

Deciphering the Drivers Favorable for Summer Monsoon Precipitation Extremes over the Indian Himalayas

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Abstract

This study investigates the physical processes behind extreme precipitation events (EPEs) in the Himalayas, notorious for causing frequent floods and significant loss of life and property. Due to the presence of complex terrain, understanding the driving factors behind these EPEs has proven challenging. Here, we decipher the driving conditions responsible for the occurrence of EPEs in the western Himalayas (WH) for the period 1979 to 2020. Our findings provide compelling evidence for the role of large-scale circulation patterns and their associated dynamics and thermodynamics in instigating EPEs. The presence of distinct upper-tropospheric gyres flanking the WH, alongside a prominent zonal wave pattern, underscores the conducive atmospheric configuration during EPEs. This configuration promotes a southward extension of the trough, intensifying the convergence of moisture-laden winds from the adjoining seas, leading to substantial moisture availability for the EPEs. Moreover, the southward advancement of cyclonic vorticity further aids in northward moisture advection towards the region. At a regional scale, using moisture budget analysis, we find that vertical moisture advection plays a significant role, emphasizing the dominance of local dynamics driving these EPEs. Furthermore, the intensifying diabatic heating structure over the WH leads to intensified convection through stronger vertical motions, facilitating the development of deep convection. Our results also pinpoint the role of the shifting of the Intertropical Convergence Zone (ITCZ), strongly linked to the dynamics of convective clouds, resulting in changes in the intensity of EPEs over the WH. Additionally, Quasi-Resonance Amplification is linked with the most intensified/persistent EPEs over the Himalayas.

Keywords: Western Himalayas, Extreme Precipitation, Physical drivers, Arctic warming

1. Introduction

The Himalayas, as the world's highest mountain range, feature a unique topography and climate dynamics that exert a significant effect on weather and climate patterns across northern India and neighbouring regions downstream. The hydrological cycle is heavily dependent on the abundant rivers, which sustain millions of people in the north Himalayan region (Hegdahl et al., 2016; Immerzeel et al., 2009; Jain et al., 2017; Li et al., 2016; Vellore et al., 2016; Saini and Attada, 2023). The region's large-scale topography is important in shaping the monsoon characteristics either by thermal or mechanical forcing. The Himalayas, on the other hand, encounter a substantial challenge due to their high vulnerability to extreme precipitation events (EPEs), particularly during the Indian Summer Monsoon (ISM) season (June through September-JJAS). These EPEs can have devastating consequences, including flash floods, landslides, and the loss of human lives and property (e.g. Houze, 2014; Rasmussen and Houze, 2012; Kotal et al., 2014; Ranalkar et al., 2016; Singh et al., 2015; Nischal et al. 2024). The vulnerability of the region to such catastrophic events is a matter of great concern. The destructive consequences of EPEs during the ISM have been made clear through recent past events. For example, torrential rainfall in Uttarakhand in 2013 led to substantial economic damages surpassing 3.5 billion US dollars and a heart-breaking toll of more than 6,000 lives lost (Chevuturi and Dimri, 2016; Joseph et al., 2015; Ranalkar et al., 2016; Shen et al., 2017). In recent years, a multitude of disasters triggered by extreme precipitation have unfolded, underscoring the region's susceptibility to EPEs. These include the Leh flood in July 2010 (e.g. Houze, 2012; Rasmussen and Houze, 2012), the Chamoli river flood in Uttarakhand (July 2016), Bilaspur and Shimla flood in August 2019 (S. Singh & Lal Kansal, 2022), and the Jammu & Kashmir's Kishtwar district floods in July 2021 (Ahmad et al., 2023). In the years 2022 and 2023, occurrences within the context of the ISM have contributed to an expanding catalogue of rain-triggered calamities. Notable among these incidents are the Amarnath flood in Kashmir (Sain et al., 2022), the inundation of Chhoj panchayat and Malana villages in Kullu, Himachal Pradesh (HP), and the devastating Nainital and Uttarkashi floods in Uttarakhand (UK). These events have inflicted significant human and economic losses.

In recent decades, the Western Himalayas (WH) have witnessed a notable increase in the frequency and intensity of EPEs, as reported by (Bharti et al., 2016; Malik et al., 2016; Shekhar et al., 2017). The pronounced warming observed in the Himalayas compared to other regions of India has directly influenced EPEs, impacting atmospheric dynamics and contributing to the occurrence of EPEs (Das and Meher, 2019; Krishnan et al., 2019; Negi et

34 al., 2021; Sabin et al., 2020; Saini et al., 2023). Considering the projected rise in both frequency
35 and intensity of EPEs due to climate change, studying and comprehend the mechanisms
36 underlying these EPEs in the WH is crucial which remain relatively unexplored and warrant
37 comprehensive study.

38 Few research studies (Rasmussen and Houze, 2012; Bharti, 2015; Dimri et al., 2016)
39 have investigated the fragile nature of the Himalayan region, which encompasses high
40 mountain ranges and deep valleys, creates a unique environment for atmospheric processes to
41 occur. The interaction of moist air masses with the mountains and the complex topography can
42 lead to significant heterogeneity in the regional spatiotemporal distribution of precipitation and
43 the formation of localized convective storms and heavy precipitation (Dahri et al., 2016; Priya
44 et al., 2017; Roy et al., 2021). Some observational and numerical modelling works have
45 explored the exceptional occurrence of EPEs in the WH region. However, the aforementioned
46 studies are constrained by limited spatial coverage, often employing a case-by-case approach
47 focusing on only a few stations. Some case studies have presented the probable causes of EPEs
48 over the Himalayas (Chevuturi & Dimri, 2016; Dube et al., 2014; George & Kutty, 2021;
49 Houze et al., 2017; Medina et al., 2010; Nandargi & Dhar, 2011; Ranalkar et al., 2016; Shrestha
50 et al., 2015). EPEs are often associated with convection prompted by orographic lifting,
51 whereby the rugged Himalayan terrain compels the condensation of moisture, leading to
52 precipitation (Bhardwaj et al., 2019; Bohlinger et al., 2017; Houze, 2012; Martius et al., 2013;
53 Vellore et al., 2016). Furthermore, research studies have identified moisture advection as a key
54 mechanism behind EPEs in the Himalayan region (Hunt & Parker, 2016; Vellore et al., 2020).
55 Moist air masses from the BoB and AS are transported into an area by prevailing winds,
56 enhancing the low-layer moisture flux and convergence over the foothills of Himalayas
57 (Bohlinger et al., 2017; Hunt et al., 2018b; Martius et al., 2013; Roy et al., 2021; Vellore et al.,
58 2020). In addition, the presence of warm and moist low-level air masses is constrained by a dry
59 continental air mass originating from Afghanistan and the Tibetan plateau (Karki et al., 2018a).
60 This vertical capping, along with horizontal obstruction by the mountain barriers of the
61 foothills of the Himalayas, effectively impedes the premature release of convective available
62 potential energy. This atmospheric configuration prevents the destabilization of the
63 atmospheric stratification, thereby initiating the occurrence of extreme convective precipitation
64 events (Houze, 2012; Karki et al., 2018b; Kotal et al., 2014; Kumar et al., 2014)

65 The rise in moisture triggers various microphysical processes, resulting in the formation
66 of hydrometeors and the development of deep clouds in the region (S. Das et al., 2006; Hazra
67 et al., 2016; Schomburg et al., 2012). Therefore, moisture advection leads to the formation of

68 persistent precipitation events, which can result in flooding and landslides over the Himalayas
69 (Chaudhuri et al., 2015; Jiang et al., 2014). Furthermore, study Vellore et al., (2016) attempts
70 to explain monsoon-extratropical circulation interactions across the Himalayas.

71 Although a few case-based studies have shed light on the significant impacts of EPEs
72 over the Himalayan region, there is still much unknown about their underlying large-scale
73 drivers and its associated mechanisms. The existence of knowledge gaps pertaining to the
74 primary drivers causing the EPEs and improving the understanding of how large scales factors
75 along with localised and synoptic factors responsible for EPEs necessitates further in-depth
76 investigations. Therefore, conducting research in this area is crucial to better comprehending
77 the contributing factors to EPEs and developing effective strategies for mitigating their adverse
78 impacts. We aim to address the following major objectives that are (a) to explore the
79 distribution of EPEs over the WH during ISM, and (b) to investigate the synoptic and large-
80 scale drivers of EPEs over the Himalayas and exploring the dynamic and thermodynamic
81 responses. The study objectively characterizes the composite anomaly of precipitation-related
82 variables of EPEs at the near-surface and upper troposphere. Finally, the present study will
83 better understand the complex interactions between the large-scale factor and regional weather
84 patterns and inform strategies for building climate resilience in the Himalayan region. It will
85 help shed light on the mechanisms and factors contributing to EPEs.

86 The remainder of the paper is as follows: Section 2 provides an overview of the data
87 and methodology employed in this study. In Section 3, we delve into the synoptic conditions
88 during EPEs, elucidating the associated dynamic and thermodynamic responses. Additionally,
89 this section explains the moisture and heat budget, concurrently investigating cloud
90 microphysical characteristics. Lastly, it explores the role of Quasi Resonance Amplification
91 (QRA) in EPEs over the Himalayas. Section 4 encapsulates the study's findings, presenting a
92 summary and drawing conclusions.

93

94 **2. Data and Methodology**

95 **2.1 Study area**

96 The study area lies in the northern part of the Himalayan range, spanning from 25.5° N to 37.5°
97 N and 72° E to 86° E (outlined in Fig. 1a), comprised of the foothills of the Himalayan range,
98 the Shivalik ranges, and the Siwalik Hills. The elevation of the study varies hundreds of meters
99 from sea level to more than 7000 meters as shown in Figure 1(a) and foothills of Himalayas
100 are outlined with the blue rectangular box. The magenta color contour shows the topographic

101 complexity of the WH surpassing the 60 percent mark on the 0 to 100 scale. It indicates a
102 significantly higher level of topographical intricacy, signifying the region as severe and
103 complex compared to the global average. The region's climate system is highly diverse,
104 encompassing a wide range of factors that influence precipitation distribution and extreme
105 weather events. Understanding the dynamics of the foothill of Himalayas is essential for
106 unraveling the intricate climatic patterns within the broader WH region.

107 **2.2. Data used**

108 We used ERA5 dataset, which is a comprehensive and high-resolution fifth-generation
109 reanalysis dataset developed by the European Centre for Medium-Range Weather Forecasts
110 (ECMWF). It provides extensive and detailed data with a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$
111 (Hersbach & Dee, 2016). ERA5 is generated using an advanced 4D-Var assimilation system
112 that incorporates multiple sources of data such as surface observations, weather station
113 measurements, satellite data, and weather radar information (Hersbach & Dee, 2016). In the
114 present study we have used daily ERA5 data spanning from 1979 to 2020 to investigate the
115 EPEs throughout the ISM using composite analysis approach. We have focused on various
116 atmospheric variables, such as surface pressure, 2-meter air temperature, vertical pressure
117 velocity, geopotential height, horizontal wind components. ERA5 data is used to derive
118 dynamic and thermodynamic variables like moist static energy (MSE), Ertel potential vorticity
119 (EPV), and vertically integrated moisture transport (VIMT), were obtained from the ERA5
120 dataset. We also used the same dataset to examine the cloud microphysical properties such as
121 total column cloud ice, snow water, ice water and supercooled liquid water during summer
122 monsoon EPEs over Himalayas. We used soil moisture and topography complexity data from
123 the ESA CCI Soil moisture climate change initiative. The detailed description is available on
124 the website (<http://www.esa-soilmoisture-cci.org/node/139>) for the data. We have also used the
125 gridded daily rainfall data IMD, regional reanalysis dataset – Indian Monsoon Data
126 Assimilation and Analysis (IMDAA), and satellite-based datasets Integrated Multi-satellite
127 Retrievals (V3) for Global Precipitation Measurement (GPM-IMERG), a merged high-
128 resolution satellite product for detecting the EPEs over WH.

129 **2.3. Methodology**

130 In this study, EPEs are identified using the percentile approach during ISM over the WH, with
131 EPEs defined as instances where precipitation exceeds the 99th percentile. So far, there has yet
132 to be an established standard definition for EPEs as it depends on the region of interest and its

133 severity. Notably, the IMD employs a threshold value to categorize various levels of rainfall,
 134 ranging from light to extremely heavy. However, due to the diverse nature of the Himalayas,
 135 encompassing heterogeneity, varied terrains, and overall complexity, the common practice for
 136 defining precipitation extremes in this region involves the use of percentile thresholds (Bharti
 137 et al., 2016; Nischal et al., 2023, 2024). The threshold is selected based on the potential impact
 138 of cumulative precipitation above this level across all grid points within the region, which can
 139 lead to downstream flooding and landslides, affecting crops in the study area (Hunt et al.,
 140 2018b). To ensure consistency, the precipitation dataset is re-gridded to match the resolution
 141 of the ERA5 dataset ($0.25^\circ \times 0.25^\circ$). This study uses the Mann-Kendal (Mann 1945; Kendall
 142 1948) for trend detection. The M-K test is a rank-based non-parametric based method and is
 143 usually used in hydrometeorological time series (Wang et al., 2020).

144 Furthermore, this study delves into the role of large-scale circulation in EPEs. It unveils
 145 synoptic features and atmospheric circulation patterns linked to EPES in the Western
 146 Hemisphere (WH) through the examination of composite anomalies of atmospheric variables
 147 associated with precipitation. EPEs are obtained from an IMD gridded precipitation dataset
 148 over the foothills of Himalayas. To obtain insights into the fundamental physical mechanisms
 149 driving changes in EPEs, a composite map is generated by subtracting the average conditions
 150 of non-extreme days from those of extreme days, spanning the period from 1979 to 2020.
 151 Additionally, the study investigates the dynamic and thermodynamic aspects of EPEs, as they
 152 provide valuable information about the atmospheric conditions associated with EPEs.

153 **Vertical Integrated Moisture Transport (VIMT):** VIMT measures the total amount of
 154 moisture in the atmosphere that is moved up or down within a vertical column of air (Zhang
 155 et al., 2001). It is an essential metric for understanding the atmospheric dynamics of weather,
 156 climate, and water resources (Chansaengkrachang et al., 2018; Fasullo & Webster, 2003; Ullah
 157 & Shouting, 2013). The following equation (1) is used to calculate the VIMT.

$$158 \quad VIMT = -\frac{1}{g} \int_{1000 \text{ hPa}}^{300 \text{ hPa}} q \left(\frac{du}{dx} + \frac{dv}{dy} \right) dp \dots \dots \dots (1)$$

159 g represents the gravitational acceleration, q indicates specific humidity, and u and v zonal and
 160 meridional velocity, respectively. VIMT is obtained by vertically integrating moisture fluxes
 161 of the u and v in pressure level from surface to 300hPa, as shown in equation (1).

162 **Moist Static Energy (MSE):** MSE serves as a thermodynamic parameter that provides insight
 163 into the energy content of moist air present in the atmosphere. It considers the latent heat
 164 released during the condensation of water vapor in the parcel into liquid or solid precipitation,
 165 as well as the potential energy related to the parcel's height (Andersen & Kuang, 2012; Dube

166 et al., 2014). This definition highlights the fundamental principles of conservation applicable
 167 during moist adiabatic processes and within a state of hydrostatic (Dube et al., 2014; Maloney,
 168 2009). Within a stable, any variations in gravitational potential energy find equilibrium through
 169 corresponding changes in enthalpy due to pressure fluctuations. An increase in MSEs
 170 integrated into a column means importing MSEs from the environment. This destabilizes the
 171 atmospheric column through heating and humidification processes, which are then induced by
 172 deep convective precipitation. Conversely, the decline in column integrated MSE suggests
 173 tropospheric stabilization due to cooling and drying mechanisms, resulting in the export of
 174 MSE to the affected regions. Under the standard approximation, MSE (value per total air mass)
 175 is defined by equation (2).

176
$$MSE = C_p T + gz + L_v q \dots \dots \dots (2)$$

177 where C_p is specific heat capacity at constant pressure ($1004 \text{ J kg}^{-1} \text{ K}^{-1}$), T denotes the air
 178 temperature, g represents the gravitational acceleration (9.8 m s^{-2}), z is the geopotential height,
 179 L_v is the latent heat of vaporization, and q is the specific humidity. In the equation (2), the first
 180 term corresponds to dry-air enthalpy (or heat content), the second term represents specific
 181 gravitational potential energy, and the last terms potentially contribution to the first term due
 182 to latent heating.

183 **Moisture Budget:** The study emphasized the crucial role of ample moisture availability in order
 184 to generate high precipitation amounts, employing a moisture budget analysis. To evaluate the
 185 individual components of the moisture budget, we used daily measurements of total
 186 precipitation, specific humidity, omega, and the u and v components of winds at various levels
 187 spanning from the surface to the troposphere. Employing the vertically-integrated water budget
 188 methodology at a daily temporal scale enables us to dissect and thoroughly investigate the
 189 distinct facets contributing to precipitation extreme (Oueslati et al., 2019; Sudharsan et al.,
 190 2020). In accordance with the vertically-integrated water budget, precipitation can
 191 deconstructed as equation (3) (Trenberth, K.E., Houghton, J.T. & Filho, 1995; Trenberth &
 192 Guillemot, 1998)

193
$$P = E - \frac{1}{g} \int_0^P \omega \frac{\partial q}{\partial p} - \frac{1}{g} \int_0^P V \nabla q - \frac{1}{g} \int_0^P \frac{\partial q}{\partial t} \dots \dots \dots 3$$

194 In the given equation (3), E (mm/day) denotes evaporation, ω (Pa/day) represents the vertical
 195 velocity, V (m/day) stands for horizontal wind, q (kg/kg) indicates specific humidity, and
 196 p(Pa) denotes atmospheric pressure. This equation can alternatively be expressed as

197
$$P = E + V_{adv} + H_{adv} - \partial_t q \dots \dots \dots 4$$

198 As the contribution of $\partial_t q$, to the moisture budget in equation 4 is usually negligible compared
 199 to the other terms, we can omit $\partial_t q$, and rewrite it as equation (5)

200
$$P = E + V_{adv} + H_{adv} \dots \dots \dots 5$$

201 where, V_{adv} , H_{adv} and $\partial_t q$ denotes the vertical moisture advection, the horizontal moisture
 202 advection, and the time derivative of q, respectively. Further, the vertical moisture advection
 203 is decomposed by

204
$$V_{adv} = \text{Dynamic} + \text{Thermodynamic}$$

205

206
$$V_{adv} = - \left[\frac{1}{g} \int_0^p \Delta \omega \frac{\partial q}{\partial p} \right] - \left[\frac{1}{g} \int_0^p \bar{\omega} \Delta \frac{\partial q}{\partial p} \right] \dots \dots \dots 6$$

207 The dynamic component in vertical moisture advection corresponds to the changes in vertical
 208 velocity during the EPEs, while the thermodynamic component primarily pertains to alterations
 209 in atmospheric water vapor, aligning with the concept of the Clausius-Clapeyron equation.
 210 (Allen & Ingram, 2002; Pall et al., 2007; Pfahl et al., 2017).

211 ***Estimation of Apparent Heat Source (Q1) and Moisture Sink (Q2):*** This study presents the
 212 computations of diabatic heating over the Himalayas in terms of apparent heat source (Q1) and
 213 apparent moisture sink (Q2). The studies by (Yanai, 1961; Johnson, 1987; Yanai and Tomita,
 214 1998) which have also been utilized in other research works (Attada et al., 2020;
 215 Mukhopadhyay et al., 2010) underscores the significance of vertical heating distribution in
 216 driving monsoon circulation and contributing to substantial rainfall amounts. We calculated
 217 the apparent heat source (Q1) and apparent moisture sink (Q2), along with their vertical
 218 integrations within an air column following (Yanai & Tomita, 1998). The expressions for Q1
 219 (equation 7) and Q2 are (equation 9)

220
$$Q_1 = C_p \left(\frac{P}{P_0} \right)^k \left(\frac{\partial \theta}{\partial t} + V \cdot \nabla \theta + \omega \frac{\partial \theta}{\partial P} \right) \dots \dots \dots 7$$

221
$$k = \frac{R}{C_p} \dots \dots \dots 8$$

222 and

223
$$Q_2 = L \left(\frac{\partial q}{\partial t} + V \cdot \nabla q + \omega \frac{\partial q}{\partial P} \right) \dots \dots \dots 9$$

224 where θ represents the potential temperature, q signifies the specific humidity, denotes the
 225 horizontal velocity, ω stands the vertical velocity, and p indicates the pressure in equation 7.
 226 R and C_p are the gas constant and the specific heat at constant pressure, respectively. Q1 is
 227 determined by combining the latent heating linked to phase changes, vertical eddy transport,

228 surface sensible heat flux, and radiative heating. Likewise, Q2 consists of net condensation,
 229 vertical eddy transport of moisture, and subgrid mixing (Liu and Moncrieff., 2007). The
 230 heating profiles are significantly influenced by microphysical phenomena such as evaporation
 231 and condensation, as demonstrated by (Rajeevan et al., 2010; Rogers et al., 2007) in their
 232 studies. These processes, in turn, hinge on the hydrometeor mixing ratios specified within
 233 different microphysics schemes. We have expanded our investigation to explore the presence
 234 and behaviour of hydrometeors within the atmosphere, aiming to enhance our comprehension
 235 and predictive capabilities related EPEs. Several studies (Hazra et al., 2016; Luo et al., 2009)
 236 revealed that alterations in cloud microphysical properties can have an effect on mesoscale
 237 dynamics of any extreme event, as hydrometeors size, shape, and density can impact how they
 238 interact with other particles and with the atmospheric environment, which, in turn, affects the
 239 formation and intensity of precipitation. Therefore, we have investigated the composite
 240 anomaly of hydrometeors (total column of total column cloud liquid water, total column cloud
 241 ice water, total column snow water, total column supercooled liquid water, and total column
 242 water vapour. We further investigated the extratropical influences and the dynamical and
 243 thermodynamical characteristics of the synoptic condition's setup prior to the EPEs over the
 244 Himalayas.

245 **Ertel Potential Vorticity (EPV):** EPV is calculated to investigate the extratropical influences
 246 in triggering extreme precipitation events over the Himalayas. It is particularly important to
 247 understand the dynamics of upper-level troughs and ridges, which are crucial in developing
 248 and stirring weather systems (Raju et al., 2015; Sandhya et al., 2015). Extreme precipitation
 249 and flood events in the Himalayas are frequently linked to synoptic condition characterized by
 250 interactions between equatorward moving upper-level extratropical circulations and moisture-
 251 rich tropical monsoon circulation. Therefore, this study calculated composite anomaly EPV
 252 (PV; on the 350 K surface) to analyze the extratropical interaction over the heavy rainfall region
 253 HFR. IPV is formulated by following the equations.

$$254 \quad P = -g(\zeta_{\theta} + f) \frac{d\theta}{dp} \dots \dots \dots (10a)$$

$$255 \quad \zeta_{\theta} = -\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)_{\theta} \dots \dots \dots 10(b)$$

256 Here P is the isentropic potential vorticity (or Ertel's PV), ζ_{θ} is relative vorticity calculated on
 257 the isentropic surface, f is earth's vorticity (latitude dependent), $\frac{d\theta}{dp}$ Lapse rate of potential

258 temperature. IPV is denoted in potential vorticity unit (P.V.U.) where for synoptic scale
259 motions 1PVU is equal to $10^{-6} \text{ m}^2 \text{ s}^{-1} \text{ K kg}^{-1}$.

260 **3. Result and Discussions**

261 This section presents the synoptic conditions responsible for the occurrence of EPEs over the
262 WH. Furthermore, this section interprets the dynamic and thermodynamic feedback
263 mechanisms that play a role in the genesis of EPEs in the Himalayan region.

264 **3.1 Synoptic dynamics of EPEs**

265 We investigate the composite anomalies of precipitation, total precipitable water, outgoing
266 longwave radiation (OLR), 2-meter air temperature and soil moisture to explore the associated
267 atmospheric variables for precipitation events that trigger EPEs in WH. The most copious
268 amount precipitation (exceed 35 mm day^{-1}) is noticeable in the vicinity of foothills of the
269 Himalayas as shown in Figure 2a. This geographical distribution of the EPEs implies that
270 extreme precipitation in the foothills of the Himalayas exhibits regional consistency, indicating
271 that these events could be modulated by large-scale circulation along being localized drivers.
272 In addition, positive anomalies of total precipitable water are clearly seen over the foothills of
273 Himalayas, showing enhanced atmospheric moisture content during extreme events
274 contributing to excess precipitation (Figure 2b). It is to be noted that extreme precipitation
275 amounts are usually proportional to precipitable water (e.g. Ccoica-López et al., 2019; Kunkel
276 et al., 2020). This excess moisture aids for producing more precipitation and, thereby, provides
277 conducive environment for the occurrence and persistence of extreme precipitation in the
278 Himalayas. Furthermore, composites of OLR (Figure 2c) anomalies during EPEs exhibits
279 lower OLR values is covered over the WH region, and intensified more along with foothills of
280 Himalayas, highlighting the presence of deep convective activity in the region. It is noteworthy
281 that the convection is triggered by the forcing of monsoon winds over the topography. This
282 extreme rainfall induces a significant surface cooling in the Himalayan foothills and its adjacent
283 regions as shown in Figure 2d. This process cools the surface and warms the atmosphere, where
284 water vapor condenses and releases heat in the mid-troposphere. In addition, the positive
285 anomaly of soil moisture (Figure 2d) indicate that higher soil moisture is available for the
286 precipitation region. As the lower tropospheric monsoon flow advances the Himalayan
287 foothills, it encounters significant surface heat flux, primarily driven by evaporation and
288 evapotranspiration processes (Figure S1). Consequently, by the time it reaches the Himalayas,
289 this flow becomes saturated with moisture and becomes highly prone to potential instability.

290 This soil-precipitation feedback helps in increasing atmospheric moisture which leads to more
291 precipitation which further saturates soil and lower the surface temperature.

292 **3.1.1 Dynamical Characteristics**

293 The spatial distributions of upper (200hPa) tropospheric geopotential height composite
294 anomalies (Figure 3a) depicts an anomalous low-pressure system is formed over the northern
295 Himalayan region and its vicinity, whereas two high-pressure systems are observed over the
296 western (Eurasia) and eastern (Tibetan) peripheries of the WH during EPEs. Notably, the
297 Eurasia high, northwestern Himalayan low pressure and Tibetan high form a characteristic
298 wave-like pattern with canters of alternating polarities extending across the northwest India
299 belt. The wave-like pattern (zonal wave) position at 500hPa shows strong equatorward
300 protrusion of the westerly trough over WH, suggesting a baroclinic feature, leads to
301 atmospheric instability that trigger the extreme precipitation. The dynamical mechanism
302 driving the equatorward extension of the midlatitude westerly trough into the WH region
303 involve a blocking high situated over western Eurasia and a Tibetan high on its east (Figure
304 3a). This configuration induces a robust anomalous south-westerly airflow from the Arabian
305 Sea toward the WH region. The equatorward movement of the low trough also aligned with
306 the cyclonic vorticity (details shown in the result section 3.4). In addition, the vertical pressure
307 velocity at 500hPa has been shown in (Figure 3b) during ISM over the Himalayas. The large-
308 scale vertical pressure velocity during the ISM regime represents the strong ascent of moist air
309 parcel at 500hPa that prevails over the WH along with a gigantic plain region, and its
310 manifestation can be seen in the dominance of EPEs of cloud burst nature (Vellore et al., 2020).
311 In addition, the combination of elevated moisture levels, orography, and midlatitude diabatic
312 heating results in high-pressure vertical velocity. This facilitates the ascent of moisture to
313 higher altitudes, where it releases latent heat, thereby initiating deep convection over the
314 Himalayas. Regarding EPEs, the areas with significant vertical motion align consistently with
315 the regions of intense precipitation, as illustrated in (Figure 2a). Overall, from the EPEs
316 composite analysis, study highlights the predominant role of vertical velocity in triggering
317 extreme precipitation. Finally, the wind composites over the WH region shown in Figure 3(c,
318 d). The lower tropospheric anomalous circulations show stronger south-westerlies
319 (southeasterlies) over the AS (BoB), merging along the foothills of the Himalayas Figure 3(c).
320 It is clearly noticed that the south-westerly wind from the AS dominates more than the
321 southeasterly flow BoB and is directed and intensifying towards the WH region during heavy
322 rainfall episodes. In addition, the positive anomaly of low-level relative vorticity (shown in

323 yellow contours) aligns with an intensified cyclonic circulation pattern over the Himalayas
324 during EPEs. The presence of anomalous low-level cyclonic vorticity over western India and
325 the lower altitude areas of the Himalayan foothills creates favourable conditions for wind
326 convergence towards the WH. Upper-level wind composite anomalies shown in Figure 3(d)
327 exhibit cyclonic circulation over the Hindu Kush Mountainous region and anticyclonic flow
328 over Tibetan, which couple to generate strong cyclonic-anticyclonic pairs of gyres (west and
329 east sides of the study region). Interestingly the point of interaction of the pairs of gyres of
330 cyclonic-anticyclonic are observed over the northern flank of the Himalayas and make the
331 favourable condition divergence of wind at the upper levels (200hPa), thereby enhancing the
332 low-level meridional winds poleward of the WH region. As the moist air masses approach the
333 Himalayas, they are orographically lifted, finally triggering convection (Houze, 2014; Medina
334 et al., 2010; Paula Barros & Lettenmaier, 1994). These circulation patterns provide favourable
335 dynamical conditions for the occurrence of extreme summer precipitation events over the WH.
336 In addition, mass stream function has been used to understand role of ITCZ location during the
337 EPEs over WH. According to the Byrne and Schneider, 2016 location of the ITCZ is defined
338 as the latitude nearest to the equator where the zonal mean stream function, average vertically
339 between 700 and 300hPa, equals zero. Figure 3 (e) shows the zonal mean stream function area
340 averaged over the longitudinal range of 70°E to 100°E in yellow line for non-extreme days and
341 in magenta line for extreme days. Our results indicate that the ITCZ is located at 33.1°N during
342 the non-extreme days, while it shifts by 2.49°N to the north during the extreme days. This shift
343 is significant as it can enhance the precipitation amounts in the WH, potentially causing
344 localized flooding. Our findings are also consistent with those of Kad and Ha, 2023,
345 underscoring the influence of ITCZ in wet years. These research findings underscore the
346 significant impact of large-scale dynamics on shaping the local atmospheric thermodynamic
347 conditions over the WH during EPEs.

348 Based on the above analyses, it has been found that the zonal wave pattern over the mid
349 and upper troposphere. Notably, the western Siberian High, western trough, and the Tibetan
350 high are identified as profound weather systems during EPEs. These deep weather systems
351 significantly influence the vertical structure of the atmosphere. Therefore, examining the
352 atmospheric vertical structures associated with EPEs during the ISM is crucial. Figure 4
353 displays the composite vertical-meridional and vertical- zonal cross-sections of geopotential
354 height and vertical pressure velocity anomalies along the longitude spanning from 30° E to
355 120° E, and latitude spanning 22° N to 38° N respectively. As depicted in Figure 4a, negative

356 anomalies in the geopotential height field span the entire troposphere (from the surface to
357 300hPa) around 72°E, extending eastward over the Himalayan range, and it has the strongest
358 anomaly up to 30 m at around mid-troposphere (500hPa). This anomalous baroclinic structure,
359 with stronger responses observed at 500hPa, implies the influential role of the upper-
360 tropospheric circulation associated with the anomalous wave pattern. These results are
361 consistent with the result shown in Figure 4(a). Collectively Figures 3a and Figure 4a suggest
362 that the deep western trough characterizes the EPEs during ISM over the Himalayas, with two
363 highs, the Siberian high and the Tibetan high. We also notice in Figure 4b high negative
364 pressure velocity in the mid-troposphere around 72° - 80°E suggesting an ascending air column
365 that spans the entire troposphere over the Himalayan region, which causes strong convective
366 activities, therefore, more cloud formation and heavy precipitation. In addition, vertical-zonal
367 cross-sections of geopotential height and vertical velocity along the latitude spanning from
368 20N° to 38°N, are shown in Figure 4 (c, d) respectively. Finding exhibits the cyclonic features
369 at lower tropospheric and anticyclonic feature at upper tropospheric level that promote the
370 lifting of warm, moist air and trigger the development of EPEs. Result also shows north-south
371 strong mid tropospheric low-pressure gradient and high negative pressure velocity in the mid-
372 troposphere around 28°- 32°N indicating ascending air column over the WH. Overall, the
373 vertical structure of geopotential height and vertical pressure velocity contribute to favourable
374 dynamical conditions for the occurrence of extreme precipitation over the WH. Furthermore,
375 Figure S2 presents a display of vertical-meridional cross-sections showing anomalous wind
376 components along the meridian 72°-80°E. The results notably show an increase in meridional
377 winds along with significant mid-tropospheric vertical motion has been observed shown in
378 (Figure S2) over the Himalayan foothill region. The convergence in the foothill region
379 coincides with enhanced convergence extending up to 400hPa at high elevations within the
380 study region. Simultaneously, upper-level divergence evidently contributes to the acceleration
381 of the upper-level jet.

382 **3.1.2 Thermodynamical characteristics**

383 Atmospheric moisture is a major contributor to EPEs, so investigating extreme precipitation
384 requires monitoring its changes and sources of moisture. Thus, moisture transport analysis
385 provides insight into the dominant modes of precipitation variability as well as the moisture
386 sources feeding the EPEs over the Himalayas. A composite analysis was carried out to study
387 moisture sources and moisture transport via VIMT in the atmospheric column from 1000 to
388 300hPa, with vectors depicting the direction of moisture transport shown in Figure 5a. The

389 findings show that moisture transport appears from the southwest and southeast of the study
390 area towards WH from the AS and BoB during the EPEs. Strong moisture with moisture
391 components from the AS and BoB towards WH is carried by a south-westerly wind and
392 southeasterly winds during the EPEs. The Positive anomaly of VIMT provides clear evidence
393 of available moisture over WH, which helped form the intense convective system and resulted
394 in a severe storm over the Himalayan region. Previous studies (Aggarwal et al., 2021;
395 Chevuturi & Dimri, 2016; Karki et al., 2018b) also found that anomalous high moisture
396 incursions from the AS and BoB along with monsoon troughs are the significant contributor
397 for moisture sources generates precipitation over the foothills of the western Himalayas. In
398 addition, the analysis reveals a notable feature in the lower Himalayan foothill belt, where there
399 is a significant positive anomaly in Convective Available Potential Energy (CAPE) and an
400 intense negative anomaly in Convective Inhibition (CIN) shown in Figure 5b. CAPE
401 representing atmospheric instability, indicates the potential energy available for convection,
402 while CIN quantifies the energy required to overcome stability and initiate deep moist
403 convection. The finding indicates heightened atmospheric instability and reduced inhibition,
404 facilitating the increase in available parcel energy. Consequently, the increase in CAPE fosters
405 strong moist convection, thunderstorms, and ultimately leads to EPEs in the region.

406 Further analysis of the MSE was carried out to study the large-scale climatic influences
407 on EPEs as depicted in Figure 5c. MSE mainly signifies a thermodynamic indicator of the
408 atmospheric column. An increase in MSE signifies the influx of MSE from the surrounding
409 environment, which destabilizes the atmospheric column through heating and moistening
410 processes (Maloney, 2009; Zheng et al., 2020). The finding highlights an anomalously strong
411 MSE build-up within the mid-tropospheric layer. The presence of positive composite of MSE
412 exhibit a pronounced gradient as it increases in the south-north direction, culminating with a
413 maximum value over the windward side of the WH (as depicted in Figure 5c). These findings
414 suggest the initiation of convection over the low-lying regions and its intensification over the
415 foothills of the Himalayas. This escalation indicates a high atmospheric instability,
416 subsequently leading to the development of intense convective extreme precipitation.
417 Conversely, the decrease in the MSE seen over the leeward side of the Himalayas indicates that
418 the troposphere is stabilized by cooling and drying processes. In addition, the occurrence of
419 deep convection is dependent on the availability of moisture and the degree of moist convective
420 instability (CI). One method of assessing CI, as defined by (Krishnamurti and Bhalme, 1976;
421 Pattanaik, 2003), involved calculating the difference in moist MSE between 700hPa and
422 1000hPa. A greater the magnitude of the difference between MSE (at 700hPa) and MSE (at

423 1000hPa), indicate higher degree of moist convection instability. In the present study, the
424 degree of moist CI is calculated over the WH region during EPEs as illustrated in Figure 5d. A
425 positive anomaly of the CI clearly reveals higher moist convective instability over the foothills
426 of the Himalayas. This moist convective instability, coupled with sufficient moisture
427 availability during the EPEs, amplifies the occurrence of deep convection and, hence, intensify
428 extreme rainfall events.

429 **3.2 Moisture budget and diabatic heating during EPEs**

430 After exploring the dynamic and thermodynamic characteristics, we have now focus on
431 understanding the causes of changes in EPEs during ISM by analysing the moisture budget
432 components based on Equation 5, as proposed by Oueslati et al., (2019). Our analysis provides
433 a physically based quantification of the dynamic and thermodynamic contributions that are
434 useful for EPEs attribution over WH. Figure 6a illustrates all components of the moisture
435 budget and its contribution in percentage during an EPE over the WH. Result highlights that
436 vertical moisture advection is the dominant factor, contributing significantly more than
437 horizontal advection or evaporation to the EPEs. The finding emphasizes that the positive
438 anomaly of vertical advection (goes more than 40 mm day) is the main driver for EPEs, as it
439 prompts the moistening of the troposphere predominantly through vertical moisture transport,
440 sustaining low-level moisture convergence (as shown in Figure 6b). In contrast, horizontal
441 moisture advection, though positive (goes up to 15 mm day), has a smaller impact, it helps
442 minimize the drying of the troposphere by transporting dry air away from rainy regions, which
443 can also aid in increasing precipitation intensity while, changes in evaporation are negligible
444 during the EPEs (Figure 6a, c). The findings underscore the importance of atmospheric
445 circulation, particularly vertical motions, in causing EPEs over WH.

446 To delve deeper into the mechanisms driving EPEs in these regions, we specifically
447 examine the primary factor: vertical moisture advection. Utilizing equation 6, we decompose
448 vertical moisture advection into dynamic and thermodynamic components. This breakdown
449 allows for the quantification of vertically-integrated changes in dynamic and thermodynamic
450 processes, while accounting for the influence of temperature lapse-rate variations (Goswami et
451 al., 2014; Yanai & Tomita, 1998). Figure 6(d, e) illustrates the contributions, showing that the
452 dynamic term is the primary driver of vertical moisture advection over the study region. It is
453 found that dynamic processes contribute more than 90% to the overall vertical moisture
454 transport. According to equation 4, changes in the vertical pressure velocity (ω) play a
455 crucial role in driving the dynamic contribution. Conversely, alterations in specific humidity

456 are more directly associated with the thermodynamic component. Further manifestations on
457 the spatiotemporal distribution of EPEs, apparent heat source (Q1), moisture sink (Q2), are
458 analyzed to determine the thermodynamic feedback. The monsoon circulation primarily results
459 from large-scale distribution of heat source, which governs convective activity. Thus, the
460 tropical-subtropical deep convection resulted in heavy precipitation is accompanied with the
461 atmospheric diabatic heating which representative of thermodynamic forcing induced by
462 convective activity in the atmosphere (Bhide et al., 1997). Q1 and Q2 are basic measures for
463 analysing the mechanisms of the heating process. The prominent location of Q1 and Q2 align
464 closely with the heavy precipitation centre during the same time over the WH. Q1 denotes the
465 heating generated by convection, radiation, condensation, and eddy heat flux processes, while
466 Q2 is related to the moisture sink resulting from net condensation and divergence in eddy
467 moisture transport. (Han et al., 2021; Son et al., 2021; Xing et al., 2016). Figure. 7 (a, b) show
468 the distribution of vertically integrated heat source Q1 and moisture sink Q2 respectively for
469 EPEs. An intense heat source is observed over the foothills of Himalayas that indicates
470 dominance in convection and radiative heating (Figure 7a). We also noted that the centre of
471 maxima in the spatial distribution of Q2 is also over the same region of WH as Q1 but lesser
472 in magnitude (Figure 7b) indicating that condensation also play significant role to the extreme
473 precipitation. However, the anomalous Q2 extends not as broadly as the Q1, but their centers
474 lie over the same place. A glance at these figures reveals that heating over the foothills of the
475 Himalayas is not only contributed by radiative heating and convection but also by condensation
476 due to latent heating. The vertical distribution of Q1 and Q2 is shown in Figure 7(c, d),
477 respectively in the latitude plain along a WH. The south–north alignment of Q1 and Q2 over
478 the WH is observed. The whole troposphere is occupied by relatively high Q1 in the WH with
479 a peak in the 400hPa–600hPa. Overall, the apparent heating intensity indicates that the mid-
480 troposphere experiences warming during heavy precipitation. The intensified heating in the
481 atmospheric column increases instability in the mid-troposphere and reinforces convective
482 motion. This process involves the upward pumping of warm, moist air from lower levels to
483 higher levels. Furthermore, Figure (7e, f) illustrates the area-averaged vertical profiles of Q1
484 and Q2 over the WH to elucidate the vertical structure of diabatic heating during EPEs. The
485 findings indicate that the heating maxima are observed in the middle to upper troposphere in
486 the WH, while below 600hPa, the moisture sink exhibits its highest intensity (Figure 7f). In
487 contrast, the heat source appears relatively weaker in the same region (Figure 7e). These results
488 suggest that the latent heat released from the net condensation of water vapor in the lower
489 troposphere does not promptly contribute to atmospheric heating at the corresponding height.

490 Instead, a substantial amount of latent heat generated at lower levels is rapidly transported
491 upwards by the ascending motion induced by orography, leading to increased convection and
492 the occurrence of extreme precipitation.

493 **3.3 Cloud Microphysical Characteristics**

494 The characteristics of heating profiles are significantly influenced by microphysical processes
495 and its crucial for understanding EPEs in complex regions such as the Himalayas (Baisya et
496 al., 2018; Ganjir et al., 2022; Luo et al., 2009; Rajeevan et al., 2010). Cloud hydrometeors play
497 a pivotal role in shaping precipitation patterns during EPEs, impacting convective dynamics
498 and precipitation intensity (Rogers et al., 2007). The interaction between dynamics,
499 thermodynamics, and cloud microphysics is a key factor in precipitation formation, with
500 microphysical process rates holding significant influence (Chaudhuri et al., 2015; Hazra et al.,
501 2016, 2017). Thus, to fully understand the formation of precipitation leading to EPEs, it is
502 important to consider the accumulation of moisture content coinciding with high vertical
503 velocity, which triggers updrafts and generates deep convective clouds with various
504 microphysical classes such as cloud liquid water, cloud ice water, snow water, supercooled
505 liquid water, and water vapour. This study elucidates to understand the role of the hydrometeor
506 type by linkages between cloud microphysics and large-scale dynamics. Firstly, the spatial
507 distribution of composite anomalies of total column hydrometeors are examined shown in
508 Figure (8a, d). Results clearly show that total column cloud snow water is dominating, followed
509 by total column liquid water specifically over the foothills of Himalayas core precipitation area
510 of the Himalayas. Although total column of cloud ice water (Figure 8b) and supercooled liquid
511 water (Figure 8d) has lesser magnitude than other hydrometeors, but their maximum values
512 concentrated just over foothills of Himalayas, suggesting a sustained contribution during EPEs
513 over WH. Further, vertical-zonal cross-sections of the anomalies of hydrometeors (cloud ice,
514 cloud liquid and, snow water) averaged over the longitude (74°E–82°E) are presented in Figure
515 S3(a-c). Result reveals a highly coherent pattern of cloud ice and cloud snow (as shown in
516 Figure S3(b-c). The finding suggests that snow hydrometeors (Figure S3.c) are the dominant
517 source of rainwater at lower to middle tropospheric levels (800hPa–400hPa). Additionally,
518 there is a noticeable consistency in the distribution of ice hydrometeors (Figure S3b) from
519 middle to upper-pressure levels (500hPa–100hPa). This significant finding indicates that EPEs
520 such as intense cloud bursts over the Himalayan orography region exhibit typical
521 characteristics with large snow water accumulation contributing to liquid and supercooled
522 liquid water. The coherent vertical distribution of cloud snow and ice hydrometeors highlights

523 the importance of snow as a significant component in the formation of rainwater, especially at
524 lower to middle troposphere, while ice hydrometeors play a crucial role in the upper levels of
525 the atmosphere.

526 **3.4 Influence of Extratropical circulation on Himalayan EPEs**

527 We further analyse EPV fields as a potential dynamical precursor of EPEs over the Himalayas.
528 The composite anomaly of isentropic potential vorticity (EPV; on the 330 K surface) displays
529 potential vorticity intrusions indicating the deepening trough and southward advancing
530 cyclonic vorticity stream shown in Figure 9. Upper-level strong cyclonic flows typically
531 accompany positive EPV anomalies, whereas negative EPV anomalies are anticipated to result
532 in high-pressure and anticyclonic flows. The intrusion of positive EPV is associated with
533 strengthening the subtropical jet stream, which can trigger the transport moisture from the AS
534 and the BoB towards the WH. This moisture-laden air encounters the low-pressure system
535 associated with positive EPV, leading to the formation of heavy rainfall. Here, heavy
536 precipitation is generally allied with upper-level EPV intrusions with well-defined features. In
537 addition, Figure 9(b) shows the intrusion of EPV two days before the extreme precipitation
538 over the Kedarnath flood 2013, Figure 9(c) during the extreme precipitation day (16-18) June
539 2013, and Figure 9(d) two day after the extreme precipitation over Kedarnath flood. Result
540 exhibits that due to the entrainment of high EPV air of stratospheric origin, the PV values over
541 the WH are above 4 PV unit associated with tropopause folding during the heavy precipitation
542 days shown in Figure 9(c). Our analysis, however, shows that EPEs during summer impacting
543 the southwest monsoon are linked to positive EPV intrusions and cyclonic patterns of moisture
544 advection. The breaking of Rossby waves, a dominating characteristic contributing to
545 convective severe precipitation, has been linked to incursions of high EPV air from the
546 stratosphere into the tropopause, according to research investigations (Martius et al., 2013;
547 Vellore et al., 2016).

548 **3.5. Role of QRA on the EREs**

549 We further investigate the influence of QRA on the mountain EPEs over the Himalayas. Recent
550 findings (Kornhuber et al., 2017; Mann et al., 2018; Nischal et al., 2024) highlight the
551 significant role of quasi-stationary Rossby waves in shaping weather patterns over the middle-
552 latitude regions across the southern and northern hemispheres. To assess the impact of QRA
553 during EPEs, we adopt the QRA detection scheme proposed by (Kornhuber et al., 2017).
554 Meridional and zonal wind data at 200hPa for extreme events are obtained using ERA5.

555 Subsequently, these data are subjected to a one-dimensional simple harmonic oscillator
556 analysis. Figures 10(a, b) show the meridional profiles of mean surface temperature for the
557 Kedarnath flood (16-18 June) 2013 and another extreme event in 04-05 September 1995,
558 represented by the red lines, along with their respective climatological averages shown by the
559 blue lines. Finding shows that the temperature gradient decreases to near-zero values around
560 40°N and peaks in the subpolar latitudes. This variation in temperature is associated with QRA,
561 as a rapid warming of the polar regions can affect the jet stream and make it wavier and more
562 prone to QRA. These temperature gradient variations are consistent with the minimum zonal
563 wind and strong westerlies over the mid and polar latitudes shown in Figure 10 (c, d). The
564 double-peaked latitudinal structure in the zonal winds exhibits the expected QRA features.
565 Moreover, Figure 10 (e, f) display the zonal mean of meridional wind at 200hPa, exhibiting a
566 wavy pattern that reflects the high- and low-pressure systems across the poles and tropics,
567 indicating the presence of wave numbers up to eight during both the extreme events. These
568 circumglobally wave patterns show QRA amplification of waves trapped in waveguides and
569 its association of the arctic warming. Results are in lined with recent studies have highlighted
570 the connection between extreme events such as droughts and floods in various parts of the
571 world and the presence of slow-moving amplified Rossby waves, particularly in the midlatitude
572 region of the Northern Hemisphere., QRA (Kornhuber et al., 2017; Lakshmi Kumar et al.,
573 2021; Mann et al., 2018) particular the midlatitude region of Northern Hemisphere. In addition,
574 the zonal wavenumber spectra for the zonally averaged meridional wind from 27°N to 60°N
575 latitudes reveal the peak amplitude at wave numbers five and eight, which are higher than those
576 for the climatological period, as shown in Figure 10 (g, h). These waves can break and cause
577 the transport of moist air from the tropics to the subtropic, and the transport of dry air from the
578 stratosphere to the troposphere. This can create favourable conditions for EREs over the
579 Himalayas, as the moist air can condense and release latent heat, which can enhance
580 atmospheric instability. Based on these results, a schematic representation by connecting
581 important mechanisms responsible for EPEs over the Himalayas is presented in Figure 11.

582 **4. Summary and Conclusion**

583 The Himalayas are a region that is highly vulnerable to the impacts of climate change, including
584 changes in summer precipitation patterns resulting extreme events. Our study is pivotal in
585 unravelling the intricate dynamical, thermodynamical, processes associated with EPEs
586 occurrence over the WH. In summary, studies have shown that the occurrence of EPEs over

587 the WH is linked to large-scale drivers along with localise factors. The following are the main
588 findings from the analysis.

- 589 • The findings indicate that the synoptic features and the mesoscale orography forcing
590 contribute significantly to EPEs in the WH. The study proves that favourable synoptic
591 scale conditions, such as low OLR anomaly, high precipitable water, high soil moisture,
592 and surface cooling processes over the WH region, leads to cloud formation and heavy
593 precipitation. Foothills of Himalayan creates the base of steep mountains that influence
594 moisture transport and produce strong gradients for deep convection that leads in EPEs
595 over the Himalayas.
- 596 • Study reveals that EPEs occurring over the WH are linked to large-scale circulation
597 patterns that prevail during these EPEs' evolution. This pattern consists of the formation
598 of zonal waves at mid-latitudes and the equatorward movement of westerly troughs. In
599 Addition, low-level wind composites indicate that moisture-laden monsoonal winds
600 from the AS and BoB intensify during EPEs, which is further strengthened by the
601 development of a divergence (cyclonic and anticyclonic gyre) feature in the upper
602 troposphere over the WH. The study result suggests that the interaction between the
603 monsoon circulation and a penetrating mid-latitude westerly trough increases the
604 likelihood of EPEs over WH.
- 605 • The results reveal strong MSE build-up in the middle tropospheric over the foothills of
606 Himalayas give the signal initiation of convective activity resulting intense
607 precipitation over WH. In addition, greater degree of moist convective instability,
608 couple with available high moisture during the ISM, can increase the occurrence of
609 deep convection and hence make favourable condition for EPEs.
- 610 • Our study comprehensively shown that EPEs over WH are primarily dynamically
611 driven by the induction of stronger vertical motions. This process leads to an increase
612 in the moisture content of the atmospheric column, consequently reinforcing
613 convection. Overall, it has been demonstrated that the dynamic contribution (more than
614 90 percent) surpasses the contribution from thermodynamic for EPEs. Additionally,
615 diabatic heat forcing showed a maximum in the mid-tropospheric region, indicating the
616 presence of a dominant heat source Q1 and a positive anomaly of apparent moisture
617 sink (Q2) indicated increased moisture sinking at the low-level maximum over the WH.
- 618 • Cloud microphysics plays a significant role in modulating the precipitation over such
619 complex terrain regions in the Himalayas. As the wind ascending over the mountains,

620 it cools and condenses, forming different types of Hydrometeors in clouds. The finding
621 shows that total column cloud snow and liquid water is dominating, followed by total
622 column liquid water, specifically over the WH leading to the formation of large and
623 heavy raindrops that contribute intensification of precipitation.

624 • The tropical–extratropical interaction involving the intrusion of positive Ertel PV fields
625 provides valuable information for understanding the potential dynamical precursor of
626 EPEs over the Himalayas. The extratropical cyclonic EPV intrusion has been observed
627 over the WH that started deepening southward during the EPEs and provided the
628 external force to enhance the low-level moisture-laden monsoonal wind toward the
629 Himalayas.

630 • The findings of this study provide compelling evidence supporting the role of QRA as
631 an amplifying mechanism for planetary Rossby waves in the Northern Hemisphere,
632 contributing to the persistence of extreme rainfall episodes over the Himalayas. The
633 distinct imprint of QRA is evident in the atmospheric circulation patterns, notably the
634 double jet zonally averaged zonal wind and the presence of circumglobally meridional
635 wave patterns, both associated with Arctic warming. The observed wavenumber spectra
636 emphasize the significance of waves at higher numbers, primarily five and eight, during
637 EPEs. These results elucidate the intricate dynamics linking QRA, Arctic warming, and
638 the manifestation of specific atmospheric patterns, providing valuable insights into the
639 mechanisms influencing prolonged and intense precipitation events over the Himalayan
640 region insights into the linkages between large-scale atmospheric phenomena and
641 localized extreme weather occurrences.

642 In conclusion, this comprehensive study sheds light on the cause behind in escalating EPEs
643 over the WH. By delving into synoptic, mesoscale, and large-scale factors, our findings
644 underscore the intricate dynamics governing EPEs in this vulnerable region. The identified
645 links between large-scale circulation patterns, orographic features, and microphysical
646 processes provide crucial insights for understanding and predicting intensified precipitation.
647 This research not only advances our comprehension of Himalayan climate dynamics but also
648 underscores the pressing need for continued investigation into the nuanced interactions shaping
649 extreme weather events in this critical geographical expanse.

650

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658

659 **Author Statement**

660 **Rohtash Saini:** Writing-Original draft preparation, Methodology, Software, Formal Analysis,
661 Visualization. **Raju Attada:** Conceptualization, Formal Analysis, Supervision, Resources,
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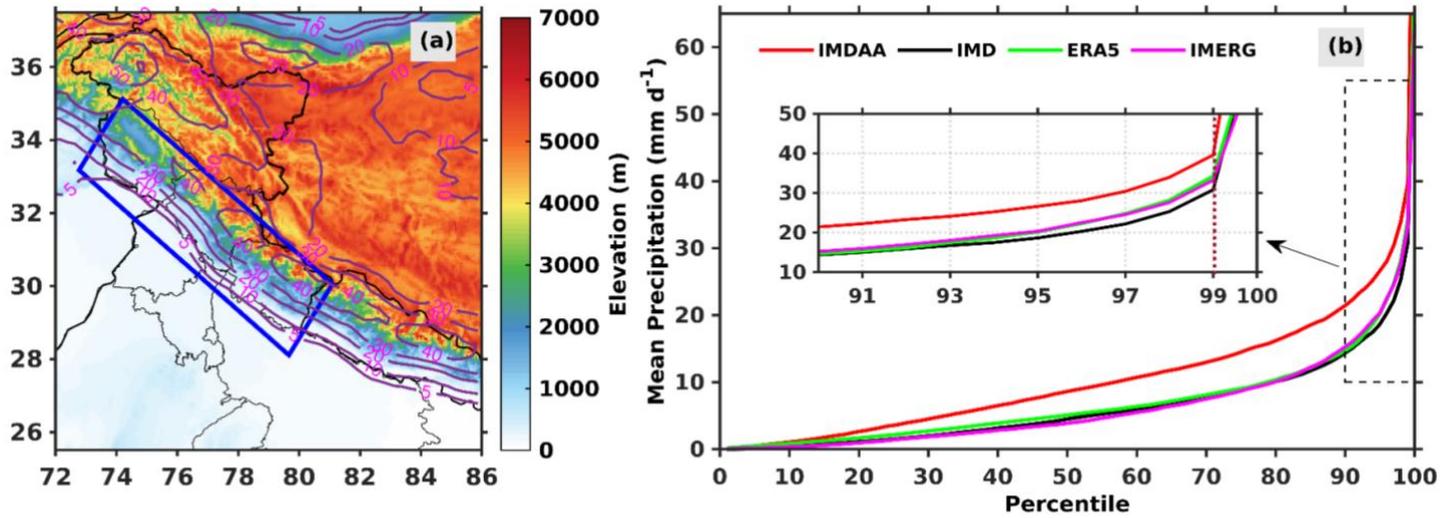
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1027 **Figure1:** (a) Topography (shaded units in meters) map of Indian Himalayas with blue rectangle
1028 indicating Himalayan foothills region. Magenta counters represent the topography complexity
1029 (%) derived from GTOPO30 data, and (b) Mean precipitation (mm day⁻¹) versus percentile over
1030 Himalayan foothills.

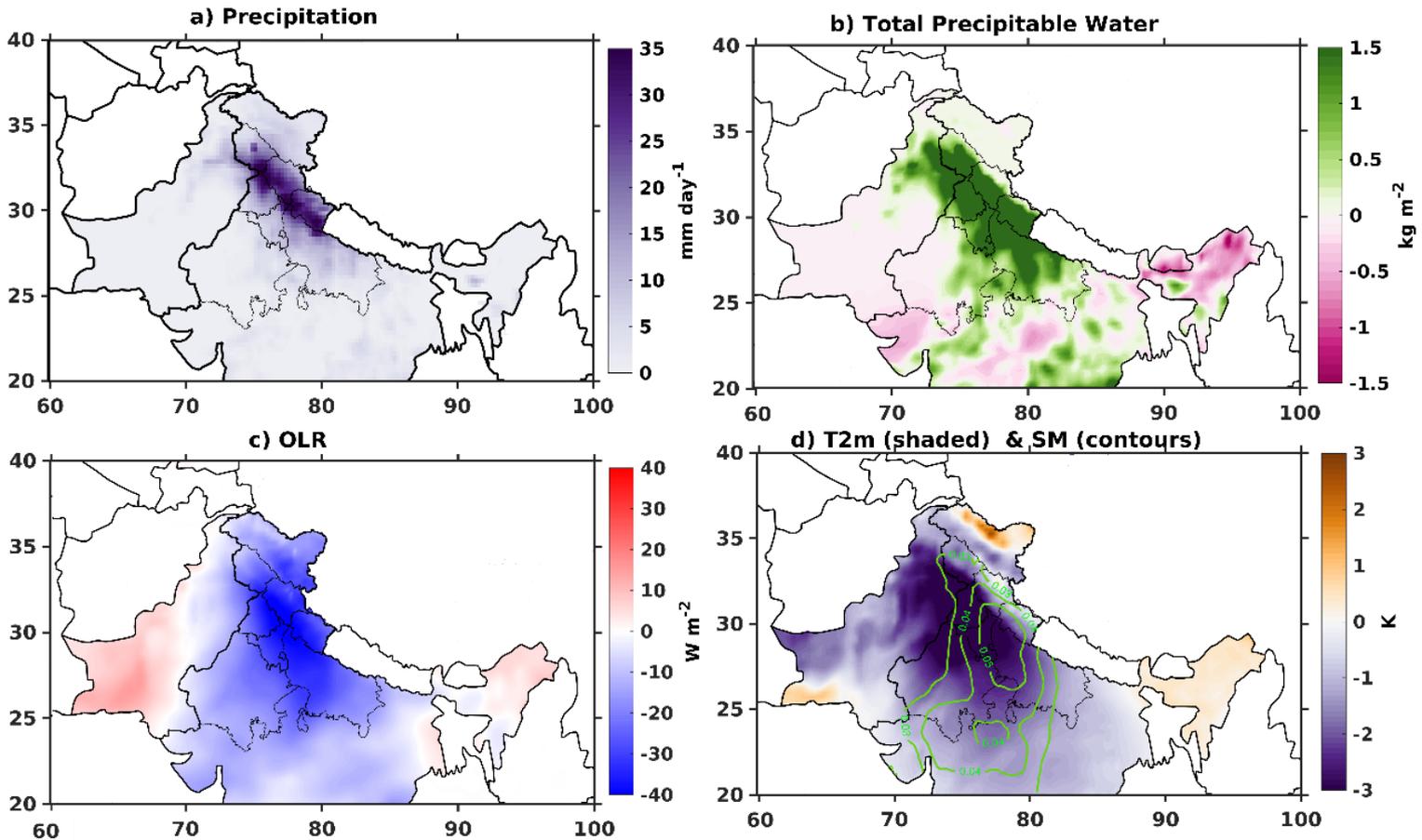
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1037 **Figure 2:** Composite anomalies of (a) precipitation, (b) total precipitable water, (c) outgoing
1038 longwave radiation (OLR), (d) 2-meter air temperature and green color contours represents the
1039 soil moisture during ISM extreme precipitation events occurring over the Himalaya during
1040 1979-2020.

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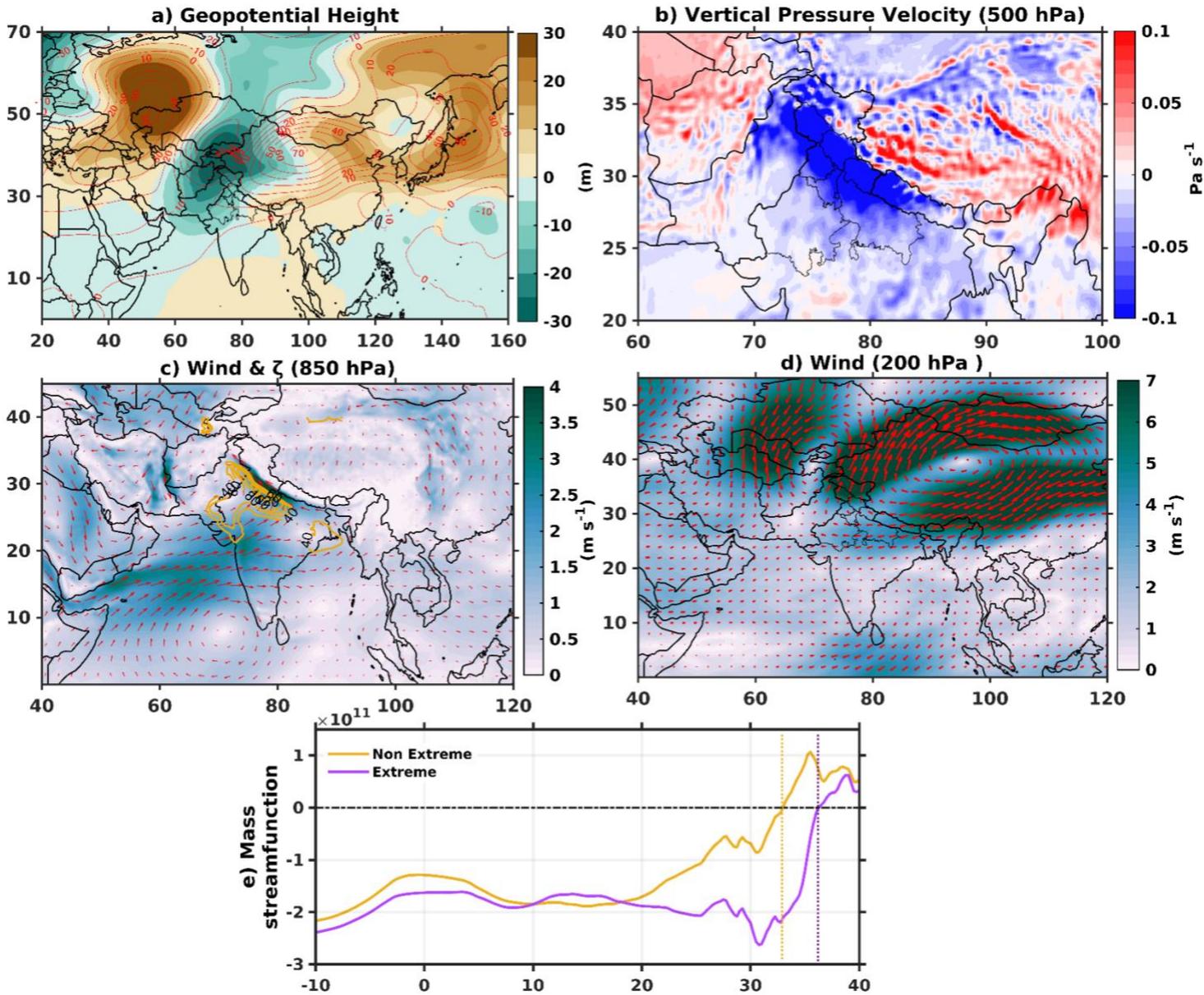
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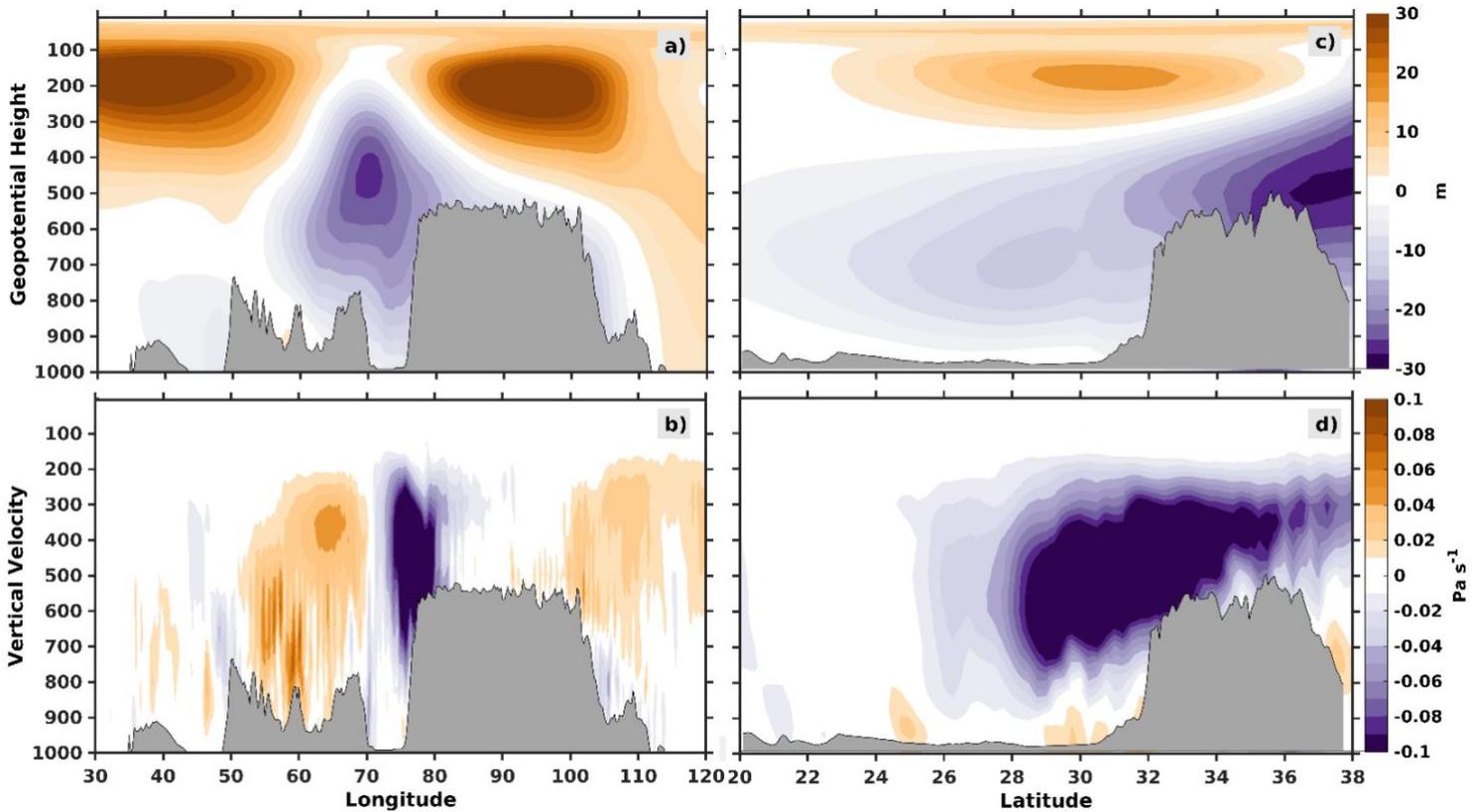
1052 **Figure 3:** Composite anomalies of (a) geopotential height at 200hPa (contours) and 500hPa
1053 (shaded), (b) mid-tropospheric vertical pressure velocity (c) wind at 850hPa (vectors), and the
1054 relative vorticity (counters), (d) tropospheric wind at 200hPa for summer monsoon extreme
1055 precipitation events, and (e) represents the mass stream function (kg sec^{-1}) during extreme days
1056 and non-extreme days (shown in yellow line) over the Himalayas during 1979-2020.

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1063 **Figure 4:** Composite vertical-meridional cross-sections of the anomalies of (a) geopotential
 1064 height and (b) vertical velocity along 28°N–35°N for ISM extreme precipitation events
 1065 occurring over Himalayas. Plots (c, d) represents vertical-zonal cross-sections of the anomalies
 1066 of geopotential height and vertical velocity respectively along the 72°E–82°E.

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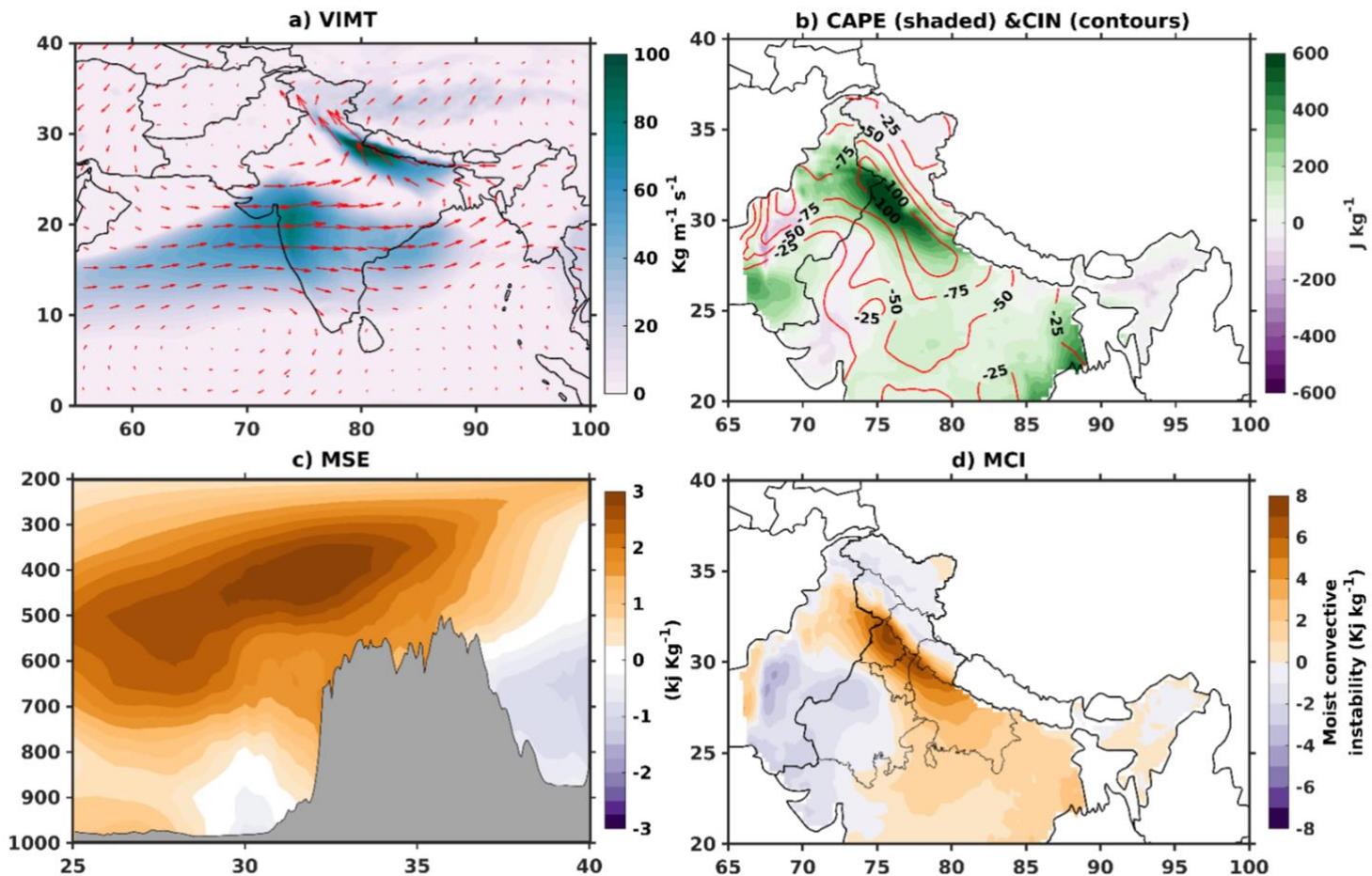
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1083 **Figure 5:** a) Composites of vertically integrated moisture transport ($\text{Kg m}^{-1} \text{s}^{-1}$) during EPEs
1084 over Himalayas. b) shows the convective available potential energy (shaded) and convective
1085 inhibition (contours). c) represents the composite of vertical-zonal cross-sections anomalies of
1086 moist static energy, and c) shows the moist convective instability during summer monsoon
1087 EPEs.

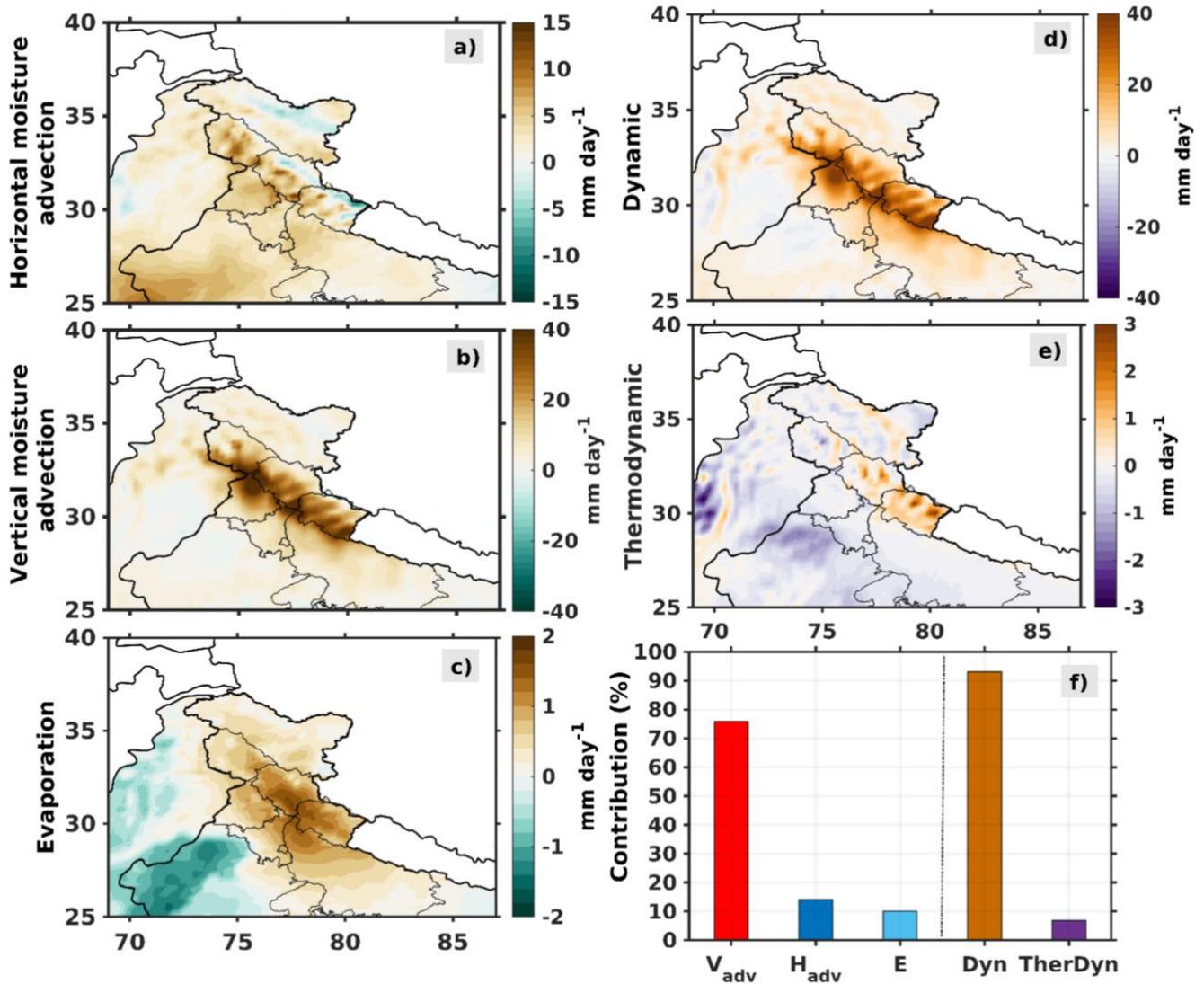
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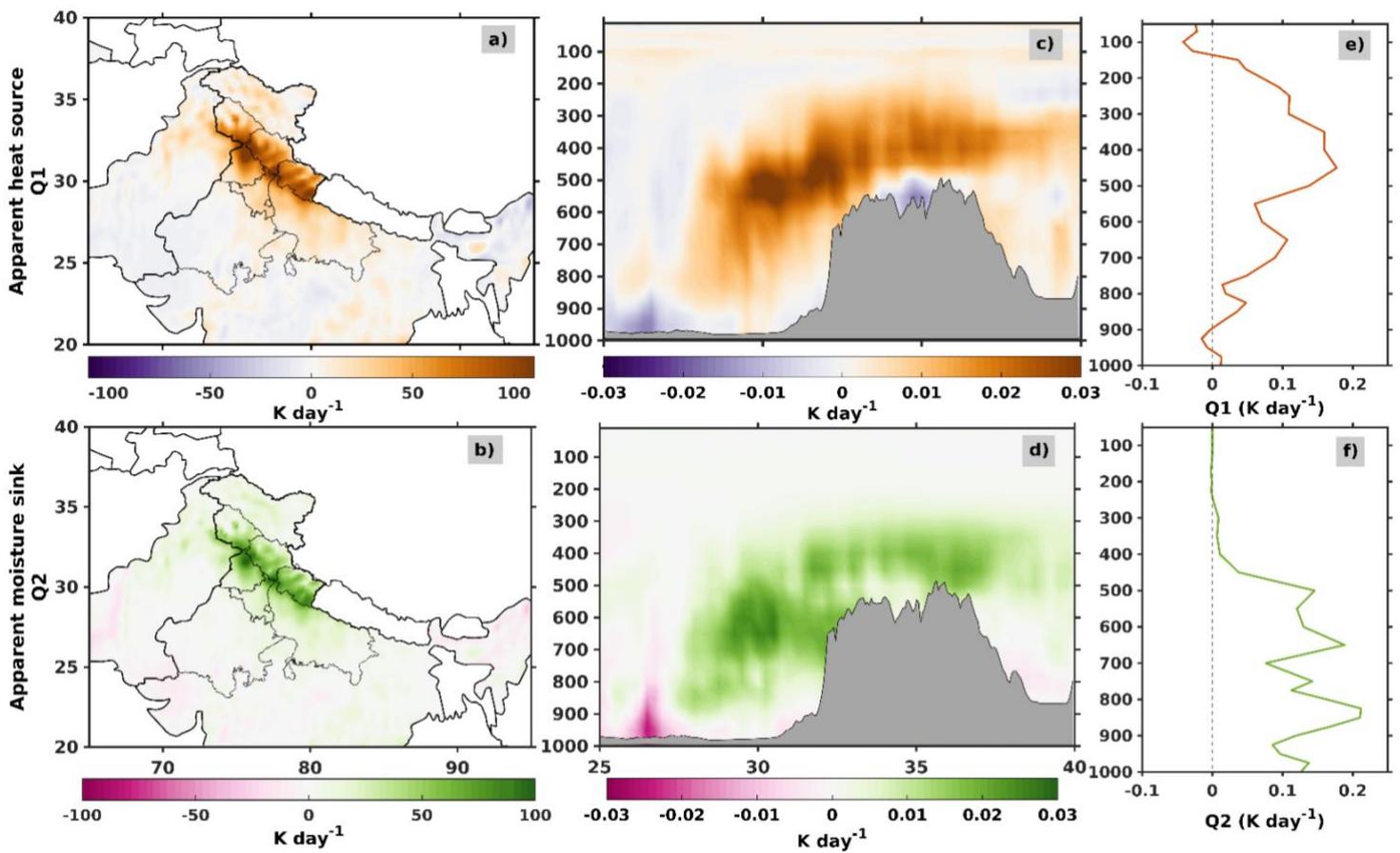
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Figure 6. Composite anomalies of moisture-budget components during the EPEs over Himalayas. (a) Horizontal moisture advection, (b) Vertical moisture advection, (c) Surface evaporation (d) Dynamic component, and (e) thermodynamic component of vertical advection term over Himalayas during ISM extremes. (f) represent contributions of moisture budget components spatially aggregated over the foothills of Himalayas as indicated in Figure. 2a.

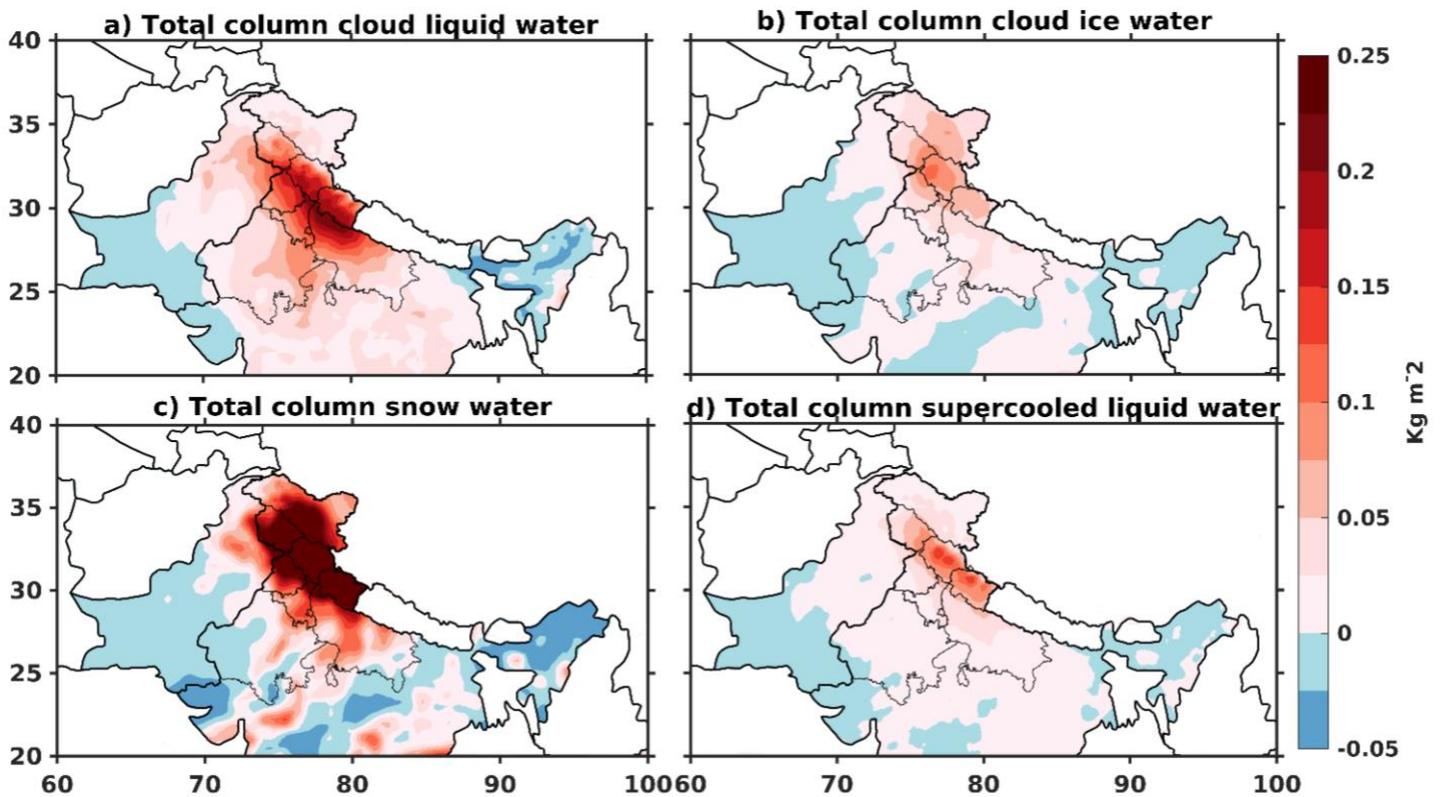
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1112 **Figure 7.** The spatial distribution of composites of a) apparent heat source (Q1), and b)
1113 moisture sink (Q2) during summer monsoon EPEs over Himalayas. Figure (c) and (d) represent
1114 the vertical cross section of composite of Q1 and Q2 respectively. Area average vertical
1115 structure of composite of the apparent heat source, and moisture sink over the HFB are shown
1116 in (e, f) respectively.

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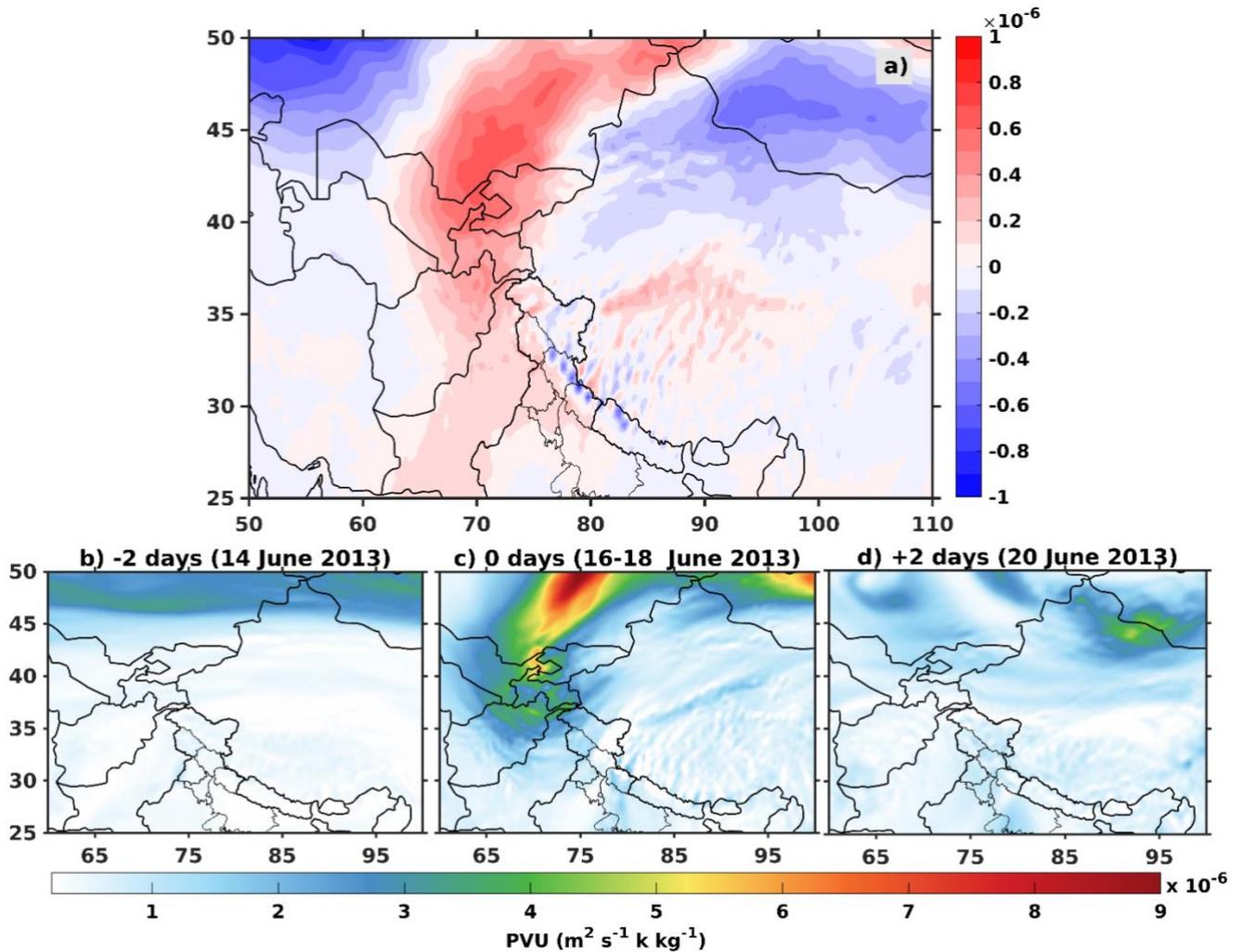
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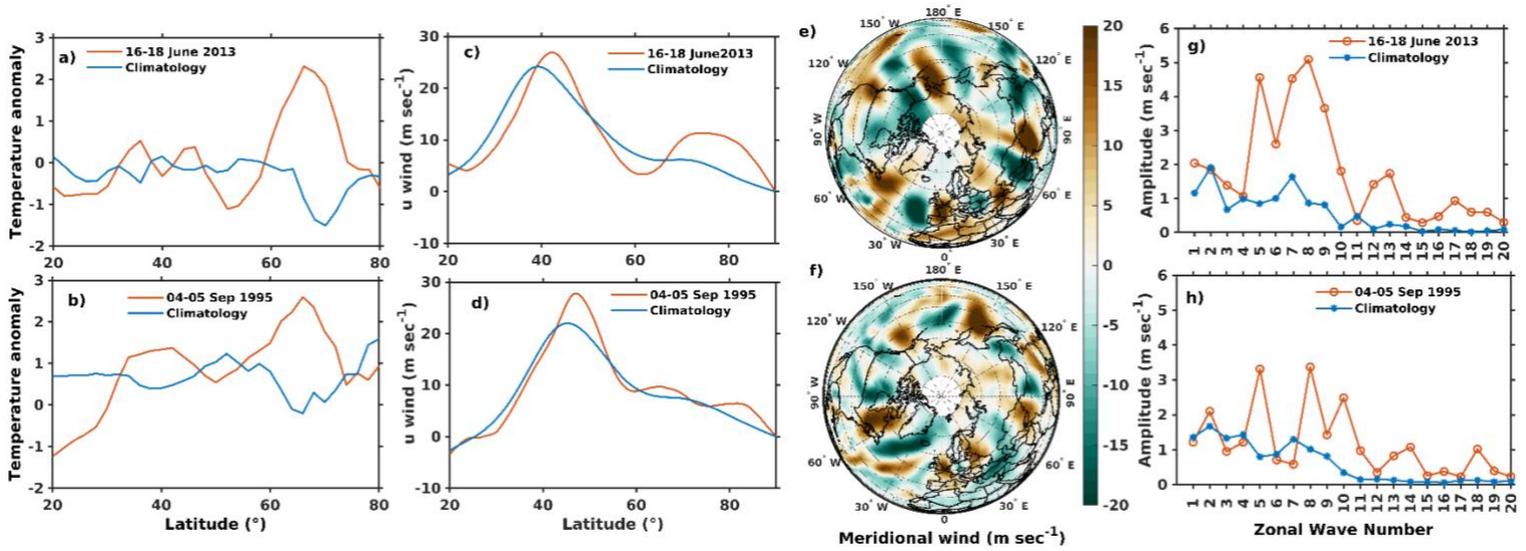
Figure 8: Composites of total column of hydrometeors a) total column cloud liquid water b) total column cloud ice water c) total column snow water d) total column supercooled liquid water during summer monsoon EPEs over Himalayas.

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1139 **Figure 9:** A composite map of Ertel potential vorticity ($\times 10^{-6}$ PVU) on 330 K isentropic surface
1140 during ISM extreme precipitation events. (b) represent two days before (14 June 2013) the
1141 extreme precipitation Ertel potential vorticity ($\times 10^{-6}$ PVU) on 330 K isentropic surface for
1142 Kedarnath flood 16-18 June 2013. (c) shows during extreme precipitation days (16-18) June
1143 2013 and, (c) represents two days after (20 June 2013) the extreme precipitation day for
1144 Kedarnath flood.

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1151 **Figure 10:** Meridional 2-meter air temperature anomalies averaged over the region 20°N to
 1152 80°N during extreme precipitation days (16-18) June 2013, and 04-05 September 1995 extreme
 1153 rainfall event shown (a, b) respectively. The blue line indicates the anomaly for the extreme
 1154 event, and the red line shows the climatology of these event days (1979–2020). (c, d) zonal
 1155 wind profiles associated average over (25°N to 65°N) with extreme events. (e, f) represents the
 1156 upper-troposphere (200hPa) meridional wind fields over Northern Hemisphere, and subplots
 1157 (g) and (h) show the zonal wave number spectra for the meridional wind fields at 200hPa over
 1158 27° to 60°N during the extreme precipitation days in 16-18 June 2013 and 04-05 September
 1159 1995, respectively.

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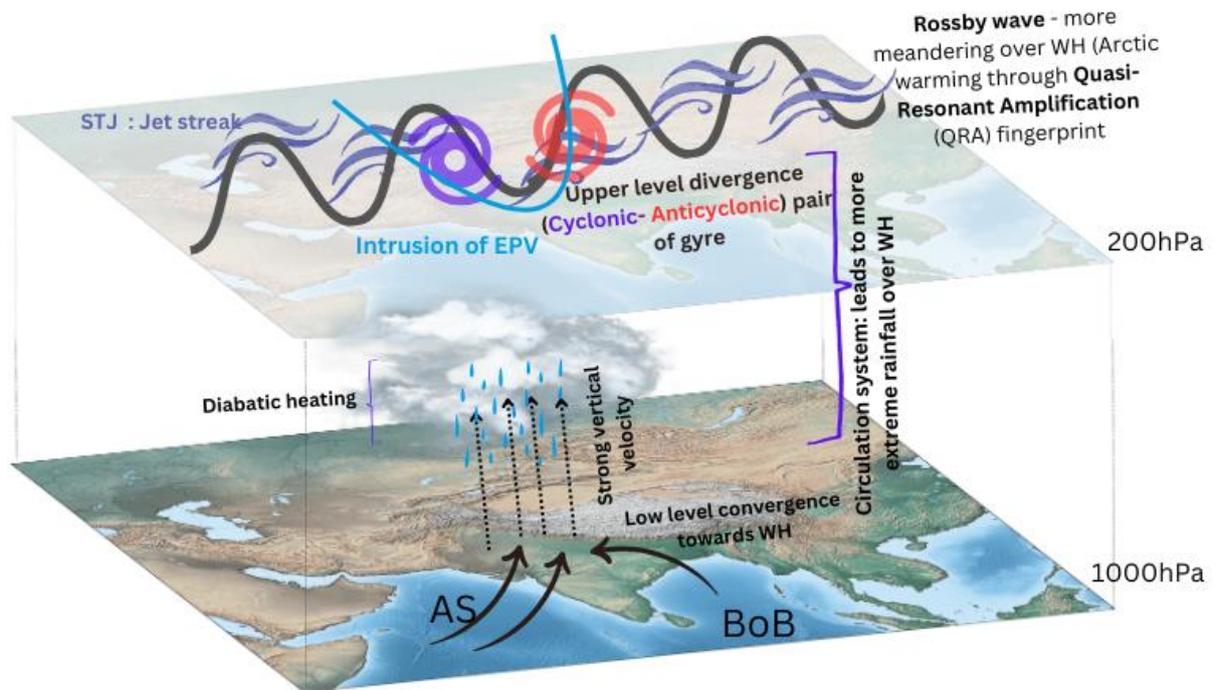
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1173 **Figure 11:** Proposed mechanism of EPEs over the Himalayas during ISM

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