ADVANCING EARTH AND SPACE SCIENCE

# Earth's Future

RESEARCH ARTICLE
10.1029/2022EF002992

**Key Points:**

- Tropical cyclone (TC)-Heat stress events occur 20% of the time in the Indian region, while they are rare in other parts of the world
- India has witnessed a rise in TC-heat stress events in the recent decade
- Landfalling TCs directly influence the occurrence of post-cyclone moist heat, substantially raising the risk associated with these events

**Supporting Information:**

Supporting Information may be found in the online version of this article.

**Correspondence to:**
V. Mishra,
vmishra@iitgn.ac.in

**Citation:**
Rajeev, A., & Mishra, V. (2022). Observational evidence of increasing compound tropical cyclone-moist heat extremes in India. *Earth's Future*, *10*, e2022EF002992. https://doi.org/10.1029/2022EF002992

Received 20 JUN 2022
Accepted 15 OCT 2022

# Observational Evidence of Increasing Compound Tropical Cyclone-Moist Heat Extremes in India

**Akshay Rajeev[1] and Vimal Mishra[1,2]**

[1]Earth Sciences, Indian Institute of Technology (IIT) Gandhinagar, Gandhinagar, India, [2]Civil Engineering, Indian Institute of Technology (IIT) Gandhinagar, Gandhinagar, India

**Abstract** Moist heat stress can lead to the inability of the human body to cool itself due to the impact of high temperature and humidity. The co-occurrence of tropical cyclones (TCs) and moist heat stress has considerable implications for India's dense population and infrastructure. However, the crucial linkage between TCs and moist heat extremes remains unrecognized. We used the cyclone eAtlas and ERA5 reanalysis to examine the temporally compounding TC and moist heat extremes over India from 1980 to 2021. We find that TC-Heat stress events in India have increased recently, which can be attributed to the high-intensity TCs originating from the Arabian Sea. The risk of TC-Heat stress events is higher (than in other parts of the world) in India due to an overlap of peak moist heat and TCs occurrence during the pre-monsoon (April–June) season. Landfalling TCs alter the thermodynamic environment causing the moist heat to peak over the region with increased frequency and intensity. The direct and compounded influence of TCs on moist heat can have substantial implications.

**Plain Language Summary** Tropical cyclones (TCs) in India occur during the pre-monsoon and post-monsoon season. The pre-monsoon season overlaps with the summer with high temperature. TCs damage infrastructure related to electricity and communications, however, the linkage between TCs and moist heat stress in India has not been explored. We show that compound extremes of TC and moist heat extremes are rare in other parts of the world, however, these occur more frequently over India. In addition, the risk of TCs and moist heat stress occurring together has increased in the recent past in India. Our findings have implications for the planning and management of infrastructure and public health implications of compound extremes.

## 1. Introduction

India has recently witnessed a rise in moist heat extremes, which adversely impacted public health (Im et al., 2017; Mazdiyasni et al., 2017; Mishra et al., 2017, 2020). Due to rising temperature and population, moist heat stress is projected to increase under the warming climate (Coffel et al., 2017; King et al., 2016; Knutson & Ploshay, 2016; Matthews et al., 2017). Air conditioning reduces vulnerability to extreme humid heat (Barreca et al., 2016; Biardeau et al., 2019; Burgess et al., 2017; IEA, 2022). Nevertheless, dependence on air conditioning increases the chance of blackouts and infrastructure damage due to increased electricity demands during the heatwaves (Stone, Mallen, Rajput, Broadbent, et al., 2021; Stone, Mallen, Rajput, Gronlund, et al., 2021; Yu et al., 2012). In addition, a considerable challenge to the energy infrastructure is posed by landfalling tropical cyclones (TCs) that cripple the power supply over a region (Oh et al., 2022; RSMC, 2021).

Compared to other regions, the North Indian Ocean (NIO) produce fewer TCs with a distinct bimodal seasonal pattern peaking during pre-monsoon and post-monsoon seasons (Evan & Camargo, 2011; Gray, 1968; Li et al., 2013). The TC frequency is higher during the post-monsoon. However, the pre-monsoon TCs have higher intensity (Li et al., 2013). Temporally compounding post-monsoon TCs caused flooding in Indian river basins due to wetter antecedent moisture conditions (RSMC, 2000). In contrast, pre-monsoon TC-driven flooding is less likely due to drier conditions, effectively reducing the hazard associated with them (Rajeev & Mishra, 2022). Apart from flooding, TCs can significantly influence moist heat extremes. For instance, Matthews et al. (2019) demonstrated the potential of the increased occurrence of sequentially compounding TC-Heat stress events. In these events, TCs first damages the infrastructure and disrupt the power supply in an area. Subsequently, a rise in heat stress threatens the population is recovering from the TC impact.

Novel combinations of various extremes have resulted in the rise of compound events under the warming climate (Seneviratne et al., 2012; Zscheischler et al., 2018). As compound extremes adversely affect human systems, they have received wide attention recently (Abatzoglou et al., 2021; Bevacqua et al., 2019; He et al., 2022; Martius et al., 2016; Zscheischler et al., 2021). Subsequently, compound extremes linked to cyclones in various regions have also been investigated, with most of them focusing on the rise in TC-driven wet and windy extremes (Dullaart et al., 2021; Gori et al., 2020; Messmer & Simmonds, 2021; Owen et al., 2021; Rajeev & Mishra, 2022; Raveh-Rubin & Wernli, 2015; Villarini et al., 2014; Woodruff et al., 2013). Despite being affected by TCs annually (NDMA, 2022), TC-driven compound extremes in India have not been critically examined. Moreover, the compounding effect of the TC and moist heat stress has not been examined in India, notwithstanding a considerable population exposure and enhanced risk of both extremes under the warming climate. Therefore, we examine the changes in temporally compounding TC-Heat stress events in India during the observed period (1980–2021). The questions we address are (a) How often do TC-Heat stress events occur in India, and to what extent has the frequency of TC-Heat stress events changed during the observed record? (b) what are the characteristics of TC-Heat events in India? and (c) does the passage of TC directly influence the subsequent rise in moist heat over the region? We used Cyclone eAtlas from India Meteorological Department (IMD) to evaluate the area affected by TCs. We employed the ERA5 reanalysis data set to examine the land-atmospheric processes that drive the TC-Heat stress compound extremes.

## 2. Data and Methods

### 2.1. Data

We used the ERA5 reanalysis data set developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) at 31 km spatial resolution (Hersbach et al., 2020) to assess extreme moist heat stress following the passage of TCs over various parts of India. We obtained hourly 2 m air temperature, dew point temperature, downward surface solar radiation, volumetric soil moisture for the top three layers (0–7 cm, 7–28 cm, 28–100 cm), evaporation, boundary layer height, cloud cover fraction, and vertically integrated moisture divergence for 1980–2021 period. Subsequently, we estimated root zone (0–60 cm) soil moisture content using volumetric soil moisture from ERA5 (Mishra et al., 2018). The variables were converted from hourly to daily timescales to investigate their role in TC-Heat stress events better. The availability of multiple variables at high spatial and temporal resolutions is crucial for examining the impact of temporally compounding TC-Heat stress events. The reanalysis data set has been widely used for the assessment of moist heat stress (Koteswara Rao et al., 2020; Matthews et al., 2017; Mishra et al., 2020) and TC impact (Matthews et al., 2019; Messmer & Simmonds, 2021; Owen et al., 2021; Rajeev & Mishra, 2022).

We extracted the TC tracks from the Cyclone eAtlas of the IMD, an electronic atlas of the NIO Cyclonic Disturbances (CD), which provides data from 1891 to 2020 (Cyclone eAtlas-IMD, 2022). Tracks for CDs of three categories are available in the atlas - Depressions (D), Cyclonic Storms (CS), and Severe Cyclonic Storms (SCS). The SCS category is further divided based on sustained wind speeds by IMD. We used TCs, which according to the TC classification of IMD, fall under the following categories: CS, SCS, Very Severe Cyclonic Storms (VSCS), Extremely Severe Cyclonic Storms (ESCS), and Super Cyclonic Storms. We only considered TCs that made landfall over India from 1980 to 2021. In addition to the Cyclone eAtlas, we also used the IMD best track data for the tracks of the 2021 TCs. We used the maximum intensity of the cyclone as the decline in the intensity of the TC points to a reduction in wind speed and does not provide information about rainfall associated with the event. The size of the TC in terms of area affected by TC rainfall is what we focus on as the amount of moisture carried over to land can influence moist heat over the region. Furthermore, the amount of moisture uptake over oceans is closely related to the maximum intensity of the TCs (Rajeev & Mishra, 2022). Hence the maximum intensity is more critical for heat stress rather than the intensity during landfall as it does not provide information about the moisture transport by the TC.

### 2.2. Estimation of Dry and Moist Heat

We calculated the daily maximum temperature using hourly 2-m surface air temperature from ERA5 for the 1980–2021 period to determine dry heat extremes in India (Mishra et al., 2020). While dry heat is directly dependent on hourly temperatures, variation in moist heat is complex as it varies primarily with air temperature and humidity. Despite its significance and complexity, wet-bulb global temperature (WBGT) observations are limited and are usually approximated (de Lima et al., 2021). One of the most common approximations is the simplified WBGT requiring only temperature and humidity, assuming fixed values for solar radiation and wind speed (ABM, 2010). We approximate WBGT using the environmental stress index (ESI) (Moran et al., 2001; Moran & Epstein, 2006). ESI was developed using a multiple regression model including air temperature ($T_a$), relative humidity (RH), surface downward solar radiation ($S_{down}$), and their interaction terms as independent variables as:

$$\mathrm{ESI} = 0.63T_a - 0.03\mathrm{RH} + 0.002SR + 0.0054\,(T_a \cdot RH) - 0.073(0.1 + SR)^{-1} \tag{1}$$

Relative humidity was estimated using the hourly 2 m air temperature ($T_a$) and dew point temperature ($T_d$) from ERA5 reanalysis as:

$$\mathrm{RH} = 100 \cdot e^{\left(\frac{243.04 \cdot 17.625(Td - Ta)}{(243.04 + Ta)\cdot(243.04 + Td)}\right)} \tag{2}$$

We used hourly ESI to estimate the daily maximum ESI for determining moist heat stress over the cyclone-affected region.

### 2.3. Estimation of Compound TC-Heat Stress

We estimated the region affected by each TC after landfall using the cyclone tracks. Cyclones from different categories have different areal extent, with SuCS potentially affecting a large part compared to CS. However, the area within the 100-km radius is the region of the highest impact of most landfalling TCs, even if the TC size is considerably large (NDMA, 2022). Therefore, we considered the area within 100-km of the TC tracks by selecting the grids over land within the cyclone-affected region. We used this region to extract spatially averaged daily ESI to identify compounding TCs and moist heat stress.

We considered ESI greater than 31°C as extreme moist heat since physical labor becomes difficult under such conditions (Buzan & Huber, 2020). We defined the TC-Heat stress event as a TC followed by an extreme moist heat day within 30 days of passage of the cyclone over the region. Matthews et al. (2019) used a similar 30-day window following TCs to define such events. However, while we use spatially averaged values, Matthews et al. (2019) define a TC-Heat Stress event if moist heat exceeds the threshold in just one of the grid cells along the cyclone track. Considering the area affected by landfalling TCs, we expect moist heat stress to develop over a large part of the cyclone-affected region. We used the Rank-Sum test to determine the significance levels in the study, particularly the difference in the pre- and post-cyclone periods.

## 3. Results

### 3.1. TC-Heat Stress Events in the Observed Period (1980–2021)

We examined 96 TCs from 1980 to 2021 in the NIO and identified 19 TCs followed by moist heat extremes (Figure 1a, Tables S1 and S2 in Supporting Information S1). While nearly 20% of TCs in NIO during this period resulted in temporally compounding TC-Heat stress events (Table S2 in Supporting Information S1), such events in other parts of the world are not so frequent (Matthews et al., 2019). The asynchronous seasonal cycle of TC occurrence and extreme moist heat contributes to the extremely low frequency of TC-Heat events in the Northwest Pacific, South Indian, and North Atlantic basins (Matthews et al., 2019). The higher frequency of TC-Heat stress events in India can be due to the increased formation of TCs during the pre-monsoon season (April–June) when the temperatures peak over land. We used the long-term daily averages for the years that did not experience TCs to examine the regional moist heat stress anomalies. In the years with no TCs, the moist heat in the area affected by TCs peaks (exceeding 31°C) during May, which often persists till early June before the onset of the Indian summer monsoon over north India (Figure 1b).

Next, we examined the spatial, seasonal, and categorical distribution of TC-Heat Stress events over India. We estimated the fraction of TCs followed by heat stress in the Arabian Sea, the Bay of Bengal, and the North Indian Ocean. Moreover, we also considered the decadal variability in the occurrence of such events. Our results show that in NIO, TC-Heat Stress events have increased substantially from 10% during 1980–1990 to nearly 40% in the recent decade (Figure 1c). Most TC-Heat Stress events are associated with Arabian Sea cyclones, which have recently increased due to climate change (Deshpande et al., 2021). Hence, the rise in TC-Heat stress events over India can be attributed to the increase in cyclones from the Arabian Sea. Deshpande et al. (2021) reported that

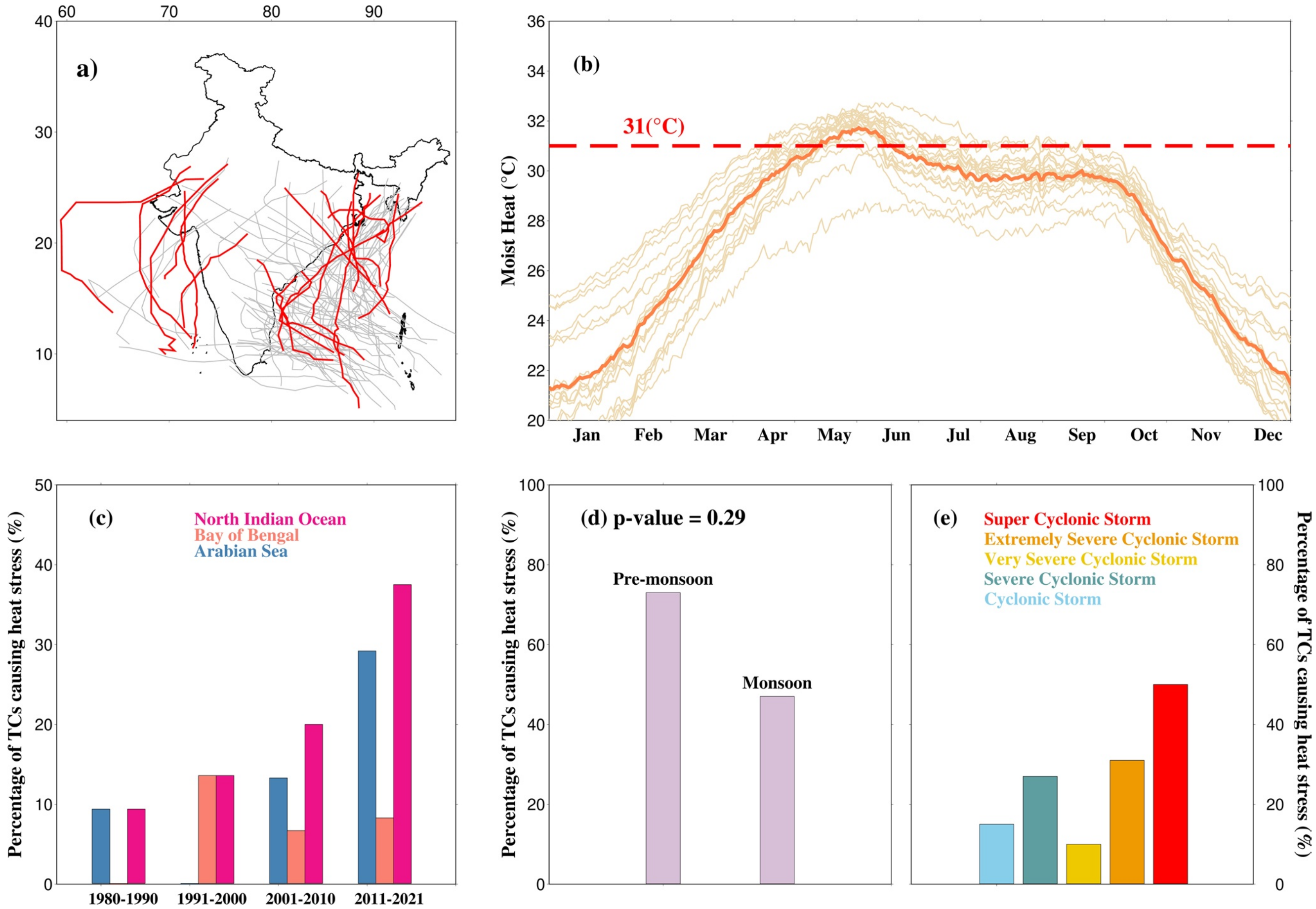


**Figure 1.** (a) Tracks of Cyclone which made landfall in India during 1980–2021. Tropical cyclones (TCs) which were followed by heat stress are shown in red. (b) Long-term averages (excluding TC years) of daily moist heat in TC affected areas. The darker shade corresponds to composite mean of all the time series. (c) Decadal variation in TC-Heat events in India. (d) Seasonal distribution of TC-Heat events. (e) Distribution of TC-Heat events in the Indian region based on intensity of cyclones.

the rise in TCs is more prominent during May and June (pre-monsoon), which subsequently overlaps with the period of extreme moist heat over land (Mishra et al., 2020). Consequently, we find that the highest percentage of TC-Heat stress compound events occur during the pre-monsoon season, with few such events happening in the monsoon season, while no compound events occur during the post-monsoon season (Figure 1d).

Compared to post-monsoon TCs, pre-monsoon TCs have higher intensities over the North Indian Ocean (Li et al., 2013). As a result of the frequent high-intensity TCs in the pre-monsoon, most TC-Heat stress compound extremes are associated with Super Cyclonic Storms and Extremely Severe Cyclonic Storms (Figure 1e). However, the frequency of SuCS is relatively lower than other categories of TCs (Table S1 in Supporting Information S1). Nevertheless, both TCs of the SuCS category that occurred during the pre-monsoon season caused moist heat stress (Table S3 in Supporting Information S1). High-intensity TCs such as SuCS and ESCS cause immense damage upon landfall as they are associated with extreme winds affecting large areas (Lavender & McBride, 2021; Rajeev & Mishra, 2022). Hence, following such events, extreme moist heat stress can devastate the region and increase the hazard posed by TCs. TCs in VSCS category cause lower moist heat stress compared to SCS and CS category cyclones, as the percentage of TCs causing moist heat stress were estimated based on the total number of TCs (Pre-monsoon, Monsoon, and Post-monsoon) in that category. While the total number of VSCS TCs that made landfall in India is 20, these have rarely occurred during the pre-monsoon and monsoon seasons (Table S3 in Supporting Information S1).

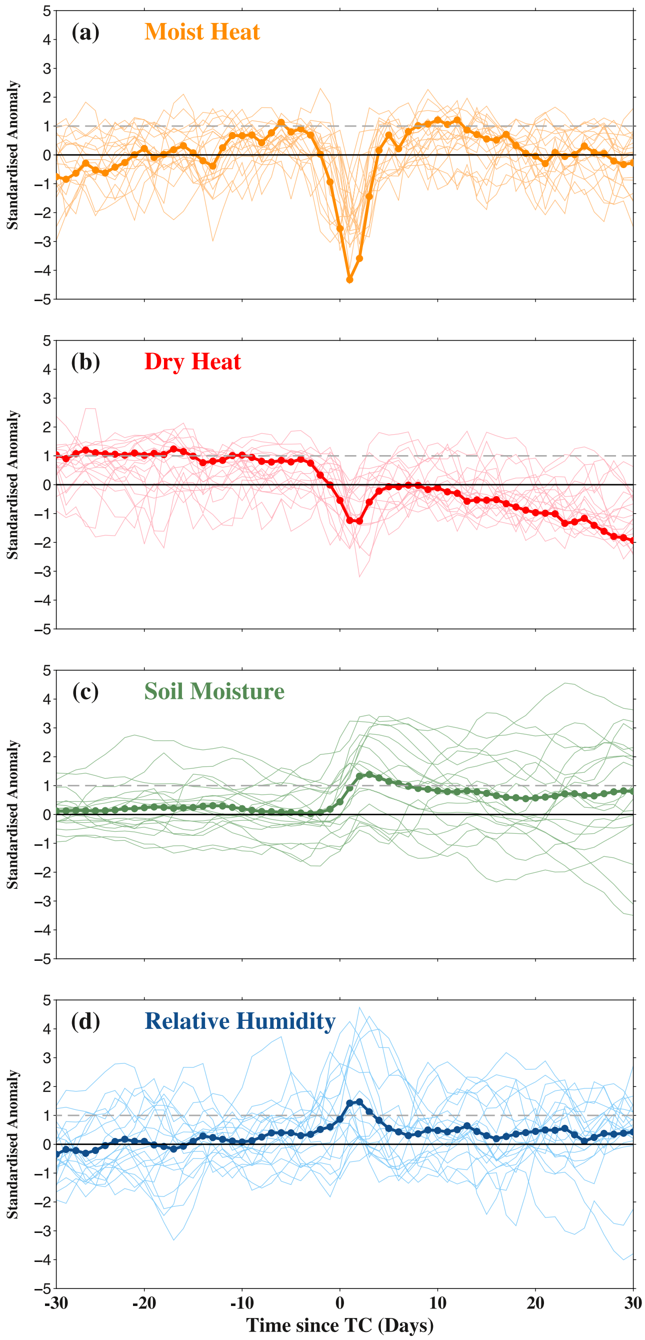


**Figure 2.** Composite impact of 19 tropical cyclones (TCs) on (a) moist heat, (b) dry heat, (c) root-zone soil moisture and (d) relative humidity over the affected region. Here we use a 61-day window to assess the impact before and after the TCs. Here the thin lines represent change in variables over individual TC affected areas and the thick line represents their composite means.

### 3.2. Characteristics of TC-Heat Stress Events

Next, we examine the influence of TC passage on the dry and moist heat. We used the composite mean of the standardized anomalies of ESI and the daily maximum temperature for all 19 TCs. We focus on 61 days centred on the day of landfall that is, 30 days before and after a TC. Similarly, we use the composite mean of standardized relative humidity anomalies and soil moisture anomalies. While TCs cause a decline in dry heat over a region (Sriver & Huber, 2007), moist heat stress may not be similarly affected (Matthews et al., 2019). We find that the standardized anomalies associated with dry heat undergoes a significant drop ($p < 0.01$) due to TC passage (Figure 2b). Moist heat also exhibits a substantial and statistically significant reduction ($p = 0.014$) due to TCs, from a pre-cyclone peak of 1.1 standard deviation to approximately −4 standard deviation. However, moist heat quickly returns to the pre-cyclone values (+1 standard deviation) and continues to rise (Figure 2a). Even though dry heat increases after the TC passage, it gradually declines over time due to the rise in relative humidity through evaporative cooling. Despite reducing air temperatures post-TCs, the primary driver of heat stress is the increased humidity due to the influx of moisture by TCs (Chen et al., 2010; Fritz & Wang, 2014). Furthermore, such an influx of moisture by TCs also results in heavy precipitation over the region, causing a drastic increase in root-zone soil moisture (Figure 2c) (Rajeev & Mishra, 2022). Following TCs, soil moisture remains elevated for a prolonged period, increasing relative humidity and elevated moist heat stress (Figure 2d).

As we observe the rise in heat stress following TCs, it is necessary to determine the time lag between the two events to reduce the risk to communities in the region. Moreover, the number of heat stress days and the intensity of moist heat stress also influence the hazard posed by TC-Heat stress compound events. We estimated the days between TC passage and the first day of extreme moist heat for all the 19 TC-Heat Stress events. We find that in most cases, moist heat peaks within 10 days of TC passage (Figure 3a). The mean time lag between the two events in the observed period has been estimated to be about 5 days. Such a small interval between the two events has implications for the compound impacts caused by TCs and moist heat stress. For instance, TC passage can adversely impact regional power distribution, which can cause blackouts and power disruptions for a considerable period (Matthews et al., 2019). Moreover, an ensuing lack of air conditioning results in the population being more susceptible to heat stress than in years with no TCs. The period following TCs is also when post-disaster management operations occur (T. Matthews et al., 2019; NDMA, 2022), which can be impacted by the elevated moist heat stress. Increased heat stress during such labor-intensive tasks can affect the health of the rescuers with detrimental effects on the operations (Buzan & Huber, 2020; Sherwood & Huber, 2010).

While the interval between TC and heat stress peak is low, we find that more than half of the 30 days following TCs experience elevated moist heat extremes (Figure 3b). Moreover, we also estimated the distribution of peak intensity of moist heat. We determined the day following the TC for each cyclone when the maximum moist heat (ESI) above the threshold (31°C) occurred. Despite the threshold of 31°C for extreme moist heat, nearly half of these events exceeded 33°C. Furthermore, moist heat stress is projected to increase due to anthropogenic climate change in the future (Mora et al., 2017), which can exacerbate the intensity of such extremes with large implications due to the compounding nature of the two extremes (Matthews et al., 2019).

10.1029/2022EF002992

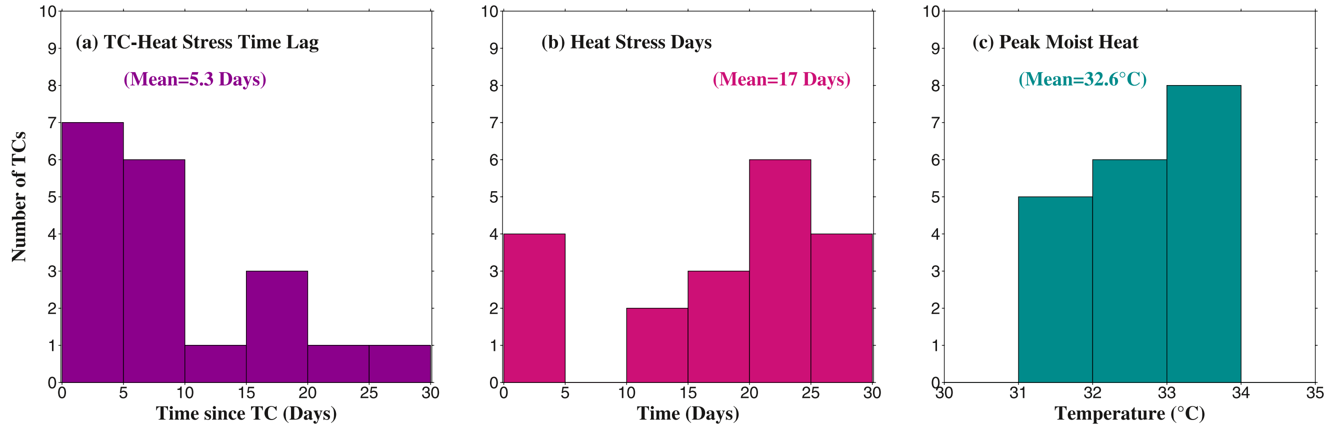


**Figure 3.** (a) Interval between tropical cyclone (TC) and first peak moist heat. (b) Number of days with extreme moist heat within 30 days of TC passage. (c) Distribution of peak moist heat associated with various TCs.

### 3.3. Mechanism of TC-Heat Stress Events

TC-Heat stress events mainly occur because of the overlap between the periods of TC formation and peak heat stress (Matthews et al., 2019). Moreover, TC passage does not lead to a decline in moist heat in the following days. The hazard posed by these events is primarily attributed to their compounding nature (Matthews et al., 2019). However, moist heat stress has a higher frequency and intensity in the post-cyclone period than before the TC (Figure S1 in Supporting Information S1). Such disparity between the pre-and post-TC periods indicates that TC passage may induce the rise in moist heat over the region. Hence, we examined the processes during the TC passage that led to extreme moist heat stress over the area. For this, we use the TC Tauktae as it is the most recent cyclone that originated in the Arabian Sea in May 2021 and affected the west coast of the Indian peninsula (RSMC, 2021).

We find that TC Taukte was associated with a moisture flux extending over a large area (Figure 4a). This resulted in moderate to heavy rainfall along the cyclone's path, particularly over western India (RSMC, 2021). As a result of the TC rainfall, the standardized anomaly of soil moisture in the affected region rises from approximately 0.7 to 2 (Figure 4e). Over the ocean, the latent heat flux associated with TCs is above normal (more than 300 $W/m^{-2}$) and gradually declines after the cyclone's landfall (Hlywiak & Nolan, 2021). Following landfall, the high latent heat flux causes the evaporation of the rising soil moisture and significantly raises the relative humidity over the region (Figures 4d and 4e) (Hlywiak & Nolan, 2021). The increasing humidity lowers the air temperature over the region leading to the collapse of the atmospheric boundary layer (ABL, Figure S2a in Supporting Information S1), similar to that was observed due to intensive irrigation over the Indo-Gangetic Plain (Mishra et al., 2020). However, evaporation decreases once the latent heat flux is reduced due to lowered temperature. During this time, soil moisture and relative humidity decline as evaporation decreases.

The cloud cover over the affected region reduces to less than 40% in the days (10-day composite) following TC passage, facilitating a radiation-driven temperature rise (Figure 4b, Also see Figure S2b in Supporting Information S1). Rising temperature again raises evaporation but is limited by the soil moisture content. The reduction in soil moisture also lowers the relative humidity of the region. However, the relative humidity decline rate slowly stabilizes for a short period despite a lack of evaporation. While the ABL gradually expands due to temperature rise, it does not reach the pre-cyclone level. The lowered ABL traps the moisture, resulting in prolonged enhanced relative humidity over the region (Sudeepkumar et al., 2020). Even though moist heat diminished due to TC passage, it quickly returned to pre-cyclone values following the TC due to elevated humidity and rising temperature. However, prolonged moisture entrapment by the collapsed ABL facilitated the overlap of high temperature and humidity, resulting in extreme moist heat over the region. The moist heat extremes sustained for a few days and affected western India and parts of Pakistan (Figure 4c). Therefore, TC passage influences a region's formation and intensity of moist heat stress.

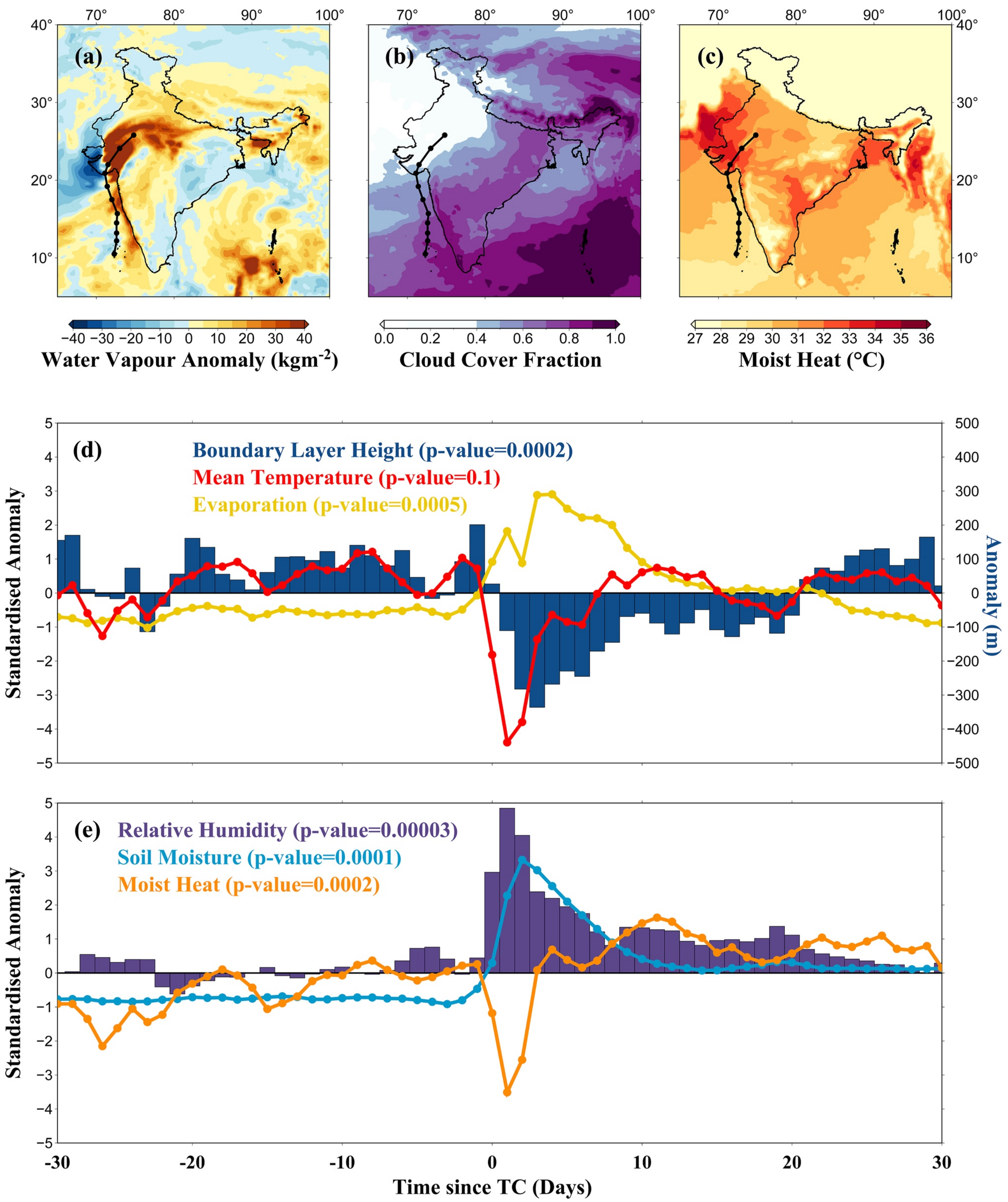


**Figure 4.** (a) Water vapor flux (kgm$^{-2}$) associated with tropical cyclone (TC) Taukte after landfall, 10-day composite of (b) cloud cover fraction and (c) moist heat (°C) following Taukte's passage. The spatial average of (d) boundary layer height, mean temperature, evaporation, (e) relative humidity, root-zone soil moisture and moist heat over the region affected by TC. Here we use a 61-day window to assess the impact before and after the TC. *P*-value less than 0.05 indicates that difference for the pre and post cyclone is statistically significant at 5% level.

## 4. Discussion and Conclusions

Climate change can fuel the development of new compound extremes by novel combinations of various extremes (Zscheischler et al., 2018). The study focuses on temporally compounding TC-Heat stress events, a novel extreme that is not well investigated (Matthews et al., 2019), especially in India. Globally only 3% of TCs are associated with such events owing to the asynchronous seasonal cycles of TC formation and extreme moist heat (Matthews et al., 2019). In the Indian region, the moist heat peaks during May-June, which coincides with the pre-monsoon cyclone season. Due to this overlap, 20% of TCs in NIO are followed by extreme moist heat. Hence, while the probability of TC-driven flooding is low during the pre-monsoon (Rajeev & Mishra, 2022), TC-Heat events increase the risk associated with TCs in this period. Moreover, the decadal distribution of such events reveals a substantial rise in TC-Heat stress events in the recent decade. The majority of such events are associated with Arabian Sea TCs. Recently, the Arabian Sea has witnessed a rise in TC frequency due to climate change (Deshpande et al., 2021) which could influence the number of TC-Heat stress events in the region. TC-Heat stress events are projected to increase with anthropogenic warming (Matthews et al., 2019). Matthews et al. (2019) also demonstrate that the population increase will expose more people to such hazards. We also find that many TC-Heat stress compound events are associated with high-intensity cyclones, characteristic of most pre-monsoon cyclones (Li et al., 2013).

Our results reveal that while TC passage reduces the dry heat over a region (Sriver & Huber, 2007), moist heat may not be similarly affected. The influx of moisture by the TC compensates for the drop in temperature due to TC passage and retains moist heat (Matthews et al., 2019). We also find that following TC passage, moist heat increases over the region. In most of these events, the interval between TC passage and the first heat stress day is less than 10 days. Such a short interval can be highly hazardous for the population considering the damage to infrastructure due to cyclones. For instance, TCs cause prolonged blackouts, negatively affecting the power supply. Furthermore, the increased frequency and intensity of heat stress following TCs substantially impact public health as people require several days to acclimatize and improve their physiological response to extreme heat (Hanna & Tait, 2015). Finally, we demonstrate that TC passage directly influences subsequent rise in moist heat over a region. The collapse of the ABL following the evaporative cooling-induced decline in temperature traps the moisture for a prolonged period (Sudeepkumar et al., 2020). The subsequent temperature rise due to increasing solar radiation after TC passage overlaps with this period of elevated humidity, raising moist heat stress.

Compound extremes like TC-Heat stress events are particularly hazardous as they can significantly impact human systems more significantly than individual extremes (Hao, Singh, et al., 2018; Leonard et al., 2014; McPhillips et al., 2018; Seneviratne et al., 2012). For example, concurrent dry-hot extremes directly impact regional food systems (Alizadeh et al., 2020; Hao, Hao, et al., 2018; Lu et al., 2018; Wang et al., 2021), whereas compound flood events threaten human life and critically damages the infrastructure over a region (Bevacqua et al., 2019, 2020; Santos et al., 2021; Wahl et al., 2015). The frequency of compound extremes has increased globally in the recent decade due to anthropogenic climate change. However, TC-related compound events have not been explored in India, even though 80% of the world's fatalities due to TCs occur in this region (Needham et al., 2015). While TC activity in the NIO was thought to have declined toward the end of the twentieth century (Singh et al., 2000; Srivastava et al., 2000), the frequency of intense TCs has increased in the recent period primarily due to the rise in Arabian Sea TCs (Deshpande et al., 2021; Holland & Bruyère, 2014; Singh, 2010). Moreover, there has been a marked increase in TC impact in the region due to the rising coastal development (Raghavan & Rajesh, 2003). Anthropogenic warming and increased agriculture in India have caused a rise in moist heat extremes in the recent period (Mishra et al., 2020). Such extremes are also projected to increase over the region resulting in a 40% decline in the work performance by the end of the century (Koteswara Rao et al., 2020). With rising TC intensities and heat stress posing increased destruction and mortality, it is necessary to examine these events from a compound events perspective. While moist heat has not been associated with TCs, their sequential nature can result in increased exposure to heat stress, making the findings of this study extremely relevant.

Based on our findings, we can conclude that:

1. While TC-Heat events are rare in other parts of the world, in the Indian region, such events occur 20% of the time. The rise in moist heat over land coincides with the pre-monsoon cyclone season, enhancing the risk associated with pre-monsoon TCs.

2. The anthropogenic warming-driven increase in the frequency of Arabian Sea TCs has resulted in the rise of TC-Heat events in the recent decade. Most TC-Heat events are associated with high-intensity Arabian Sea TCs during the pre-monsoon season.
3. Following TC passage, moist heat stress peaks over a region despite a decline in dry heat due to the influx of moisture by the TC. The *TC* impact and heat stress peak gap is less than 10 days. The short interval compounded with the higher frequency and intensity (ESI > 33°C) of heat stress during this period can potentially result in a public health crisis.
4. The landfalling TC modify the thermodynamic environment, driving up the moist heat over a region. Rather than just the risk of occurring successively, extreme heat stress in the post-cyclone period is directly influenced by TC.

## Data Availability Statement

The ERA5 reanalysis data set is freely available from the Copernicus Climate Change Services (C3S) https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels. The cyclone tracks are freely available from the Cyclone eAtlas-IMD http://14.139.191.203/AboutEAtlas.aspx.

**Acknowledgments**
The authors acknowledge the funding from the Ministry of Earth Sciences (MoES) under the Monsoon Mission.

## References

Abatzoglou, J. T., Rupp, D. E., O'Neill, L. W., & Sadegh, M. (2021). Compound extremes drive the Western Oregon wildfires of September 2020. *Geophysical Research Letters*, *48*(8), e2021GL092520. https://doi.org/10.1029/2021GL092520

ABM. (2010). Thermal comfort observations. Retrieved from http://www.bom.gov.au/info/thermal%5Fstress/%23approximation

Alizadeh, M. R., Adamowski, J., Nikoo, M. R., AghaKouchak, A., Dennison, P., & Sadegh, M. (2020). A century of observations reveals increasing likelihood of continental-scale compound dry-hot extremes. *Science Advances*, *6*(39), 4571–4594. https://doi.org/10.1126/SCIADV.AAZ4571

Barreca, A., Clay, K., Deschenes, O., Greenstone, M., & Shapiro, J. S. (2016). Adapting to climate change: The remarkable decline in the US temperature-mortality relationship over the twentieth century. *Journal of Political Economy*, *124*(1), 105–159. https://doi.org/10.1086/684582

Bevacqua, E., Maraun, D., Vousdoukas, M. I., Voukouvalas, E., Vrac, M., Mentaschi, L., & Widmann, M. (2019). Higher probability of compound flooding from precipitation and storm surge in Europe under anthropogenic climate change. *Science Advances*, *5*(9), 5531. https://doi.org/10.1126/SCIADV.AAW5531

Bevacqua, E., Vousdoukas, M. I., Zappa, G., Hodges, K., Shepherd, T. G., Maraun, D., et al. (2020). More meteorological events that drive compound coastal flooding are projected under climate change. *Communications Earth & Environment*, *1*(1), 1–11. https://doi.org/10.1038/s43247-020-00044-z

Biardeau, L. T., Davis, L. W., Gertler, P., & Wolfram, C. (2019). Heat exposure and global air conditioning. *Nature Sustainability*, *3*(1), 25–28. https://doi.org/10.1038/s41893-019-0441-9

Burgess, R., Deschenes, O., Donaldson, D., & Greenstone, M. (2017). Weather, climate change and death in India.

Buzan, J. R., & Huber, M. (2020). Moist heat stress on a Hotter Earth (Vol. *48*, pp. 623–655). https://doi.org/10.1146/ANNUREV-EARTH-053018-060100

Chen, L. S., Li, Y., & Cheng, Z. Q. (2010). An overview of research and forecasting on rainfall associated with landfalling tropical cyclones. *Advances in Atmospheric Sciences*, *27*(5), 967–976. https://doi.org/10.1007/S00376-010-8171-Y

Coffel, E. D., Horton, R. M., & de Sherbinin, A. (2017). Temperature and humidity based projections of a rapid rise in global heat stress exposure during the 21st century. *Environmental Research Letters*, *13*(1), 014001. https://doi.org/10.1088/1748-9326/AAA00E

Cyclone eAtlas-IMD. (2022). Web cyclone ATLAS::About EAtlas. Retrieved from http://14.139.191.203/AboutEAtlas.aspx

de Lima, C. Z., Buzan, J. R., Moore, F. C., Baldos, U. L. C., Huber, M., & Hertel, T. W. (2021). Heat stress on agricultural workers exacerbates crop impacts of climate change. *Environmental Research Letters*, *16*(4), 044020. https://doi.org/10.1088/1748-9326/ABEB9F

Deshpande, M., Singh, V. K., Ganadhi, M. K., Roxy, M. K., Emmanuel, R., & Kumar, U. (2021). Changing status of tropical cyclones over the north Indian Ocean. *Climate Dynamics*, *57*(11–12), 3545–3567. https://doi.org/10.1007/S00382-021-05880-Z

Dullaart, J. C. M., Muis, S., Bloemendaal, N., Chertova, M. v., Couasnon, A., & Aerts, J. C. J. H. (2021). Accounting for tropical cyclones more than doubles the global population exposed to low-probability coastal flooding. *Communications Earth & Environment*, *2*(1), 1–11. https://doi.org/10.1038/s43247-021-00204-9

Evan, A. T., & Camargo, S. J. (2011). A climatology of Arabian Sea cyclonic storms. *Journal of Climate*, *24*(1), 140–158. https://doi.org/10.1175/2010JCLI3611.1

Fritz, C., & Wang, Z. (2014). Water vapor budget in a developing tropical cyclone and its implication for tropical cyclone formation. *Journal of the Atmospheric Sciences*, *71*(11), 4321–4332. https://doi.org/10.1175/JAS-D-13-0378.1

Gori, A., Lin, N., & Xi, D. (2020). Tropical cyclone compound flood hazard assessment: From investigating drivers to quantifying extreme water levels. *Earth's Future*, *8*(12), e2020EF001660. https://doi.org/10.1029/2020EF001660

Gray, W. M. (1968). Global view of the origin of tropical disturbances and storms. *Monthly Weather Review*, *96*(10), 669–700. https://doi.org/10.1175/1520-0493(1968)096%3C0669:GVOTOO%3E2.0.CO;2

Hanna, E. G., & Tait, P. W. (2015). Limitations to thermoregulation and acclimatization challenge human adaptation to global warming. *International Journal of Environmental Research and Public Health*, *12*(7), 8034–8074. https://doi.org/10.3390/IJERPH120708034

Hao, Z., Hao, F., Singh, V. P., & Zhang, X. (2018). Changes in the severity of compound drought and hot extremes over global land areas. *Environmental Research Letters*, *13*(12), 124022. https://doi.org/10.1088/1748-9326/AAEE96

Hao, Z., Singh, V. P., & Hao, F. (2018). Compound extremes in hydroclimatology: A review. *Water*, *10*(6), 718. https://doi.org/10.3390/W10060718

He, Y., Hu, X., Xu, W., Fang, J., & Shi, P. (2022). Increased probability and severity of compound dry and hot growing seasons over world's major croplands. *The Science of the Total Environment*, *824*, 153885. https://doi.org/10.1016/J.SCITOTENV.2022.153885

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Hlywiak, J., & Nolan, D. S. (2021). The response of the near-surface tropical cyclone wind field to inland surface roughness length and soil moisture content during and after landfall. *Journal of the Atmospheric Sciences*, *78*(3), 983–1000. https://doi.org/10.1175/JAS-D-20-0211.1

Holland, G., & Bruyère, C. L. (2014). Recent intense hurricane response to global climate change. *Climate Dynamics*, *42*(3–4), 617–627. https://doi.org/10.1007/S00382-013-1713-0

IEA. (2022). The future of cooling—analysis—IEA. Retrieved from https://www.iea.org/reports/the-future-of-cooling

Im, E. S., Pal, J. S., & Eltahir, E. A. B. (2017). Deadly heat waves projected in the densely populated agricultural regions of South Asia. *Science Advances*, *3*(8), e1603322. https://doi.org/10.1126/SCIADV.1603322

King, A. D., Black, M. T., Min, S. K., Fischer, E. M., Mitchell, D. M., Harrington, L. J., & Perkins-Kirkpatrick, S. E. (2016). Emergence of heat extremes attributable to anthropogenic influences. *Geophysical Research Letters*, *43*(7), 3438–3443. https://doi.org/10.1002/2015GL067448

Knutson, T. R., & Ploshay, J. J. (2016). Detection of anthropogenic influence on a summertime heat stress index. *Climatic Change*, *138*(1–2), 25–39. https://doi.org/10.1007/S10584-016-1708-Z

Koteswara Rao, K., Lakshmi Kumar, T. v., Kulkarni, A., Ho, C. H., Mahendranath, B., Desamsetti, S., et al. (2020). Projections of heat stress and associated work performance over India in response to global warming. *Scientific Reports*, *10*(1), 1–14. https://doi.org/10.1038/s41598-020-73245-3

Lavender, S. L., & McBride, J. L. (2021). Global climatology of rainfall rates and lifetime accumulated rainfall in tropical cyclones: Influence of cyclone basin, cyclone intensity and cyclone size. *International Journal of Climatology*, *41*(S1), E1217–E1235. https://doi.org/10.1002/JOC.6763

Leonard, M., Westra, S., Phatak, A., Lambert, M., van den Hurk, B., Mcinnes, K., et al. (2014). A compound event framework for understanding extreme impacts. *Wiley Interdisciplinary Reviews: Climate Change*, *5*(1), 113–128. https://doi.org/10.1002/WCC.252

Li, Z., Yu, W., Li, T., Murty, V. S. N., & Tangang, F. (2013). Bimodal character of cyclone climatology in the Bay of Bengal modulated by monsoon seasonal cycle. *Journal of Climate*, *26*(3), 1033–1046. https://doi.org/10.1175/JCLI-D-11-00627.1

Lu, Y., Hu, H., Li, C., & Tian, F. (2018). Increasing compound events of extreme hot and dry days during growing seasons of wheat and maize in China. *Scientific Reports*, *8*(1), 1–8. https://doi.org/10.1038/s41598-018-34215-y

Martius, O., Pfahl, S., & Chevalier, C. (2016). A global quantification of compound precipitation and wind extremes. *Geophysical Research Letters*, *43*(14), 7709–7717. https://doi.org/10.1002/2016GL070017

Matthews, T., Wilby, R. L., & Murphy, C. (2019). An emerging tropical cyclone–deadly heat compound hazard. *Nature Climate Change*, *9*(8), 602–606. https://doi.org/10.1038/S41558-019-0525-6

Matthews, T. K. R., Wilby, R. L., & Murphy, C. (2017). Communicating the deadly consequences of global warming for human heat stress. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(15), 3861–3866. https://doi.org/10.1073/PNAS.1617526114

Mazdiyasni, O., AghaKouchak, A., Davis, S. J., Madadgar, S., Mehran, A., Ragno, E., et al. (2017). Increasing probability of mortality during Indian heat waves. *Science Advances*, *3*(6), e1700066. https://doi.org/10.1126/SCIADV.1700066

McPhillips, L. E., Chang, H., Chester, M. v., Depietri, Y., Friedman, E., Grimm, N. B., et al. (2018). Defining extreme events: A cross-disciplinary review. *Earth's Future*, *6*(3), 441–455. https://doi.org/10.1002/2017EF000686

Messmer, M., & Simmonds, I. (2021). Global analysis of cyclone-induced compound precipitation and wind extreme events. *Weather and Climate Extremes*, *32*, 100324. https://doi.org/10.1016/J.WACE.2021.100324

Mishra, V., Ambika, A. K., Asoka, A., Aadhar, S., Buzan, J., Kumar, R., & Huber, M. (2020). Moist heat stress extremes in India enhanced by irrigation. *Nature Geoscience*, *13*(11), 722–728. https://doi.org/10.1038/S41561-020-00650-8

Mishra, V., Mukherjee, S., Kumar, R., & Stone, D. A. (2017). Heat wave exposure in India in current, 1.5°C, and 2.0°C worlds. *Environmental Research Letters*, *12*(12), 124012. https://doi.org/10.1088/1748-9326/AA9388

Mishra, V., Shah, R., Azhar, S., Modi, P., & Kumar, R. (2018). Reconstruction of droughts in India using multiple land-surface models (1951–2015). *Hydrology and Earth System Sciences*, *22*(4), 2269–2284. https://doi.org/10.5194/hess-22-2269-2018

Mora, C., Dousset, B., Caldwell, I. R., Powell, F. E., Geronimo, R. C., Bielecki, C. R., et al. (2017). Global risk of deadly heat. *Nature Climate Change*, *7*(7), 501–506. https://doi.org/10.1038/nclimate3322

Moran, D. S., & Epstein, Y. (2006). Evaluation of the environmental stress index (ESI) for hot/dry and hot/wet climates. *Industrial Health*, *44*(3), 399–403. https://doi.org/10.2486/INDHEALTH.44.399

Moran, D. S., Pandolf, K. B., Shapiro, Y., Heled, Y., Shani, Y., Mathew, W. T., & Gonzalez, R. R. (2001). An environmental stress index (ESI) as a substitute for the wet bulb globe temperature (WBGT). *Journal of Thermal Biology*, *26*(4–5), 427–431. https://doi.org/10.1016/S0306-4565(01)00055-9

NDMA. (2022). Cyclone | National Disaster Management Authority, Government of India. Retrieved from https://ndma.gov.in/Natural-Hazards/Cyclone

Needham, H. F., Keim, B. D., & Sathiaraj, D. (2015). A review of tropical cyclone-generated storm surges: Global data sources, observations, and impacts. *Reviews of Geophysics*, *53*(2), 545–591. https://doi.org/10.1002/2014RG000477

Oh, S., Jufri, F. H., Choi, M. H., & Jung, J. (2022). A study of tropical cyclone impact on the power distribution grid in South Korea for estimating damage. *Renewable and Sustainable Energy Reviews*, *156*, 112010. https://doi.org/10.1016/J.RSER.2021.112010

Owen, L. E., Catto, J. L., Stephenson, D. B., & Dunstone, N. J. (2021). Compound precipitation and wind extremes over Europe and their relationship to extratropical cyclones. *Weather and Climate Extremes*, *33*, 100342. https://doi.org/10.1016/J.WACE.2021.100342

Raghavan, S., & Rajesh, S. (2003). Trends in tropical cyclone impact: A study in Andhra Pradesh, India: A study in Andhra Pradesh, India. *Bulletin of the American Meteorological Society*, *84*(5), 635–644. https://doi.org/10.1175/BAMS-84-5-635

Rajeev, A., & Mishra, V. (2022). On the causes of tropical cyclone driven floods in India. *Weather and Climate Extremes*, *36*, 100432. https://doi.org/10.1016/J.WACE.2022.100432

Raveh-Rubin, S., & Wernli, H. (2015). Large-scale wind and precipitation extremes in the Mediterranean: A climatological analysis for 1979–2012. *Quarterly Journal of the Royal Meteorological Society*, *141*(691), 2404–2417. https://doi.org/10.1002/QJ.2531

RSMC. (2000). Report on cyclonic disturbances over north Indian Ocean during 1999. Retrieved from http://www.rsmcnewdelhi.imd.gov.in/uploads/report/27/27_510109_35_66a331_1999.pdf

RSMC. (2021). Report on cyclonic disturbances over north Indian Ocean during 2021. Retrieved from https://rsmcnewdelhi.imd.gov.in/uploads/report/27/27_6f8db1_rsmc-2020.pdf

Santos, V. M., Wahl, T., Jane, R., Misra, S. K., & White, K. D. (2021). Assessing compound flooding potential with multivariate statistical models in a complex estuarine system under data constraints. *Journal of Flood Risk Management*, *14*(4), e12749. https://doi.org/10.1111/JFR3.12749

Seneviratne, S., Nicholls, N., Easterling, D., Goodess, C., Kanae, S., Kossin, J., et al. (2012). Changes in climate extremes and their impacts on the natural physical environment (pp. 109–230). https://doi.org/10.7916/D8-6NBT-S431

10.1029/2022EF002992

Sherwood, S. C., & Huber, M. (2010). An adaptability limit to climate change due to heat stress. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(21), 9552–9555. https://doi.org/10.1073/PNAS.0913352107

Singh, O. P. (2010). Recent trends in tropical cyclone activity in the North Indian Ocean. *Indian Ocean Tropical Cyclones and Climate Change*, 51–54. https://doi.org/10.1007/978-90-481-3109-9_8/COVER/

Singh, O. P., Ali Khan, T. M., & Rahman, M. S. (2000). Changes in the frequency of tropical cyclones over the North Indian Ocean. *Meteorology and Atmospheric Physics*, *75*(1), 11–20. https://doi.org/10.1007/S007030070011

Srivastava, A. K., Ray, K. C. S., & De, U. S. (2000). Trends in the frequency of cyclonic disturbances and their intensification over Indian Seas. *Mausam*, *51*(2), 113–118. https://doi.org/10.54302/MAUSAM.V51I2.1766

Sriver, R. L., & Huber, M. (2007). Observational evidence for an ocean heat pump induced by tropical cyclones. *Nature*, *447*(7144), 577–580. https://doi.org/10.1038/NATURE05785

Stone, B., Mallen, E., Rajput, M., Broadbent, A., Krayenhoff, E. S., Augenbroe, G., & Georgescu, M. (2021). Climate change and infrastructure risk: Indoor heat exposure during a concurrent heat wave and blackout event in Phoenix, Arizona. *Urban Climate*, *36*, 100787. https://doi.org/10.1016/J.UCLIM.2021.100787

Stone, B., Mallen, E., Rajput, M., Gronlund, C. J., Broadbent, A. M., Krayenhoff, E. S., et al. (2021). Compound climate and infrastructure events: How electrical grid failure alters heat wave risk. *Environmental Science and Technology*, *55*(10), 6957–6964. https://doi.org/10.1021/ACS.EST.1C00024

Sudeepkumar, B. L., Babu, C. A., & Varikoden, H. (2020). Atmospheric boundary layer height and surface parameters: Trends and relationships over the west coast of India. *Atmospheric Research*, *245*, 105050. https://doi.org/10.1016/J.ATMOSRES.2020.105050

Villarini, G., Goska, R., Smith, J. A., & Vecchi, G. A. (2014). North Atlantic tropical cyclones and U.S. flooding. *Bulletin of the American Meteorological Society*, *95*(9), 1381–1388. https://doi.org/10.1175/BAMS-D-13-00060.1

Wahl, T., Jain, S., Bender, J., Meyers, S. D., & Luther, M. E. (2015). Increasing risk of compound flooding from storm surge and rainfall for major US cities. *Nature Climate Change*, *5*(12), 1093–1097. https://doi.org/10.1038/nclimate2736

Wang, R., Lü, G., Ning, L., Yuan, L., & Li, L. (2021). Likelihood of compound dry and hot extremes increased with stronger dependence during warm seasons. *Atmospheric Research*, *260*, 105692. https://doi.org/10.1016/J.ATMOSRES.2021.105692

Woodruff, J. D., Irish, J. L., & Camargo, S. J. (2013). Coastal flooding by tropical cyclones and sea-level rise. *Nature*, *504*(7478), 44–52. https://doi.org/10.1038/nature12855

Yu, J., Ouyang, Q., Zhu, Y., Shen, H., Cao, G., & Cui, W. (2012). A comparison of the thermal adaptability of people accustomed to air-conditioned environments and naturally ventilated environments. *Indoor Air*, *22*(2), 110–118. https://doi.org/10.1111/J.1600-0668.2011.00746.X

Zscheischler, J., Naveau, P., Martius, O., Engelke, S., & Raible, C. (2021). Evaluating the dependence structure of compound precipitation and wind speed extremes. *Earth System Dynamics*, *12*(1), 1–16. https://doi.org/10.5194/ESD-12-1-2021

Zscheischler, J., Westra, S., van den Hurk, B. J. J. M., Seneviratne, S. I., Ward, P. J., Pitman, A., et al. (2018). Future climate risk from compound events. *Nature Climate Change*, *8*(6), 469–477. https://doi.org/10.1038/s41558-018-0156-3