Recent tangible interannual variability of monsoonal orographic rainfall in the Eastern Himalayas

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Key Points:

- This study extends our understanding of natural variability across the Eastern Himalayan steep orography using reanalysis data.
- Composite analysis reveals that orographic siege strongly modulates moisture flux convergence, resulting in wet and arid events.
- This study can be helpful in the predictability of recurrent Himalayas floods.

Abstract

Himalayas hydroclimate is a lifeline for South Asia's most densely populated region. Every year flooding in the Himalayan rivers is usual during monsoon, which impacts millions of inhabitants of the Himalayas and downstream regions. Recent studies demonstrate the role of melting glaciers and snow, in the context of global warming, along with monsoonal rain causing recurrent floods. Here, we highlight the interannual variability in the eastern Himalayan hydroclimate as a natural hazard using observed reanalysis for the last 43 years (1979-2021). We found anomalous extreme years with eight dry years and eight wet years after removing the climate change signal. Monsoon rainfall is a significant contributor, and melting snow is not a potential contributor to these anomalous extreme years. The variability of Himalayan monsoonal rainfall is strongly regulated by local monsoonal Hadley circulation associated with Walker circulation. Our findings demonstrate mechanisms associated with Himalayan wet and dry response. The insights provided in this study underscore the impact of natural variability-driven challenging events that could be predictable. Thus, this mechanism could improve the predictability of the Himalayas floods.

1 Introduction

The Himalayas are essential to the global water cycle(Immerzeel et al., 2020). It also holds the most dominant biodiversity hotspots in the Himalayan ranges, including natural heritage like Chitwan National Park, Kaziranga National Park, Khangchendzonga National Park, Manas Wildlife Sanctuary, etc. The Himalayas is one of the most young mountain range on Earth, which emerged around 50 million years ago, resulting from a continental collision according to plate tectonics(Besse et al., 1984; Yin, 2006). These mountain ranges penetrate the atmosphere and regulate monsoonal circulation(Sandu et al., 2019), tropical easterly jets, and river systems. The Intergovernmental Panel on Climate Change (IPCC) special report about the cryosphere has pointed out that the Himalayan snow cover has reduced, and their glaciers underwent substantial ice loss during the last half-decade (Hock et al., 2019; Maurer et al., 2019; Shukla & Sen, 2021).

Previous studies predominantly concentrated over the Tibetan Plateau and its warming (e.g. (Guo et al., 2021, 2016; Rangwala et al., 2009)). On the other hand, studies on the Himalayan hydroclimate and its variability are limited, which is an essential aspect of the Indian subcontinent. Himalayan range comes under the Indian Monsoon framework, which is intensively studied and the most eminent domain of the global monsoon system. Northeast India gets the highest rainfall during Indian monsoon analogized to any other part of Indian subcontinent(Mahanta et al., 2013). This region also includes Cherrapunji and Mawsynram, reportedly the wettest place on Earth(Kuttippurath et al., 2021). Indian monsoon has different flavors such as decadal, interannual, annual, semi-annual, seasonal, and diurnal. Rainfall over the south-facing terrain of the Himalayas is distinguished by an orographic diurnal cycle(Bhatt and

Nakamura, 2006; Hunt et al., 2022). However, a recent study highlights drying due to amplification in the diurnal cycle(Norris et al., 2020). Additionally, the analysis also confirmed the rising temperature over the Himalayas(Pepin et al., 2015; Sabin et al., 2020), along with decreasing trend in monsoon rainfall(Mathew Koll Roxy et al., 2015). These all pointed to the minor role of monsoon and multi-year flooding that might be attributed to ice loss and snow melting.

Summer monsoon representation employing global climate models over the Himalayas and downstream regions is still challenging(Palazzi et al., 2015; Pathak et al., 2019; Salunke et al., 2018). Here, we preferred reanalysis data as rainfall observation reliability across mountainous regions is limited(Hock et al., 2019; Zandler et al., 2019) due to less spatial coverage of situ measurement. Also, ERA5(Hersbach et al., 2020) shows a more acceptable spatial pattern of observed precipitation over the southern central Himalayas than available coarse resolution datasets(Chen et al., 2021). This analysis intends to disentangle the interannual linkage between anomalous rainfall in the Himalayas and underline mechanisms.

2 Materials and Methods

2.1 Data

We use atmospheric variables at 0.25° horizontal resolution from the European Center for Medium Range Weather Forecasting (ECMWF) reanalysis ERA5(Hersbach et al., 2020) for 1979–2021. Sea surface temperature from ERA5 is similar to HadSST obtained from the Met Office Hadley centre, and we thus only use ERA5 in our analyses for consistency. The topography elevation at a five-minute grid resolution (etopo5) is obtained from NASA. Daily MSWEP(Beck et al., 2019) rainfall product data with 0.1° x 0.1° horizontal resolution obtained from GloH_2O. Daily mean river discharge at 0.1° x 0.1° horizontal resolution reanalysis data downloaded from GloFAS-ERA5(Harrigan et al., 2020) reanalysis. The global population density estimates in 2020 from the Gridded Population of the World(CIESIN, 2018) at a resolution of 15 arc-minute (approx. 30km).

2.2 Methodology

We are motivated to explore monsoonal flooding over the Himalayas in the context of natural variability. First, we considered detrended anomalies at each grid point in order to remove the influence of the annual climatological cycle, along with the linear global warming trend. Then we removed externally forced low-frequency variability using a high-pass filter to isolate the interdecadal variability. The result is similar even if using bandpass filtering for interannual to the quasi-decadal window (at 2-13 years). The variability is computed by taking the standard deviation of the filtered time window. Then, we have chosen a high variability amplitude region for futhur analysis when the grid points exceed the amplitude threshold of 4 mm per day, as shown in Fig.1(b).

2.2.1 Moisture flux convergence

We computed the three-dimensional Moisture flux convergence (MFC) as it can tell more about topographic features. The horizontal MFC can be expressed as follow:

$$MFC = -\nabla.(qV_h)$$

Where $V_h(u, v)$ is horizontal wind velocity; u and v are the zonal and meridional components of the wind.

Furthermore, Anomalous MFC can be decomposed into dynamical MFC and thermodynamical MFC. Delta indicates the anomaly with reference to mean state climatology.

$$\Delta\big(-\nabla.(qV_h)\big) = -\nabla.(\overline{q}\Delta V_h) - \nabla.\big(\Delta q\overline{V_h}\big)$$

2.2.2 Local Hadley circulation

We consider the mass stream function (Peixto & Oort, 1984) to understand the mean local meridional circulation. The local meridional mass stream function is expressed as follows:

$$\Psi = \frac{2\pi\,\mathrm{a}\cos\phi}{g}\int_{p}^{p_s}\vec{V}\,dp$$

Where a is the Earth's radius, and ϕ is latitude, g is the acceleration due to gravity, V is the zonal mean meridional velocity, p is the pressure, and Ps is the surface pressure.

4 Results

Himalayan rainfall distribution mainly depends on moisture availability via southwest monsoon flow and earns massive rainfall during the summer monsoon season (JJAS). Floods and droughts regularly occur in the monsoon zone, and eventually thosecause socio-economic consequences. Traditionally, the land-sea thermal contrast is a primary physical mechanism that drives monsoon circulation. When this moist wind is lifted over the Himalayas and mountain ranges, it cools and condensates in the form of orographic rainfall. Synoptic features are complicated on the spatial and temporal scale over Himalayan regions due to complex elevation topography and characterized by the steep gradient (Fig.1a and b). Himalaya is the source of earth's major rivers, the Ganges and Brahmaputra, essential water resources for the Indian subcontinent, which also provides irrigation and transportation in a densely populated region (Fig.1c). The Himalayan Rivers flooded yearly during the monsoon season, especially the Brahmaputra. Thus, an advanced early warning system in the Himalayan ranges is necessary for policymakers and stakeholders. Mean monsoon rainfall climatology (Fig. 2a) dominates in the steep mountain ranges and monopolizes from west to east, due to orographic lifting by the orographic blocking effect. However, more orographic rainfall spread can be seen over Eastern Himalayas due to its unique orientation. The linear trend in rainfall (Fig. 2b) shows the tripolar pattern, a slight decline over the Western Himalayas, an increasing pattern over the central Himalayas peripheral to the Ganges basin, and a strong reduction in orographic rainfall over the eastern Himalayas in the vicinity of Brahmaputra basin. Interestingly, monsoonal variability (Fig. 3c) is also substantial over a steep Himalayan range, similar to its climatology feature.

In order to confirm interannual single in hydroclimate over the Himalayan region, we used bandpass of 2-8 years for detrended anomalies, which show evident variability patterns (Fig. 3a and b) in surface runoff and rainfall in the Himalayan range. The Eastern Himalayas region holds high variability and is dominated by steep topographic elevation. The considerable rainfall variations over this region are highly associated with flooding and arid events. For composite analysis (see methods and Fig.3c), we found eight wet years (1984, 1993, 1995, 1998, 2004, 2007, 2010, and 2020) and eight dry years (1981, 1986, 1992, 1994, 2001, 2006, 2011, and 2013) from interannual scale pinpointed based on multi-year standard deviation over last 43 years (1979-202). To further understand the variability of Himalayan rainfall, we look at composite maps for wet and dry years. Anomalous rainfall patterns are almost identical and heightened in the eastern Himalayas, showing consistent signs in wet and dry years (Fig. 4a and b). A similar feature is replicated in river discharge anomalies (Fig. 4c and d); river discharge is the volume of water streaming through a river routing. Here, Ganges and Brahmaputra show a tight relationship with Himalayan high rainfall variability region. Rainfall anomlies is responsible for runoff, which can further aggravate river floods hazard(Jian et al., 2009). Brahmaputra river flooding years are matching a previous study (see ref (Jian et al., 2009; Rao et al., 2020)) reflecting the role of natural climate variability. However, we can see it's not just limited to the Brahmaputra basin, and it can be considered as the whole Himalayan reserve system. The anomalous surface runoff pattern follows a steep southeast part of the great Himalayan (Supplementary fig. 2), highlighting dependency of elevation topography for dry or wet years. However, snow melting (Fig. 5 b and c) mostly shows a reduction upstream of the Himalayas. Its contribution to interannual variability seems less than monsoon rainfall in dry and wet years. Moreover, the pattern did not fit well with the Himalayan rainfall natural variability, which implies snow melting might be a function of the global warming trend (Fig. 5 a).

Local atmospheric conditions and topography significantly modulate rainfall events(Zhang & Liang, 2020). The primary contributor to the precipitation anomalies is atmospheric humidity over the mountain terrain(Smith, 2018; Tao et al., 2020), followed by large-scale circulation via the tropical ocean. Thermal structure climatology (Supplementary Fig. 3(a)-(d)) suggests atmospheric variables influenced by the topographic elevation of the Himalaya. Composite analysis reveals that warming temperature anomalies with increased relative humidity and MSE are responsible for wet years (Supplementary Fig. 3(e) to (g)). Conversely, cooling temperature anomalies with declined relative humidity and MSE are responsible for dry years (Supplementary Fig. 3(i) to (k)). Usually, environmental moist static energy enhances buoyancy. Also, We found moist buoyancy upward over the steep topography during wet years and downward during dry years (Supplementary Fig. 3(h) to (l)). This suggests the need to employ the moist dynamics analysis to interpret correctly. We found a distinctive anomalous MFC pattern in a cross-section at 94°E (as shown in figure 6a and d) at a lower level from valley to upslope terrain. This anomalous MFC shows an increased anomaly in wet years while a reduction in dry years. The beauty of this 3-dimension MFC is we can diagnose a cross-section to comprehend the vertical distribution and control of the elevation configuration. Furthermore, we decompose MFC in the dynamical and thermodynamical parts, which relate to the circulation effectand the moisture effect, respectively. Most of these changes are contributed by dynamical MFC (figure 6c-d), which suggests an essential role of circulation. Likewise, Thermodynamical MFC (figure 6e-f) shows a similar agreement dominated over slope terrain. The anomalous MFC clearly indicates an enhancement of processes between the surface to 500 hPa, underscoring the role of moisture. However, it should be noted that thermodynamical MFC is nearly ten times smaller in magnitude as compared to dynamical MFC. These results reveal that dynamical MFC modulates rainfall anomalies in the steep terrain of the Himalayas.

The Indian monsoon is modulated by interannual climate mode features such as El Niño–Southern Oscillation (ENSO)(Jian et al., 2009), Indian Ocean dipole (IOD)(Saji et al., 1999), Atlantic Niño (AN)(Sahoo & Yadav, 2021; Zebiak, 1993). Tropical SST condition has been examined for composite dry and wet years. It shows (Supplementary Fig 7) that Himalayan interannual fluctuation can be associated with combined variability patterns in the Atlantic and Indo-Pacific. Positive Atlantic Niño, Negative Indian Ocean Dipole, and La Niña conditions seem favorable for Wet monsoons. A recent teleconnection study also found that Atlantic Nino enhances the MFC over northeast India(Sahoo & Yadav, 2021). Negative Atlantic Niño, Indian Ocean cooling, and neutral Pacific conditions seem favorable for dry monsoons. We illustrated local monsoonal Hadley circulation to understand large-scale circulation linkage with dynamical MFC for dry and wet years. This meridional mean overturning circulation consists of an ascending branch of warm moist air commonly known as a tropical rain belt or Intertropical Convergence Zone (ITCZ). The shift in ITCZ can influence Himayalan rainfall variability. Therefore, we also investigate the its location and associated width(Byrne and Schneider, 2016) as given in Supplementary Table S1. The ITCZ location shifted by 0.47° latitude to the Northward(Hari et al., 2020) with the narrowing of ITCZ width during wet years. The ITCZ location is almost the same as the 43-year climatological mean, with the widening of ITCZ width during wet years. Moreover, the counterclockwise rotation during wet years is stronger than in dry years. As a result, the mean local Hadley cell is narrow during wet years and extends wider during dry years. However, the atmospheric tropical bridge is more important than the background tropical ocean SST anomalies. Zonal Walker circulation and the meridional This is because Walker circulation(Bjerknes, 1969) links these ocean basins and has an ascending branch of the zonal and meridional circulation merged over Maritime Continent. Hadley circulations are connected locally (Karnauskas and Ummenhofer, 2014; Liu and Zhou, 2017; Ma et al., 2018; Yun et al., 2021). Here, we expect a physical linkage between a local headly cell with walker circulation, which reflects rainfall anomalies in the Himalayan region. Walker circulation climatology is represented (see Figure 9a and b; black vectors) during JJAS, An ascending branch over the Indo-Pacific warm pool, and the Eastern Pacific sector and African landmass. The most dominant vertical velocity anomaly can be found near the Indo-Pacific warm pool region in wet years (Figure 9a)—amplified ascending anomalies in the Eastern Indian Ocean and reduced anomalies over Western Pacific. Conversely, in the case of dry years (Figure 9b), increased ascending anomalies were observed in the Western Pacific Ocean and reduced anomalies Eastern Indian Ocean. These results from the composite analysis suggest that anomalous Walker circulation feeds the local Hadley circulation, which impacts precipitation in the Eastern Himalayan region.

5 Conclusions

To conclude, here we found a strong interannual variability signal in the Eastern Himalayan ranges over steep relief and dominated over south-facing slopes. Himalayan monsoon rainfall has complexity due to its orographic features. Our work suggests this Himalayan variability has two phases, which are responsible for the wetting and drying Himalayan hydroclimate. Additionally, we did not capture any snow melting contribution in interannual variability, underscoring its minor role in river discharge. The Brahmaputra seems more significantly impacted during amplified monsoonal wet years in the Himalayas are favorable for flood risk downstream. The flooding in this region can be the ultimate red alert for Humanity and our ecosystem(Elsen et al., 2020), and threats like degradation of soil(Borrelli et al., 2020) and biodiversity loss(Peters et al., 2019). Composite analysis reveals that moist-orographic features enormously modulate variation patterns through moist processes. A dynamical MFC has been leading in the Himalayan monsoon rainfall variability, also supported by moist buoyancy and relative shift in ITCZ. Our investigation underscores the association between rainfall variability and anomalous convection over Indo-Pacific warm pool driven by local head circulation. This study can be helpful in the predictability of Himalayan rainfall variability and extremes. Even though our study emphasizes natural variability, there is a need to explore in detail the role of climate change as a further study. The Indo-Pacific warm pool(M. K. Roxy et al., 2019; Weller et al., 2016) is expanding substantially under global warming, which could favor more flooding events in Himalayan rivers. The Brahmaputra and Ganges merge in Bangladesh and flow into the Bay of Bengal. This natural variability would have its signature in the Bay of Bengal, which might be fascinating to explore further.

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Author contributions:

PK and KH conceived the study and wrote the draft manuscript. PK performed the analysis, prepared all figures and wrote the initial draft of the manuscript. Both authors contributed to the interpretation of the results, discussion of the associated mechanisms, and refinement of the paper.

Data Availability Statement:

ERA5 reanalysis data is publicly available from the ECMWF on their Climate Data Store (CDS), https://cds.climate.copernicus.eu/cdsapp#!/home

HadSST data are available at the Met Office Hadley Centre website, https://www.metoffice.gov.uk/hadobs/hadisst/

Earth topography five-minute grid (etopo5) is publicly available at National Geophysical Data Center, https://www.ngdc.noaa.gov/mgg/global/etopo5.HTML

Multi-Source Weighted-Ensemble Precipitation (MSWEP) rainfall product data from GloH2O is publicly available, http://www.gloh2o.org/mswep/

The GloFAS-ERA5 river discharge reanalysis product is publicly available on the CDS, https://cds.climate.copernicus.eu/cdsapp#!/dataset/cems-glofas-historical?tab=overview

The global population density estimates in 2020 from the Gridded Population of the World version 4 (GPWv4), https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-rev11

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