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Impacts of irrigation expansion on moist-heat stress: first results from IRRMIP

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Impacts of irrigation expansion on moist-heat stress: first results from IRRMIP

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Irrigation rapidly expanded during the 20th century, thereby affecting climate via changes in water, energy, and biogeochemical cycling. Previous assessments of these historical climate effects of irrigation expansion predominantly relied on a single Earth System Model, and therefore suffered from structural model uncertainties. Here we quantify the impacts of historical irrigation expansion on climate by analysing simulation results from six Earth system models participating in the Irrigation Model Intercomparison Project (IRRMIP). Despite the large range of simulated irrigation water withdrawal from those models (~ 900 to ~ 4000 km³ after the year 2000), our results show that irrigation expansion causes a rapid increase in irrigation water withdrawal, which leads to less frequent 2-meter air temperature heat extremes across heavily irrigated areas (≥ 4 times less likely). However, due to the irrigation-induced increase in air humidity, the cooling effect of irrigation expansion on moist-heat stress is less pronounced or even reversed, depending on the heat stress metric. In summary, this study suggests the priorities in irrigation dataset collection and parameterisation development, and shows that irrigation deployment is not an efficient adaptation measure to escalating human heat stress under climate change, calling for carefully dealing with the increased exposure of local people to moist-heat stress.

Irrigation increases crop yield and currently accounts for more than 70 % of total human freshwater use¹. Irrigation-related water withdrawal and application have substantial impacts on global and regional water, energy, and biogeochemical cycles²⁻⁵, and therefore can change the magnitude and pattern of some meteorological conditions⁶⁻⁸. Notably, irrigation has a cooling effect on near-surface temperature⁹⁻¹¹, especially during hot extremes^{12,13}. For that reason, irrigation has been proposed as a potential land management strategy for balancing extreme heat escalation under anthropogenic climate change¹³⁻¹⁵.

Most previous studies only focused on temperature differences, ignoring that human comfort is also affected by heat dissipation¹⁶. Evaporative cooling is the main way humans lose heat¹⁷, and air humidity and wind speed greatly influence evaporation efficiency¹⁸. These metrics can also be altered by irrigation^{19,20}, suggesting that irrigation-induced impacts on human comfort

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73 during heat stress may be complex. Multiple moist-heat metrics were developed to quantify
74 the compound effects of different meteorological conditions on heat stress^{21,22}, and some of
75 them have been used in irrigation-related studies. For example, over intensely irrigated regions
76 in India, the wet bulb temperature (T_w) was simulated to increase due to irrigation, despite
77 a lowering of the temperature^{23,24}. In addition to the ignorance of changes in air humidity,
78 existing modelling studies generally use a static irrigated land map and rely on a single Earth
79 System Model (ESM), which can introduce uncertainties in their results.

80
81 To address these limitations, we launched the Irrigation Model Intercomparison Project (IR-
82 RMIP) to comprehensively explore the impacts of irrigation expansion on climate and water
83 resources during the 20th century. The IRRMIP protocol consists of two transient AMIP-style²⁵
84 historical climate experiments, one with and one without irrigation expansion, during the pe-
85 riod 1901-2014. Here we analyse IRRMIP simulations from six ESMs to study the impacts of
86 irrigation expansion on historical (moist-)heat stress. We calculate several moist-heat metrics
87 based on 3-hourly 2-meter air temperature (T_{2m}), 2-meter air relative humidity, and 10-meter
88 wind speed. By comparing the results from different experiments and periods, we separate the
89 effects of irrigation expansion and other forcings on high percentiles of these metrics. We aim
90 at consolidating the understanding of irrigation-induced impacts on (moist-)heat stress, facili-
91 tating the inclusion of these impacts in future local land-use and land-management planning.

92 **Irrigation expansion drives the increase in water withdrawal** Global area equipped
93 for irrigation has experienced substantial expansion from 1901 to 2014, increasing almost six-
94 fold from 0.5×10^6 km² to around 3×10^6 km² (Figure 1a). Expansion mainly happened in
95 some irrigation hot spots, including South Asia (SAS), East Asia (EAS), and Central North
96 America (CNA) (Figure 2a, b). In 1901, most of the global irrigated land was concentrated
97 over the regions where rice is the main staple food, such as India, China, and Japan (Figure
98 A1a). Since 1901, irrigated land has risen slowly over many regions until the 1950s, followed
99 by an accelerated increase during the second half of the century (Figure 1a). Until 2014, the
100 irrigated areas in India and China experienced intensification and expansion, with some grid
101 cells having a $\geq 40\%$ (of the grid cell area) increase in irrigated area (Figure 2a, A1d). Over
102 North America, some new densely irrigated grid cells appear in CNA, while for other regions,
103 the expansion is limited (mostly below 10% of the grid cell area).

104
105 The spatial pattern of simulated irrigation water withdrawal (IWW) is in agreement with the
106 distribution of the area equipped for irrigation (Figure 2c-d). India is still the most intensively
107 irrigated region, consisting of many grid cells ($0.9^\circ \times 1.25^\circ$) with more than 250 mm yr^{-1} of IWW.
108 The six IRRMIP models simulate a broad range of global IWW (900 to $4000 \text{ km}^3 \text{ yr}^{-1}$ after the
109 year 2000), but the temporal trend of simulations with transient irrigation extent (hereafter
110 referred to as *tranirr*) generally aligns with that of the area equipped for irrigation. Consis-
111 tent with a previous review⁵, simulated annual IWW during the post-2000 period ranges from
112 ~ 900 to $\sim 4000 \text{ km}^3 \text{ yr}^{-1}$ (Figure 1c-h), due to different representations of irrigation in these

113 models. CESM2, CESM2_gw, and NorESM2 show high similarity because they share the same
114 atmosphere and land models, with comparably small differences in specific sub-models (see
115 Supplementary Note 1).

116
117 Based on IWW and irrigated area, we select several regions, including West North Amer-
118 ica (WNA), CNA, North Central America (NCA), Mediterranean (MED), west Central Asia
119 (WCA), SAS, EAS, and Southeast Asia (SEA) (Figure 2b), to calculate regional irrigation
120 water quantities (Figure 1c-h). SAS is the region with the highest IWW in all models, but
121 its relative importance varies. For example, after the year 2000, SAS accounts for around one-
122 third of global IWW simulated by CESM2 (32.4% to 35.8%), CESM2_gw (31.4% to 35.1%),
123 E3SM (27.5% to 41.8%), and NorESM (32.8% to 35.1%), but in IPSL-CM6, this fraction is less
124 than one-fourth (16.0% to 20.4%). WCA consumes the second-highest quantity of IWW, even
125 though its area equipped for irrigation is less than EAS. This indicates that simulated IWW
126 is dependent not only on the area equipped for irrigation but also on other factors, such as
127 background climate conditions.

128 **Different feedback from heat and moist-heat stress to irrigation expansion** Here we
129 focus on T_{2m} , HUMIDEX (HU), and T_w warm extremes, as many other metrics are weighted
130 average values of T_{2m} and T_w . Changes in high percentiles of these three metrics could be inter-
131 preted as the impacts of irrigation expansion and other forcings on dry heat stress (T_{2m}), human
132 comfort (HU), and humid heat stress (T_w) (Table 1). In the *tranirr* experiment, climate change,
133 land use change, and irrigation expansion, are all transient throughout the simulation period, so
134 by comparing the last-30-year of *tranirr(1985-2014)* to the first-30-year of *tranirr(1901-1930)*,
135 we can quantify the impacts of all forcings (greenhouse gas emissions, land use and land man-
136 agement change, irrigation expansion, etc.). Similarly, in the experiment with fixed irrigation
137 extent (*1901irr*), the difference between the first- and the last-30-year periods (*1901irr(1901-*
138 *1930)* and *1901irr(1985-2014)*) gives the impacts of all forcings minus irrigation expansion.
139 Finally, by subtracting the outputs of *tranirr(1985-2014)* from *1901irr(1985-2014)*, we obtain
140 the impacts of irrigation expansion. Hence, in this study, the sum of all forcings minus irrigation
141 expansion (ALL-IE) and irrigation expansion (IE) does not exactly equal to all forcings (ALL).

142
143 Since we focus on extreme events, we first calculate the 99.9th percentile values (one-in-1000 time
144 steps warm event) of three metrics in all four exp-periods, and take the one of *1901irr(1901-*
145 *1930)* as the reference (Figure 3). Several irrigation hot spots, like SAS, WCA, NCA, and
146 CNA, are also extreme heat hot spots, with a 99.9th percentile value of T_{2m} exceeding 40 °C in
147 many grid cells. Other forcings cause a general warming signal (+0.5 to +2 °C), except in some
148 conventional irrigation hot spots like SAS and EAS, which may be attributed to the increas-
149 ing aerosol concentrations^{26,27}. irrigation expansion has substantial cooling impacts in heavily
150 irrigated grid cells (>1 °C) and weaker impacts over surrounding grid cells (<0.5 °C). This
151 cooling effect creates regional irrigation-induced 'cooling islands' against the global warming
152 background, like the Indo-Gangetic Plain and several grid cells in Central USA. Interestingly,

153 irrigation expansion's cooling impacts on the extreme value of HU are much less substantial,
154 and mainly occur over the surrounding regions of intensely irrigated pixels. One reason for this
155 could be that increased air humidity over these regions dominates the impacts on HU.

156
157 To quantify the changes in extreme heat events frequency, we then calculate the probability
158 ratio (PR) of T_{2m} , HU, and T_w warm extremes between different exp-periods (Figure 4). We
159 find that the pattern of these impacts is similar to those on the absolute value of heat extreme
160 events (Figure 3). Other forcings, especially greenhouse gas emissions, contribute to a warmer
161 world, with > 4 times increased frequency for the events of all three metrics in most grid cells in
162 tropical and sub-tropical regions. Most models agree that irrigation expansion substantially re-
163 duces the frequency of T_{2m} extremes, especially in SAS, WCA, and CNA. However, its impacts
164 on HU and T_w are much less pronounced and are also less consistent among models. Similarly,
165 for T_w , the dampening impacts of irrigation on extreme high events disappear over the most
166 intensely irrigated area like India and are reversed to an intensifying effect in the Central CNA
167 and WCA, where the 99.9th percentile T_w event happens more than 3 times more often due to
168 irrigation expansion. Consistent with a previous study using the Goddard Institute for Space
169 Studies (GISS) climate model, the frequency in moist-heat extremes does not increase in some
170 regions with intense irrigation, like the North India and California. One reason may be the high
171 background temperature and air humidity in this region, as (i) more water in the air is needed
172 to increase relative humidity under a higher temperature; and (ii) more extra relative humidity
173 is needed to increase T_w when the relative humidity is higher²⁸. In India, another reason may be
174 the temporal mismatch between the irrigation activities and moist-heat extremes, as indicated
175 by a previous study²⁹.

176
177 The more extreme the T_{2m} heat events are, the more pronounced irrigation expansion-induced
178 impacts become (Figure A2). The impacts of irrigation expansion on T_{2m} are mainly limited
179 to irrigation hot spots for the 99th percentile heat event, e.g., large changes in PR (that is, $>$
180 2 times less likely) are only found in North India and Central USA. When the events get more
181 extreme (99.5th percentile and 99.9th percentile), the affected areas expand around these hot
182 spots and also appear in other regions like Europe and East China. The slight cooling impacts
183 on HU and warming effects on T_w are also more pronounced when events get more extreme
184 (Figure A3 and A4). Interestingly, in a previous study based on GISS model simulations³⁰, the
185 heat extremes of equivalent temperature are widely increased in many regions, indicating the
186 importance of considering different metrics, so we also calculate irrigation expansion's impacts
187 on other moist-heat metrics (Figure A5). We find that the significance of irrigation expansion's
188 impacts on the apparent temperature is similar to HU, and as for other moist-heat metrics, the
189 magnitude and consistency depend on the weight of T_w and T_{2m} .

190
191 We calculate the average annual hours (weighted by areas) exposed to extreme events of the
192 grid cells with more than 40% (of the grid area) irrigation expansion (Figure 5). The average

193 annual hours exposed to T_{2m} extreme events show a slight increase in the first half of the
194 century, then increases rapidly between 1950 and 1980, and keeps steady in the last decades.
195 Irrigation expansion causes a decreasing trend in the hours exposed to heat extremes in heavily
196 irrigated regions, in spite of global warming. However, for HU, the cooling impacts of irrigation
197 expansion are quite small, thus the hours exposed to extreme HU events still increase, but
198 at a slightly slower speed than those without irrigation expansion. Interestingly, the hours
199 exposed to T_w extreme events for both *1901irr* and *tranirr* remain almost unchanged until
200 1980. After 1980, this starts to rise rapidly. In the case of *tranirr*, the hours are slightly higher
201 than *1901irr*, indicating the intensifying impact of irrigation expansion over these grid cells.
202 Since T_{2m} extremes are the most substantially affected events, we also calculate the average
203 annual hours exposed to different magnitude of T_{2m} extreme events (the 99.0th, the 99.5th
204 and the 99.9th percentile events) over different groups of grid cells (with 0%-20%, 20%-30%,
205 30%-40%, and more than 40% of irrigation expansion) (Figure A8). Despite the difference in
206 magnitudes, irrigation expansion has similar reducing impacts on all degrees of T_{2m} extreme
207 events, which become more substantial with the extent of irrigation expansion.

208 **Limited irrigation expansion-induced impacts on radiation fluxes** Changes in sur-
209 face energy fluxes may induce changes in temperature. However, the impact of irrigation on
210 some energy fluxes, especially up/downwelling short/longwave radiation, still lacks consistency
211 across model simulations^{7,10,31-33}. It is known that irrigation practices enhance evapotranspira-
212 tion processes, contributing to wetter air. As a result, irrigation expansion increases latent heat
213 flux (LHF) and decreases sensible heat flux (SHF), especially in irrigation expansion hot spots
214 (Figure A6). The impact on LHF is slightly larger than on SHF both in magnitude and range.
215 The effects on net radiation (Rnet) are smaller and less consistent among models, but in SAS,
216 WCA, and CNA, most models agree that irrigation expansion increases Rnet. The IRRMIP
217 models show little agreement in the magnitude and even sign of the change of the surface radi-
218 ation components in response to irrigation expansion, except for upwelling longwave radiation
219 (LWup) (Figure A7). A decrease in LWup caused by irrigation expansion could be linked to the
220 decrease in surface temperature, which then results in an increase in Rnet.

221

222 **Discussion** Six ESMS simulate a broad range of IWW (~ 900 to ~ 4000 $\text{km}^3 \text{yr}^{-1}$ after the
223 year 2000) with a median value of around 1500 $\text{km}^3 \text{yr}^{-1}$ (Figure 1), which is lower than the
224 value of 2761 $\text{km}^3 \text{yr}^{-1}$ reported for the period 2005-2007³⁴. Most models, especially those which
225 have CLM5 as their land model, substantially underestimate the global IWW, which could be
226 attributed to its over-conservative irrigation water demand calculation³¹. A new modification
227 has been made by implementing different irrigation techniques³¹, in which the non-effective
228 water consumption is more comprehensively considered, outperforming substantially compared
229 to the original module at global or regional levels. In E3SM a slightly higher IWW is simulated,
230 possibly due to the higher spatial resolution and its added features like surface/groundwater de-
231 mand separation³⁵, and an interactive surface water withdrawal module³⁶. The overestimation

232 of CNRM-CM6-1 originates from an external dataset reconstructed with a global hydrological
233 model³⁷, in which the irrigation water abstraction from groundwater is not limited by water
234 resources³⁸. In IPSL-CM6³⁹, a constraint is imposed on IWW based on the water availabil-
235 ity, with the parameters sensitivity tests and calibratio, showing a superior performance of
236 reproducing global IWW despite the slight underestimation. Overall, the implementation of ir-
237 rigation techniques, groundwater withdrawal, water resources management, water availability,
238 and the calibration and validation of irrigation-related parameters, should all be considered in
239 the next generation of irrigation representations in ESMs.

240
241 Despite the wide range of simulated IWW, ESMs used in this study agree that irrigation has
242 a cooling impact on local hot extremes, which is consistent with previous studies^{10,13,14}. This
243 cooling impact has the potential of mitigating the heat exposure of both local inhabitants and
244 crops⁴⁰. However, reduced temperature does not decrease the frequency of moist-heat stress
245 by a similar magnitude, and most ESMs even believe that historical irrigation expansion has
246 an intensifying impacts on T_w extremes in some regions like the Central USA and West Asia
247 (Figure 3), possibly endangering local population. Many moist-heat metrics are calculated in
248 this study, and the impacts of irrigation expansion on extreme events of those metrics vary
249 A5, mainly depending on the relative contribution of air humidity and temperature. Generally,
250 the more important role temperature plays, the more substantial cooling impact of irrigation
251 expansion is found.

252
253 Similar to previous ESM-based impact studies regarding moist-heat metrics^{41,42}, we use tem-
254 perature, moisture, and wind speed at the grid-cell level which are averaged based on values
255 from different land cover tiles. Thus, coarse-resolution simulations' suitability to calculate hu-
256 man heat metrics may be questionable, as sub-grid scale extreme values could be masked.
257 Constrained by computational resources, conducting long-term high-resolution global simula-
258 tions at less than 100 km resolution is very expensive. However, those simulations at coarser
259 resolution remain important for understanding the spatial distribution and temporal trend of
260 irrigation-induced impacts on moist-heat stress.

261
262 In summary, our study stresses an over-optimism regarding irrigation's health benefits, which
263 ignores the impacts of increased air humidity on human comfort. Different metrics extremes
264 have various feedback to irrigation expansion, highlighting the importance of better understand
265 the most suitable metrics for people with different races, genders, ages, health conditions, etc. As
266 a metric commonly used in outdoor activities guidance, T_w extreme events are even intensified
267 by irrigation expansion in some regions. Under global warming scenarios, intolerable T_w events
268 will occur more frequently, especially in SAS, CNA, and EAS⁴³. Even more troublesome, the
269 maximum T_w is tied to atmospheric buoyancy, which is determined by global mean surface
270 temperatures^{45,46}. T_w will increase to the new irrigated value, and scale with global mean
271 temperature changes¹⁷. This calls for better monitoring of local moist-heat metrics to inform

272 exposed communities of the potential danger, and the exploration of potential solutions.

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293 supervision of W.T. The IRRMIP simulations were performed by Y. Y., S. D. H., P. L., D. M.
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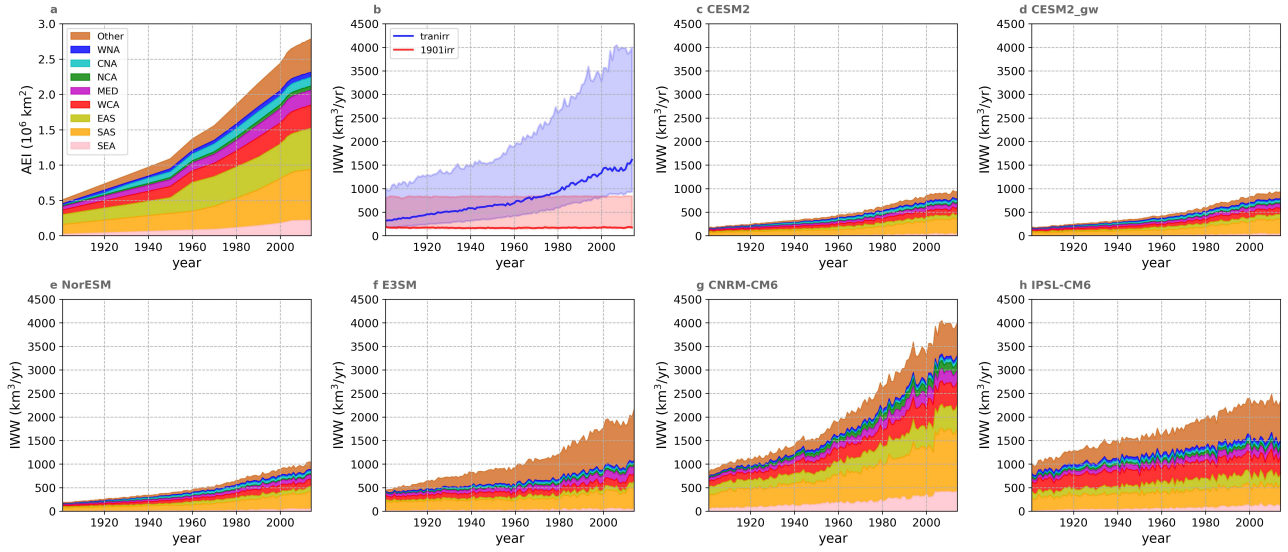


Figure 1: **Historical increase in area equipped for irrigation and simulated irrigation water withdrawal.** **a** Global and regional time series of area equipped for irrigation (AEI) in 1901-2014. The area equipped for irrigation data is from the Land-Use Harmonization phase 2 (LUH2) project⁴⁷, and the grid cells corresponding to IPCC reference regions are indicated in Figure 2b. **b** Simulated mean global irrigation water withdrawal (IWW) with (blue: *tranirr*) and without (red: *1901irr*) irrigation expansion by all six models. The line indicates the median value of six models and the range indicates the maximum and minimum values. Note that IWW of CNRM-CM6-1 is applied as an external input, which is the irrigation fluxes from a global reconstructed hydrological dataset based on simulations³⁷., and for the *1901irr* experiment of IPSL-CM6, irrigation is switched off. **c-h** Global and regional IWW simulated by CESM2 (**c**), CESM2_gw (**d**), NorESM (**e**), E3SM (**f**), CNRM-CM6-1 (**g**) and IPSL-CM6 (**h**).

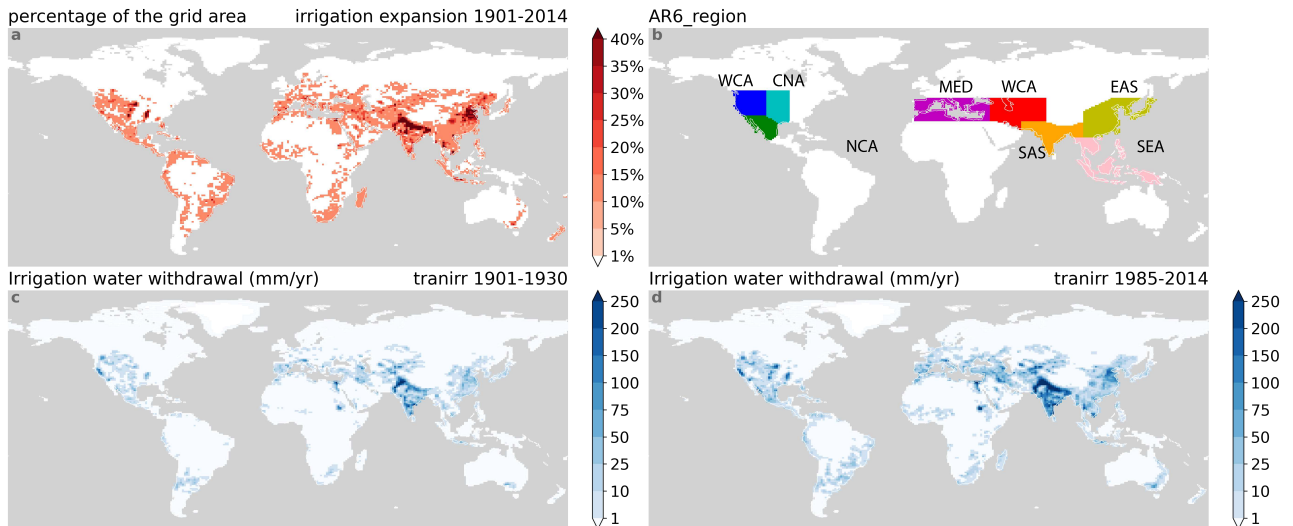


Figure 2: **Spatial pattern of irrigation expansion and simulated irrigation water withdrawal in different periods.** **a** Increase in irrigated fraction between 1901 and 2014. **b** Grid cells of the IPCC reference regions⁴⁸ used in the analysis. The grid resolution is the simulation resolution of CESM2, CESM2_gw, and NorESM ($0.9^\circ \times 1.25^\circ$). **c-d** Multi-model mean simulated annual IWW with transient irrigation (*tranirr*) extent during the first 30 years (1901-1930: **c**) and the last 30 years (1985-2014: **d**)

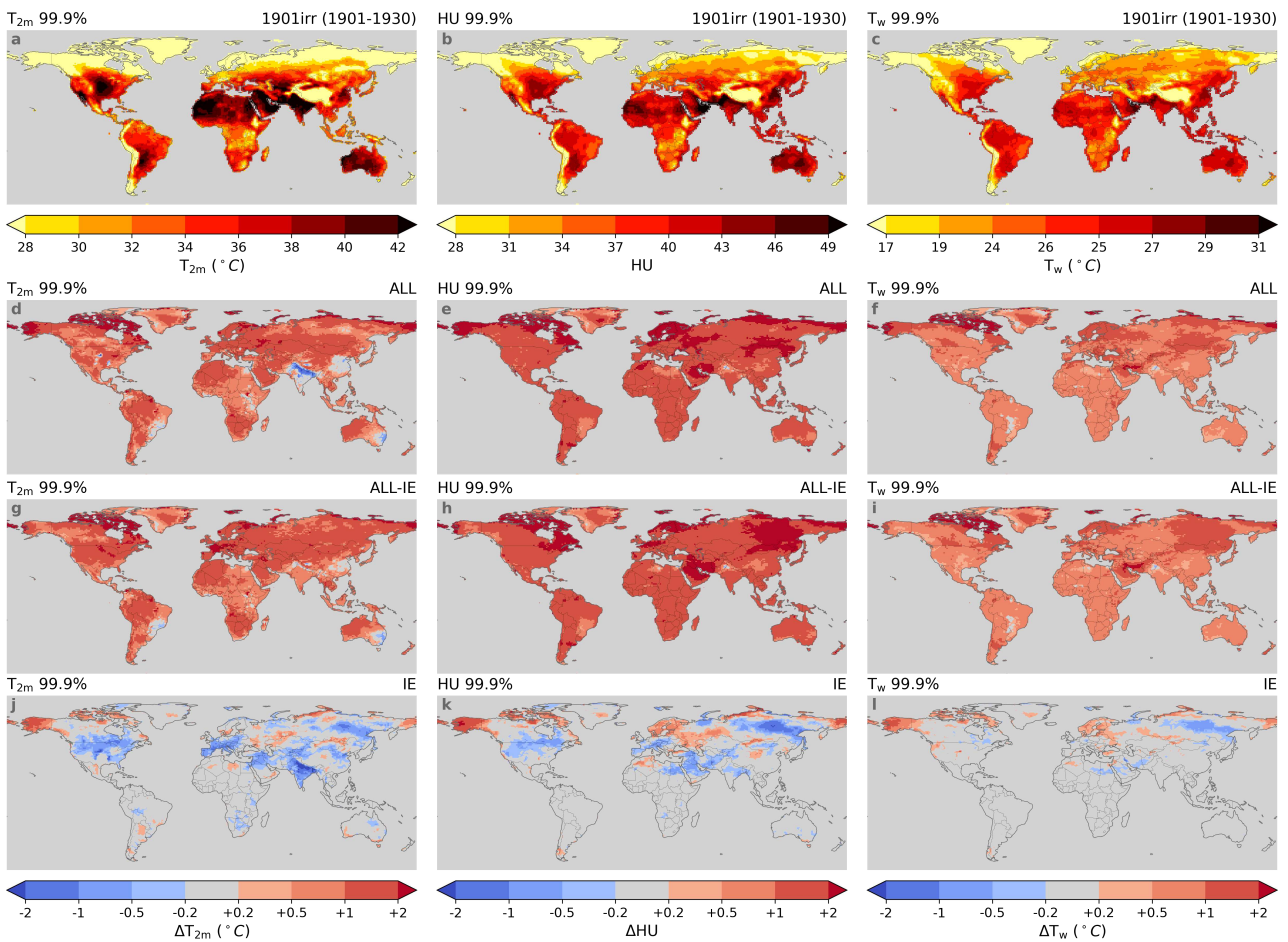


Figure 3: **Heat and moist-heat extremes and impacts of different forcings on them.** **a-c** Multi-model mean absolute values of the 99.9th percentile values of 2-meter air temperature (T_{2m} : **a**), HUMIDEX (HU: **b**), and wet-bulb temperature (T_w : **c**) of the first 30 years (1901-1930) in the simulations without irrigation expansion (1901irr). **d-l** Multi-model mean impacts of all forcings (ALL: greenhouse gas emissions, land use and land management change, irrigation expansion, etc.) (**d**, **e**, **f**), all forcings except irrigation expansion (ALL-IE: **g**, **h**, **i**), and irrigation expansion (IE: **j**, **k**, **l**) on the 99.9th percentile values of T_{2m} (**d**, **g**, **j**), HU (**e**, **h**, **k**), and T_w (**f**, **i**, **l**). Impacts are calculated by subtracting the values in the new exp_period by those in the reference exp_period (see Table 1). Only signals (>0.2 or <-0.2) agreed by ≥ 4 of 6 models are shown.

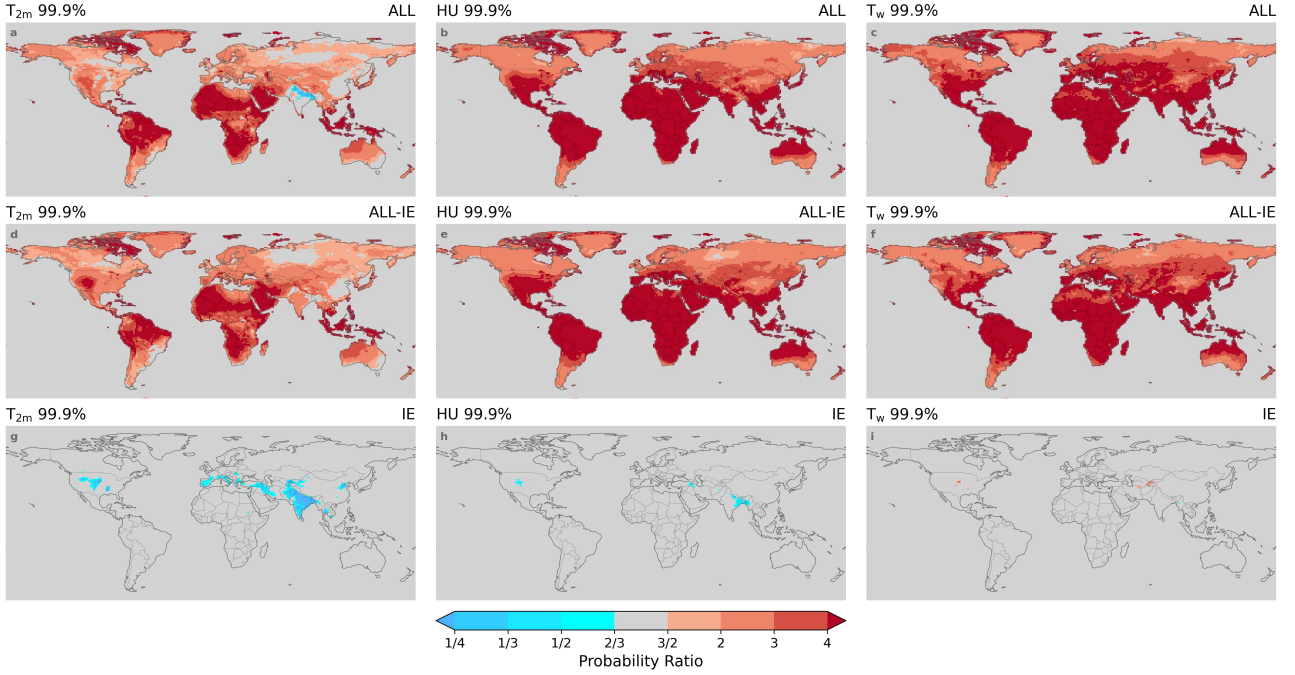


Figure 4: **Changes in the frequency of (moist-)heat extreme events induced by different forcings.** **a-i** Impacts of all forcings (ALL: **a, b, c**), all forcings except irrigation expansion (ALL-IE: **d, e, f**), and irrigation expansion (IE) on the frequency of the events in which 2-meter air temperature (T_{2m} : **a, d, g**), HUMIDEX (HU: **b, e, h**), and wet bulb temperature (T_w : **c, f, i**) exceed their 99.9th percentile values of the first 30 years (1901-1930) in the simulations without irrigation expansion (*1901irr*) shown in Figure 3a-c. Impacts are quantified by probability ratio (PR) which is calculated by dividing the events frequencies in the new exp-period by those in the reference exp-period (see Table 1), and the values are the sixth root of the product of PR calculated from the outputs of six ESMs. Only signals ($>3/2$ or $<1/2$) agreed by ≥ 4 of 6 models are shown.

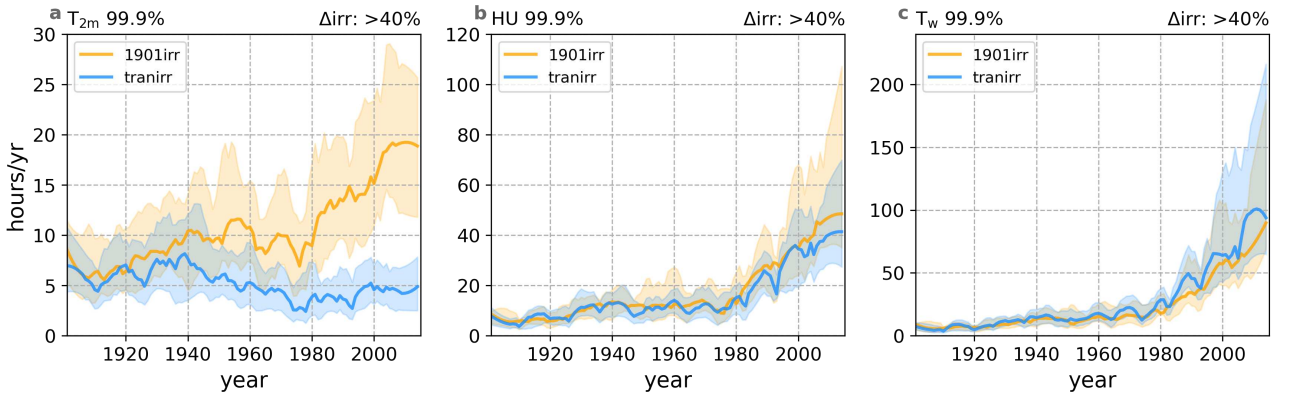


Figure 5: **Increase in annual hours exposed to (moist-)heat extreme events over the grid cells with the most substantial irrigation expansion.** **a-c** Time series of the annual hours over the grid cells with $\geq 40\%$ of irrigated fraction increase (in the year 2014 compared to the year 1901) of 2-meter air temperature (T_{2m} : **a**), HUMIDEX (**b**), and wet bulb temperature (T_w : **c**) warm extremes. The warm extremes are defined as the period when T_{2m} , HU, and T_w exceed their 99.9th percentile values of the first 30 years (1901-1930) in the simulations without irrigation expansion (*1901irr*). Lines indicate the median value among six models and ranges indicate the middle four of six models. Curves were smoothed using Savitzky-Golay filtering (order = 2, window = 15)⁴⁹. The range of the y-axes are different for three sub-plots.

Table 1: Approach to separate the impacts of different forcings

Reference exp_period	New exp_period	Forcings
tranirr_1901-1930	tranirr_1985-2014	all forcings (greenhouse gas emissions, land use change, irrigation expansion, etc.)
1901irr_1901-1930	1901irr_1985-2014	all forcings except irrigation expansion
1901irr_1985-2014	tranirr_1985-2014	irrigation expansion

300 Methods

301 **Participating ESMs and simulation protocol** Six combinations of state-of-art Earth
302 system models (ESMs) and irrigation parametrizations are used in this study: the Community
303 Earth System Model version 2 (CESM2)⁵⁰, CESM2 with groundwater withdrawal and flow rep-
304 resentation (CESM2_gw)⁸, the Institut Pierre-Simon Laplace Climate Model version 6 (IPSL-
305 CM6)⁵¹ with a newly developed irrigation scheme³⁹, the Norwegian Earth System Model version
306 2 (NorESM2)⁵², the Energy Exascale Earth System Model Version 2 (E3SMv2)⁵³ with active
307 two-way coupled irrigation scheme³⁶, and the Centre National de Recherches Météorologiques
308 Climate Model version 6 (CNRM-CM6-1)^{54,55}. Irrigation is represented in different ways in
309 these models, which can be divided into two categories: soil-moisture-based schemes and ex-
310 ternal forcing applications (only for CNRM-CM6-1). Differences between soil-moisture-based
311 irrigation modules relate to irrigation triggers, start time, duration, amount, and the method
312 of water application. The employed ESMs provide the option to customise irrigation-related
313 parameters, but in this study, all ESMs used default parameter values. CESM2, CESM2_gw,
314 and NorESM2, share identical or similar land system models, which explains why they show
315 strong consistency between each other. However, their differences in atmospheric models and
316 features in the irrigation scheme, still represent an added value to this study. More detailed
317 description of ESMs and their irrigation representations could be found in Supplementary Note
318 1.

319
320 We design two historical experiments in this study: with (*tranirr*) and without (*1901irr*) histor-
321 ical irrigation expansion. The simulations of both experiments follow the protocol of AMIP sim-
322 ulations in CMIP6 with the same input data⁵⁶, which means that the ocean model is switched
323 off and sea surface temperatures are prescribed. To better capture the signal of irrigation extent
324 increase in the 20th century, we select a simulation period of 1901 - 2014. The only difference
325 between the two experiments is that in *tranirr*, irrigation extent is transient, while in *1901irr*,
326 the irrigation extent is fixed at the level in the year 1901. One exception is IPSL-CM6, where
327 irrigation is entirely switched off for *1901irr*, and we include outputs of this ESM in the analysis
328 as in the year 1901, irrigated fraction is very limited (Figure A1a). The land-use map and time-
329 series data used in these simulations are from the Land-Use Harmonization phase 2 project
330 (LUH2⁴⁷), in which all crop management activities-related data, including irrigated land dis-
331 tribution, is obtained from the History Database of the Global Environment 3.2 (HYDE 3.2)⁵⁷.
332 The irrigated land data from HYDE 3.2 during the period 1901-2014 has two sources: for the

333 period pre-1960, the data is directly collected from FAO⁵⁸, and for the post-1960 period, the
 334 numbers are calculated by multiplying the term "area equipped for irrigation" in FAO statis-
 335 tics by the fraction of actual irrigated area in area equipped for irrigation from Global Map of
 336 Irrigation Areas version 5 (GMIA_v5)⁵⁹.

337 **Climate extremes** Most models report output variables at the 3-hourly frequency to enable
 338 analysis of sub-daily extremes, but CNRM-CM6-1 only provides daily mean, maximum, and
 339 minimum values, so we calculate several moist-heat metrics based on daily maximum temper-
 340 ature and minimum air relative humidity to calculate the maximum metrics consistent with a
 341 previous study⁶⁰, thereby assuming that the lowest relative humidity occurs when the temper-
 342 ature is maximum.

343
 344 HUMIDEX (HU) is a feel-like heat stress metric developed in the late 1970s, and it was first
 345 used for the meteorological service in Canada⁶¹. It is calculated as:

$$HU = T_C + \frac{5}{9} \left(\frac{e_{RH}}{100} - 10 \right)$$

where T_C is the temperature at 2-meter height ($^{\circ}\text{C}$), e_{RH} (Pa) is the vapour pressure calculated based on relative humidity (RH) and saturated vapour pressure (e_s in Pa):

$$e_{RH} = RH e_s,$$

346 HU is still used by the Canadian Centre for Occupational Health and Safety (CCOHS) to in-
 347 form the general public if the weather conditions may be comfortable based on the following
 348 thresholds: 20-29, 30-39, 40-45, and over 46 represent the warning of 'little discomfort', 'some
 349 discomfort', 'great discomfort', and 'dangerous', respectively⁶².

350
 351 T_w is a measure of heat stress considering the maximum potential evaporative cooling impact⁶³.
 352 It can be measured by a thermometer covered in water-soaked cloth over which air is passed⁶⁴.
 353 The calculation of T_w is very computationally expensive, so we employ a simplified method²⁸:

$$\begin{aligned} T_W = & T_C \arctan(0.151977\sqrt{RH + 8.313659}) \\ & + \arctan(T_C + RH) - \arctan(RH - 1.676331) \\ & + 0.00391838RH^{3/2} \arctan(0.023101RH) - 4.68035 \end{aligned}$$

354
 355
 356 Based on previous studies^{63,65}, when T_w is over 31 $^{\circ}\text{C}$, physical labour becomes impossible, and
 357 exposure to T_w exceeding 35 $^{\circ}\text{C}$ for more than 6 hours is dangerous even for healthy individuals.
 358 However, the maximum evaporative cooling (swamp cooler) is not easy to approach, as in
 359 previous heatwave events, high casualties already existed even if the T_w is less than 28 $^{\circ}\text{C}$ ⁶⁶.
 360 Other metrics are described in Supplementary Note 3.

361 **Data processing** Outputs from E3SM, IPSL-CM6, and CNRM-CM6-1 are firstly regridded
362 to the resolution of CESM2, CESM.gw ($0.9^\circ \times 1.25^\circ$), and then the moist-heat metrics are cal-
363 culated. After calculating the moist-heat metrics, we further processed the results to separate
364 the impacts of irrigation expansion from other forcings. We first calculated irrigation expan-
365 sion’s impacts on the absolute values of extreme events as well as surface energy fluxes. We
366 select two periods, the first 30 years (1901-1930) and the last 30 years (1985-2014), for both
367 simulations (*tranirr* and *1901irr*) to calculate the impacts of all forcings, all forcings except
368 irrigation expansion, and irrigation expansion, on near-surface climate (see Table 1). For the
369 *tranirr* simulations, we assume that the difference between the results during the two periods
370 is the consequence of all forcings. Similarly, the difference between the results during the two
371 periods for the *1901irr* simulations is assumed to be the consequence of other forcings. The
372 difference between these two simulations during the 1985-2014 period is assumed to represent
373 the impacts of irrigation expansion as the only difference between them is whether irrigation
374 extent is transient.

375

376 Apart from the absolute value of extreme events, we also calculate the probability ratio (PR) for
377 several extreme events, which has been used in previous studies to show the changes in climate
378 extreme events frequency^{13,67}. The extreme events defined in this study are based on percentile
379 values, e.g., a 99th percentile event means that in the reference period, it happens once per
380 100 time steps (3 hours per 300 hours for 3-hourly outputs), or in other words, it indicates the
381 1% time steps with the most extreme values. Considering that outputs from CNRM-CM6-1
382 is at a daily frequency, we select the 92th, 96th, and 99.2th percentile events for this ESMs to
383 represent the 99th, 99.5th, and 99.9th percentile events simulated by other ESMs. This is based
384 on an assumption that those extreme events calculated based on maximum temperature and
385 minimum humidity last 3 hours during the day, so a 92th percentile value means 8 days per 100
386 days and then 24 hours per 2400 hours, which is equal to 3 hours per 300 hours for 3-hourly
387 outputs. The PR is calculated as:

$$PR = \frac{P_{new}(X_{ext})}{P_{ref}(X_{ext})},$$

388 where $P_{new}(X_{ext})$ is the probability of a certain kind of extreme event (X_{ext}) during the new
389 exp-period and $P_{ref}(X_{ext})$ is the probability of the same kind of event during the reference
390 exp-period. Let us assume, for example, that the 99th percentile value of T_{2m} is 33 °C in
391 the reference exp-period, meaning the extreme events are the ones with $T_{2m} > 33$ °C: if the
392 frequency of these events is 4% in the new exp-period, then the PR is 4. Thus, a PR of more
393 than 1 indicates that this event occurs more frequently in the new exp-period compared to
394 the reference exp-period, and vice versa. Similar to absolute values, we also select two periods
395 (1901-1930 and 1985-2014) for both *tranirr* and *1901irr*, then calculate the PR between them
396 for the 99.0th, 99.5th, and 99.9th percentile events for T_{2m} , HU, and T_w . To further investigate
397 the temporal trend of irrigation expansion’s impacts, we calculated the mean value of annual
398 hours exposed to warm extremes for four groups of grid cells, with irrigation expansion of 0%

399 - 20%, 20% - 30%, 30% - 40%, and more than 40%.

400 **Data Availability**

401 **Code Availability**

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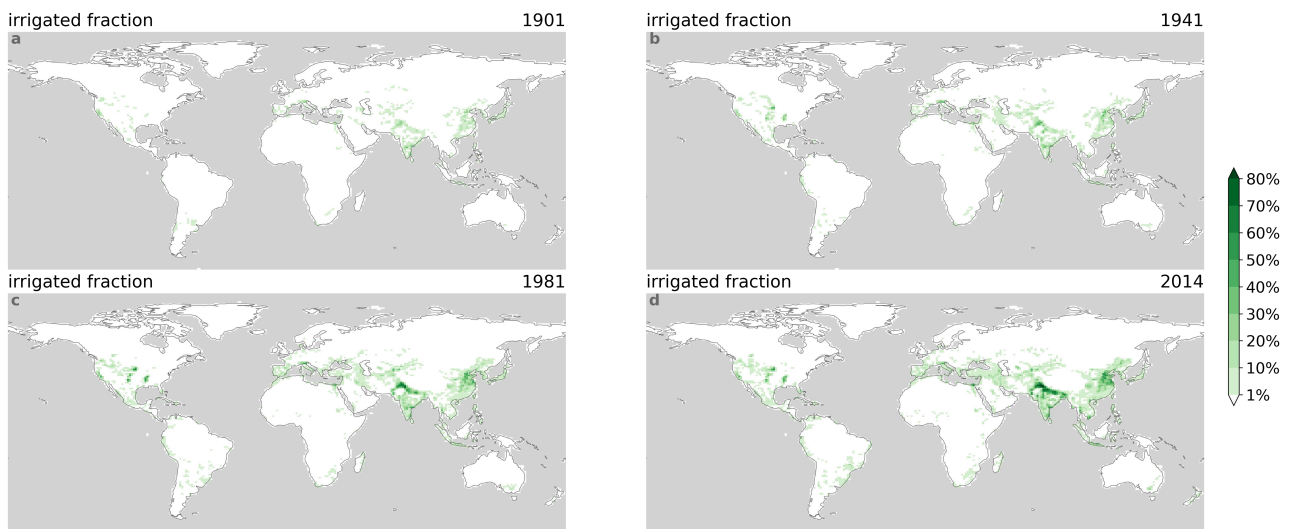


Figure A1: Irrigated fraction information is from LUH2 dataset⁴⁷. **e** Increase in irrigated fraction between 1901 and 2014.

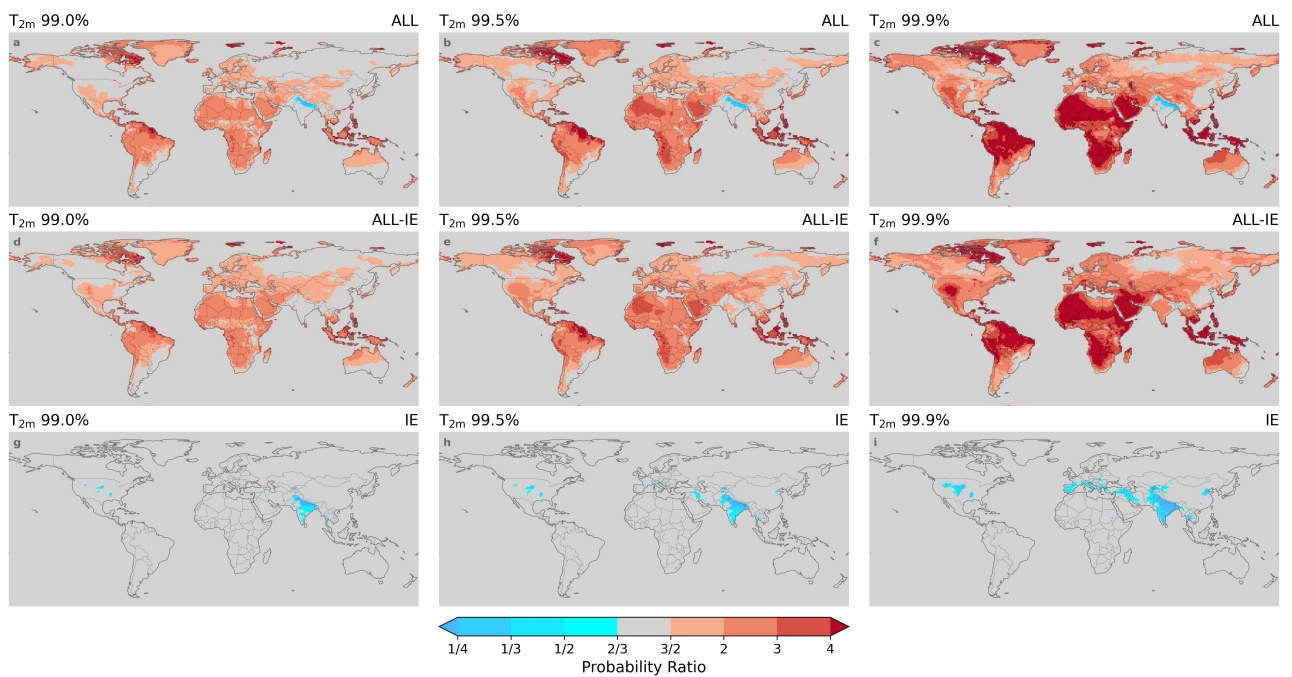


Figure A2: Similar to Figure 4 but for the 99.0th (a, d, g), the 99.5th (b, e, h), and the 99.9th (c, f, i) percentile events for 2-meter air temperature T_{2m} .

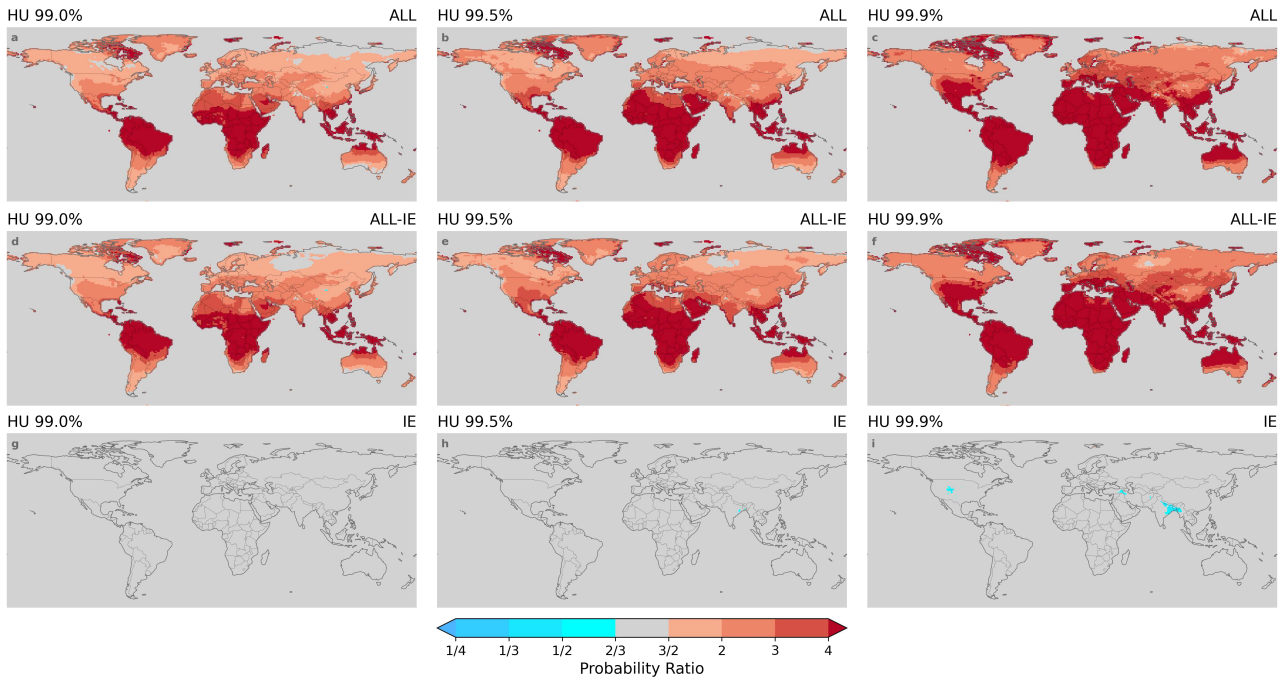


Figure A3: Same as Figure A2 but for HU.

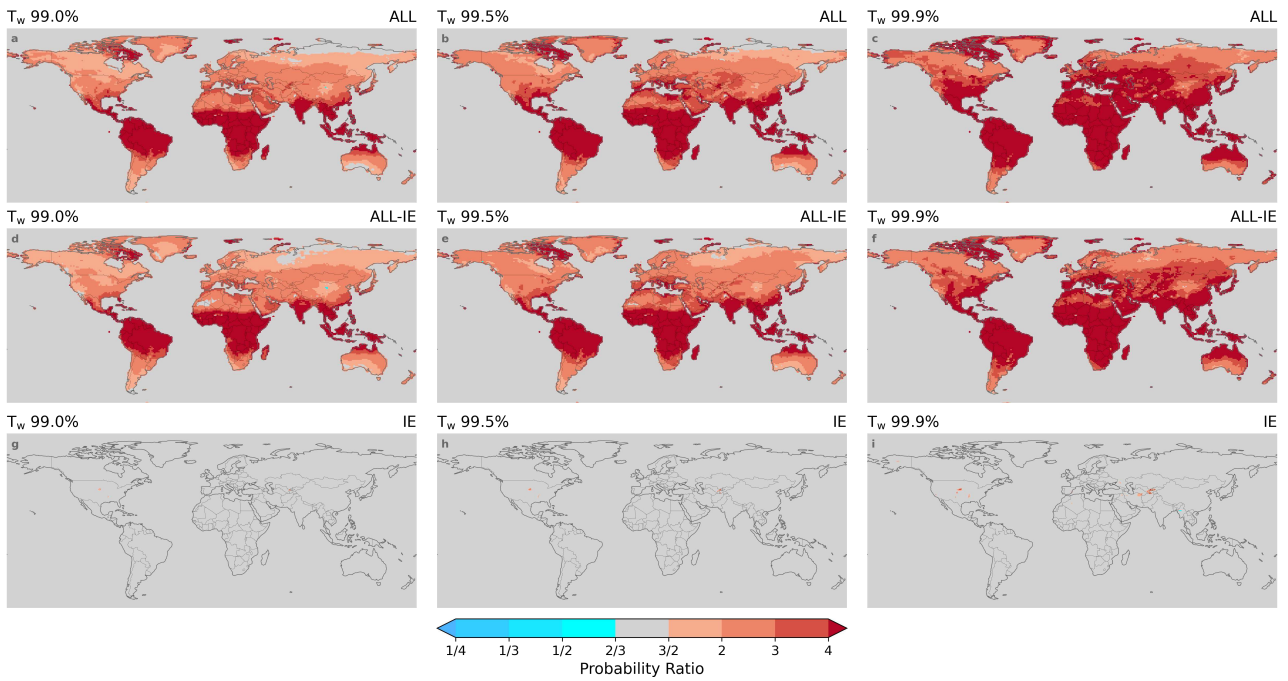


Figure A4: Same as Figure A2 but for T_w .

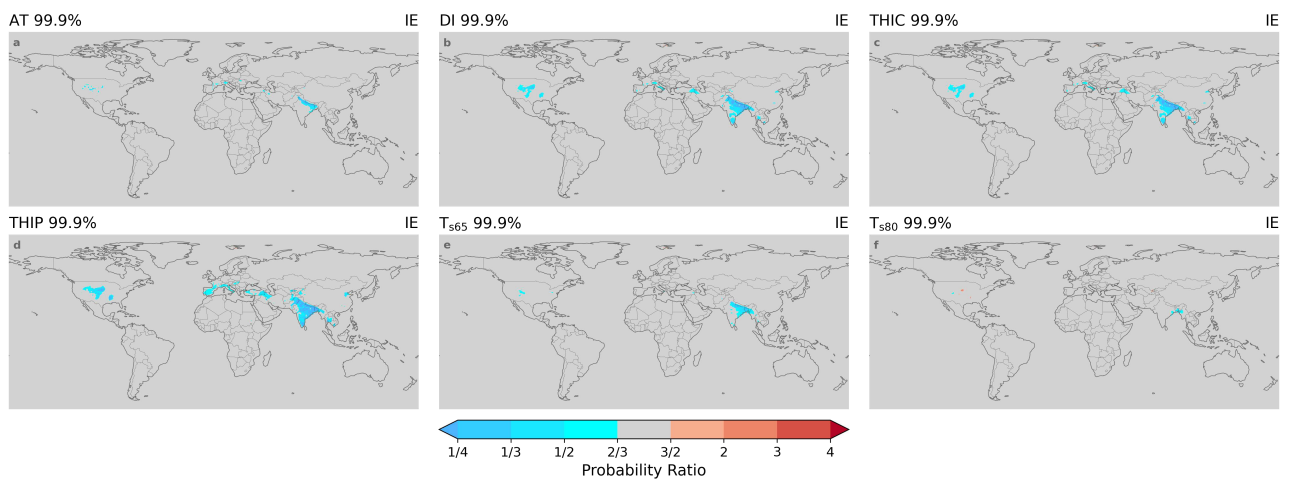


Figure A5: Similar to Figure 4 but for the 99.9th percentile events for apparent temperature (AT: **a**), Discomfort Index (DI: **b**), Thermal Humidity Index for Comfort (THIC: **c**), Thermal Humidity Index for Physiology (THIP: **d**), Temperature with 65% swamp cooler (T_{s65}: **e**) and 80% swamp cooler (T_{s80}: **f**).

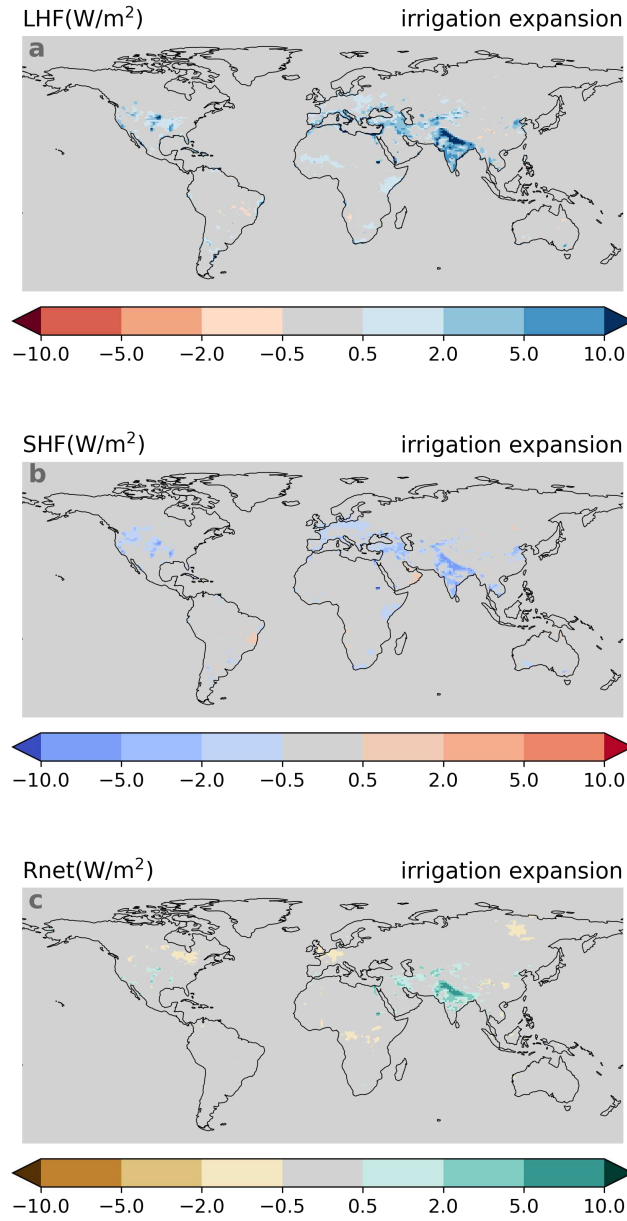


Figure A6: Impacts of irrigation expansion on latent heat flux (LHF: **a**), sensible heat flux (SHF: **b**), and net radiation (Rnet: **c**). Only signals (>0.5 or <-0.5 W/m^2) agreed by ≥ 4 of 6 models are shown.

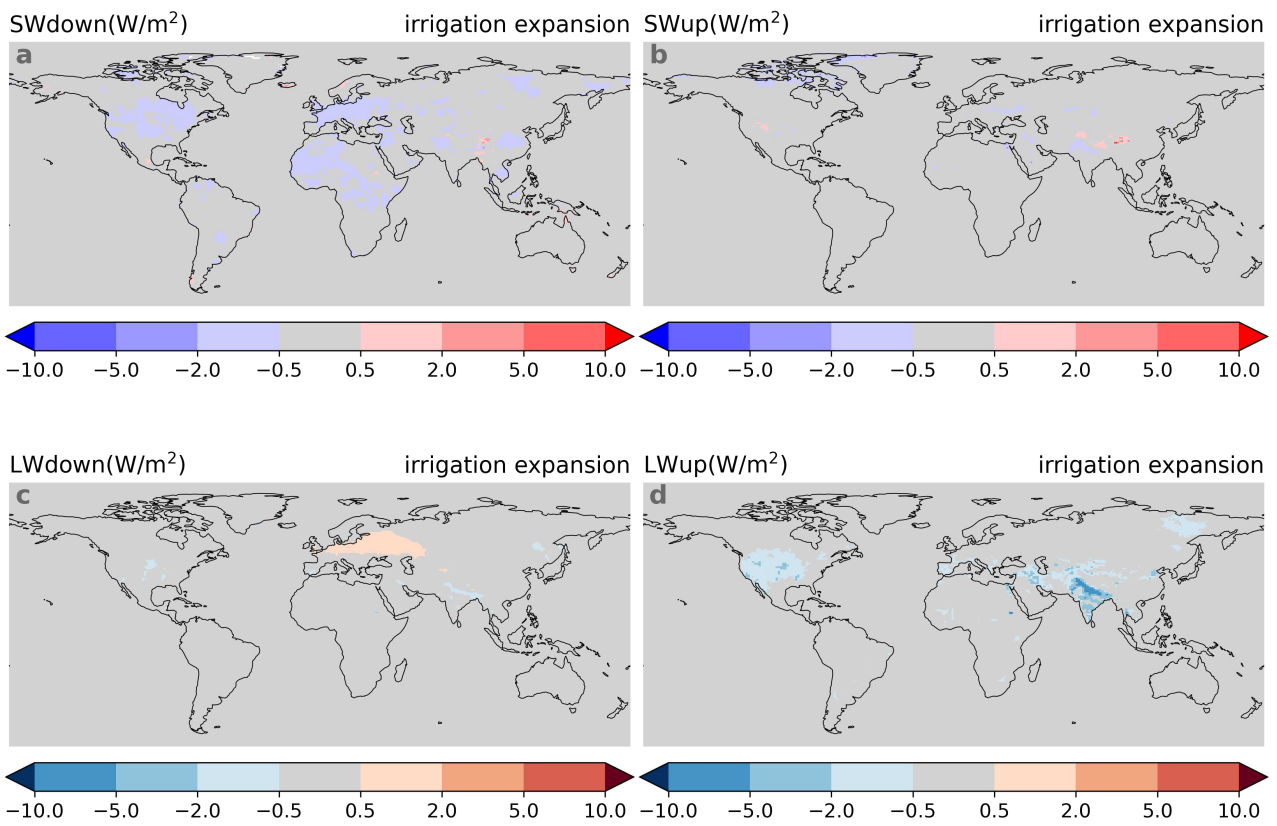


Figure A7: Same as Figure A6 but for downwelling and upwelling, short- and longwave radiation (SWdown: **a**, SWup: **b**, LWdown: **c**, and LWup: **d**.)

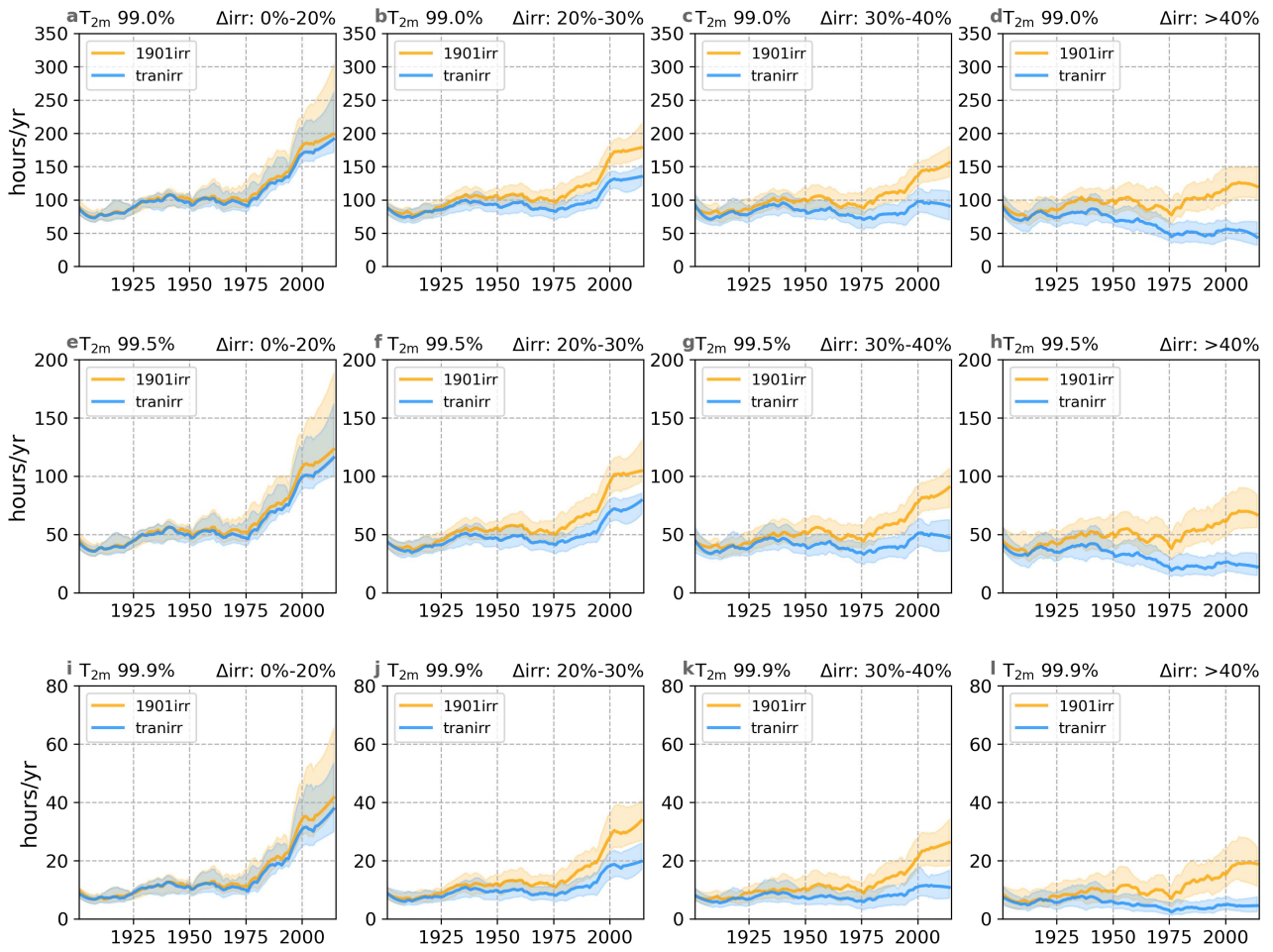


Figure A8: Similar to Figure 5 but for T_{2m} 99th (a-d), 99.5th (e-h), and 99.9th (i-l) percentile extremes over grid cells with irrigation expansion of 0-20% (a, e, i), 20%-30% (b, f, j), 30%-40% (c, g, k) and >40% (d, h, l).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryMaterials.pdf](#)