decadal variability in the all-Nepal as well as regional (within Nepal) precipitation records. The lack of a long-term increasing trend in the precipitation records, despite the fact that climatic models predict an increase in monsoon precipitation because of GHG-induced warming, could be an indication of the countering effects of the recent increases of atmospheric sulphate aerosol resulting from the combustion of fossil fuels in Asia.

Indications of an association between precipitation in Nepal with ENSO events were found. Furthermore, precipitation records from Nepal compare much better with the precipitation from the northern part of India compared with the aggregated record for all of India. This suggests that the precipitation climatology of the Himalaya and its vicinity behave differently from the southern part of the subcontinent, and the all-India precipitation record does not provide a valid representation of the entire subcontinent.

The exceptionally dry year of 1992 coincided with two important climatic events: an elongated El Niño event and the eruption of Mount Pinatubo. A drop in the Tibetan Plateau temperature record, similar to that in the all-Nepal precipitation record for 1992, supports a strong role for the Pinatubo aerosol in the observed dry event. Over the entire period of record, a strong anti-correlation between the all-Nepal precipitation record and temperature over the Indian Ocean and India exists, while there is a lack of significant correlation between the all-Nepal precipitation record and the temperature record from the Tibetan Plateau. The all-Nepal monsoon correlates better with concurrent and succeeding SOI. Nevertheless, because of a lack of significant anti-correlation between the ESC and the all-Nepal precipitation record this study does not support the postulated European snow cover–monsoon–ENSO connection.

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