1. Introduction

Heat waves are one of the most dangerous climate extremes and serve as a main contributor to weather-related morbidity and mortality (IPCC 2021; Buzan and Huber 2020; Ebi et al. 2021; Costello et al. 2023). Heat stress has been tied to a large number of negative social issues, including increased crime, sociopolitical conflict, and decreased labor productivity, among others (Buzan and Huber 2020; Kjellstrom et al. 2009; Horton et al. 2016). The presence of heat stress also has significant ramifications for ecosystem health, agricultural productivity, and critical infrastructure (Moore et al. 2021; Hassan et al. 2021; Teixeira et al. 2013; Siebert and Ewert 2014; Rübbelke and Vögele 2011). As our climate continues to warm, occurrences of heat stress and heat waves are expected to become more frequent and intense (IPCC 2012; Meehl and Tebaldi 2004; Fischer and Knutti 2015), making the study of heat events increasingly relevant in understanding and preparing for future climate risks.

While the presence of moisture has been acknowledged as a key driver of the intensity of heat stress, moist or humid heat as a phenomenon distinct from dry heat is still understudied (Buzan and Huber 2020; Matthews 2018). Existing heat-wave and heat-stress literature focuses heavily on dry-bulb (or air) temperature metrics to define heat events (Horton et al. 2015; Difenbaugh and Ashfaq 2010; Mazdiyasni et al. 2017; Perkins-Kirkpatrick and Lewis 2020). However, the lack of inclusion of humidity causes dry heat metrics to omit a crucial component of heat when identifying and quantifying these events. Humidity has the ability to intensify heat stress and has even been shown to be more critical than temperature in driving extreme heat in regions in the United States (Raymond et al. 2017; Sherwood 2018). The nonlinear nature of the relationship between humid heat and air temperature (Matthews et al. 2017) also has the potential to amplify heat-related risks to a degree not adequately conveyed by temperature alone.

Although there is a growing body of work related to humid heat (Willett and Sherwood 2012; Fischer and Knutti 2013; Russo et al. 2017; Raymond et al. 2017; 2020), there is still much to learn with regard to the natural and anthropogenic influences on both dry and humid heat events. While major changes in climate are driven by large-scale anthropogenic emissions of greenhouse gases and aerosols (IPCC 2021), irrigation has also been shown to significantly impact local and remote climate conditions (Cook et al. 2015; Puma and Cook 2010; Sacks et al. 2009; Boucher et al. 2004). While many studies have established the cooling effect of irrigation on high temperatures (Li et al. 2023; Lu and Kueppers 2015; Lobell et al. 2008; Thiery et al. 2017), the impact of irrigation on humid heat stress is less straightforward (Buzan and Huber 2020). The presence of irrigation has been shown to amplify humid heat in South Asia (Guo et al. 2022; Ambika and Mishra 2022). Meanwhile, Mishra et al. (2020) showed irrigation-driven increases in high wet-bulb temperatures in South Asia but decreases in extreme heat index values derived from dry heat events (Willett and Sherwood 2012; Fischer and Knutti 2013; Russo et al. 2017; Raymond et al. 2017; 2020), there is still much to learn with regard to the natural and anthropogenic influences on both dry and humid heat events.
from temperature and humidity with the Weather Research and Forecasting (WRF) Model. In contrast, Jha et al. (2022) detected a limited impact of irrigation in the Indo-Gangetic Plain during the premonsoon (April–May) season. Additionally, Krakauer et al. (2020) found varying responses to irrigation in regions across the globe, with significantly increasing changes in parts of North America and the Middle East, and mixed changes in South and East Asia.

In light of these findings, we examine and compare the effect of irrigation on global dry and humid heat-wave occurrences using climate simulations with and without modern irrigation and with all other anthropogenic forcings set at present-day conditions. We use two metrics to represent dry and humid heat, with dry heat defined by maximum temperature and humid heat defined by equivalent temperature, which has been highlighted as a more accurate and complete heat metric, accounting for both latent and sensible heat (Matthews et al. 2022; Pielke et al. 2004; Song et al. 2022). We also explore the differences in how the presence of irrigation locally and remotely affects dry and humid heat, which remains an underexplored area of study in the literature (Mahmood et al. 2014; Pielke et al. 2011).

2. Method

a. GISS Model configuration and irrigation runs

We use the NASA Goddard Institute for Space Studies (GISS) atmospheric general circulation model, ModelE, coupled with the GISS ocean model (hereinafter referred to as GISS-E2.1-G) at 2° by 2.5° latitude by longitude resolution (Kelley et al. 2020). GISS-E2.1-G output has demonstrated the ability to model observed climate conditions as well as produce realistic responses to climate forcings (Miller et al. 2021). GISS ModelE has also been employed in several studies to demonstrate the impacts of irrigation on historical climate conditions (Cook et al. 2015; Puma and Cook 2010; Singh et al. 2018). Because of this, we use GISS-E2.1-G to examine how the presence of modern irrigation impacts dry and humid heat event occurrences.

Using phase 6 of the Coupled Model Intercomparison Project (CMIP6) historical climate forcings (Eyring et al. 2016), we conduct three model runs: 1) NONIRR, where irrigation is set to the year 1850 and all other anthropogenic forcings are set to the year 2000; 2) IRR2000, where all anthropogenic forcings, including irrigation, are set to the year 2000; and 3) IRRHALF, where the applied irrigation from the year 2000 is halved (Fig. 1). The third experiment is intended to account for the fact that the relatively coarse ModelE grid could result in overestimations of applied irrigation and the associated climate response and allows us to assess the sensitivity of the model response to the amount of irrigation water applied. The irrigation values used are based on the Irrigation Water Demand (IWD) dataset from Wisser et al. (2010), which accounts for crop-specific calendars, paddy production, and efficiencies of irrigation delivery across different cropping systems (Cook et al. 2020). The IWD values used are water applications added as a flux to the top of the soil column underneath the canopy, assuming no interception. We linearly extrapolate the values of the IWD dataset (1901–2005) to find the theoretical 1850 irrigation values. In all model runs, we prescribe sea surface temperatures (SST) and sea ice (SICE), with the detrended SST variability from 1850 to 1985 superimposed onto the climatology from the year 2000 (McDermid et al. 2022). Each model run spans 136 years and we discard the first 5 years of each run to account for model spinup time.

b. Heat-wave definitions

For each grid cell, we use daily maximum near-surface air temperature (t Tmax) and equivalent temperature (Teq) to define dry and humid heat days, respectively. A day qualifies as a dry (t Tmax) or humid (Teq) heat day if the value of the respective variable exceeds the 90th-percentile thresholds based on a 15-day centered moving window (Perkins and Alexander 2013), calculated using all available years in the NONIRR simulation. Heat waves are defined as consecutive periods of heat that persist for three or more days. We focus our analyses specifically on heat during the boreal summer [June–August (JJIA)], which is the season associated with the annual peak in global average irrigation applied in the irrigated model runs. We also include the irrigation extents over all seasons in the online supplemental material for reference (Fig. S1).

Equivalent or effective temperature represents what the ambient air temperature would be if all of the latent heat were translated into sensible heat, and essentially incorporates latent heat changes into the term (Matthews et al. 2022; Pielke et al. 2004). As stated in the introduction, we use equivalent temperature to define our humid heat events as the term directly includes latent heat to more comprehensively represent total heat content (Matthews et al. 2022). Equivalent temperature is proportional to moist enthalpy, allowing for a direct correspondence to thermal discomfort, one of the key motivators for studying humid heat extremes (Matthews et al. 2022). Consequently, equivalent temperature is also a physically rather than empirically based metric, in contrast to other common moist heat indices (Matthews et al. 2022). We find equivalent temperature as follows. First, we calculate daily saturation vapor pressure with the following equation:

\[ e_s = 6.1078 \exp(\frac{aT}{T+b}), \]

where \( e_s \) is daily saturation vapor pressure (hPa), \( a = 17.2693882, \)
\( b = 237.3, \) and \( T \) is daily maximum air temperature (°C) (Murray 1967). Then, we find daily actual vapor pressure:

\[ e_a = e_s \times \frac{RH}{100}, \]

where \( e_a \) is daily actual vapor pressure (hPa) and \( RH \) is daily minimum relative humidity (%). RH values are capped at 100%, and grid cells with more than 5% of RH values greater than 100% are masked from the results. We then derive daily specific humidity \( q \) as
where $p$ is the corresponding monthly surface pressure (hPa) (Bolton 1980). From there, we find daily equivalent temperature $T_e$:

$$q = \frac{0.622e_u}{p - 0.378e_u},$$

where $T$ is maximum air temperature ($\degree C$); $c_p$, the specific heat of air at constant pressure, is 1005.7 J kg$^{-1}$ K$^{-1}$; and $L$ is the latent heat of vaporization as a function of $T$. Latent heat of vaporization is calculated as

$$L = L_{ref} \left( \frac{374.15 - T}{274.15} \right)^{0.38},$$

where $L_{ref} = 2.25 \times 10^6$ J kg$^{-1}$ (Martin and Edwards 1965).

c. Data analysis

At each grid cell, we find the total number of heat waves that occur in each irrigation run and analyze the effect of
irrigation by comparing the NONIRR simulation with the IRR2000 and IRRHALF irrigation runs. Following this, we examine the JJA seasonal averages of relevant background climate variables—latent heat flux (W m⁻²), sensible heat flux (W m⁻²), specific humidity (g kg⁻¹), precipitation (mm day⁻¹), incoming solar radiation at the surface (W m⁻²), and total cloud cover (%)—to better understand the physical drivers behind irrigation-based changes in dry and humid heat. Then, we use the Wilcoxon signed-rank test, with an alpha level of 0.01, to understand whether the seasonal averages are significantly different between the irrigated and nonirrigated runs (Wilcoxon 1945).

To investigate the local versus remote effects of irrigation on heat waves, we separate land grid cells into irrigated and nonirrigated groups. Locally irrigated grid cells are defined as grid cells where JJA average irrigation is more than or equal to 0.05 mm day⁻¹, and nonirrigated cells are all other land grid cells that fall within 60°S–60°N, excluding polar regions far from any major irrigated area (Fig. S2 in the online supplemental material) (Cook et al. 2020). We demonstrate the differences between the local and remote grid cells by plotting the spatial distributions of the total numbers of maximum-temperature and equivalent-temperature events and the background climate differences. Last, we investigate how the number of heat events and background climate conditions compare across selected IPCC Special Report on Extremes (SREX) regions that have strong mixtures of irrigated and nonirrigated grid cells (IPCC 2013).

3. Results

Here, we first present the number of maximum-temperature JJA heat-wave occurrences during each model run (Figs. 2a–c). Overall, the spatial variations in dry heat-wave occurrences are generally very similar across the runs, with more frequent heat waves occurring outside the tropical latitude bands. Once we examine the differences between the irrigated and nonirrigated runs (Figs. 2d,e), we are able to visualize more distinct differences due to the presence of irrigation. Both the IRRHALF and IRR2000 irrigated runs show decreases in the total number of dry heat waves in most land regions relative to the NONIRR run, with more substantial reductions occurring in arid and temperate regions such as northern Africa, the Middle East, northeastern Asia, and North America. It is interesting to note that some of the regions experiencing strong reductions in dry heat waves, such as northern Africa and the Middle East, are thought of as classically dry hydroclimatological regimes more insensitive to variations in precipitation and soil moisture (Koster et al. 2009). However, due to irrigation providing a steady addition of water into the climate system, our results show that the added moisture surpasses this insensitivity and affect the occurrence of dry heat.

We then show the number of equivalent-temperature JJA heat-wave occurrences during each of the model runs (Fig. 3). As we saw with dry heat-wave occurrences in Fig. 2, humid heat-wave occurrences also have very similar spatial patterns across the model runs, with heat waves occurring more frequently in the extratropical regions (Figs. 3a–c). However, in contrast to dry heat, humid heat waves generally occur more frequently under the presence of irrigation, especially in the Mediterranean Sea region, northern Africa, southern Africa, and the Middle East (Fig. 3d,e). We note that these regions are also generally classified as semiarid and arid climate regions, which may contribute to their sensitivity to the increased available moisture through irrigation (Beck et al. 2018). We also highlight that the responses in maximum-temperature and equivalent-temperature heat waves are fundamentally similar between the IRRHALF and IRR2000 runs, underscoring the sensitivity of the model to the presence of a sustained supply of external moisture, even when applied at half the volume. The similarities between the two irrigated runs indicate the importance of the presence of irrigation on the climate system and the occurrence of heat extremes. In the online supplemental material, we also show the difference in the number of days falling under either a dry or humid (or both) heat wave for the irrigated and nonirrigated runs (Fig. S3).

Overall, Figs. 2 and 3 show that the presence of irrigation produces wide-reaching global changes in both dry and humid
heat during the boreal summer season. To disentangle how irrigation drives these changes in dry and humid heat waves, we investigate how irrigation has influenced key climate variables. Specifically, we examine how JJA seasonal average latent heat, sensible heat, specific humidity, precipitation, incident solar radiation, and total cloud cover differ under NONIRR and IRR2000 conditions (Fig. 4). In the online supplemental material, we also provide an analogous figure showing broadly similar JJA seasonal average differences between the NONIRR and IRRHALF runs (Fig. S4).

In response to irrigation, latent heat fluxes significantly increase in the Mediterranean, northern Africa, the Middle East, parts of western North America, and the northwestern part of the Indian subcontinent (Fig. 4a). These increases correspond with significant declines in sensible heating across these same regions (Fig. 4b), though the significance and magnitude of these changes are more muted. Meanwhile, specific humidity and precipitation both increase strongly across the Mediterranean, northern Africa, the Middle East, and the northwestern Indian subcontinent (Figs. 4c,d). Finally, incident solar radiation decreases and total cloud cover increases across these same regions (Figs. 4e,f). Reductions in dry heat extremes are likely a consequence of the combined effects of more localized cooling from shifts toward latent over sensible heating and the reduction in incoming solar energy as a result of increases in cloud cover. For humid heat waves, however, the direct cooling effect on dry air temperatures is more than compensated by large and widespread increases in atmospheric moisture, resulting in overall increases in humid heat extremes. One region that does stand out is eastern and southern India, where dry heat extremes increase in response to irrigation. Irrigation has been shown to weaken the South Asian summer monsoon in ModelE (Shukla et al. 2014; Puma and Cook 2010; Singh et al. 2018), resulting in decreased cloud cover and precipitation and increased incident solar radiation in the region. These broader changes in climate ultimately contribute to the increases in dry heat waves in these regions. Overall, we are also able to see seasonal shifts in maximum temperature and equivalent temperature (Figs. 4g,h), which reflect the dry and humid heat-wave occurrences shown in Figs. 2 and 3. The areas with significant differences in seasonal average maximum and equivalent temperatures mirror the areas with the largest changes in dry and humid heat waves due to the presence of modern irrigation.

Next, we separately examine the impact that irrigation has on local and remote land areas for dry and humid heat-wave occurrences by plotting the number of heat-wave events aggregated across local and remote grid cells (Fig. 5). Dry heat waves decrease in the irrigated runs for both local (Fig. 5a) and remote (Fig. 5b) grid cells, though the magnitude of the effect is larger for locally irrigated grid cells. Local humid heat-wave occurrences show dramatic increases in response to irrigation (Fig. 5c), with little apparent difference between the IRRHALF and IRR2000 irrigation runs. In addition, we observe a distinct shift to the right in remote humid heat-wave occurrences moving from nonirrigated to irrigated conditions, with similar responses occurring in both the IRRHALF and IRR2000 runs as well (Fig. 5d). These plots highlight that while irrigation has more influence on local dry heat relative to remote dry heat, the added moisture that irrigation provides has strong impacts on humid heat in both local and remote regions. These plots also show that the added moisture from the IRRHALF run produces a response comparable to the IRR2000 run in the total number of humid heat-wave events, suggesting that the frequency of humid heat events is less sensitive to the amount of irrigation applied in comparison with dry heat waves.

We also examine how key climate variables have responded to the presence of irrigation (IRR2000) in local and remote areas, focusing on latent and sensible heat flux, specific humidity, and precipitation to relate their responses to the local and remote changes occurring with dry and humid heat. Figure 6 shows probability distributions of the percent differences (IRR2000-NONIRR) in these variables for local and remote grid cells. We provide an analogous figure with the percent differences between IRRHALF and NONIRR in the online supplemental material, showing similar responses to the presence of halved irrigation (Fig. S5). We note that the local and remote distributions for the key climate variables (especially latent heat flux) vary significantly due to the wide range of climate regimes included in these distributions. This contrasts with the local and remote distributions of dry and humid heat-wave occurrences, which are locally calibrated and detected using a fixed 90th percentile approach at each grid cell.
Latent heat experiences much larger relative changes between the IRR2000 and NONIRR runs in locally irrigated grid cells, showing that the effect of irrigation on latent heat is more locally concentrated (Fig. 6a). At a smaller scale, sensible heat also experiences larger relative decreases in local relative to remote areas (Fig. 6b). These results correspond well with how irrigation affects dry heat-wave occurrences more strongly at local grid cells, as changes in latent and sensible heat flux are both more directly connected to dry heat conditions. In contrast, the local and remote distributions for specific humidity and precipitation are similar, with moderate increases at the right tail in both areas (Figs. 6c,d). As specific humidity and precipitation are more relevant for humid heat in our simulations, these results also correspond well with how irrigation strongly impacts humid heat events in both local and remote regions.

Last, we focus on how dry and humid heat-wave occurrences and associated seasonal climate conditions differ between the IRR2000 and NONIRR runs in the Mediterranean region, which has a good mixture of both local and remote grid cells, to better understand the climate responses to irrigation at the regional scale (Fig. 7). We include additional SREX regions with ample local and remote grid cells in the online supplemental material (Figs. S6–S8). In the Mediterranean, dry heat-wave occurrences decline in both local and remote grid cells, although we see greater differences in the left tail of the local distribution, implying that local grid cells experience larger declines in dry heat waves than do remote grid cells (Fig. 7a). Meanwhile, humid heat-wave occurrences increase strongly in both local and remote grid cells (Fig. 7b). Overall, the regional event frequency responses in the Mediterranean broadly match the global responses in Fig. 5. Next, we see large increases in latent heat and decreases in sensible heat in the region; however, we highlight that the region experiences greater increases in latent heat in remote relative to local grid cells (Figs. 7c,d). Specific humidity and precipitation also

**Fig. 4.** Relative difference in JJA seasonal averages of climate variables between IRR2000 and NONIRR for (a) latent heat flux, (b) sensible heat flux, (c) specific humidity, (d) precipitation, (e) incident solar radiation, (f) total cloud cover, (g) maximum temperature, and (h) equivalent temperature. Grid cells where IRR2000 and NONIRR annual seasonal average values are not statistically different as evaluated by the Wilcoxon signed-rank test are cross-hatched.
experience increases in both local and remote grid cells, and mirror changes in latent heat, with greater increases occurring in remote areas (Figs. 7e,f). Although the overall regional responses correspond with the broader global responses shown in Fig. 6, the differences in how the local and remote grid cells respond in the Mediterranean accentuate that there are regional variations in the climatic responses to irrigation.

4. Discussion and conclusions

Within ModelE, irrigation reduces dry heat-wave occurrences across much of the globe through increases in latent heat and decreases in sensible heat, as well as through increases in total cloud cover and subsequent decreases in incident solar radiation. In general, this reduction is strong over local irrigated regions as compared with more remote regions. By contrast, irrigation causes substantial increases in humid heat waves, especially in the Mediterranean, northern Africa, southern Africa, and the Middle East. Irrigation strongly increases humidity and precipitation at large scales, compensating for declines in dry-bulb temperature and driving increases in humid heat across local and remote regions. With the use of two irrigation scenarios, we highlight that our results are not overly sensitive to the amount of irrigation applied and we see strong climate responses even at half the rate of present-day irrigation.

In general, our results agree with previous studies examining the impacts of irrigation on climate conditions. Using previous versions of the same climate model, Cook et al. (2015) and Puma and Cook (2010) showed that the presence of irrigation produced similar declines in air temperature and increases in specific humidity, cloud cover, and precipitation in many regions across the globe. Cook et al. also found widespread decreases in sensible heat and increases in latent heat due to irrigation. Our results are also consistent with more recent studies connecting the presence of irrigation to increases in humid heat stress, including studies using other models and approaches (Ambika and Mishra 2022; Mishra et al. 2020; Krakauer et al. 2020).

Within ModelE, irrigation produces more noticeable changes in dry heat conditions in locally irrigated versus remote regions, while humid heat is more equally influenced by irrigation in both local and remote grid cells. These differences in dry and humid heat are a consequence of the different spatial scales of responses in latent and sensible heat flux, specific humidity, and precipitation to irrigation. While declines in dry heat waves are strongly driven by localized cooling from increased latent heating, increases in humid heat extremes are primarily caused by irrigation-induced increases in humidity, which are spread over much larger areas. Although still understudied, such far-reaching impacts of irrigation have been documented in other studies. For example, de Vrese et al. (2016) researched the impacts of irrigation on...
remote rainfall through moisture advection and changes in circulation patterns demonstrating that irrigation in Asia and the Middle East can increase rainfall in Africa. In addition, Wei et al. (2013) used reanalysis products to show significant changes in precipitation in response to irrigation occurring in remote regions. In light of our results and previous findings, we encourage future studies to further disentangle the impacts of irrigation on key climate conditions in local and remote regions.

We acknowledge that our study only considers the responses of one climate model and two irrigation scenarios, and future studies using additional climate models would be beneficial to broaden our understanding of the range of possible climate responses to irrigation. Our model configuration also used prescribed SSTs, which may also dampen the remote effects of irrigation (Krakauer et al. 2020). Studies further examining the differences between the local and remote impacts of irrigation could benefit from comparing interactive ocean configurations with prescribed SSTs to better capture the climate variability in remote regions. We also acknowledge that our study design classifies “remote” grid cells based on the amount of irrigation applied to the grid cell and thus the distance of these remote grid cells from irrigated regions varies significantly, which can affect the range of quantified impacts. Additionally, “local” grid cells can also experience “remote” effects from other irrigated regions, which our study does not explicitly examine. These are topics that are worth studying in further detail. As we held the application of irrigation to the year 2000, examining time-evolving irrigation may also improve the understanding and generation of future projections of climate extremes sensitive to irrigation. Although the focus of our study was on the boreal summer season, irrigation outside of the boreal summer months has also been shown to be relevant in impacting climate conditions and studies of additional seasons can provide a more comprehensive understanding of the climate effects of irrigation. Our study also specifically examined the impact of irrigation on changes in dry and humid heat event frequency, and quantifying changes in the intensity of these heat extremes is also important for a more comprehensive understanding of the climate effects of irrigation. Our study also specifically examined the impact of irrigation on additional seasons, especially for regions experiencing peak humid heat extremes outside the boreal summer season (Jha et al. 2022).

Anthropogenic climate change is expected to increase the frequency of both dry and humid heat extremes over much of the world (IPCC 2021; Buzan and Huber 2020). How irrigation responses will change in a warming world, however, is a major unknown, with studies suggesting that the effects of irrigation could be amplified or diminished, depending on regional climate responses (Cook et al. 2011, 2020). Our study suggests irrigation may mitigate some of these increases in dry
heat extremes but can further amplify moist heat occurrences. Furthermore, our results suggest that while irrigation is more impactful on dry heat at local scales, the same forcing can also drive large increases in humid heat events, even far afield from where the irrigation was applied. We therefore emphasize that considering the near and far-reaching impacts of irrigation, as well as other human-driven land surface changes, on both dry and humid heat extremes will be critical for understanding how heat extremes will change in the future.

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Data availability statement. The data used for the study (https://doi.org/10.5281/zenodo.7806310) and the software for the study (https://doi.org/10.5281/zenodo.7806270) are both available online.

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