Improved Water Savings and Reduction in Moist Heat Stress Caused by Efficient Irrigation

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Key Points:
- Irrigated area has increased more than 20% over the Indo-Gangetic Plain
- Irrigation expansion contributed to the rise of 0.46°C wet-bulb temperature during summer
- Efficient irrigation reduces moist heat stress and improves water savings

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

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Abstract
Intensive agriculture and irrigation play a crucial role in the food security of India. However, irrigation has considerably impacted regional climate and groundwater sustainability. Notwithstanding the profound implications of irrigation on dry and moist heat and groundwater depletion, the role of efficient irrigation on moist heat stress reduction and water savings remains unexplored. Here, we use observations and simulations from the Weather Research Forecasting (WRF) model to examine the impact of efficient (drip) irrigation on moist heat stress and water savings over the Indo-Gangetic Plain. Irrigated area has increased more than 20% over the Indo-Gangetic Plain during the 1970–2005 period. As a result, irrigation water use has increased dramatically over the region. The irrigation expansion partly contributed to the rise of 0.46°C (P-value < 0.05) in the summer (April–May) season wet-bulb temperature over the Indo-Gangetic Plain, which is a measure of moist heat stress. The Indo-Gangetic plain exhibited a strong land-atmospheric coupling between soil moisture and dry and moist heat. WRF simulations conducted using ERA5 as boundary conditions show that switching from the conventional (channel) to the efficient (drip) irrigation leads to a moderate warming (~0.2°C) and a significant decrease in specific humidity over the Indo-Gangetic Plain. The reduction in specific humidity due to efficient irrigation significantly lowers the moist heat stress (wet-bulb temperature) and increases water savings. Our findings show the double benefits of efficient irrigation to curb the rapidly declining groundwater and increase moist heat stress in the region.

Plain Language Summary
India is witnessing two major challenges: (a) Increase in moist heat stress, and (b) rapid depletion of groundwater. Both of these are likely to worsen under the warming climate in the future. The Indo-Gangetic Plain is among the most populated regions in the world that have experienced intensive agriculture and irrigation expansion. Irrigation expansion in the region has caused cooling in dry-bulb temperature while increase in moist heat stress. Despite the crucial role of irrigation on moist heat stress and groundwater depletion, the benefits of efficient irrigation in reducing moist heat stress and water savings have not been quantified. We used conventional (channel) and efficient (drip) irrigation to examine the role of efficient irrigation in reducing the moist heat and water savings. We observed switching from the conventional (channel) to the efficient (drip) irrigation leads to a moderate warming (~0.2°C) and a significant decrease in specific humidity over the Indo-Gangetic Plain. The reduction in specific humidity due to efficient irrigation significantly lowers the moist heat stress (wet-bulb temperature) and increases water savings. Our findings show the double benefits of efficient irrigation to curb the rapidly declining groundwater and increase moist heat stress in the region.

1. Introduction
Irrigation expansion in India ensured food security for about 1.4 billion people, improved the socio-economic condition, and increased Gross Domestic Product (GDP; Chen et al., 2019; Narayanamoorthy, 2011). Irrigation has been a significant contributor to improving the Indo-Gangetic region’s socio-economic condition (Krishna Kumar et al., 2004; Narayanamoorthy & Deshpande, 2003). However, irrigation modulated regional climate, energy, and water budgets (Ambika & Mishra, 2019, 2020, 2021; Shah et al., 2019). Excessive moisture from agricultural expansion and irrigation combined with increased warming has affected human health, reduced labor performance, and led to economic loss (Kjellstrom et al., 2016; Venugopal et al., 2016). Moreover, detrimental impacts of increased moist heat stress due to the expansion of irrigated area causes a decline of 30%–40% in work performance (Buza & Huber, 2020). Moist heat has increased over the densely populated Ganges and Indus river basins (Im et al., 2017; Krakauer et al., 2020; Mishra et al., 2020; Raymond et al., 2020; Saeed et al., 2021). The planetary boundary layer, which is convectively coupled with the troposphere, affects moist heat and modulated...
by irrigation (Gentine et al., 2013; Kang & Eltahir, 2019). In addition, the rapid expansion of irrigated areas and excessive groundwater pumping has caused groundwater depletion over north India and Indo-Gangetic Plain (Asoka et al., 2017; Mishra et al., 2018; Rodell et al., 2009; Tiwari et al., 2009). Therefore, efficient irrigation is needed for water management and to reduce the increasing moist heat stress in the region.

Irrigation expansion in India has exacerbated the occurrence of extreme moist heat (Krakauer et al., 2020; Mishra et al., 2020), which is likely to worsen under the warming climate (Im et al., 2017; Rao et al., 2020). The summer monsoon onset controls the frequency of moist heat extremes along the Indian subcontinent (Raymond et al., 2020), emphasizing the critical role of moisture advection and regional weather system on synoptic to sub-seasonal time scale (Raymond et al., 2017). A significant increase in moist heat over the Indo-Gangetic plain during summer is enhanced by irrigation under the warming climate (Mishra et al., 2020). The concurrent increase in dry and moist heat extremes resulted in widespread mortality (Mazdiyasni et al., 2017; Mishra et al., 2020). Moreover, moist heat extremes in South Asia are likely to reach the critical threshold of 35°C in the future (Saeed et al., 2021).

The widespread expansion of irrigation in the past (Shankar et al., 2011) and projected rise in the future can negatively impact moist heat stress and water management. For instance, aquifers in the Indo-Gangetic plain are rapidly losing water and fall among the most stressed aquifers in the world (Gleeson et al., 2012). In addition to the rapid decline in groundwater primarily due to pumping for irrigation in north India (Asoka et al., 2017; Rodell et al., 2009), there have been substantial changes in the amount and characteristics of the summer monsoon rainfall (Asoka et al., 2018; Dangar et al., 2021). Sustainable water management is critical for future food and freshwater security in one of the most densely populated regions of the world. The key to sustainable water management in the Indo-Gangetic Plain remains the efficient use of groundwater for irrigation. Efficient irrigation can save groundwater without affecting food production (Fishman et al., 2015). Therefore, efficient irrigation and crop management can play a vital role in avoiding moist heat stress and water stress in the region. Despite the intensive irrigation and its impacts on water resources over the Indo-Gangetic Plain, the role of efficient irrigation on moist heat stress and water management has not been examined over India. Here we quantify the benefits of efficient irrigation on moist heat stress and water management in India using in-situ and satellite-based observations and high-resolution Weather Research and Forecasting (WRF) model.

### 2. Data and Methods

To examine the role of efficient irrigation in India, we obtained irrigation fraction from Historical Irrigation Datasets (HID; Siebert et al., 2015a, 2015b), which was used to estimate the changes in the irrigated areas. The HID data set represents the area equipped for irrigation (AEI) for the 1900–2005 period. HID maps are available at five arcmin spatial resolution, which were developed using sub-national level statistics considering the extent of pasture and cropland (Siebert et al., 2015a). We estimated the change in irrigation fractions between 1970 and 2005. In addition, the observed changes in evaporative stress index (ESI, semi-empirical relation to vegetation optical depth and root zone soil moisture) were examined during the summer to evaluate the evaporation rate in the absence of soil moisture. ESI was obtained from the Global Land Evaporation Amsterdam Model (GLEAM) for the 1980–2018 period. We considered the 95th percentile as a threshold to estimate the change in extreme ESI. We derived irrigation water withdrawal for the Indian region at 0.5° spatial resolution from Global Reconstructed Water (GRW) use data for 1971–2010 (Huang et al., 2018). The GRW irrigation water withdrawal was based on the food and agriculture organization of the united nations (FAO) global information system on water and agriculture (AQUASTAT), United States Geological Survey (USGS) estimates, and simulated global hydrological models (GHMs Huang et al., 2018). Changes in irrigation water withdrawal and ESI were estimated using the nonparametric Mann Kendall trend test (Mann, 1945) and Sen's (Sen, 1968) slope method. Changes were calculated using trend slope multiplied by the total period. More descriptions and sources related to datasets used are provided in Table S1 in Supporting Information S1.

#### 2.1. Moist Heat Stress Indicators

We obtained the hourly air temperature at 2 m from the ERA5-reanalysis (Dee et al., 2011) to estimate moist heat indices for the 1979–2018 period. ERA5 data set is available at about 31 km spatial resolution. All the moist and dry heat indices were estimated using hourly ERA5. Hourly near-surface specific and relative humidity were
estimated using the hourly dew point temperature and surface pressure from ERA5. The relative and specific humidity were calculated using Tetens’s formula (Tetens, 1930), with the parameters based on saturation over water (Buck, 1981). The mean and 95th percentile of summer (April–May) maximum daily temperature at 2 m (T\text{w}) and wet-bulb temperature (T\text{wb}) were used to characterize dry and moist heat, respectively. In addition, we used mean and 95th percentile heat index (HI) to evaluate the moist heat conditions during the summer. Our extreme dry and moist heat measures are based on the 95th percentile of dry and moist indicators (temperature, wet-bulb temperature, and HI) for the summer season. Changes in the moist heat indicators were estimated for the 1979–2018 period using the nonparametric Mann-Kendall test and Sen’s slope method.

Hourly air temperature, relative humidity, and near-surface pressure were used to estimate moist heat indices described in detail by Buzan et al. (2015). The initial value of the moist heat is calculated using the method described in Davies-Jones (2008), which was used in an efficient iterative method to calculate the final T\text{w} as provided in Buzan et al. (2015). United States National Weather Service developed HI for heat stress early warning. The HI is a measure of feel-like temperature based on discomfort, which considers the effects of both temperature and humidity. HI can be represented using different categories (caution, extreme caution, danger, and extreme danger). Further details on wet-bulb temperature and HI can be found in Buzan et al. (2015).

We calculated land-atmospheric coupling metrics to estimate the effect of soil moisture on the temperature at 2 m (T\text{w}), moist heat (T\text{wb}), and heat index (HI) using the method described in Miralles et al. (2012). We obtained evaporation (E) and potential evaporation (E\text{p}) from the GLEAM and the net radiation from the ERA5 data set for the 1980–2018 period. ERA5 and GLEAM datasets were re-gridded using bi-linear interpolation to 0.25° to make them consistent with the WRF model simulations. To estimate coupling between soil moisture and dry and moist heat, we first estimated the energy balance anomaly (e) by separating the effect of soil moisture using E and E\text{p}.

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e = [(R_n - \lambda E) - (R_n - \lambda E_p)]
\]  

Here, R_n is net radiation, \lambda E is the latent heat of evaporation, and \lambda E_p is the latent heat of potential evaporation. The energy term represents the potential of soil moisture to affect T\text{w}, T\text{wb}, and HI (Miralles et al., 2012). Further, the coupling matrices are obtained by estimating the correlation between energy balance anomaly and T\text{w}, T\text{wb}, and HI anomalies. The coupling matrices can vary from negative to positive values. Positive values of the coupling strength indicate soil moisture restrictions in partitioning the surface energy. Negative values of coupling strength denote no coupling, while higher positive values indicate stronger coupling (Miralles et al., 2014).

### 2.2. Regional Climate Model Simulations

We conducted simulations using the WRF model with ERA5 (2000–2018) as a boundary condition to examine the role of irrigation schemes on moist heat and water savings. We obtained the static irrigated area map from the Food and Agriculture Organization (FAO; Siebert et al., 2013, 2015a). The FAO irrigated area maps are prepared based on information collected from various sources such as total irrigated area from the national database, irrigated area per national statistical unit, satellite datasets, and irrigated area information based on land cover maps (Ajaz et al., 2019; Siebert et al., 2005, 2015a). Irrigated area from FAO was updated recently and provided the irrigation extent of 2013. FAO provided fractional information on the irrigated area in each grid, and it is commonly used in the climate and land surface model (LSM) simulations (Ambika et al., 2016). We remapped the FAO irrigated area from the original resolution of 0.083°–0.25°, making it consistent with the WRF spatial resolution. We used irrigated areas with a fraction greater than 0.25 in our simulations to avoid uncertainty in irrigation fractions at the lower scale. The irrigated fraction is weighted with the total amount of water required at each grid initially and further added to the model time step. The WRF simulations were conducted for the irrigation-on (drip and channel irrigation schemes) and the irrigation-off scenarios to examine the role of efficient irrigation practices in reducing moist heat stress and water savings.

We implemented drip and channel irrigation schemes in WRF model based on the method described in Valmassoi et al. (2020) for the 2000–2018 period. As irrigation method definition differs based on the specific area of implementation, we used the efficiency component, that is, water loss occurred during the application of irrigation. The primary implementation criteria for the irrigation system are the increasing amount of evaporation process after water leaves the irrigation system. The framework was implemented considering the drip and channel irrigation...
system of the Indian region. Here, the theoretical perspective of the evaporation component of the irrigation system is implemented.

The drip irrigation scheme here accounts for evaporation only from the soil, which is applied in the chosen LSM. The irrigation water is supplied in the surface rain variable, limiting the direct modulation in the atmospheric and vegetation parameterizations (Lawston et al., 2015; Valmassoi et al., 2020). The irrigation water requirement is calculated based on the GRW data set. Further, the required water is integrated into the model time step. To mimic the actual drip irrigation, canopy interception in the evaporation process was not considered. On the other hand, water interception by the canopy was considered in the channel irrigation. The channel irrigation allows evaporation from the leaves and the soil surface. The process then mimics the channel irrigation within the WRF model framework, which undergoes all the rain processes related to canopy water balances. Moreover, in the channel irrigation method, the land surface allows the partitioning of rain between interception and dripping. The daily irrigation water requirement from GRW is applied at a constant rate in both irrigation methods keeping all other parameters same in both simulations. Further details on irrigation schemes can be obtained from the previous studies (Evans & Zaitchik, 2008; Lawston et al., 2015; Valmassoi et al., 2020).

Land atmospheric feedback on moist heat was examined using the WRF model. Irrigation was implemented in the WRF model, as explained in Valmassoi et al. (2020), which uses a constant irrigation water demand. The various schemes used in the WRF simulations (irrigation-on and irrigation-off) are provided in supplemental Table S2 in Supporting Information S1. We used the Noah LSM in the WRF simulations due to its vast representation of irrigation in different climatic zones, simplistic land surface schemes, and minimal error in simulated variables with observation/reanalysis data. The near-surface temperature at 2 m, 10 m wind, mean sea level pressure, sea surface temperature, land surface temperature, snow density, snow depth, volumetric soil water and soil temperature at different levels and surface pressure from ERA5 were used as input to WRF simulations. In addition, we used specific humidity, temperature, $U$ and $V$ wind direction components ($U$—positive for the west to east flow, and $V$—positive for the south to north flow), and geopotential height at pressure levels as meteorological inputs to the WRF model. Further, we used the previously standardized convective parameterization to achieve a realistic extent of precipitation (Iacono et al., 2008; Janjić, 1994; Kain, 2004; Mitchell, 2005; Qian et al., 2013). We also derived moist heat indices from the irrigation-off scenario for the 2000–2018 period. In addition, we examined the role of efficient irrigation practices on moist heat stress and water savings during the summer.

### 3. Results and Discussion

#### 3.1. Expansion in Irrigation and Changes in Irrigation Water Use

First, we estimated the changes in the irrigated fraction from 1970 to 2005 (Figure 1a). The irrigated area over the Indo-Gangetic plain has increased by 20% during 1970–2005 as per the Historical Irrigation Datasets (HID; Figure 1a). The massive irrigation expansion in India started after the Green revolution in the 1970s due to increased tube wells and mechanical pumps in the region (Mishra et al., 2018). The Indo-Gangetic Plain experienced a considerable irrigation expansion (Figure 1a). Apart from the agricultural and irrigation growth, the Indo-Gangetic Plain has witnessed substantial changes in climate over the last few decades. For instance, potential
evaporation has increased considerably over the Indo-Gangetic Plain (Rehana & Monish, 2020) and arid and semi-arid regions of northwestern India during 1980–2017 (Figure S1a in Supporting Information S1). Increases in potential evaporation indicate the rising atmospheric water demands (Massmann et al., 2019), which derive increased demands for irrigation. Moreover, the Indo-Gangetic plain witnessed a significant (p-value ≤ 0.05) increase in net irrigation water use (Figure 1c). For instance, irrigation water use has increased approximately by 14 mm in the Indo-Gangetic Plain during 1971–2010 (Figure 1c).

Irrigation expansion combined with the increased atmospheric water demands over the Indo-Gangetic Plain resulted in a significant rise in irrigation water use. The substantial rise in irrigation water use has caused several environmental implications, including alteration of dry and moist heat (Ambika & Mishra, 2020; Mishra et al., 2020) and rapid groundwater depletion (Mishra et al., 2018). In addition, an extensive irrigation water withdrawal during the summer (April–May) significantly alters the surface energy and radiation budget (Ambika & Mishra, 2020, 2021; Douglas et al., 2006; Qian et al., 2013; Yang et al., 2019). Further, a significant increase in evaporative stress is observed along extensively irrigated Indo-Gangetic plain (Figure S1b in Supporting Information S1). Change in evaporative stress indicates phenological constraints acting on evaporation over the Indo-Gangetic plain (Figure S1c in Supporting Information S1), which are associated with the changes in vapo due to the soil moisture desiccation (Zhou et al., 2019).

For instance, lower sun-induced chlorophyll fluorescence (SIF; Ambika & Mishra, 2021) indicates a decline in leaf and canopy photosynthetic rates when atmospheric VPD increases due to stomatal closure (Yuan et al., 2019). Overall, a massive irrigation expansion combined with the increased atmospheric water demands caused a rise in the irrigation water use in the Indo-Gangetic Plain.

3.2. Increase in Moist Heat Stress

Moist heat over the Indo-Gangetic Plain is primarily driven by the combined increase in dry heat and irrigation (Krakauer et al., 2020; Mishra et al., 2020). We estimated the wet-bulb temperature (Tw) changes during 1979–2018 using the ERA5 (Figure 2). The moist heat measured using Tw has increased over most of the Indian region. However, the rise in moist heat is more prominent over the Indo-Gangetic plain (Figure 2a). We find a significant (P-value < 0.05) increase of 2.0°C in mean wet bulb temperature over the Indo-Gangetic plain during 1979–2018. Furthermore, the Indo-Gangetic plain witnessed a significant increase in extreme wet-bulb temperature (Tw) exceeding the 95th percentile during summer (Mishra et al., 2020). Extreme Tw has increased by 0.34°C during the 1979–1998 period (P-value = 0.01796). Moreover, a more prominent and significant rise of 0.46°C in extreme wet-bulb temperature was found during 1999–2018 over the Indo-Gangetic plain (Figure 2b). Further, we estimated changes in the wet-bulb temperature for each month in a calendar year for the two periods (1979–1998 and 1999–2018). A significant rise in wet-bulb temperature was found for the 1999–2018 period compared to the 1979–1998 period. Like the observed increase in wet-bulb temperature, a significant rise in HI was found during the 1999–2018 period (Figure S2 in Supporting Information S1). Overall, our results show that the rise in moist heat (wet-bulb temperature and HI) over the Indo-Gangetic Plain has been more prominent during the recent decades, which can be attributed to the expansion in irrigation in the region (Mishra et al., 2020).
The Indo-Gangetic Plain experiences extreme (exceeding 95th percentile) dry and moist heat during the summer (Figure S3 in Supporting Information S1). For instance, extreme dry bulb temperature and HI exceed 43°C during the summer. In addition, parts of the Indo-Gangetic plain experience extreme wet-bulb temperatures higher than 27°C (Figure S3 in Supporting Information S1). Extreme dry and moist heat over the Indo-Gangetic plain can result in significant mortality (Figure S3a in Supporting Information S1; Lima et al., 2021; Mazdiyasni et al., 2017). The extreme dry heat consistently affects the Indo-Gangetic Plain and the central and western parts of India during the summer (Figure S3a in Supporting Information S1). However, extreme HI and wet-bulb temperature are more prominent over the Indo-Gangetic plain and coastal region (Figures S3b and S3c in Supporting Information S1). Our results based on the ERA5 show extreme moist heat has reached the threshold of 27°C (Krakauer et al., 2020) in the majority of India, especially over the Indo-Gangetic Plain (Figures S3b and S3c in Supporting Information S1). The climatological mean extreme (exceeding 95th percentile) specific humidity is also higher along the coastal and Indo-Gangetic plain than (Figure S4a in Supporting Information S1). Moreover, relative humidity (%) in the summer season has considerably increased over the Indo-Gangetic Plain and parts of central India during the 1979–2018 period (Figures S4b and S4c in Supporting Information S1). The localized rise in extreme moist heat and relative humidity centered over the Indo-Gangetic region is attributable to intensive irrigation and warming climate (Ambika & Mishra, 2020; Puma & Cook, 2010).

Summer moist heat has significantly increased over India (Mishra et al., 2020). Partitioning of net radiation into sensible heat and latent heat fluxes plays a critical role in dry (Miralles et al., 2014) and moist heat (Krakauer et al., 2020) and its coupling with the land surface (Haghighi et al., 2018; Lu et al., 2017; Miralles et al., 2012; Williams & Torn, 2015). Soil moisture is a major driver for energy partitioning at the surface to examine the coupling between land and atmosphere (Figure 3). We examined the coupling of soil moisture with dry-bulb temperature, wet-bulb temperature, and HI to understand the role of land-atmospheric feedback during 1979–2018 (Figure 3, see methods for more details). Further, the coupling of soil moisture with dry and moist heat indicators was estimated for the pre- and post-1998 periods (Figure S5 in Supporting Information S1). A strong and positive coupling between soil moisture and summer dry-bulb temperature was found over most of the Indian region (Figure 3a). Moreover, the soil moisture and dry-bulb temperature coupling are more prominent over the Indo-Gangetic plain (Figure 3a). A positive soil moisture-dry bulb coupling during the summer (Figure S5 in Supporting Information S1) signifies soil moisture restrictions in the partitioning of the energy budget. For instance, the variability in soil moisture and temperature coupling contributes to the partitioning of surface sensible heat flux is derived using the reanalysis and satellite-based observations (Miralles et al., 2012, 2014). We find a positive coupling between soil moisture and wet-bulb temperature over the Indo-Gangetic Plain (Figure 3b), which indicates an increase in the partitioning of latent heat flux contributes to the rise in wet-bulb temperature (Figures 3b and 3c). Consistent with the dry-bulb temperature (Figure 3a), a positive soil moisture-heat index coupling was found over the majority of India (Figure 3b), which can be attributed to the higher contribution from dry-bulb temperature to HI than relative humidity (Buzan et al., 2015; Figures 3c and 3d). The positive coupling between soil moisture and dry and moist heat over the Indo-Gangetic Plain signifies the co-occurrence of extreme temperatures and the modulation of soil moisture and energy budget by irrigation (Figure 3b).

3.3. Influence of Efficient Irrigation on Moist Heat and Water Savings

Our results based on ERA5 showed that wet-bulb temperature during the summer had increased considerably over the Indo-Gangetic Plain during the 1979–2018 period. Further, a strong coupling between soil moisture and temperature exists over the Indo-Gangetic plain. Next, we employed the WRF model to quantify efficient irrigation (drip) benefits on moist heat stress and water savings. We implemented channel and drip irrigation systems in the WRF model using the boundary condition from the ERA5. The simulations using different irrigation schemes show less variability with the reanalysis datasets for the Indian region (Figures S6 and S7 in Supporting Information S1). Further, we evaluated the climatological mean of specific humidity, temperature at 2 m, and surface pressure between the WRF simulated scenarios and ERA5. The evaluation on the Indo-Gangetic plain and Indian region shows minimal variability in $T_2$ (Figures S7h and S7j in Supporting Information S1). However, we observed consistency between ERA5 and WRF drip irrigation simulation scenario of specific humidity (Figures S7g and S7i in Supporting Information S1).

We estimated the differences in the summer energy budget, specific humidity, and temperature at 2 m for the drip and channel irrigation scenarios simulated from WRF to evaluate the role of the efficient irrigation systems.
We find a decrease in the total available energy (latent heat + sensible heat) due to the efficient irrigation (Figure 4a). However, efficient irrigation does not significantly differ in the total available energy compared to the Indo-Gangetic plain (Figure 4b). The reduction in total available energy indicates a decline in

Figure 3. Land-atmospheric coupling during the summer in India. (a) Soil moisture (SM) and near surface air temperature ($T_2$) coupling for the summer during 1980–2018 period. The coupling strength was estimated using datasets from the Global Land Evaporation Amsterdam Model and ERA5, (b) mean coupling strength between SM and surface air temperature for India and Indo-Gangetic plain, (c) same period as (a) but coupling between SM and wet-bulb temperature ($T_W$), (d) same period as (b) but for wet bulb temperature ($T_W$), (e) same as (a) but for SM and heat index (HI), and (f) same period as (b) but for heat index (HI). Gray areas in (a,c, and e) show no coupling while the positive value indicates a stronger coupling.
soil moisture (Eltahir, 1998). The increased soil moisture favors an increase in near-surface moist static energy. Therefore, reduction in soil moisture reduces the total heat flux from the surface to the boundary layer (Evans & Zaitchik, 2008). Further, the fluctuation in total heat flux at the surface is dominant in modulating moist static energy.

Figure 4. Role of efficient irrigation on energy budget, specific humidity, and temperature. (a) The difference (drip-channel) in the total energy (sensible + latent heat fluxes) between the drip and channel irrigation in the summer for the 2000–2018 period, (b) kernel density function of the total energy under the drip and channel irrigation over the Indo-Gangetic plain (c and d) same as (a and b) but for the specific humidity (Kg/Kg), and (e and f) is same as (a and b) but for near-surface temperature at 2 m ($T_2$). The statistical significance for mean and distribution was tested at 5% significance level using the two-sided Rank-sum and KS tests, respectively. The role of different irrigation methods (drip and channel) was estimated using the WRF simulations for the 2000–2018 period with boundary conditions from ERA5.
energy. Efficient irrigation significantly reduces specific humidity across India and more prominently over the Indo-Gangetic Plain (Figures 4c and 4d). Drip irrigation reduces soil moisture-induced evaporation (Figure S8b in Supporting Information S1) and a nearly compensating decline in specific humidity (Figure 3b).

Dry-bulb temperature increases by about 0.2°C over the Indo-Gangetic plain for the efficient irrigation than channel irrigation (Figure 4c). As for the total available energy and specific humidity, switching from the channel irrigation to drip irrigation results in warming over the Indo-Gangetic Plain (Figures 4e and 4f). The change in dry bulb temperature due to efficient irrigation was statistically significant at a 5% level (Figure 4f). The drip irrigation system implemented in the WRF model provides an optimal amount of water with minimal transpiration, reducing evaporation losses (Evans & Zaitchik, 2008; Lawston et al., 2015). Since water is added directly to soil layers in drip irrigation, the land surface temperature increase is expected (Figure 4c). Further, we observed a statistically significant (P-value < 0.05) increase in nighttime temperature (Figure S9 in Supporting Information S1). The higher moisture content contributes to thermal inertia as it increases the heat capacity in drip irrigation. The non-significant change in net radiation over the irrigated area signifies higher sensitivity of diurnal amplitude of the surface temperature to the thermal inertia (Cheruy et al., 2017). Our results show that switching from conventional to efficient irrigation can significantly impact the energy balance, specific humidity, and dry-bulb temperature over the Indo-Gangetic plain (Figure 4).

Next, we examined the role of efficient irrigation in modulating wet-bulb temperature and water savings using the WRF simulations (Figure 5). As the moist heat is controlled by cooling and moistening (Kang & Eltahir, 2018), we estimated the difference in equivalent potential temperature, wet-bulb temperature, and water savings using the drip and channel irrigation scenarios WRF simulations. Since the dry-bulb temperature (\(T_d\)) does not represent energy content at the lower atmosphere, we used equivalent potential temperature, which accounts for both static energy and temperature at 2 m. We find a considerable difference between the efficient and channel irrigation in the climatological mean of all the three variables (equivalent potential and wet-bulb temperatures and water savings) during summer 2000–2018 (Figure 5). The significant change of equivalent potential temperature indicates the rapid increase in specific humidity with temperature (Lutsko, 2021).

Switching from channel to the efficient irrigation system results in a significant decline in equivalent potential temperature over the Indo-Gangetic plain (Figures 5a and 5b). On the other hand, a significant (at 10% significance level) decrease in wet-bulb temperature was found over the Indo-Gangetic plain when switching from channel to drip irrigation system (Figures 5c and 5d). The extreme wet-bulb temperature has increased due to irrigation (Krakauer et al., 2020; Mishra et al., 2020), while dry bulb temperature declined during the summer (Ambika & Mishra, 2021) in the Indo-Gangetic Plain. However, switching from channel to drip irrigation in the Indo-Gangetic Plain can decline wet-bulb temperature and enhanced water savings over the Indo-Gangetic Plain (Figure 5).

4. Discussion and Conclusions

Global warming caused the increased severity and frequency of deadly heatwaves over majority of the globe. The compound increase in atmospheric moisture and heatwaves results in a rapid rise in moist heat stress over the last four decades, which is more prominent in subtropic regions (Wouters et al., 2022). For instance, the subtropic areas are close to the 35°C survivability limit (Raymond et al., 2020). Moreover, the survivability limit of extreme heat stress has been underestimated in several parts of the coastal regions. However, to meet the future food demand by 2050, expansion in irrigated areas is likely. Therefore, extreme heat stress may become a significant challenge due to intensive irrigation for meeting the future food demands.

India and especially the Indo-Gangetic Plain, has witnessed considerable irrigation expansion after the Green Revolution. Intensive agriculture and growth in irrigation caused cooling in dry-bulb temperature (Ambika & Mishra, 2019). On the other hand, irrigation exacerbated moist heat primarily due to an increase in relative humidity and decreased planetary boundary layer height (Mishra et al., 2020). Anthropogenic warming (Oldenborgh et al., 2018; Rupp et al., 2015) and irrigation driven rise in specific humidity considerably modulate moist heat (Im et al., 2014; Marcella & Eltahir, 2014; Mishra et al., 2020; Qian et al., 2013). One of the most profound implications of irrigation expansion over the Indo-Gangetic Plain has been the rapid groundwater depletion in the region (Asoka et al., 2017; Long et al., 2016; Mishra et al., 2018). Rapid groundwater depletion was primarily driven by the groundwater pumping for irrigation, and the decline in the summer monsoon precipitation played a
secondary role (Asoka et al., 2017). Sustainable use of groundwater is essential for India’s future food and water security (Khare & Varade, 2018; Wada et al., 2016). Efficient irrigation is one of the most critical factors that can play a role in water sustainability in India.

Figure 5. Role of efficient irrigation on moist heat and water savings. (a) The difference (drip-channel) in equivalent potential temperature between the drip and channel irrigation in the summer for the 2000–2018 period, (b) kernel density function of equivalent potential temperature under the drip and channel irrigation over the Indo-Gangetic plain (c and d) same as (a and b) but for wet-bulb temperature, and (e and f) is same as (a and b) but for irrigation water savings. The statistical significance for mean and distribution was tested at 5% significance level using the two-sided Rank-sum and KS tests, respectively. The role of different irrigation methods (drip and channel) was estimated using the Weather Research Forecasting simulations for the 2000–2018 period with boundary conditions from ERA5.
We examined the role of efficient irrigation on the reduction in moist heat and water savings using the WRF simulations. Switching from conventional channel irrigation to more efficient drip irrigation increases dry-bulb temperature and reduces specific humidity. Overall, a significant reduction in wet bulb temperature and an increase in water savings can be achieved by switching from channel to drip irrigation. We propose a framework to understand the impacts of different irrigation schemes on moist heat and water savings. The adaptation of efficient irrigation is vital to reduce the extreme wet-bulb temperature under the warming climate (Im et al., 2017; Mazdiyasni et al., 2017; Seneviratne et al., 2018). Notwithstanding the negative impact of irrigation practices, irrigation has been a significant factor in ensuring food security for the Indian region (Narayanamoorthy, 2011; Narayananmoorthy & Deshpande, 2003). Food demands can rise in the future (Tilman et al., 2011). Since irrigation acts as one of the essential adaptation measures under the warming climate (Fraiture, 2007; Mueller et al., 2012), irrigation demands are likely to further increase in the future (Fischer et al., 2007; Konzmann et al., 2013). Further expansion in irrigation and enhanced irrigation demands is likely to exacerbate moist heat stress and worsen already depleting groundwater in the irrigation intensive regions. Therefore, efficient irrigation can significantly curb the negative impacts on heat stress and water resources, which are occurring otherwise.

Based on our findings, we conclude the following:

1. A significant increase in potential evaporation over the Indo-Gangetic region can be attributed to the increasing water withdrawal. Further, the ESI indicates the phenological constraints on evaporation during the April-May period due to the increased VPD
2. A noticeable increase in the wet and dry bulb temperature was during the recent decades. Moreover, extreme wet and dry temperatures significantly increased over the Indo-Gangetic plain for the 1999–2018 period
3. Strong positive coupling of soil moisture with dry and moist heat indicators signifies that soil moisture restrictions in the partitioning of the energy budget are more prominent over the Indo-Gangetic plain
4. The WRF simulated drip and channel irrigation scenarios showed a significant difference in temperature, specific humidity, potential temperature, wet bulb temperature, and water-saving

**Conflict of Interest**

The authors declare no conflicts of interest relevant to this study.

**Data Availability Statement**

Precipitation from the India Meteorology Department (IMD) can be obtained from http://imd.gov.in/Climate_Prediction_Centre/LRF_New/Grided_Data_Download.html. ERA-5 reanalysis can be downloaded from ERA5 hourly data on pressure levels from 1979 to present (copernicus.eu) & ERA5 hourly data on single levels from 1979 to present (copernicus.eu). The GLEAM can be obtained from Global Land Evaporation Amsterdam Model. The global gridded monthly sector water use can be downloaded from Global gridded monthly sectoral water use data set for 1971-2010 (Zenodo). The global map of irrigated area version 5 were collected from https://www.fao.org/aquastat/en/geospatial-information/global-maps-irrigated-areas/latest-version/.

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