Climate Change in the Northwestern Himalayas

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Abstract The paper examines the magnitude of warming in Northwestern Himalaya during the period from 1866 to 2006. The analyses of the temperature data show an average rate of increase of about 1.1 °C/100 years during this period. Warming effect is particularly significant during the winter season. Winter temperature has shown an elevated rate of increase (1.4 °C/100 years) than the monsoon temperature (0.6 °C/100 years), due to rapid increase in both, the maximum as well as minimum temperatures, with the maximum increasing much more rapidly. Statistically significant decreasing trends (at 95 % confidence level) in the monsoon and overall annual precipitation during the study period are indicated. In contrast, the winter precipitation has shown an increasing but statistically insignificant trend (at 95 % confidence level). Rising winter air temperatures have caused decreasing snowfall component in total winter precipitation on the windward side of the Pirpanjal Range. The studies also indicate reduced the duration of winter by about two weeks in the last three decades. Role of anthropogenic activities influencing climate change in last three decades can not be ruled out.

Keywords Climate change · Warming · Temperature · Precipitation · Northwestern Himalaya

1 Introduction

The Earth's climate has undergone many changes in the geological past. It was the study of these changes in the 19th Century which led to the postulation of the concept of existence of former glacial and inter-glacial periods (Brönnimann 2002). This discovery sparked off a discussion on the reasons behind them and consequently, many scientific studies were initiated to understand the driving

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mechanisms. Considerable data have been amassed since then, from more and more lines of evidence—instrumental records, historical records, proxy records such as dendrochronology based on tree-ring analysis, lake, continental and marine sediments, fossils and pollen grains. Attempts have also been made to reconstruct past climatic fluctuations by studying the response of the glaciers and relative concentration of oxygen isotopes from trapped air samples in the ice-cores drilled in areas like Greenland, Tibetan Plateau and the Himalaya.

Studies have confirmed two types of driving mechanisms or forcings that have caused the climate changes; natural (solar and volcanic) and anthropogenic (human-activity related) (IPCC 1995, 2001, 2007). While variation in solar radiation received on the surface of the Earth due to changes in its orbital parameters (on the time-scales of tens and thousands of years) cause solar forcing, episodes of volcanic eruptions injecting large amounts of sulphur dioxide aerosols in the upper air have caused periodic cooling of the Earth's lower atmosphere. Anthropogenic forcing is the climate change brought about by man's activities. Excessive burning of fossil fuels and changes in land use patterns have increased concentration of gases like CO_2, methane, nitrous oxide, etc. in the atmosphere and have caused the greenhouse effect. Because of their natural origin, solar and volcanic forcings are unavoidable. It is the anthropogenic forcing which has been a matter of great concern. It is believed to be responsible for significant climatic changes that have occurred all over the world in the recent past, with alarming consequences for the mankind.

The climatic changes experienced during the periods of solar forcing were gradual, because they were on fairly long time-scales, spread over tens and thousands of years and on some occasions, a few hundred thousand years. Their gradual nature provided adequate time for the flora and fauna to adapt and undergo suitable changes and flourish in new environment. They even led to the extinction of some species. But the rapidity with which these changes have been experienced in the last two and half centuries has raised certain doubts about their genesis, making it difficult to attribute them to natural causes alone. Coincidentally, this period was also marked by an industrial revolution that started in Europe and had its repercussions all over the globe. Rapid industrialization led to an increase in fossil fuel consumption and in the concentration of greenhouse gases in the atmosphere. Consequent rise in global air temperature, by a modest estimate, of about 0.5 °C to 1.1 °C/100 years in the last 150 years (IPCC 2001, 2007), has led to radical changes in the way we receive precipitation and discharge in our rivers. Probable consequences of these changes are likely to manifest in sea-level rise due to enhanced melting of polar ice-caps and mountain glaciers the world over and short-term increase and long-term decrease in discharge in the rivers (Bhutiyani et al. 2008).

2 Climate Change and Himalayan Mountains

The impact of climate change can be best studied in regions which experience stressed climatic conditions such as deserts and high altitude mountainous areas affected by permafrost conditions (e.g. Tibet, Siberia, and Antarctica etc.). Such areas are characterized by arid climate with scanty precipitation and extreme temperature regimes. The evidences of temporal climate variations, reflected in the deposition of sediments, pollen grains, etc. in deserts and changes in the relative concentration of O^{18} and O^{16} isotopes in glacier and permafrost ice are likely to be better preserved in these areas rather than in regions characterized by heavy rainfall and moderate temperature regimes. Mountain areas such as the Himalayas, the Alps, the Andes, the Rockies etc., because of their great altitudinal range within short distances and high biodiversity, amplify the effects and exhibit climatic regimes that are similar to those of widely separated latitudinal belts (Liu and Chen 2000; Thompson et al. 2000). Besides this, the river systems in mountainous areas, being a key element of hydrological cycle, show good impacts of the shifts in climate. They also bring about the disruption of existing socio-economic structures of population inhabiting their basins (Beniston et al. 1997).

The climate in the Himalaya exercises a dominant control over the meteorological and hydrological conditions in the Indo-Gangetic plains as majority of rivers derive significant portion of their discharge from seasonal snowmelt and/or melting of Himalayan glaciers. In view of their overall importance in the context of Indian sub-continent, the study of long-term and short-term climate changes in the Himalaya and their perilous impacts on its fragile eco-system assumes importance. Because of the vast spread and large variations in hydro-meteorological conditions in different parts and impracticability of carrying out such work for the entire Himalaya, this paper covers the northwestern portion only, comprising of the states of Jammu and Kashmir and Himachal Pradesh (Fig. 1). This region, besides being influenced by, more or less, similar meteorological conditions, has a significant concentration of glaciers in its river basins, and better network of meteorological stations as compared to the central and eastern Himalaya.

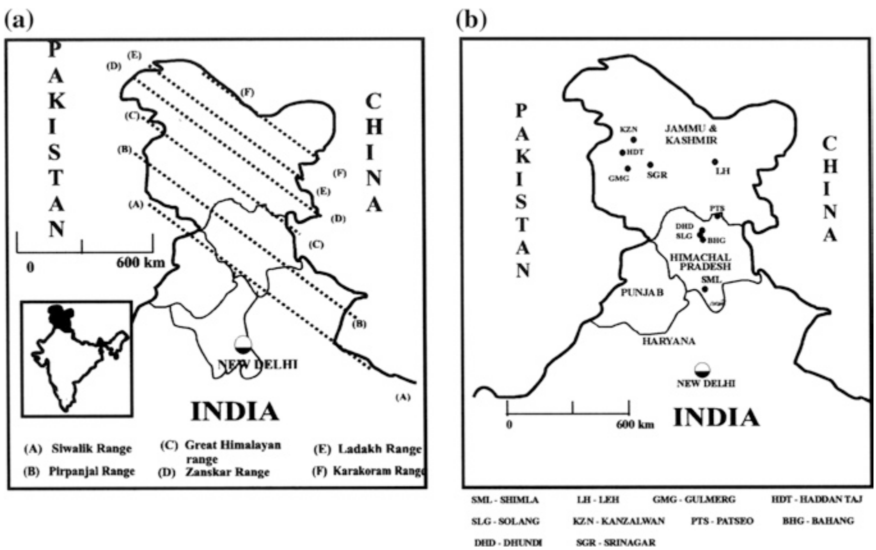

Fig. 1 Map of the northern western Himalaya showing approximate location of various range (**a**) and the meteorological stations (**b**)

3 Magnitude of Climate Change in the NW Himalaya

The climate in northwestern Himalaya (NWH) is influenced by the western disturbances during the winter months from October to May and southwest monsoon from July to September. Precipitation during monsoon period is highest in Siwalik and Pirpanjal Ranges and it reduces as one traverses northwards into the Great Himalaya, Zanskar, Ladakh and Karakoram ranges (Rakhecha et al. 1983). Significant variation is also observed in annual winter snowfall due to western disturbances in the NWH as various ranges in the NWH receive different amounts of snowfall ranging from about 100 to >1,600 cm (snow depth). It is maximum in the Pirpanjal Range and decreases as one goes northwards. Because of the variation in the mean air temperature, the changes occur in the percentage of solid precipitation (snowfall) to rainfall, duration of seasonal snowcover, snow settlement (densification) rates and ablation rates in different ranges of the NWH (Mohan Rao et al. 1987; Bhutiyani 1992).

As compared to some studies on high elevation regions round the globe such as by Diaz and Bradley (1997), Beniston et al. (1997), Beniston (2003), Diaz et al. (2003), Rebetez (2004), very few studies have been carried out on the fluctuations in the climate in the Himalayan Mountains, primarily because of inaccessible terrain and inadequate database. Using the instrumental records, a few studies have examined the rainfall and temperature variations in the Nepal Himalaya and the Tibetan Plateau (Li and Tang 1986; Seko and Takahashi 1991; Borgaonkar et al. 1996) and Upper Indus Basin in Karakoram Himalaya (Fowler and archer 2006). Temperature trends at Katmandu in Nepal Himalaya and the Kosi Basin in Central Himalaya have been studied from the point of view of long-term trends (Sharma et al. 2000). The precipitation trends in the western Himalaya and northwestern Himalaya have also been studied in the last century (Borgaonkar et al. 1996; Bhutiyani et al. 2000, 2004, 2007, 2009; Borgaonkar and Pant 2001; Yadav et al. 2004). Based on proxy data of the ice-cores from Tibetan Plateau and tree-ring analyses from the hill regions of Uttaranchal, some authors have attempted to reconstruct the past climatic conditions during the last few centuries (Pant and Borgaonkar 1984; Liu and Chen 2000; Thompson et al. 2000).

With a view to understand climate change in NW Himalaya on a yearly and decadal basis better, a systematic and detailed study was undertaken to analyze and evaluate climatic as well as hydrological trends in the NWH using instrumental data. The main results and findings of the study are summarized below.

3.1 Temperature Variations

The analyses of the temperature data show that significant increasing trends exist in annual temperature in almost all three main stations namely, Shimla, Srinagar and Leh in the northwestern Himalaya (NWH) in the last century. The

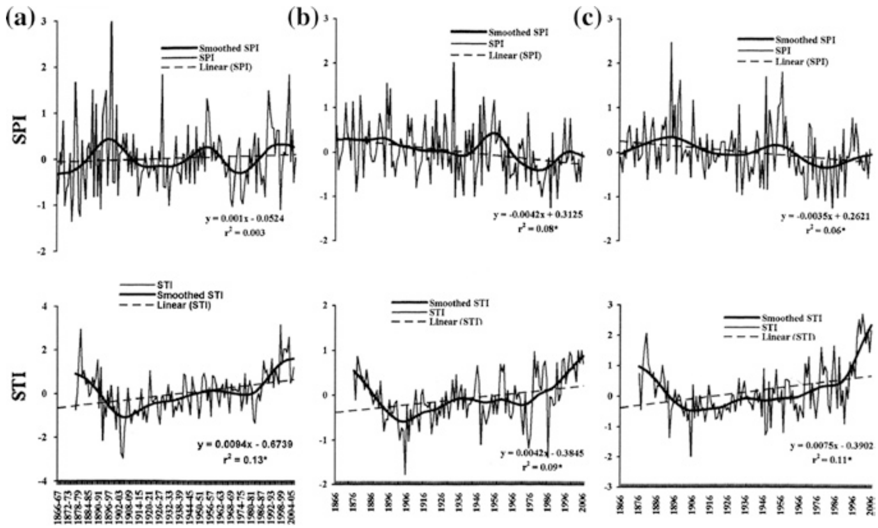

Fig. 2 Temporal variation of winter (**a**), monsoon (**b**) and annual (**c**) standardised precipitation index (SPI) and standardised temperature index (STI) in the northwestern Himalaya (NWH) during the period 1866–2006

annual air temperature has shown an increase of about 1.1 °C during this period. Warming effect is particularly significant during the winter season. For northwestern Himalayan region as a whole, average winter temperature has shown an elevated rate of increase (1.4 °C/100 years) than the monsoon temperature (0.6 °C/100 years) during the period from 1866 to 2006 (Fig. 2). Increase in winter air temperature during three decades is unusually high (about 4.4 °C), as compared to an average rate of about 1.4 °C/100 years in the entire last century. The 'warming' in the NWH has been primarily due to rapid increase in both, the maximum as well as minimum temperatures, with the maximum increasing much more rapidly. Consequently, the diurnal temperature range (DTR) has also shown a significantly increasing trend in both winter and monsoon seasons in the last century (Bhutiyani et al. 2007, 2009). This is in contrast to the findings of studies in the Alps and Rockies (Beniston 1997; Brown et al. 1992) and similar observations on the global scale (Karl et al. 1995), where the minimum temperatures have increased at a higher rate.

Based on the analyses of the temperature data, three different epochs/periods were identified. An episode of comparatively higher (above-average) temperatures from 1876 to 1892 was followed by three more periods of temperature variation. Below-average mean air temperature persisted from 1893 to 1939 indicating a cooler episode, followed by a period of relatively stable/average temperatures till around 1969. The periods from 1969 to 1990 and from 1991 till 2006 are characterized by above-normal temperatures indicating warmer episodes. Temperature seems to have increased at markedly different rates during these two periods. The rate of increase appears to be highest since 1991 as compared to the period prior to 1991

Table 1 Linear trends in monthly air temperatures during winters in the NWH in last three decades

Station	Altitude in m	Data span	Months					
			Nov	Dec	Jan	Feb	Mar	Apr
Bahang	2,192	1977–1978 to 2009–2010	(+)	(+)	(+)*	(+)	(+)*	(+)
Kanzalwan	2,440	1996–1997 to 2009–2010	(+)*	(+)*	(+)	(+)	(+)*	(+)*
Solang	2,480	1996–1997 to 2009–2010	(+)	(−)	(−)*	(−)	(+)	(+)
Gulmerg	2,800	1996–1997 to 2009–2010	(+)*	(−)	(−)	(+)	(+)	(−)
Dhundi	3,050	1989–1990 to 2009–2010	(+)	(+)	(−)	(−)	(+)*	(+)
Haddan Taj	3,080	1996-1997 to 2009-2010	(+)	(+)	(−)	(−)	(+)*	(−)
Patseo	3,800	1996–1997 to 2009–2010	(+)	(+)	(−)	(+)	(−)	(−)

(+) Increasing trend
(−) decreasing trend
* significant at 95 % confidence level

(Bhutiyani et al. 2009), indicating unusual warming in last two decades. This is also confirmed by the analysis of short-term data available for seven stations for the recent decades.

With regard to variation in monthly air temperatures during winter in the last three decades, the studies have indicated non-uniform rate of increase through the winter. Although the beginning of winter (November) has shown an increasing, but statistically insignificant trend, the onset of spring (March) has been marked by substantial warming (Table 1).

3.2 Precipitation Variations

Certain variations have occurred in precipitation patterns on the global scale in response to rising temperatures and resultant changes in evaporation from the oceans (Srivastava et al. 1992; Fallot et al. 1997; Zhai et al. 1999). Because of its high temporal and spatial variability and high sensitivity to circulation characteristics, precipitation has rarely been studied in as much details as temperature, as an index of climatic change (Thapliyal and Kulshreshta 1991; Srivastava et al. 1992).

Present study shows a statistically significant decreasing trend (at 95 % confidence level) in the monsoon and overall annual precipitation during the study period. In contrast, the winter precipitation has shown an increasing but statistically insignificant trend (at 95 % confidence level) (Fig. 2). This is generally in good agreement with the results of other studies carried out in western parts of Himalayan foothills (Borgaonkar et al. 1996), Nepal Himalaya (Shtreshta et al. 2000) and in Upper Indus Basin in the Karakoram Himalaya (Archer and Fowler 2004). It can also be seen from the above data that during the period under study, episodes of above-average and below-average winter and monsoon precipitation almost alternated each other with a periodicity varying from 20 to 60 years.

With regard to last few decades, it is seen that whereas monsoon precipitation has remained below-average from 1965 to 2006, winter precipitation has been above-average during the period between 1991 and 2006.

4 Winter Warming and Its Relationship with Winter Snowfall

Although winter precipitation was above-average during the period between 1991 and 2006, studies have shown that rising winter air temperatures have caused decreasing snowfall component in total winter precipitation. This effect is more prominent on the windward side of the Pirpanjal Range and to a lesser extent, some portions on the leeward side. Increasing temperatures during the months of November and March during last three decades probably point towards late onset of winter and early advent of spring season in the NWH. The studies have also indicated that the onset of winter has been delayed by about 2 days per decade and onset of spring has been advanced by about 3 days per decade. This has effectively reduced the duration of winter and consequently the snowfall duration period by 5–6 days per decade and approximately by about 2 weeks in the last three decades (Bhutiyani et al. 2009). Identical results have also been reported from studies in Upper Indus Basin in Karakoram Himalaya (Archer and Fowler 2004), Nagaoka in Japan (Nakamura and Shimizu 1996), the Swiss Alps (Beniston 1997; Laternser and Schneebeli 2003) and Bulgarian mountainous region (Petkova et al. 2004; Brown and Petkova 2007).

Effects of winter warming in last three decades are visible on the Eurasian landmass as a whole. Temporal variation of Eurasian Snowcover Area (ESCA) in March (Data source: Brown 1997, 2002) and winter mean air temperature in the NWH (Fig. 3) demonstrate insignificant trend in the variation of ESCA from 1922 till late-1960s. Consequent decrease in ESCA thereafter is marked by a period of rapidly increasing winter air temperatures in the NWH, indicating a direct inverse relationship between these two parameters. Depleting snowcover area as a result of rising winter temperatures in last three decades may have further amplified the magnitude of winter warming in the Himalayas.

Snow, being a highly reflective material, looses back a large portion of incoming radiation to the atmosphere, thus making a very small portion of energy available for transfer to the ground below. It also acts as a thermal insulator between the ground and the atmosphere, inhibiting the heat transfer between them by conduction and convection.

As more and more land area gets exposed because of decreasing snowcover, larger amount of energy is now available for heating the ground. Consequent higher terrestrial radiation because of elevated ground surface temperatures and higher energy from incoming shortwave radiation increase the net energy balance of the area, which further raises the air temperature of the contiguous areas giving

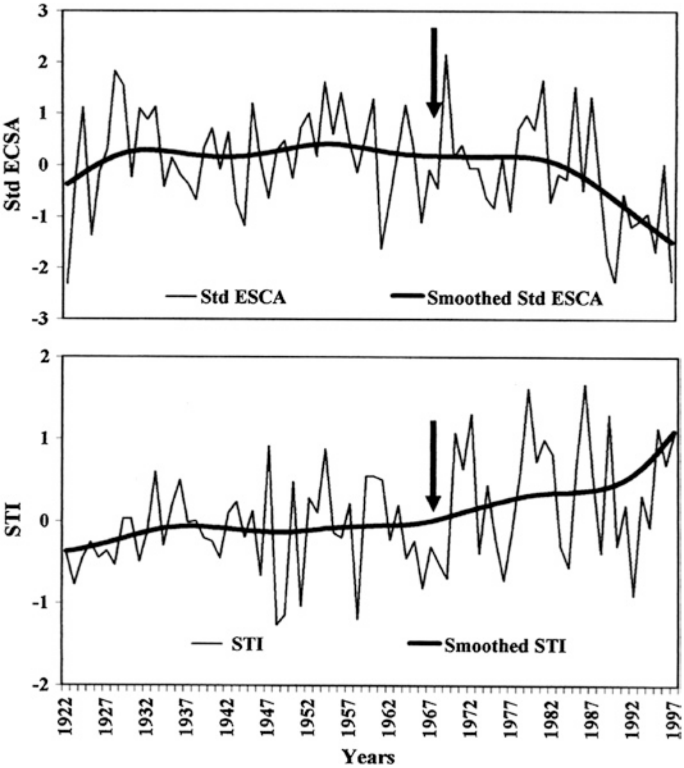

Fig. 3 Temporal variation of standardised Eurasian snowcover Area (ESCA) (March) (*Data Source* Brown (2002)) and winter standardised temperature index (STI) in the northwestern Himalaya (NWH) during the period 1922–1997. An onset of period of rapidly increasing winter air temperature and decreasing Euarsian Snowcover Area (ESCA) is indicated by *black arrows*

rise to a positive ‘feedback mechanism’. This effect, which is similar to ‘Urban Heat Island’ phenomenon generally associated with highly polluted cities, could be termed as ‘Mountain Heat Island’ effect.

5 Possible Role of Anthropogenic Activities

The studies have demonstrated that although, the temperatures continued to increase from the beginning of the last century, the epochal behaviour of the precipitation ensured presence of comparatively cooler and warmer periods till the early-1970s. The analysis of the diurnal temperature range (DTR) data shows regular periodicity. This periodicity, however, breaks after mid-1970s (Bhutiyani et al. 2007).

It is evident from the foregoing discussion that some natural extra-regional factors such as the Quasi-Biennial Oscillations (QBO) on higher frequency scale of few years and the sunspot activity on the comparatively smaller frequency scale of multi-decades appear to be largely responsible for the precipitation variation in the NWH till early-1970s. The equatorial eastern and central Pacific sea surface temperature (SST) and the ENSO related events had a very limited role to play in these fluctuations. Although, the temperatures continued to increase from the beginning of the last century, the epochal behaviour of the precipitation ensured presence of comparatively cooler and warmer periods (Krishna Kumar et al. 1999). The periods of excess (deficient) annual precipitation, with overall increase (decrease) in cloud-cover, were associated with lower (higher) temperatures, because of the decrease (increase) in net radiation balance. A remarkable feature from the standpoint of the climate change in the NWH is that these tele-connections appear to have weakened considerably in the last three decades i.e. after the early-1970s (Fig. 4) (Krishna Kumar et al. 1999; Baines and Folland 2007; Bhutiyani et al. 2007, 2009).

This convincingly indicates the waning effect of the natural factors in this period. The rise in air temperature has continued unabatedly in this period with both maximum and minimum temperature increasing at an alarming rate. This 'warming' is unusually high and it is difficult to be fully accounted for by the natural forcings alone, as discussed above and there appear to be some additional factors, which may have played a significant role (Easterling et al. 1997; Crowley 2000). One of the external factors could be the increasing concentration of greenhouse gases in the atmosphere. The largest sources of the production of these greenhouse gases are the anthropogenic activities related to rapid industrialization and urbanization. Therefore, monitoring of changes in population and land use patterns and the greenhouse gases emissions may provide an insight into the probable causes of the climatic change in the NWH.

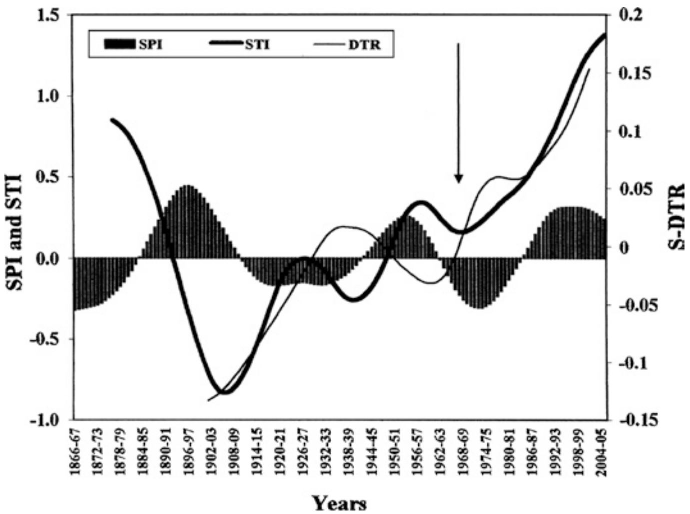

Fig. 4 Relationship between Winer standardised precipitation index (SPI), the standardised temperature index (STI), and standardised diurnal temperature range (S-DTR) in the NWH. *Balck arrow* indicates the period when tele-connections appear to have broken

6 Conclusions

The study has confirmed conclusively that the climate change in northwestern Himalayas is an inevitable reality today and not a myth anymore. The region has ‘warmed’ significantly during the last century at a rate, which is disturbingly higher than the global average. Unlike other high mountainous regions such as the Alps and Rockies, where the minimum temperatures have increased at a higher rate, the rise in air temperature in the northwestern Himalaya (NWH) has been primarily due to rapid increases in both, the maximum as well as minimum temperatures, with the maximum temperature increasing more rapidly. With regard to precipitation, statistically significant decreasing trends in the monsoon and overall annual precipitation are observed during the study period. In contrast, the winter precipitation has shown an increasing but statistically insignificant trend. Rising winter air temperatures have caused decreasing snowfall component in total winter precipitation, particularly on the windward side of the Pirpanjal Range. The studies have indicated reduction in effective duration of winter by about 2 weeks in the last three decades.

The present study has demonstrated the existence of possible tele-connections between the extra-regional factors such as the Quasi-Biennial Oscillations (QBO), the sunspot activity etc. and the precipitation variation in the NWH till early-1970s in the last century. However, post-1970s, these links appear to have grown weaker considerably, signifying the diminishing effect of the natural forcings during this period and indicating a vital role played by other factors, such as increasing concentration of greenhouse gases in the atmosphere.

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