Global warming amplifies outdoor extreme moist heat during the Indian Summer Monsoon

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Abstract

Because of the climatological prevalence of hot, humid conditions, moist heat extremes are a significant challenge to the health and wellbeing of the people in India. While research has demonstrated the importance of summer monsoon to moist heat in India, impact of monsoon-break and warm spells in modulating extreme moist heat regionally has not been fully investigated. Here we investigate moist heat extremes, as measured by the Wet-Bulb Globe Temperature (WBGT) metric, specifically during monsoon and monsoon-break periods and find that they pose a major threat to physical labor and health relative to other seasons. During the 1951-2020 break period, an increasing trend in areas exposed (~42.76 million km^2), representing at least 670 million people, were exposed to extreme and detrimental WBGT values >31°C. Our results imply that future studies on extreme moist heat must pay close attention to the variation of weather systems on synoptic to subseasonal time scales that are superimposed on the seasonal monsoon migration.

Key Points

- Extreme monsoon-break moist heat is detrimental to physical labor relative to other seasons in the Indian region.
- The substantial rise in extreme moist heat has contributed to elevated risk and population exposure over the country.
- Rising global temperature drives extreme moist heat during the monsoon-break, similar to regional temperature change.

Plain Language Summary

A significant increase in temperature extremes associated with high humidity has been observed recently in India. While the Indian population is susceptible to moist heat owing to the current agricultural sector, the recent rise in construction employment can exacerbate its impact. Prolonged exposure to elevated moist heat during any period can lead to a health hazard that can be fatal during certain climatic conditions. We show that India has been exposed to dangerous levels of moist heat during monsoon-break, significantly affecting millions of people. While moist heat extremes occur during monsoon-breaks, it's recent rise is primarily due to global warming. Additionally, the risk associated with the rise in monsoon-break moist heat is substantially higher than other seasons in India. Our findings have implications for public health and subsequent policy development. In recent decades, the increasing agricultural and construction activities in India have drawn immediate attention to policy revision in outdoor working hours.

1. Introduction

Extreme temperature events are increasing in prevalence in India and are becoming a major health hazard(Masson-Delmotte et al., 2021; Seneviratne et al., 2021). The change in summer heat waves has contributed to a 146 % increase in heat-related mortality(Mazdiyasni et al., 2017). Many rural and urban areas in India have already witnessed the moderate work threshold of heat stress incorporating moisture, wind speed, and radiative inputs (Wet-Bulb Globe Temperature; WBGT) > 31 °C (Kong & Huber, 2022) where physical labor begins to become challenging and dangerous. The prevalence of such conditions is expected to increase substantially with only 1.5 °C warming above pre-industrial values (Saeed et al., 2021) and elevated moist heat (> 31 °C) can result in a decline of 30-40 % in work performance (de Lima et al., 2021; Parsons, 2006). Summer monsoon agriculture is inextricably linked to improving the socio-economic condition of at least a billion people in the Indian subcontinent (Gadgil & Gadgil, 2006). A major health hazard due to elevated wet-bulb temperature is expected to occur over the densely populated South Asian region (Im et al., 2017), where one can experience a decline in the body's ability to regulate the internal temperature, which can deteriorate metabolic cooling and cause mortality (Buzan & Huber, 2020). Raymond et al. 2020 show that the human tolerance threshold value of 35 °C (wet-bulb temperature) already occurred in multiple locations in South Asia for at least 1- to 2-hours' duration. The current and future increase in Indian moist heat will be a function of a myriad of factors: irrigation expansion (Mishra et al., 2020), summer monsoon onset (Raymond et al., 2020), moisture advection (Monteiro & Caballero, 2019), aerosol loading (Dey et al., 2021), soil moisture coupling (Wouters et al., 2022), and regional synoptic weather events (Ivanovich et al., 2022).

While an expanding body of literature so far has demonstrated that moist heat is detrimental in pre-monsoon or during monsoon onset the potential role that the synoptic scale break (also known as dry spell or monsoon-break) that typically occurs during an active monsoon phase has been less studied. Considerable effort has been devoted to documenting dry-wet spells and hot-dry conditions during the summer monsoon (Rajeev et al., 2022; Singh et al., 2014) and its projections (Mishra et al., 2020; Rajeev et al., 2022; Singh et al., 2014). During an active monsoon, the synoptic scale break period can instigate a substantial increase in extreme temperature embedded within the broader structure of the summer monsoon (Krishnan et al., 2000; Rajeevan et al., 2010). Given the tight coupling of moist heat extremes with relative humidity and temperature extremes (Buzan et al., 2015), understanding the changes in moist heat during the monsoon can better inform projections of the impact of the reduction in outdoor labor activities (Dunne et al., 2013).

While large-scale experiments and observations are consistent in identifying the moist heat increase over the Indian region and we have also long understood the importance of monsoon-break (Raghavan, 1973; Singh et al., 2014), little to no investigation has been carried out on how monsoon breaks might affect moist heat stress extremes within the broader monsoon context. Here, we address this critical gap by revisiting the documented heat stress values through answering the question: Does warming intensify extreme monsoon-break moist heat in India?

2. Data and Methods

First, we calculated the hourly Wet-Bulb Globe Temperature [WBGT; (Liljegren et al., 2008)] using the temperature, specific humidity, wind velocity and solar radiation from ERA5 reanalysis data for the 1951-2020 period (Kong & Huber, 2022). The specific humidity was calculated using Tetens's formula (Tetens, 1930), with the parameters based on saturation over water (Buck, 1981). Here, we used WBGT as an indicator for the moist heat stress. The WBGT model of (Liljegren et al., 2008) was based on the principle of heat and mass transfer derived from meteorological data. WBGT obtained from (Liljegren et al., 2008) method can achieve an accuracy close to 1 ºC or better, as compared to its station measurements, independent of location. We derived WBGT using the iterative method (Liljegren et al., 2008). For the sake of comparison with other work, we also calculated moist heat using the Environmental Stress Index [ESI; (Moran et al., 2003)] and modified WBGT [(mWBGT); Kong et al. 2022; Fig S1&2]. However, there is a significant underestimation from ESI up to 2 ºC during extreme moist heat identified along the Indian region (Kong & Huber, 2022). Since, ESI and mWBGT are approximation of actual WBGT, we used the (Liljegren et al., 2008) formulation for further analysis. WBGT metric, is an the Occupational Safety and Health Administration /the American Society of Heating, Refrigerating and Air-Conditioning Engineers /ISO standard (Parsons, 2006) and has been in use as a heat stress metric since 1950 and is very well validated. The WBGT was used here for evaluating climatological mean change in moist heat and work performance decline. Labor rates typically drop off at a rate of about 2% per degree above 24 ºC WBGT (Flouris et al., 2018). A value above 31 ºC WBGT during heavy work intensity can reduce the labour performance from 100 to 20 % on outdoor activity (Kjellstrom et al., 2009). For instance, a moderate work condition above 31 ºC WBGT requires thirty minutes of rest for the same duration of activity (Epstein & Moran, 2006). Since six hourly data or higher resolution is necessary to capture the interactions of the components of WBGT (Jonathan R Buzan & Huber, 2020), we calculated the six hourly mean daily maximum WBGT for the 1951 – 2020 period. Our analysis focuses on characterising extreme moist heat during June – September (monsoon). Here, extreme moist heat is defined as the WBGT value above 31ºC. Further, climatological 95th percentile frequency was obtained to understand the change in extreme moist heat.

Next, the areal extent of regions experiencing 31 °C moist heat exceedance for at least six continuous hours for the summer (March, April, and May), monsoon (June, July, August, and September), and monsoon-break periods were estimated. To do so, we calculated the cumulative daily hour of WBGT above 31 °C and derived the yearly median. Population exposure to prolonged extreme moist heat was also calculated for the 1960 – 2020 period. We used world bank population data for the 1960-2020 period(World Bank, 2022).The population data is then multiplied by average yearly hours with WBGT above 31 °C. We converted the hourly data into a seasonal fraction to account for the varying length of season. Further, moist heat risk to the population during the monsoon and summer seasons was calculated for the Indian region. We estimated the risk based on the IPCC-AR5 framework, which is the product of hazard, vulnerability, and population. Hazard is the trend obtained from the moist heat intensities for the 1951-2020 period on gridded data at 31 km spatial resolution. A district-level vulnerability was obtained from the climate vulnerability using a common framework (CVAF) for India, which uses fourteen indicators to construct the district-level vulnerability ranking. More information on the district level vulnerability calculation can be obtained from the CVAF planning in India (Dasgupta et al., 2020). The vulnerability calculation mainly comprises of socio-economic features and livelihood, biophysical aspects, and institutions and infrastructure. Since the vulnerability profile for each district is developed based on the IPCC 2014 ‘ Risk and Vulnerability Framework’, the current index can be used as a function of risk evaluation (Dasgupta et al., 2020). The population data for spatial analysis is downloaded for the 1990 and 2020 period from the Socioeconomic Data and Application Centre (SEDAC). We used Population, Landscape, and Climate Estimates (PLACE) version 3 (University, 2012) for the 1990 and version 4 (University, 2022) for the 2020 population count. Here the population count is used for calculating the risk for moist heat and daily maximum temperature. Moreover, we calculated the change in work performance to extreme moist heat for 1951-1985 (period -I) and 1986-2020 (period -II). The work performance decline from moist heat was obtained following Rao et al. (2020) and Seppanen et al. (2003).Here, we estimated the percentage decline in performance using WBGT. The percentage decline is calculated by subtracting fifty from the twice of average moist heat for the period-I and period-II as shown in Rao et al. (2020). The initial formulation by Seppanen et al.(2003) was used to understand temperature increase in an indoor office building. Further, the same formulation for moist heat was used by Rao et al.(2020), considering it provides a more accurate indicator of heat-health impact and the assumption that average temperature magnitude was not different from the moist heat indices. Even though the Seppanen et al. (2003) formulation gives a relative indication of performance decline from heat stress, reasonable uncertainty can be expected since the WBGT is derived using temperature, humidity, wind, and radiation.

Finally, we calculated the monsoon-break, wet, and warm spells to disentangle the processes leading to extreme moist heat. Indian region monsoon-break are associated with the Continental Tropical Convergence Zone (CTCZ) change leading to below-average precipitation anomalies (Rajeevan et al., 2010). Various studies used longwave radiation (Krishnan et al., 2000), precipitation (Annamalai & Slingo, 2001; Mandke et al., 2007; Rajeevan et al., 2010; Singh et al., 2014), and upper-level winds (Webster et al., 1998) to identify the monsoon-break during the monsoon. We use precipitation deficit as an indicator to define monsoon-breaks. First, we calculated the climatological anomaly of the precipitation during monsoon for the 1951-2020 period. The monsoon-break event is identified based on precipitation anomalies below -1 standard deviation at least for three consecutive days. We calculated each spell's frequency and total season duration for the 1951-2020 period. Here frequency and duration for a year are the number of monsoon-breaks and the cumulative number of consecutive days with negative precipitation anomalies exceeding -1 standard deviation during a monsoon season. Next, the wet spell is defined following the same procedure as the monsoon-break but for positive anomalies (precipitation > 1 standard deviation). Further, a warm spell is calculated from the ambient temperature. Following several studies, we define a warm spell as a daily maximum temperature exceeding the 90^{th} percentile for at least three consecutive days (Mazdiyasni & AghaKouchak, 2015; Panda et al., 2017). Since moist heat is sensitive to temperature, the percentile threshold can capture sudden variations in the extreme moist heat changes. The frequency and total duration of the warm spell were obtained for the 1951 – 2020 period.

3. Results and Discussion

3.1 Observed change in extreme monsoon moist heat

Comparing across overall summer, monsoon, or monsoon-break conditions it is evident that monsoon-breaks are associated with higher frequency extreme moist heat conditions (Fig. 1a) in which WBGT > 31 °C. A six-hour maximum daily average temperature (T_{2m}) and moist heat were shown in the Figure. 1 (b-g). In contrast to the summer (90 % area > 34 °C T_{2m}) period, a small fraction of the area is above 34 °C temperature during the monsoon (Fig. 1b-g). Extreme moist heat, in general, is primarily driven by the combined increase of temperature extremes and atmospheric moisture content (Buzan et al., 2015; Raymond et al., 2021). During summer, a 24.35 °C average moist heat was observed. A mean difference of 3 °C moist heat between break and summer period signifies that outdoor physical labor can become more challenging during monsoon-break. In addition to the expected increase of moist heat during the summer and monsoon onset, we observed a significant ($p < 0.05$) difference in moist heat median and distribution during the monsoon period (Fig. S3). In fact, the moderate difference in monsoon-break, inferred from Fig. S3, can be due to an overall increase in relative humidity and temperature. The long break during the monsoon is associated with trough type circulation, which can lead to a similar temperature value before monsoon onset (Rajeevan et al., 2010). Relative humidity, by contrast, remains nearly unchanged during the monsoon period (Ivanovich et al., 2022), which can lead to extreme moist heat. Moreover, during monsoon climatological mean 95th percentile of moist heat shows that 73 % area was affected by severe (> 31 °C) moist heat conditions (Fig. S4). The extreme moist heat can cause an increase in health impacts in the Indian region. For instance, the frequency of extreme moist heat (95th percentile) has significantly increased all over the Indian subcontinent (Fig. S5). In addition, an increase in extreme moist heat intensity observed over Indian region is more prominent along the Indo-Gangetic plain and southern peninsula of India. Meanwhile, the frequency of moist heat exceeding the 95th percentile has significantly increased to 10 days between the 1951 and 2020 period. The mean, extreme, and frequency estimated for the pre- and post- 1986 periods also changed significantly (Fig. S4-7). Therefore, it is evident that in recent decades extreme moist heat has been rising during monsoon which can be detrimental to outside physical labor and potential human health.

3.2 Deadly moist heat vulnerability

The consistent increase in exposed area (~ 42.76 million km^2) above 31 °C can adversely impact the labor-intensive work during the monsoon-break (Fig. 2a). In contrast, the summer has minimal impact on the area exposed to extreme moist heat. Based on our analysis the region susceptible to extreme moist heat (> 38 °C) are primarily along the Indo-Gangetic plain and eastern coastal region (Fig. S8). The prolonged exposure to extreme moist heat during monsoon-break affected at least 670 million people in India (Fig. 2b). Moreover, prolonged exposure during moderate work can cause heat stroke and exhaustion, leading to immediate health hazards (Liang et al., 2011; Lu & Zhu, 2007). Next, to delineate the population vulnerability to extreme moist heat, we prepared a district risk map for the Indian monsoon period. During monsoon, extreme moist heat risk is more prominent over vast land regions of India (Fig. 2c). Elevated risk along the Indo-Gangetic plain is majorly driven by irrigation practices (Ambika & Mishra, 2022; Mishra et al., 2020). Further, moisture advection amplifies the moist heat risk over western India (Roxy et al., 2017). Further, our analysis indicates the summer moist heat risk is majorly only over the coastal regions (Fig. S10). With a severe moist heat risk elevated all over the country during the monsoon, the question arises of how severe extreme moist heat can potentially impact outdoor work. To address this, we estimated the performance decline for the two-time period (Period-I and Period-II; method for further information). A significant difference ($p<0.05$) in work performance is observed over the Indo-Gangetic plain and southern coastal regions (Fig. S9 - S11). The extent of extreme moist heat during the monsoon re-emphasizes the need to understand the drivers of moist heat during this period.

3.3 Drivers of extreme moist heat

We show that extreme moist heat has become detrimental to physical labor during the break period. While the extreme moist heat is primarily driven by highly humid and warm conditions, we observed a significant correlation of monsoon moist heat with global mean temperature (Fig. 3a). The change in extreme moist heat during the monsoon is driven by global warming (Fig. 3a). For instance, the observed change in global monsoon temperature (3.12 °C) is similar to moist heat (2.90 °C) in the Indian region. The warming can increase the frequency of monsoon-break and warm spells and decline peak monsoon precipitation during the monsoon season (Panda et al., 2017; Singh et al., 2014) .

To understand the changes in moist heat during monsoon, we quantified the warm and monsoon-breaks during the 1951-2020 period (Fig. S12). Consistent with previous studies (Panda et al., 2017; Singh et al., 2014), we observed a similar trend in warm and monsoon-breaks during the monsoon. In contrast to the monsoon-break, the warm spell frequency changed from 4 to 11 events post-1986 period (Fig. S12). To disentangle the monsoon-break and warm spell induced changes on moist heat, we estimated anomaly composite for the break period (Fig. 3b). The monsoon-break and warm spell modulates the moist heat during the break period. Extreme moist heat is mostly driven by the prolonged warming after the monsoon-break recovery (Fig. 3b). As we hypothesized, this contrasting increase in monsoon moist heat is partially attributed to the appearance of heat trough (Rajeevan et al., 2010) and mid-to-upper tropospheric dryness (Raymond et al., 2021) during the monsoon-break.

The high moist heat during summer can be driven by the enormous latent heat partitioning from irrigation (Mishra et al., 2020), advection from Arabian sea (Monteiro & Caballero, 2019), and the presence of atmospheric aerosol (Dey et al., 2021). The extreme moist heat in northern India is associated with upper tropospheric subsidence and high moisture presence in the lower troposphere (Raymond et al., 2021). The mid tropospheric dryness restricts the moisture from deep convection, that can lead to extreme moist heat. The increase in relative humidity compensates for the surface air temperature decline, which indicates increased atmospheric moisture during the break period (Fig.S13-S18). However, during June-July, the warm spell is associated with high relative humidity and surface air temperature, which implies moist heat is driven by latent heat partitioning (Fig. S14). Further, the increase in latent heat during warm spells can drive moist heat to extreme levels (Fig. S19 & S8). The emerging evidence from our analysis suggests that a significant part of the Indo-Gangetic plain and eastern coastal areas are consistently being exposed to extreme moist heat.

4. Conclusions

We demonstrate that the extreme moist heat has increased in monsoon season and is further exacerbated during the break period. The overall increase in the area and population exposure shows that the change in the magnitude of extreme moist heat was majorly driven by global warming. At a regional scale, the change in synoptic circulation, such as monsoon-break and warm spells during the monsoon, raise moist heat occurrence. The increase in moist heat can directly impact about 37 - 46 million people living over the Indo-Gangetic plain. A widespread increase of moist heat during the monsoon can significantly reduce physical labor, primarily due to the projected increase in monsoon-break and warm spells during this season (Mishra et al., 2020). For instance, significant part of the Indo-Gangetic plain and eastern costal region already witnessed a six-hour exposure to extreme moist heat. The continuous increase of warm spells in recent decades indicates a continuing trend towards increasing extreme moist heat, which can become a major health hazard for the coming decades.

Outdoor labor in the agriculture and construction sectors accounts for moderate to heavy working conditions in the Indian region (Maiti, 2008; Nag et al., 1980). An alarming increase in the area experiencing extreme moist heat conditions during monsoon season draws immediate attention to revising the outdoor working hours. For instance, a 3 °C increase in global warming can reduce labor productivity by 7 % and contribute to at least 4 % reduction of GDP in India (Saeed et al., 2022), which leads to inflation in crop prices (de Lima et al., 2021). In recent period, the agricultural sector's transition towards automation decreased 26 million employment between 2011 and 2015 (Bandura & Sword, 2018). Nonetheless, the agricultural sector in India still has the highest employment entailing outdoor activities (Bandura & Sword, 2018; Chowdhury, 2011; Parida, 2015; Thomas, 2012). Further, the recent increasing trend in construction sector employment (Thomas, 2012) contributes to increasing outdoor activity, leading to further loss of labor capacity. As work performance in India is projected to decline by 30 to 40 % by the end of the century (Rao et al., 2020), the rising moist heat during monsoon can be devastating in the future. Overall, our result suggests that the monsoon break period poses a considerable challenge of prolonged population exposure to extreme moist heat, which could be exacerbated many folds due to anthropogenic warming.

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Open Research

Data Availability Statement

The ERA5 reanalysis data set is freely available from the Copernicus Climate Change Services [C3S;(Hersbach et al., 2020)]. The world bank population data for India for the

1960-2020 period is freely available at World Bank Open Data portal (World Bank, 2022). The district level vulnerability calculation can be obtained from the report for climate vulnerability assessment framework (CVAF) planning in India from the Department of Science and Technology, Government of India (Dasgupta et al., 2020).

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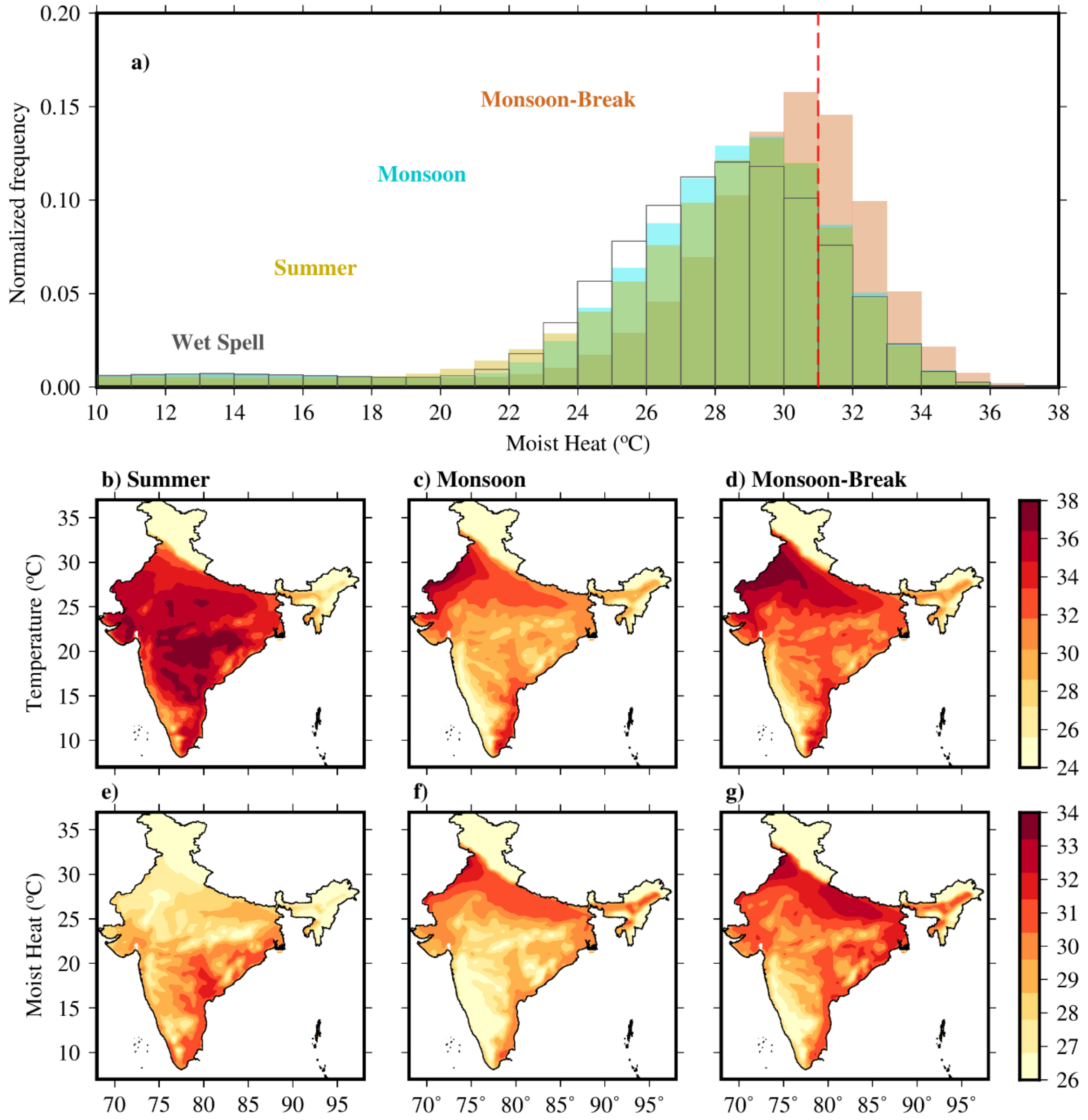


Figure1. **Observed extreme moist heat during Monsoon-Break.** (a) Normalized frequency for summer, monsoon and monsoon-break annual mean (six hour mean daily maximum) during the 1951-2020 period, **(**b) summer season (March, April, and May) six hour mean daily maximum temperature for the same period as(a), (c) same as (b) but for monsoon season (June, July, August, and September), (d) same as (b) but for monsoon break, and (e-g) same as (b-d) but for moist heat. The moist heat is derived from daily maximum of six hour mean wet bulb globe temperature. Here, monsoon season does not include break period.

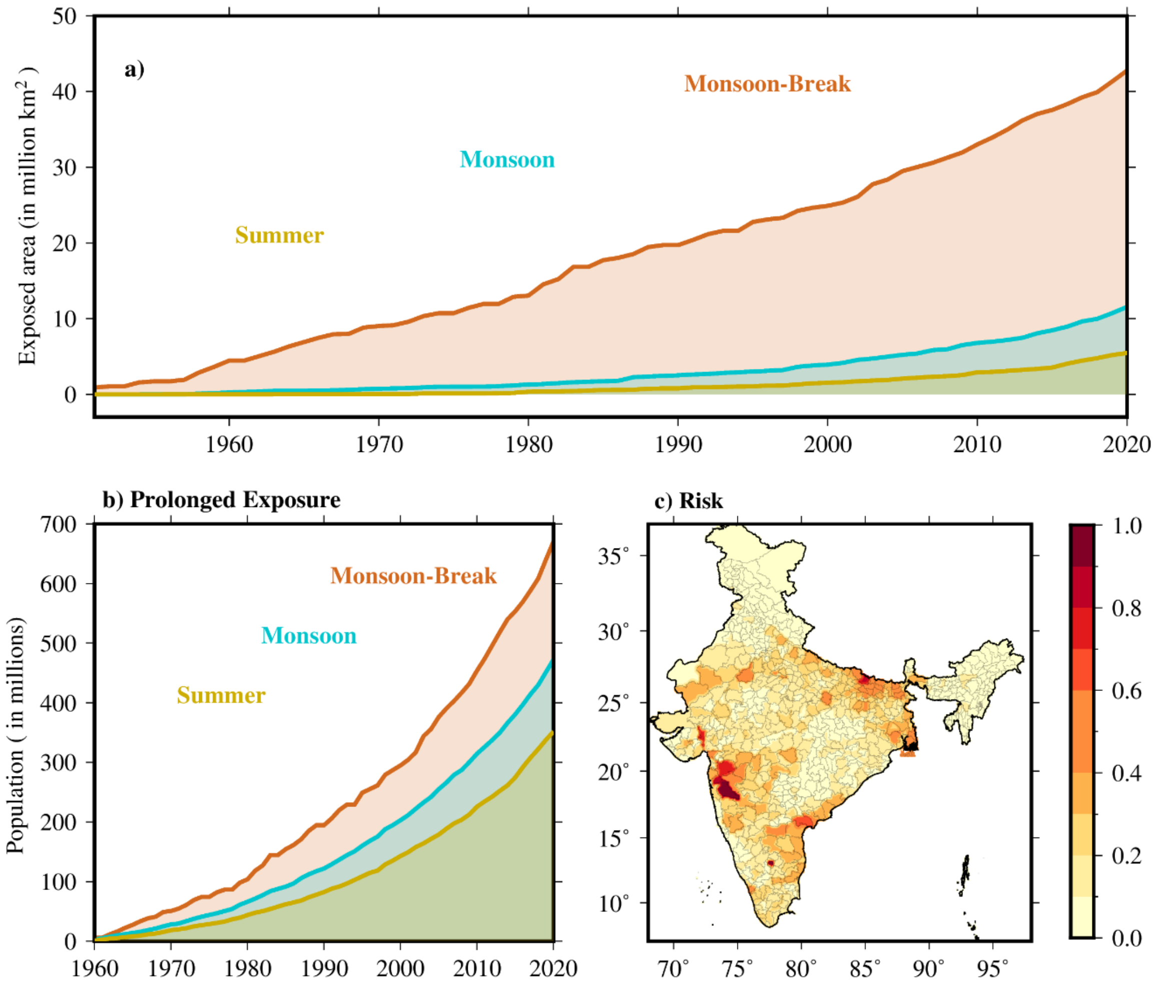


Figure 2. **Moist heat exceedence and risk for India**. (a) Accumlated surface area experiencing 31 °C moist heat exceedance for at least six continuous hours for the 1951-2020 period, (b) population exposed to 31 °C moist heat exceedance for at least six continuous hours during the 1960-2020 period, and (d) district (official boundary) wise extreme moist heat risk for the 1951-2020 period. The risk is calculated from the product of vulnerability, population, and hazard (described in text). The area exposed to exceedence is calculated for each year.

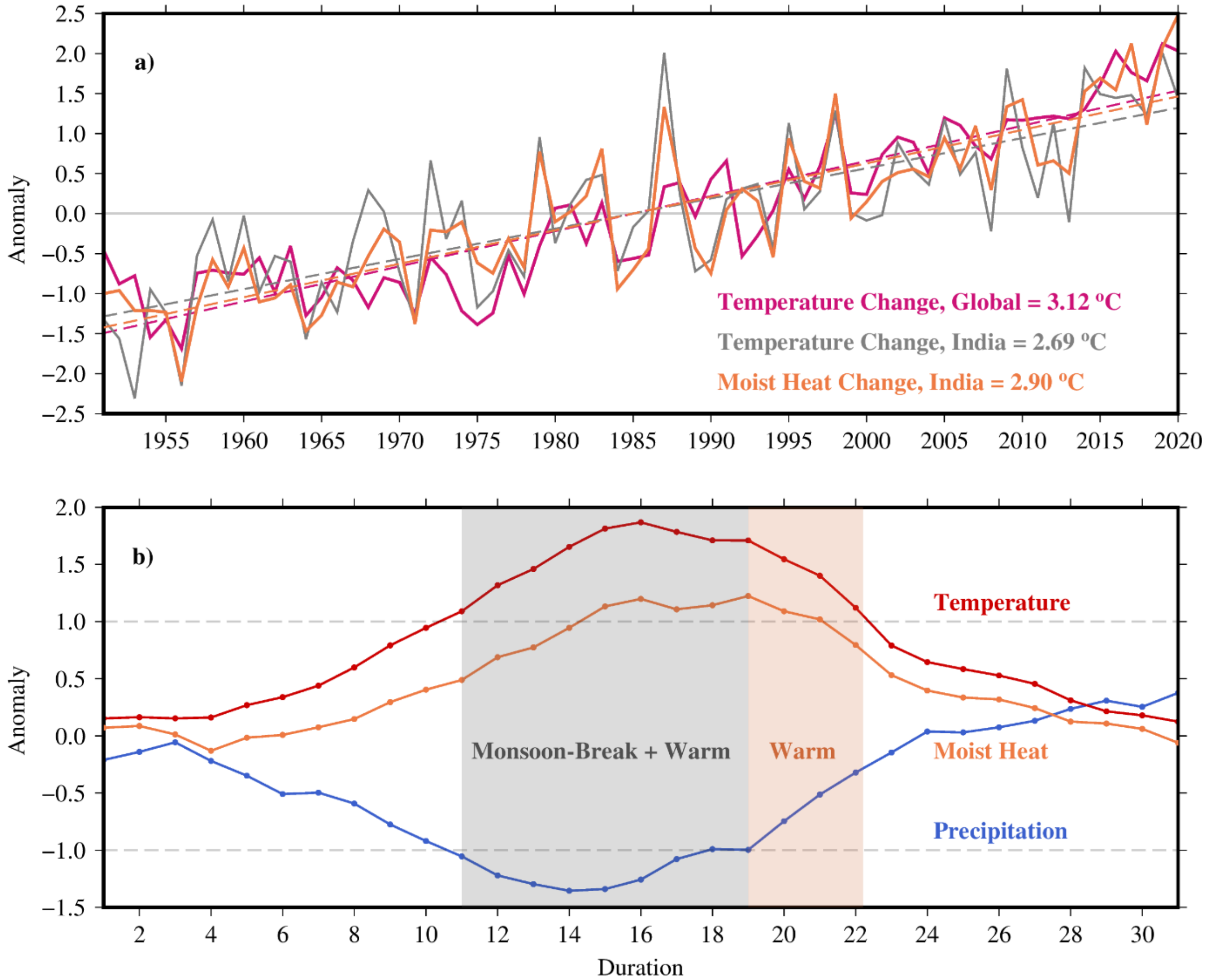


Figure 3. **Drivers of moist heat extremes in India.** (a) Mean temperature and moist heat anomalies and their trends for the globe and India for the 1951-2020 period and (b) mean anomaly composite during the break period for the 1951-2020 period. (b) is calculated for the thirty-day buffer period. The buffer period is calculated from the middle of a break period, including fifteen previous and ahead days. Here, only a break period (including warm and monsoon break) of seven days or longer is considered for the calculation.

Figure1.

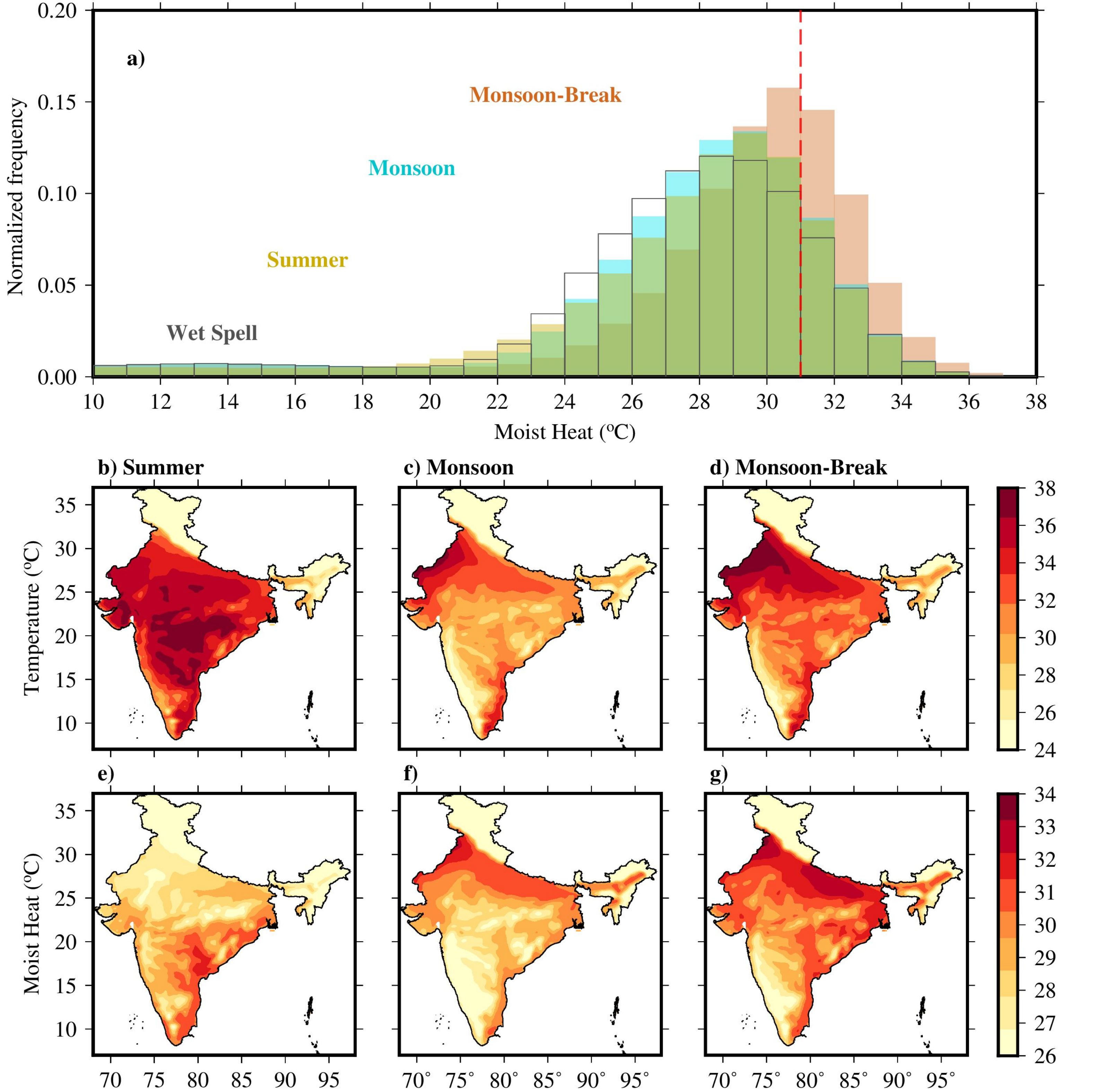
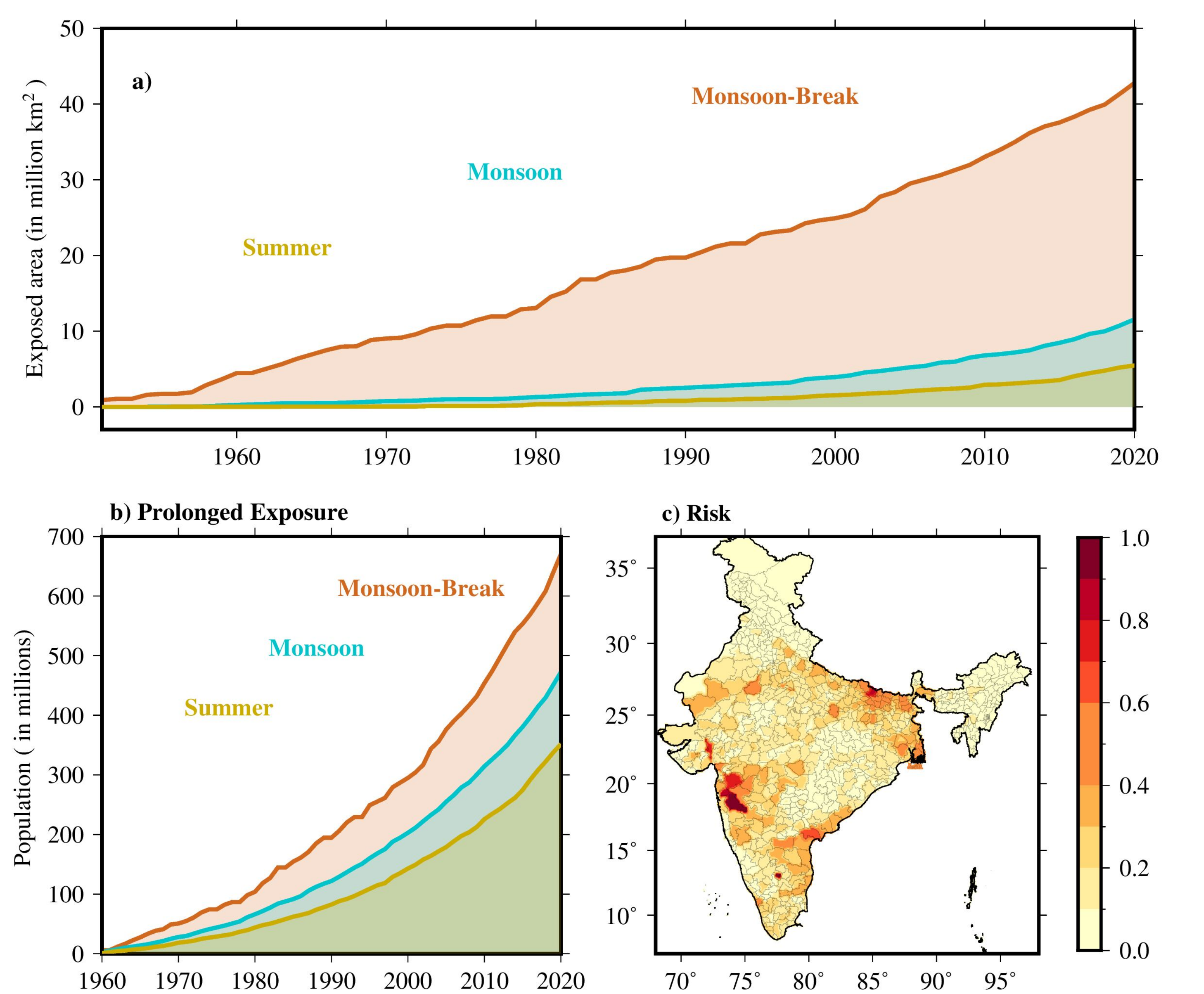
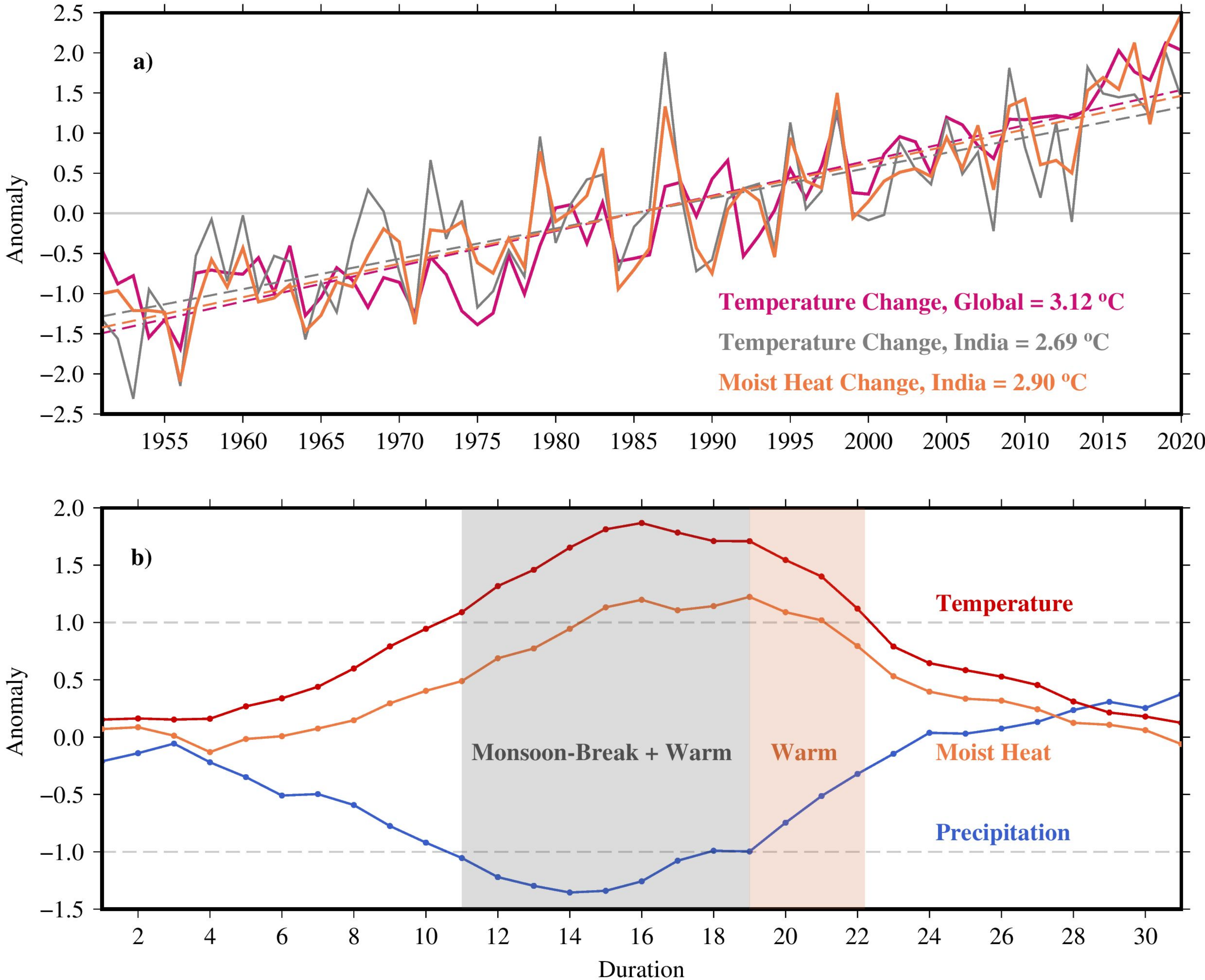

a)
Monsoon-Break
Monsoon
Summer
Wet Spell
Normalized frequency
Moist Heat (°C)
b) Summer
c) Monsoon
d) Monsoon-Break
e)
f)
g)
Temperature (°C)
Moist Heat (°C)

Figure2.



a)
Monsoon-Break
Monsoon
Summer
Exposed area (in million km^2)
50
40
30
20
10
0
1960
1970
1980
1990
2000
2010
2020
b) Prolonged Exposure
Monsoon-Break
Monsoon
Summer
Population (in millions)
700
600
500
400
300
200
100
0
1960
1970
1980
1990
2000
2010
2020
c) Risk
35°
30°
25°
20°
15°
10°
70°
75°
80°
85°
90°
95°
1.0
0.8
0.6
0.4
0.2
0.0

Figure3.


a)
Temperature Change, Global = 3.12 ºC
Temperature Change, India = 2.69 ºC
Moist Heat Change, India = 2.90 ºC
Anomaly
b)
Temperature
Moist Heat
Precipitation
Monsoon-Break + Warm
Warm
Anomaly
Duration