Bi-decadal Changes in Pre-monsoon Precipitation over Northwest Himalayas and its Large-scale Teleconnections

Deepanshu Aggarwal
Indian Institute of Science Education and Research Mohali

Rohit Chakraborty
Indian Institute of Science

Raju Attada (rajhattada@iisermohali.ac.in)
Indian Institute of Science Education and Research Mohali

Research Article

Keywords: Precipitation, Northwest Himalayas, Pre-monsoon, Subsidence, Teleconnections

Posted Date: February 2nd, 2023

DOI: https://doi.org/10.21203/rs.rs-2526858/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Version of Record: A version of this preprint was published at Climate Dynamics on September 30th, 2023. See the published version at https://doi.org/10.1007/s00382-023-06969-3.
Abstract

During pre-monsoon season, the Northwest Himalayas region receives significantly larger seasonal proportion of precipitation than the pan Indian average which makes it vulnerable to ramifications of extreme precipitation. Hence, this study investigates the precipitation variations during pre-monsoon over the Northwest Himalayas for the period 1979–2018. It has been observed that, since 1998, the mean baseline for precipitation has shifted downwards, indicating a bi-decadal transition. Notably, since 1998, the seasonal average precipitation has fallen to 50% of pre-1998 levels with the month of March being the dominant contributor towards this overall decline. Consequent analysis revealed that the western disturbances (WDs) are primarily responsible for precipitation in this area during this season as the local atmospheric conditions are not conducive for any other source of moisture and precipitation. However, the strength of zonal moisture transport and WDs aided vorticities are seen to be weakening post 1998 which also interestingly coincides with the strongest El Nino phase on record and the start of a negative PDO cycle. As a result, the role of global teleconnections is investigated, which concluded that negative PDO conditions after 1998 have changed the atmospheric circulation pattern, causing air subsidence (stronger stability) over the study region and weakening the lower-level convergence and the westerly component of moisture transport; and this leads to the observed decline in pre-monsoon precipitation in the recent decades. Following that, the hypothesis was further verified using a threefold process involving a study of the change in circulation patterns, cause-effect cluster analysis and finally by case study comparisons.

1. Introduction

Global warming induced climate change has altered the general understanding towards weather and climate all around the world. Though there is widespread agreement on the evolution of global climate under the influence of climate change, the development of regional climates remains obscure. The main reason for this is the complex response of regional climate to global climate forcing, which varies from region to region and/or season to season. As a result, understanding climate change and its effects on global and regional scales has been a focus of research in recent years.

India being a tropical country with a large population is quite vulnerable towards the impacts of climate change on its water resources, agriculture and overall economy (e.g. Mall et al. 2006; Dash and Hunt 2007). Precipitation, a key source of water, varies greatly across the country both spatially and temporally. Different areas receive divergent amounts of annual precipitation, with some experiencing a continuous deficit and others experiencing a surplus. With respect to temporal variation, there are four major meteorological seasons in India: summer monsoon, northeast monsoon, winter monsoon and the pre-monsoon. It is estimated that India receives almost 4000 km$^3$ of precipitation annually out of which almost 75% is contributed by monsoon due to which maximum scientific attention has been accorded to the latter in the past (e.g. Kumar et al. 2005). The studies related to pre-monsoon are lesser compared to summer monsoon perhaps because of scantier pan India precipitation (Fig. S1a). Nevertheless, the pre-monsoon season, which lasts from March to May, is still important to the country in a variety of ways.
The pre-monsoon season is the hottest period of the year over most of the South Asian region, making it vulnerable to climate extremes such as heat waves, thunderstorms, and dust storms, with serious societal impacts (e.g. Kothawale et al. 2010; Choudhury et al. 2019; Shukla et al. 2022). The precipitation activity during this season gives temporary comfort to people from the scorching heat in the Northern parts of the country. The plants experiencing abnormally low moisture levels due to high time gap between the pre-monsoon and the end of the rainy season are relieved as well (Kumar and Naidu 2020). In the context of agriculture, the pre-monsoon showers are critical for healthy growth of a wide variety of crops across the country which can suffer significant damage due to untimely precipitation (Sinha et al. 2019). The water resources of the country are also under great stress during this season due to high temperatures. As a result, a comprehensive analysis of pre-monsoon precipitation and its potential evolution in light of climate change is warranted.

It is well known that global warming leads to a rise in the moisture content of the atmosphere, but this is not directly replicated in precipitation, as multiple studies carried out across the globe have revealed the presence of both increasing and decreasing trends in precipitation (e.g. Modarres and Silva 2007; Kumar et al. 2010). This is due to the fact that regional-scale forcings, such as those exacerbated by regional topography, as well as land-use characteristics, modify the effect of climate change (e.g. Shekhar et al. 2010). Earlier studies on the pre-monsoon seasonal precipitation depicted mixed trends across the country thereby drawing varied conclusions on the temporal pattern of precipitation during this season. Thus, studies with a distinct and exclusive focus on different regions of the country are warranted to identify the unique physical factors pertaining to each region.

For the present study, we have chosen Northwest Himalayas, comprising of Indian states of Jammu and Kashmir (J&K), Ladakh, Himachal Pradesh and Uttarakhand as our study region. This region is interesting to study since it is the only region to receive considerable precipitation during pre-monsoon season in the whole of Northern India (Fig. S1b). The Himalayas make up about 58 percent of India's mountainous terrain and are the source of several rivers in India and its neighboring countries (e.g. Singh et al. 1995). Furthermore, the region has a complex terrain with some of the highest mountain peaks in the world which makes it vulnerable to the ramifications of extreme precipitation related disasters such as landslides and flash floods leading to the disruption in life of people and economy. From a research perspective, the monsoon precipitation over this region has been intensively studied. However, pre-monsoon precipitation has not got much attention from scientific community. The limited available studies have briefly covered this region while analyzing the entire country, and have provided different precipitation trends during the pre-monsoon season. For instance, Guhathakurta and Rajeevan (2008) showed an increasing trend over J&K and Ladakh during 1901−2003. Some studies found a decreasing precipitation trend over whole of Northwest Himalayas except Uttarakhand (e.g. Sinha et al. 2019). Non-significant decreasing trend over a major part of Northwest Himalayas was next reported by Choudhury et al. (2019). Later, Kumar and Naidu (2020) argued that the frequency of wet days is declining over J&K and Ladakh during active pre-monsoon, while that of extremely heavy rain days is increasing over parts of J&K during 1970–2015. Hence, it follows that though these studies may contribute towards the local
assessment of water resources and flood potential, yet the discrepancies among them also make it difficult to get a holistic idea about the precipitation trends especially over the Northwest Himalayas.

Therefore, the aim of the present study is to provide a robust assessment of pre-monsoon precipitation over Northwest Himalayas and explore the physical mechanisms behind the observed trends. The paper is organized as follows: section 2 describes the data and methods; section 3 presents and analyzes the results; and finally, section 4 offers the summary of the main findings of the study.

2. Data And Methods

Precipitation datasets across the pre-monsoon season (March, April and May) for the years 1979 to 2018 has been utilized to fulfil the major objectives of the present study. High resolution daily gridded precipitation archives available from the India Meteorological Department (IMD) at a spatial resolution of 0.25° × 0.25° over India is used for precipitation analysis over the Northwest Himalayas (Pai et al. 2014). The fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA5; Hersbach et al. 2020) global reanalysis fields have been used to validate IMD’s precipitation results and to understand the physical processes leading to the observed changes.

Single level fields such as 2 m temperature, 2 m dew point temperature, geopotential, surface pressure, total column water vapor (TCWV), total column liquid water (TCLW), total column ice water (TCIW), total precipitation, convective available potential energy (CAPE), convective inhibition energy (CINE), total cloud cover (TCC) and total totals index (TTI) have been obtained from the ERA5 during the study period. Three dimensional fields include specific humidity, temperature, divergence, u-component of wind, v-component of wind, vertical velocity, cloud ice water content (CIWC) and cloud liquid water content (CLWC) are also used from ERA5 database. Aerosol Optical Depth (AOD) was obtained from ECMWF Atmospheric Composition Reanalysis 4 (EAC4), the fourth generation ECMWF global reanalysis of atmospheric composition (Inness et al. 2019).

For exploring teleconnections of observed precipitation trends with global climate phenomenon, indices relating to El Nino Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Pacific Decadal Oscillation (PDO) have been utilized. Nino 3.4 anomaly SST index with positive and negative values representing occurrence of El Nino and La Nina events, respectively, is obtained from NOAA Physical Sciences Laboratory. Nino 3.4 SST index is calculated as the area averaged SST from 5°S-5°N and 170°W-120°W (https://psl.noaa.gov/gcos wgsp/Timeseries/Nino34/). Dipole Mode Index (DMI) representative of intensity of the IOD has also been obtained from NOAA Physical Sciences Laboratory. DMI is calculated as SST gradient between the western equatorial Indian Ocean (50°E-70°E and 10°S-10°N) and the south eastern equatorial Indian Ocean (90°E-110°E and 10°S-0°N) (https://psl.noaa.gov/gcos wgsp/Timeseries/DMI/). If the DMI is positive, the phenomenon is known as the positive IOD; if it is negative, it is known as the negative IOD. NOAA NCEI PDO index has been used for studying PDO events (https://www.ncei.noaa.gov/access/monitoring/pdo/). The positive and negative
values of PDO index represent warm and cool phase, respectively and are based on SST anomaly variations in North Pacific.

The trend analysis and significance test has been performed using a linear regression fitting model. For analysis of extreme precipitation, the trends of widespread events have been calculated over the study region with a widespread event defined as a day with at least 10 extreme precipitation events occurring simultaneously over the study region. An extreme precipitation event is defined when a single day precipitation over any grid point exceeds the 99.5th percentile of the local daily precipitation during 1979–2018.

3. Results And Discussion

3.1. Pre-monsoon precipitation climatology and evolution

The climatology of pre-monsoon daily precipitation from ERA5 is in close agreement with IMD with some minor disagreements (Figs. 1a and 1b). Nevertheless, it is clear that most areas of Northwest Himalayas receive average precipitation below 5 mm/day during pre-monsoon. Next, the 99.5th percentile of precipitation during pre-monsoon shows that during extreme events, precipitation can go up to and beyond 50 mm/day, which is ~ 900% over the seasonal mean precipitation (Figs. 1c and 1d). However, a closer look into the figure reveals a wider disparity between the two data sources over the Ladakh region. A very low number of rain gauges in Ladakh as compared to other areas of the study region might be one of the reasons for this (Pai et al. 2014). Also, since the stations in Himalayan region are generally installed in valley floors (Bharti et al. 2016), the run-off from surrounding areas might also contribute towards the higher estimates observed. The spatial pattern of trends in seasonal mean precipitation shows homogeneous decreasing trends over Northwest Himalayas that are significant at 95% confidence level for most of the study region (Figs. 1e and 1f). There are, however, differences in magnitudes of trends over eastern Ladakh between IMD and ERA5. The trends in frequency of EREs from IMD and ERA5 also exhibit some spatial disagreements (Figs. 1g and 1h). Such disagreements are expected because of the differences in methodologies of precipitation estimation between gauge-based observations and reanalysis products along with the potential problems in both. The gauge-based precipitation datasets are generally found to be biased against regions of high elevation, complex terrain, and arid climate that are sparsely populated (e.g. Kim et al. 2015; Nischal et al. 2022). Conversely, the estimates from reanalysis products are affected by the skills of their physical parametrization schemes, satellite retrieval algorithms and the spatio-temporal span of the analysis (Zhou et al. 2018). For instance, during their analysis of monsoon precipitation over this region, Bharti et al. (2016) noticed an overestimation in the satellite data because of its sensitivity to cloud-top temperature which gave it an opportunity for overestimating precipitation during cloud burst events. Nevertheless, both the datasets reveal the presence of strong declining tendency in precipitation activity over the study region. The seasonal mean precipitation area-averaged over Northwest Himalayas shows a significant decreasing trend from both data sources. IMD shows a decline by ~ 2 mm/day over a period of 40 years while ERA5 precipitation
reduced by ~ 1 mm/day. The widespread EREs over Northwest Himalayas also depict a significant decreasing trend with IMD showing a stronger decline compared to ERA5.

Next, it was necessary to investigate whether the weakening in pre-monsoon precipitation is homogenously distributed across its constituting months. Hence, the trends in seasonal as well as monthly precipitation over the Northwest Himalayas are depicted (Fig. S2). Interestingly, each of the periods depict a drastic decline in precipitation since year 1998. So, to better understand this sudden drop, the entire span of 40 years is taken into 2 halves: one up to year 1998 (1979–1998) hereafter referred to as the pre 1998 period and the other after it (1999–2018) referred as the post 1998 period. Consequently, the spatio-temporal distribution of average precipitation during these two periods shows a significant reduction during the latter as expected. It is also seen that the month of March provides the largest contribution to pre-monsoon precipitation while also exhibiting the strongest decline in precipitation. In fact, the months of May and April seem to weaken the reduction signal in precipitation shown by March when the whole pre-monsoon seasonal average is considered. This makes March as the dominant contributor in overall decrease in precipitation during pre-monsoon. The regions of J&K and Himachal Pradesh get relatively higher precipitation than rest of the Northwest Himalayas during pre-monsoon and are also the ones experiencing most reduction post 1998. These findings are in line with Sinha et al. (2019) who also found a significant decreasing trend in the pre-monsoon precipitation over Jammu and Kashmir, and Himachal Pradesh with maximum reduction in the month of March. Furthermore, according to IMD precipitation data, post 1998, the mean precipitation during pre-monsoon season has almost halved compared to pre 1998 values while the widespread EREs have reduced from 83 in the first two decades to 58 in later two decades. Hence, it may be believed that certain important atmospheric changes such as in circulation patterns or convective instabilities might have taken place post 1998 that needs to be studied in order to explain the reduction in precipitation activity over Northwest Himalayas.

Now, it is imperative to identify the physical factors that influence the pre-monsoon climatology of Northwest Himalayas (Fig. 2). Owing to the great heights of Northwest Himalayas, the near surface temperatures are negative throughout the season. As the season progresses, the near surface temperature increases due to the movement of sun towards North which in turns causes more evaporation resulting in an increase in water vapor content in the atmosphere. However, the presence of convective instability remains negligible throughout as is evident from the low values of CAPE and relatively higher values of CINE. According to literature, if the values of CAPE are larger than CINE, it introduces a possibility of convective precipitation while the dominance of CINE over CAPE along with low values of CAPE, as is the case here, prevents any deep moist convection from happening (Riemann-Campe et al. 2009; Chen et al. 2020). The aerosol loading is also seen to be increasing from March to May which is attributed to the transport of dust from the Northwestern deserts of India/Pakistan and the Arabian Peninsula to the Himalayan-Gangetic region (e.g. Gautam et al. 2009; Shukla et al. 2021). Due to high convection over plains of Northern India coupled with strong pre-monsoon westerly winds, the atmospheric pollutants along with dust aerosols are vertically advected to elevated altitudes and pile up on Himalayan slopes (Gautam et al. 2010). However, negligible convective activity on Northwest
Himalayas prevents aerosols from stimulating any precipitation activity over this region. The intra-seasonal evolution of precipitation over Northwest Himalayas during pre-monsoon shows that the monthly precipitation contribution decreases from March to May which is opposite to the pattern of convection parameters seen earlier and thus verifies the absence of their influence upon precipitation.

It is also important to point out that this trend is just opposite to all-India precipitation during this season which increases from March to May due to the beginning of influence by summer monsoon (Sinha et al. 2019). The intra-seasonal variation in precipitation is explained by the cloud cover that follows similar pattern as the latter. Knowing that the role of convection has been eliminated, the clouds must be introduced by an external factor. This is also evident from the intra seasonal variation in surface pressure as it exhibits lower values under a cooler environment and increases from March to May as the surface temperature increases. Furthermore, these external factors are also associated with large scale circulation features coupled with a convergence in mid troposphere and divergence in the upper troposphere and they assume maximum strength during the month of March and fades away by May.

A closer examination of these basic properties reveal that these external factors are nothing but western disturbances (WDs), cyclonic circulations in mid and lower tropospheric levels with low pressure at surface, originating over Mediterranean Sea, Caspian Sea and Black Sea which are carried eastward across North India by subtropical westerlies (Hunt et al. 2019). These extratropical depressions are global scale phenomena with moisture carried in the upper atmosphere which is sometimes shed as rain when the storm system encounters the Himalayas (Dimri et al. 2015; https://mausam.imd.gov.in/srinagar/img/wd.pdf). This explains why the western boundaries of Northwest Himalayas experiences more clouds and precipitation than rest of the study region without any support from the local thermodynamics or aerosol nucleation effects.

### 3.2. Physical changes: Pre 1998 to Post 1998

It has already been ascertained in the preceding sections that the precipitation decline from pre to post 1998 is strongest in the month of March but it weakens significantly during the rest of pre-monsoon period. Furthermore, the month of May perceives a sizable change in physical conditions as the WDs lose their influence over Northwest Himalayas by this time. Hence, to draw a sharp contrast of the changing climate within the pre-monsoon season, the months of March and May are studied simultaneously across the pre and post 1998 period (Fig. 3). As seen before, the precipitation activity has reduced most in March (almost 50%) while the month of May has experienced a reduction of almost 33%. Also, the variability in precipitation during March has reduced post 1998 thereby sustaining the drop. The near-surface temperature of Northwest Himalayas has increased post 1998 which is expected due to global warming. Further, during May, the reduction in outliers post 1998 indicate that the anomalous temperature events have reduced. Next, the dew point depression, which represents the difference in near-surface air and dew point temperature, shows a quite noticeable increase in March with no band overlapping, indicating strong aridification due to reduced precipitation over this region post 1998. In addition, this area also experiences an absence of atmospheric instability (stronger stability) throughout the troposphere and this is confirmed by the decline in total totals index (TTI), a stability index.
The TTI values are seen to be already in a range in which thunderstorms are thought unlikely and have further reduced post 1998.

Next, aerosol nucleation is another important factor impacting precipitation probability; however, it does not change much in March, with only a meagre increase observed in May. A discernible upturn in surface pressure is noticeable during March perhaps due to the weakening of WDs, which has led to reduction in cloud cover as well. The weakening signature is less intense during May since the WDs already fade away by this time. As previously shown, the water vapour content of the atmosphere rises from March to May, yet there is no discernible change from pre to post 1998, possibly because the effect of global warming is being offset by a decrease in precipitation activity. However, the cloud liquid and ice water content exhibit a downhill trend post 1998 in accordance with cloud cover. It can also be seen that the ice forms a greater proportion of clouds than liquid water especially in March which can be expected since the clouds due to WDs are mostly mid and high level (e.g. Madhura et al. 2015). Furthermore, the prevailing surface temperatures in this region are mostly less than 0°C owing to its topography.

Since the WDs are deep and large-scale systems spanning multiple vertical levels of the atmosphere, it is important to study how different levels of atmosphere have evolved post 1998. From Fig. 3f, it can be seen that the surface of Northwest Himalayas starts around 600 hPa which itself represents the mid troposphere; hence, only two pressure levels representing the near surface and the upper tropospheric heights (500 and 200 hPa, respectively) have been selected for subsequent analysis (Fig. 4). From temperature point of view, the signature of global warming is visible at both the pressure levels; however, the same is not much discernible in the specific humidity values. Besides that, cloud ice content is higher at greater elevations and declines post-1998 for both pressure levels and months. As previously stated, cloud ice water content begins to decline faster in March than in May, and the two 20-year bands overlap less. At 200 hPa, availability of liquid water is limited and does not change. At 500 hPa, cloud liquid water content exceeds ice, yet it has not changed since 1998. Next, the convergence and divergence patterns at lower and upper levels, respectively show a clear drop in March which indicates weakened vorticity and cyclonic circulations associated with WDs. To prove this point, the WDs are segregated through composite analysis of widespread EREs while assuming that the latter are caused by WDs (e.g. Dimri et al. 2015). The analysis reveals a tenfold increase in the magnitude of convergence and divergence during widespread EREs compared to the average climatological values, which validates our assumption of WDs being the cause of widespread EREs. Further, the average precipitation over Northwest Himalayas has reduced by 16% during widespread EREs post 1998 with maximum reduction of up to 10 mm/day concentrated along Himalayan Foothills (figure not shown). Similarly, the convergence at 500 hPa and divergence at 200 hPa during widespread EREs have dropped by 14% and 18%, respectively from pre to post 1998 period. Thus, it can be inferred that there has been a decline in atmospheric vorticity associated with WDs over the study region as also hinted previously by Hunt et al. (2019) through climate model simulations.

3.3. Changes in atmospheric circulation patterns post 1998
The subtropical westerly jet is an important means of transporting WDs over Northwest Himalayas (e.g. Nischal et al. 2022) and hence this component has been investigated in this section. Previous studies have found that this jet is strongest at 200 hPa with wind speeds above 30 m/s (e.g. Hunt et al. 2018). This is also observed from the pre-monsoon wind climatologies around 20° to 40° N (Fig. 5). Furthermore, the influence of orography on the flow of westerlies is seen clearly at 500 hPa which forces the winds to diverge as they encounter the wind ward western slopes of the Himalayas and converge behind them. Thus, the winds become south-westerly in the upper parts of our study region while they tend to become north-westerly in the lower parts. The difference in pre and post climatology of westerlies during pre-monsoon season does not show any clear change over Northwest Himalayas at 200 hPa. However, at 500 hPa, a definite weakening of zonal wind component is noticed over the study region. It may further be noted from the previous sections, that most of the meteorological parameters do not show any discernible change between the pre and post 1998 period when the pre-monsoon season is considered as a whole. The reason for this can be understood from the month-wise change in the circulation pattern (Fig. S3). During the month of March, a significant weakening of westerlies is observed both at 200 and 500 hPa which however is absent during the other months.

Now, the results obtained from the previous sections hint towards weakening of moisture transport in March to be the driving factor behind the sudden weakening in precipitation over the Northwest Himalayas in the recent decades. To prove this fact, the moisture transport climatologies are investigated over the study region. The product of specific humidity with meridional and zonal components of wind is computed across the southern and western boundaries of the study region in line with the average wind climatology and the results are depicted in Fig. 6. As we have seen that the weakening of winds post 1998 differs across vertical levels with middle tropospheric levels exhibiting a stronger weakening compared to the upper troposphere, hence, two vertical bands are considered for the examination of moisture transport: middle troposphere (400–600 hPa) and upper troposphere (150–300 hPa). Firstly, the overall moisture transport is observed to be about ten times larger in the middle troposphere compared to the upper troposphere even though the wind speeds are much higher in the latter owing to lack of humidity levels (shown in Figs. 4 and 5). Also, the horizontal component of the moisture transport is found to be about an order higher than the southerly component due to the obvious strength of subtropical westerly jet stream. Following that, the westerly moisture influx appears to be weakening in both vertical bands post 1998 during the pre-monsoon season as a whole, as well as in all of its constituent months except April, which shows no discernible behavior. Southerly moisture influx is negligible in the upper troposphere because orography diverges winds underneath those levels. However, in the middle troposphere, the southerly moisture influx reduces post 1998 throughout the pre-monsoon season.

Overall, a weakening in westerlies and moisture transport post 1998 is noticed over Northwest Himalayas which could be the cause of weakening in pre-monsoon precipitation activity in the latter half of the forty years study period. The weakening of subtropical jet carrying the WDs to Northwest Himalayas along with the WDs themselves also supports this hypothesis making it crucial to determine the root causes of
this weakening. According to a recent study by Hunt et al. (2019), the global warming business-as-usual scenario may lead to a reduction in cyclonic vorticities associated with such WDs and so this was considered as a critical reason behind the observed precipitation trends. However, on closer examination, the 40-year variabilities in precipitation as well as its causative factors depict an abrupt fall in the mean baseline levels after the year 1998; hence it is opposed to the previously proposed gradual decline theory in precipitation if global warming would have been the primary factor behind this phenomenon. Hence, it follows that some external factors having single or multiyear periodicities may also play a dominant role behind the precipitation reduction in this region. According to Narayanan et al. (2016), the precipitation pattern in India is influenced by the large-scale differential heating of land and sea, which makes it important to explore the relationships between precipitation and major climate indices. Now interestingly, year 1998 also experienced many external influences from global climatic activities such as the ENSO (at interannual time scale) and PDO (decadal time scale), so it can be hypothesized that these factors might also have played some role behind the concurrent fall in precipitation activity over the study region. In view of the above, it will now be attempted to demonstrate the influence of all such teleconnections on the pre-monsoon precipitation trends over the Northwest Himalayan region.

3.4. Teleconnections between bi-decadal precipitation changes and global climate phenomenon

Past studies have revealed significant links between Indian Summer and Winter Monsoon, and global climate phenomena such as El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Indian Ocean Dipole (IOD) and so on. However, the existence of any such relationships during the pre-monsoon season has not been investigated fully. The El Niño Southern Oscillation (ENSO), is an interannual time scale natural fluctuation of tropical Pacific SSTs with a periodicity of 2–7 years and has a well-established inverse relationship with the Indian summer monsoon precipitation (Hrudya et al. 2021). On the other hand, ENSO – winter monsoon relationship is not clear due to contrasting inferences by previous studies (e.g. Roy 2006; Yadav et al. 2013). In context of the present study, it may be noted that the 1997/98 El Nino event, the strongest on record coincides with the post 1998 downward shift in pre-monsoon precipitation observed in our study (Wang & Weisberg 2000). Also, the ENSO - Indian summer monsoon relationship, which appeared to be deteriorating since the 1970s, has also been found to be reviving since the end of 20th century (Kumar et al. 1999; Yang & Huang 2021). Apart from ENSO, there is another climatic factor called the Pacific Decadal Oscillations (PDO) with characteristics quite similar to ENSO except for its multi-decadal variability and a more extra-tropical presence as compared to ENSO (Zhang et al. 1997; Vishnu et al. 2018). It is well established that PDO, and Indian summer monsoon precipitation are negatively correlated (Rao 1999; Krishnan & Sugi 2003; Roy 2006; Krishnamurthy & Krishnamurthy 2014). Moreover, several studies have indicated that a warm PDO phase existed from 1977 to 1997 after which a cool phase has started, that further coincides with a weakening of pre-monsoon precipitation activity over the Northwest Himalayas region (Mantua & Hare 2002; McDonald & Case 2005). Finally, apart from PDO and ENSO, the local sea surface temperatures are also found to influence precipitation over Indian landmass by acting as moisture sources which makes the Indian Ocean Dipole (IOD) another subject of interest. For instance, previous studies have observed an
increase in pre-monsoon precipitation over Bay of Bengal and attributed it to Indian Ocean warming (Choudhury et al. 2019; Sinha et al. 2019). Moreover, climate phenomena such as ENSO and PDO have also been found to influence Indian monsoon through the Indian Ocean.

Figure 7 shows the pre and post 1998 climatology of Northwest Himalayas pre-monsoon precipitation along with the major climate indices of PDO, IOD (DMI) and ENSO (Nino3.4). Keeping view of the varied accounts of lead lag relationship between various climate indices and the Indian precipitation variabilities across seasons in past literature, it has been attempted to use the annually averaged indices and the pre-monsoon precipitation of the same year to estimate the causality involved. PDO is observed to lie in the positive phase till 1998; however, it changed to negative phase after 1998 which makes it positively correlated (~ 0.6) with the changes in pre-monsoon precipitation over Northwest Himalayas. Next, IOD appears to be transitioning from a negative to positive phase post 1998 (correlation ~ -0.4) which could hint towards dampening of precipitation reduction due to enhanced moisture supply from western Indian ocean. However, the dominance of the zonal advection component of the westerlies compared to the meridional component (as seen from their magnitudes) during pre-monsoon makes it irrelevant here. Finally, ENSO does not show any clear shift in the bi-decadal distributions pre and post 1998. The correlation between ENSO and pre-monsoon precipitation is weakly positive compared to PDO despite high similarity in both the climate phenomena. This observation may be attributed either to the difference in periodicities between them or the fact that the Northwest Himalayas lie in the subtropical region where PDO activity is predominant in contrast to ENSO which is an equatorial phenomenon.

Now, since PDO has the highest bearing on pre-monsoon precipitation changes over the Northwest Himalayas, it is critical to investigate the possible underlying physical mechanism. Prior to year 1998, PDO was in its warm phase, which is characterized by negative SST anomalies in central and western North Pacific and positive SST anomalies in the eastern North Pacific. However, post 1998, the PDO has been in a cold phase, resulting in warm SST anomalies over the central and western North Pacific and milder SST anomalies in the eastern North Pacific. Now, warm SSTs are associated with low surface pressure and presence of convergence resulting in updrafts that diverge at higher altitudes and subside over surrounding regions which leads to the establishment of high-pressure areas and clearer weather over the latter. Hence the enhancement in surface pressure over Northwest Himalayas and the reduction in total cloud cover post 1998 is proposed to be a corollary to the large-scale subsidence caused by the negative phase of PDO and thus responsible for the reduction in precipitation activity over the study region. The scientific evidence for this proposition can be found in Fig. 8, which shows the bi-decadal changes in vertical velocity and divergence at 200 hPa over the study region and the Northwestern Pacific during pre-monsoon season. It is observed that the changes are in opposite phase over the two regions with the upper tropospheric divergence showing an increase over the Northwestern Pacific which is complemented by a drop in divergence over the study region due to subsidence. Notably, such changes are most clearly discernible during March, however, the pattern is more or less maintained throughout the pre-monsoon season. Further, the enhancement in updraft over the Northwestern Pacific post 1998 along with a downwards tendency in air over the study region also validates the proposed argument.
Next, the bi-decadal changes in normalized values of zonal and vertical wind components during pre-monsoon season are plotted zonally starting from the study region covering up to Northwestern Pacific (Fig. S4). This is done to provide a better visualization to the proposed hypothesis. A strong upward shift in air movement is visible over Northwestern Pacific in the later decade due to the warm SST brought in by the negative PDO phase. Next, to the east of Northwestern Pacific, downward tendencies in air movement can be seen at multiple regions but the most prominent subsidence is experienced over the study region. This phenomenon is expected to produce high pressure zones over the study region which further weakens the chances of zonal moisture advection from westerly jets hence leading to reduced rainfall over the study region. Now, to analytically validate this cause effect relationship, forty years pre-monsoon data over Northwest Himalayas is spatio-temporally averaged and categorized into three clusters, one having years experiencing positive phase of PDO, the next with neutral PDO index and last having the negative PDO phase years. Next, the corresponding clusters of PDO, moisture transport, upper-level divergence and precipitation are plotted against each other in Fig. 9. It is revealed that the change in PDO phase has a direct bearing on the upper tropospheric divergence over the study region. Also, the absence of overlapping among the clusters validates the strength of the linear relationship between PDO index and 200 hPa divergence over the Northwest Himalayas. Next, the drop in upper-level divergence is found to lead to a net reduction in the moisture influx at 500 hPa due to the establishment of high-pressure area that weakens the westerly motion over this region, as previously hypothesized. The relationship between these two variables is not linear, however, the spacing between the extreme clusters suggest that the relation is significant enough to propel the effect. Finally, the reduction in moisture flux expectedly leads to a reduction in precipitation activity over Northwest Himalayas. This relationship again is not entirely linear which can be attributed to the mild contribution of the meridional moisture transport and local thermodynamic factors that also influence precipitation activity. Hence, it can now be conclusively inferred that negative PDO conditions post year 1998 has led to a change in the synoptic atmospheric circulation patterns resulting in air subsidence over the study region thereby weakening the lower-level convergence and moisture transport and this leads to the observed decline in pre-monsoon precipitation.

4. Summary And Conclusion

The present study investigates the pre-monsoon precipitation changes over Northwest Himalayas during the period 1979 to 2018. It is observed that the precipitation activity has undergone a bi-decadal change with a downward shift in its mean baseline after year 1998. While average precipitation has reduced to 50% of pre-1998 levels, the widespread extreme event occurrence has reduced by ~ 30% with the month of March being the dominant contributor towards this overall reduction. Consequent analysis revealed that precipitation in this region and season is mainly attributed to the WDs as the local atmospheric conditions are not conducive for any other source of moisture and precipitation. However, the strength of zonal moisture transport and western disturbance aided vorticities are seen to be weakening post 1998. Now interestingly, 1998, the year from which the downward shift in precipitation regime occurred is the year of strongest El Nino on record along with the beginning of cold phase of PDO. This led to the
investigation linking the teleconnection influences of such global climate phenomena with the observed reduction in precipitation activity over the study region. It is found that PDO index has the highest positive correlation with pre-monsoon precipitation over Northwest Himalayas compared to ENSO or IOD. To explain the interrelationship between precipitation and PDO, the following physical mechanism has been proposed:

i. The cold phase of PDO established post 1998 is characterized by warm SST over Northwest Pacific which results in strong convergence near surface and divergence up top.

ii. This diverging air subsides over the surrounding regions (with the primary lobe being over the study location) creating a high-pressure area.

iii. This high-pressure formation weakens the westerly moisture influx over Northwest Himalayas which leads to decline in precipitation activity.

To conceptualize this mechanism, the net changes in atmospheric circulation patterns have been explored. The cluster analysis of precipitation and all its key influencing components is further depicted, demonstrating the presence of significant statistical relationship between the underlying variables of the proposed mechanism. All evidence obtained from the analysis strongly support the mechanism proposed.

Finally, as a part of our discussion, a case study is presented wherein two years are compared, one being a pre-1998 positive PDO year (1987) and the other a post 1998 negative PDO year (2009). The degree of impact PDO phase change has on pre-monsoon precipitation over Northwest Himalayas can be understood from the fact that the precipitation in 2009 was almost 56% less than it was in 1987. Wet days (days with ≥ 2.5 mm precipitation) in 1987 were seven as opposed to just one in 2009 while dry days (< 1 mm precipitation) have gone up from just two in 1987 to more than twenty in 2009. Furthermore, the contribution of widespread extreme events in total seasonal precipitation has reduced from almost 40% in 1987 to 2% in 2009 thereby highlighting the impact on both the average and extreme weather conditions. Next, the effect of PDO phase change on all underlying meteorological parameters is depicted in terms of a common normalized scale in Fig. 10. It can be seen that the month of March leads the pre-monsoon season for all the meteorological parameters as expected from inferences drawn in previous sections. In accordance with the proposed mechanism, the first and possibly the determining impact of PDO phase change from positive to negative is seen on divergence over the Northwest Himalayas region. During negative PDO, both the divergence at 200 hPa and the convergence at 500 hPa weakens due to large scale subsidence. This leads to the establishment of high surface pressure that causes weakening of the incoming westerly moisture flux. Thus, a shortage of moisture is indicated by an increase in the dew point depression temperature. Consequently, a reduction in total cloud cover and all types of water and vapor content in vertical column is observed, thereby reducing all chances of precipitation over the study region thus fulfilling the proposed hypothesis.

Notably, some recent studies indicate that in a warming climate, the frequency of PDO might increase (Fang et al. 2014; Geng et al. 2019). This further highlights the importance of the current study for
Northwest Himalayas as the pre-monsoon precipitation is critical for supporting water availability in the region. Proper assessment of climatology and extremes is critical to consider optimum adaption strategies for both sustainable use of water resources and for generating preparedness against the adverse impacts of such events, including floods, landslides, crop damages etc. The incorporation of teleconnection influence of PDO on pre-monsoon precipitation in climate models shall further help to improve the multidecadal forecasts of precipitation to a great extent. Finally, further research is needed to develop a thorough justification for how regional spatio-temporal scales are impacted by global climatic factors. Regional reanalysis products have recently acquired great significance in studies concerning regional climates. For instance, Aggarwal et al. (2021) showed that India's first highest resolution regional atmospheric reanalysis, Indian Monsoon Data Assimilation and Analysis (IMDAA) has greatly enhanced the regional understanding of precipitation dynamics during Indian summer monsoon. Hence, Northwest Himalayas could be subjected to regional reanalysis to get a more detailed picture that can help understand the variation of precipitation patterns and trends across the mountain ranges as well as the varied response to global teleconnections, if any.

Declarations

Author Contribution

DA performed the complete analysis and wrote the first draft of the paper. RC and RA provided the initial concept and were primarily responsible for editing the paper. RA and RC contributed to supervision, discussion and editing the paper.

Funding

This research did not receive any specific funding from any source.

Data Availability


ERA5 reanalysis data is available at Copernicus Climate Change Service (C3S) Climate Data Store of ECMWF (https://cds.climate.copernicus.eu/cdsapp#!/home). [Last Access: 10 Nov, 2022]

CAMS global reanalysis (EAC4) is available at Atmosphere Data Store (ADS) of ECMWF (https://ads.atmosphere.copernicus.eu/cdsapp#!/home). [Last Access: 10 Nov, 2022]

NCEI PDO index is available at https://www.ncei.noaa.gov/access/monitoring/pdo/. [Last Access: 10 Nov, 2022]
Nino 3.4 anomaly SST index from NOAA Physical Sciences Laboratory is available at https://psl.noaa.gov/gcos_wgsp/Timeseries/Data/nino34.long.anom.data. [Last Access: 10 Nov, 2022]

Dipole Mode Index (DMI) is available at https://psl.noaa.gov/gcos_wgsp/Timeseries/Data/dmi.had.long.data. [Last Access: 10 Nov, 2022]

**Declaration of competing interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**References**


Figures
Figure 1

(a,b) Pre-monsoon seasonal precipitation climatology and (c,d) 99.5th percentile of daily precipitation during pre-monsoon. (e,f) Trends in pre-monsoon seasonal mean precipitation) and (g,h) trends in frequency of EREs during pre-monsoon. (i) Trend in area-averaged pre-monsoon seasonal mean precipitation from IMD (red) and ERA5 (blue). (j) Trend in frequency of widespread EREs during pre-monsoon from IMD (red) and ERA5 (blue). Black dots mark trends at 95% confidence level.
Figure 2

Intra-seasonal climatology of various meteorological parameters during pre-monsoon over Northwest Himalayas: (a) 2 meters air Temperature, (b) Total Column Water Vapor (TCWV), (c) Convective Available Potential Energy (CAPE), (d) Convective Inhibition Energy (CINE), (e) Aerosol Optical Depth (AOD), (f) Average Precipitation, (g) Total Cloud Cover, (h) Surface pressure, (i) Divergence at middle troposphere (400 to 550 hPa) and (j) Divergence at upper troposphere (150 to 300 hPa).

Figure 3

Comparison of Pre and Post 1998 climatology of various meteorological parameters during the months of March and May over Northwest Himalayas: (a) Average Precipitation, (b) Air Temperature at 2 meters, (c) 2 meters Dew Point Depression, (d) Total Totals Index (TTI), (e) Aerosol Optical Depth, (f) Surface Pressure, (g) Total Cloud Cover, (h) Total column water vapor, (i) Total column Liquid Water, and (j) Total column Ice Water. For each month (or partition) of a subplot, the left and right box indicates pre and post 1998 climatology, respectively.
Figure 4

Comparison of pre and post 1998 pre-monsoon climatology of Temperature, Specific Humidity (q), Cloud Ice Water Content (CIWC), Cloud Liquid Water Content (CLWC), and Divergence at 200 hPa (a-e) and 500 hPa (f-j) over Northwest Himalayas. For each month (or partition) of a subplot, the left and right box indicates pre and post 1998 climatology, respectively.

Figure 5
Pre-monsoon wind climatology at 200 (a) and 500 (c) hPa. Difference between pre and post 1998 pre-monsoon wind climatology at 200 (b) and 500 hPa (d).

Figure 6

Moisture influx (kg kg$^{-1}$ m s$^{-1}$) over Northwest Himalayas in mid-troposphere (400 – 600 hPa) and upper troposphere (150 – 300 hPa) during pre-monsoon season (a,e) and the months of March (b,f), April (c,g) and May (d,h). Influx from west and south is represented by ‘qu’ and ‘qv’, respectively. For each partition of a subplot, the left and right box indicates pre and post 1998 climatology, respectively.
Figure 7

Pre and Post 1998 climatology of (a) Precipitation, (b) Pacific Decadal Oscillation index, (c) Dipole Mode Index, (d) NINO 3.4 index.

Figure 8

(a-d) Divergence and vertical velocity (e-h) at 200 hPa during Pre-monsoon season, March, April and May, respectively. West denotes a region over North Pacific (30° – 40° N; 150° – 160° E) and East roughly represents our study region (30° – 40° N; 70° – 80° E). For each partition of a subplot, the left and right box indicates pre and post 1998 climatology, respectively.
Figure 9

Cluster based linear relation test between normalized (a) PDO Index and Divergence at 200 hPa, (b) Divergence at 200 hPa and Moisture Flux at 500 hPa, and (c) Moisture Flux at 500 hPa and Pre-monsoon Precipitation.

Figure 10

Comparison of various meteorological parameters during the years 1987 (positive PDO) and 2009 (negative PDO): (Left to Right) divergence at 200 hPa, divergence at 500 hPa, surface pressure, zonal moisture flux (qu), dew point depression temperature, total cloud cover, total column liquid water, total column ice water, total column water vapor and precipitation. Blue and green bars represent March and MAM 1987, respectively. Red and Yellow bars represent March and MAM 2009, respectively.
Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- ESM29123.pdf