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

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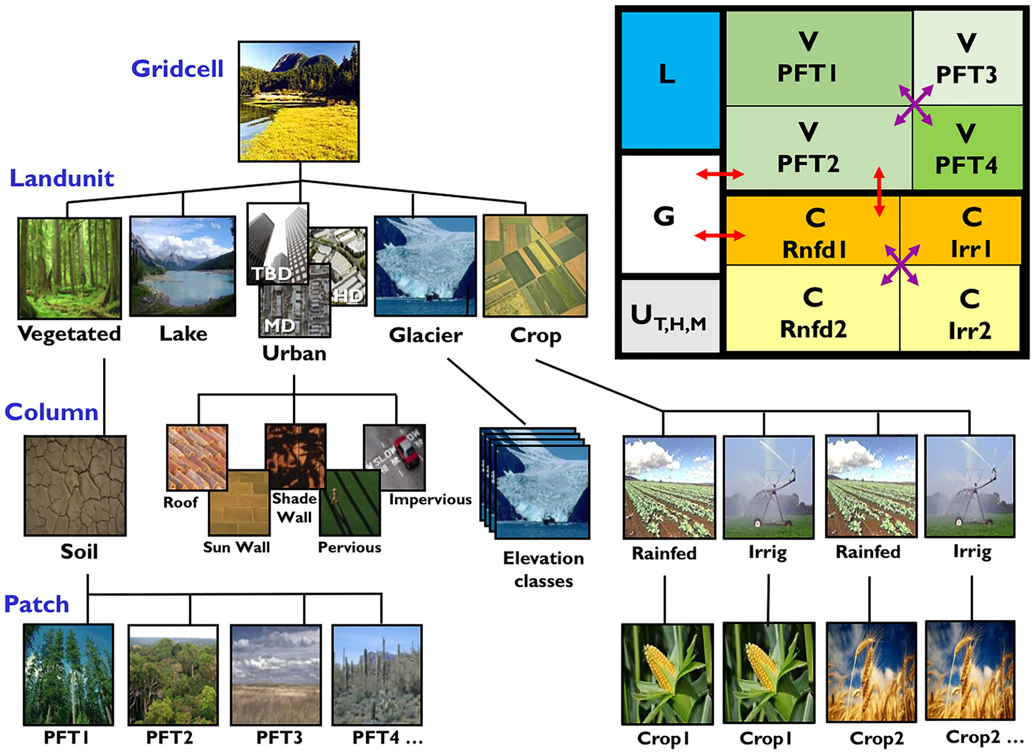
1 Supplementary Notes

1.1 Supplementary Note 1: Participating ESMs and their irrigation implementation

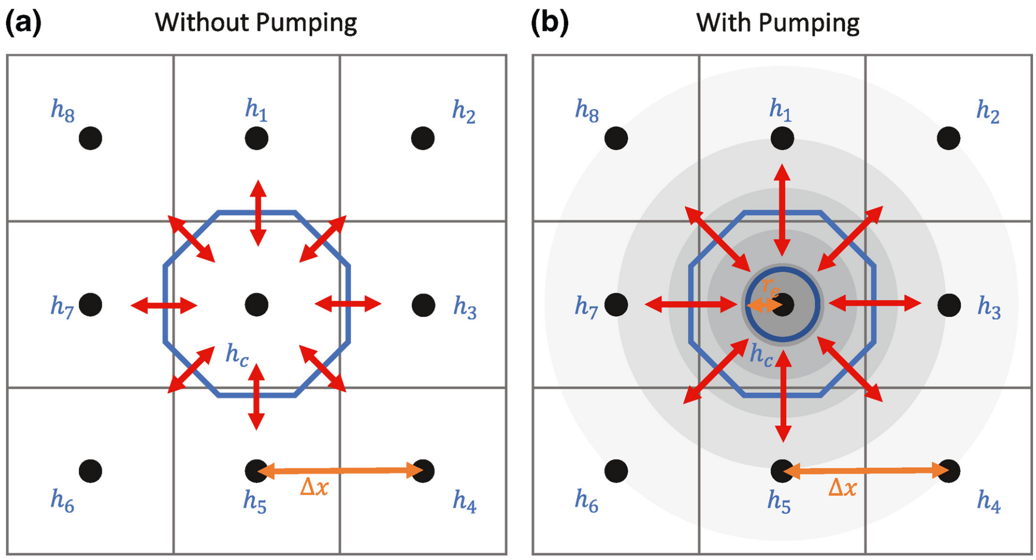
The Community Earth System Model version 2 (CESM2), is a state-of-art Earth system model, with the Community Atmosphere Model version 6 (CAM6)[1] as the atmosphere model, the Community Land Model version 5 (CLM5) as the land model, and the Model for Scale Adaptive River Transport (MOSART) as the routing model[2–5]. The CLM5 is forced by atmospheric variables from the CAM6 (in coupled simulations), or from external datasets (in off-line simulations), to simulate the biophysical and biochemical processes in the land system. A sub-grid cell level structure is used in CLM5, according to which a grid cell is formed by five land cover types: natural vegetation, lake, urban, glacier, and cropland, and all these land cover types are further divided into multiple soil columns and patches (Figure S1). The calculations of hydrological, energy, and carbon fluxes are operated individually over each column or patch, then weighted averaged to generate the grid cell level outputs, which then are exchanged with CAM6 and MOSART.



Supplementary Figure S1 | Sub-grid cell structure of the CLM5 land datasets. Figure from the description paper of CLM5.[2]

Under the cropland cover type, 31 different crops are implemented, which are then merged into 8 active crop functional types due to the lack of parameterisation of some crops. For each crop functional type, two patches are used, representing irrigated and rainfed cropland, respectively. Over each irrigated cropland patch, every day at 6:00 AM local time, the model checks (i) whether the crop LAI is more than 0, and (ii) whether the actual soil moisture (SM_{actual}) is less than the threshold (SM_{thresh}). If both conditions are satisfied, the model activates the irrigation, and the amount of water used for irrigation (IW) is calculated as the deficit between SM_{actual} and the target soil moisture (SM_{target}). Then, the water is applied as the rainfall under the canopy evenly during a period of 4 hours, namely 6:00 AM to 10:00 AM local time. The water used for irrigation is abstracted from the surface water in the main channel in MOSART, and when the available surface water is not sufficient, ocean water will be withdrawn to close the water balance. CLM5 also provide options for limiting water withdrawal and groundwater use for irrigation, which are not used in this study. A study applied over the Pacific Northwest watershed shows that CLM5 with this irrigation module generally well simulated the water, energy, carbon fluxes and crop phenology[6], but at the global level, this module substantially underestimate the irrigation water withdrawal[7].

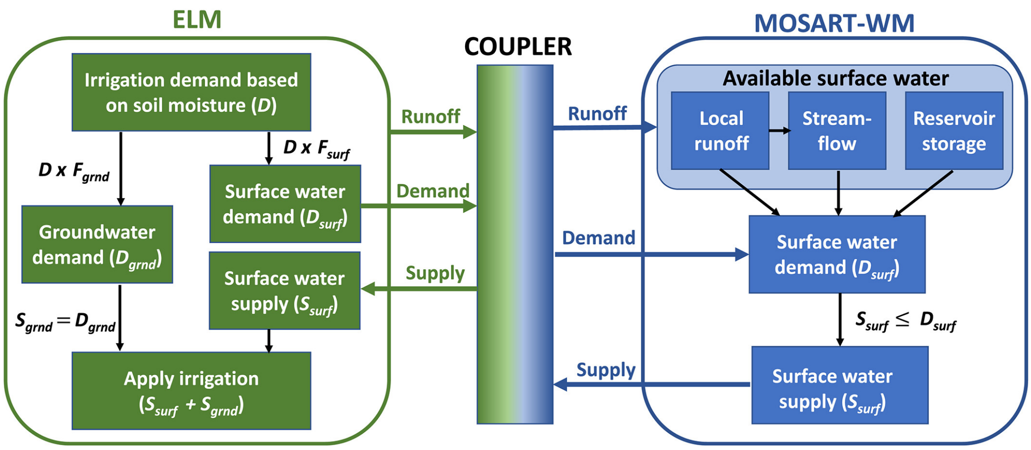
The difference between CESM2 and CESM2_gw is in CESM2_gw, an intercell lateral groundwater interaction and an aquifer pumping process are implemented[8]. When the water in the main channel cannot satisfy the irrigation water demand in the gridcell, groundwater withdrawal will be activated, with the groundwater in the soil layers firstly pumped and aquifer later. The groundwater pumping of a gridcell is assumed to be operated over a single well, and cause a decrease in groundwater table, which then pertubates the baseflow interactions with neighbouring gridcells(Figure S2). Evaluation results indicate that this newly added feature greatly improved the model's ability to reproduce the spatiotemperal groundwater-level changes over the US high Plains and Central valley Aquifer.



Supplementary Figure S2 | Conceptual pertubation on groundwater flow caused by irrigation in the groundwater module used in CESM2_gw. Figure from the description paper of this module.[8]

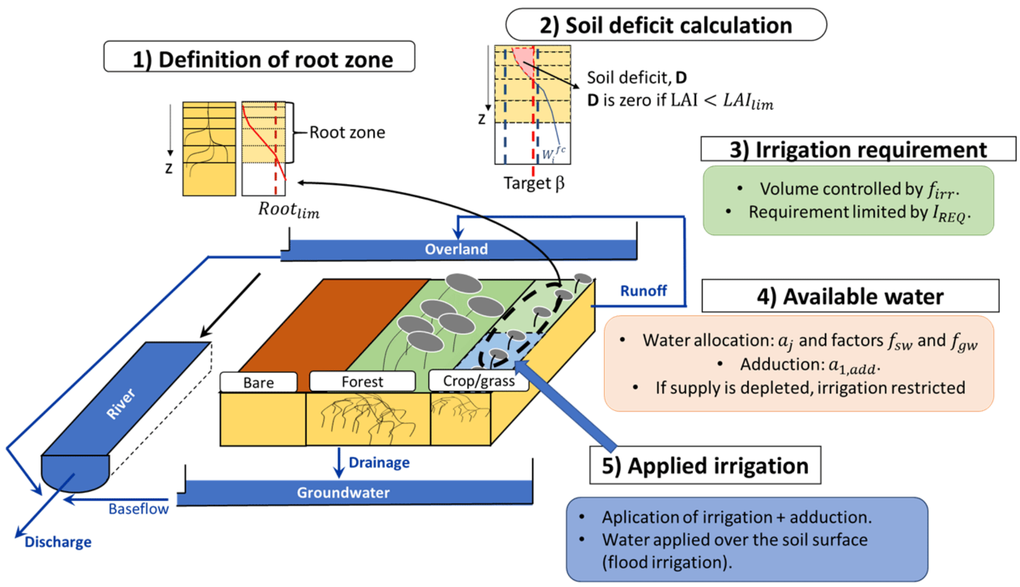
The Norwegian Earth System Model (NorESM)[9] shares the same atmosphere (CAM6) and land system model (CLM5) with CESM2, except for some additional developments like new chemistry/aerosol/cloud module (OsloAero6[10]) and improved conservation of energy and angular momentum[11].

The Energy Exascale Earth System Model (E3SMv0) was developed based on CESM1, with CAM5, CLM4.5, MOSART, and POP as the atmosphere, land, river routing, and ocean model[12]. In developing E3SMv1, the ocean model was replaced by MPAS-O, and many new model features were added to each component model, which resulted in the E3SM Land Model (ELM), the E3SM Atmosphere Model (EAM) and the routing model (MOSART-Water Management: MOSART-WM), so E3SMv1 differs quite significantly from CESM1 and CESM2[13,14]. The key changes in E3SM's irrigation module compared to that in CLM4.5 are (i) a two-way coupling between ELM and MOSART-WM, which constrains surface water withdrawal based on water availability (Figure: S3)[15]; and (ii) the introduction of a fraction (F_{grd}) that determines how much irrigation water is derived from the groundwater, which is estimated from water use statistics[15,16]. In ELM, the need for irrigation is also checked at 6:00 am local time, and the demand is then partitioned into two parts, groundwater demand and surface water demand, based on F_{grd}. The groundwater demand is always satisfied, but the surface water demand is evaluated by MOSART-WM to decide how much surface water is supplied based on the water management rules. Compared to the one-way coupling scheme used in CLM4.5, this new scheme shows some advantages in more realistically simulating groundwater level and irrigation water-use seasonal pattern[15].



Supplementary Figure S3 | The two-way coupling scheme used for irrigation in E3SM. Figure from the description paper of this module.[15]

The Institut Pierre-Simon Laplace Climate Model version 6 (IPSL-CM6[18]) uses LMDZ6 as the atmosphere model[17] and the Organising Carbon and Hydrology in Dynamic Ecosystems version 2.2 (ORCHIDEE 2.2) as the land model, here with a new irrigation module[19]. As shown in Figure S4, a soil moisture deficit is calculated by confronting the actual soil moisture in the root zone to a target soil moisture above which irrigation is not needed. The deficit is calculated for the soil column of gathering cropland and grassland, whether irrigated or not, as irrigated cropland and grassland are not treated apart. The irrigation demand, however, is obtained by multiplying the soil moisture deficit by the fraction of irrigated land. Three sources of water, from the stream, overland, and (renewable) groundwater reservoirs, are considered to supply the demand, all of them with a limitation on water withdrawal for ecological protection. The share of withdrawals between surface water (stream and overland) and groundwater is given in each grid cell by the fractional areas equipped for surface and groundwater irrigation from a global map[20], and the amount of water from the two surface sources is proportional to their available water. The withdrawn water is applied at the soil surface over the whole crop and grass column, and a maximum irrigation rate is set in the model to prevent from excessive surface runoff unrealistic irrigation application.



Supplementary Figure S4 | Irrigation scheme used in IPSL-CM6. Figure from the description paper of this scheme.[19]

In this study, the climate model used by the French National Center for Meteorological Research (CNRM) is an upgraded version of the CNRM-CM6-1 climate model[31]. It is based on the ARPEGE-Climat v6.3 atmospheric general circulation model[32], and the SURFEX v8.0 surface modeling platform[33] to simulate ocean and lake fluxes, as well as land surface processes. These land surface processes are simulated using the ISBA-CTRIP (Interaction-Soil-Biosphere-Atmosphere - CNRM version of the Total Runoff Integrating Pathways; `https://www.umr-cnrm.fr/spip.php?article1092&lang=en`) land surface model that provides a physical and realistic representation of the continental hydrology[34], as well as a simple but complete representation of the land surface carbon cycle and of the land use land cover changes that affect energy, water, and carbon exchanges[35]. Irrigation water withdrawals have recently been introduced into ISBA-CTRIP[36]. Irrigation water demand is imposed as an external forcing, preferentially in the cropland portion of each model grid cell. The irrigation water flux is then partitioned between flood, sprinkler, and drip irrigation, and withdrawn from groundwater reservoirs and conceptual small dams to close the global water budget. In this study, the irrigation water demands are from a global reconstructed hydrological dataset based on simulations[21].

Table S1: Simulation protocol

Experiment ID	Description	Notes
tranirr	Transient irrigation extent	For models in which transient irrigation extent is not possible, prescribed present-day irrigation extent can be used as an alternative
1901irr	Irrigation extent kept constant at 1901 level	For models which apply irrigation flux as a forcing, the flux should be kept constant at 1901 levels. For models whose implementation of irrigation is parameterised in the source code, the input land cover data should be modified to keep the area equipped for irrigation constant throughout the simulation.

Table S2: Simulation details of ESMs

ESMs	Spatial resolution	Output frequency	Ensemble members
CESM2	0.9°x 1.25°	3 hour	3
CESM2gw	0.9°x 1.25°	3 hour	3
NorESM	0.9°x 1.25°	3 hour	3
E3SM	0.5°x 0.5°	3 hour	2
IPSL-CM6	0.5°x 0.5°	3 hour	1
CNRM-CM6-1	1.4°x 1.4°	daily	5

1.2 Supplementary Note 2: IRRMIP simulation protocol

The configurations of simulations should be the same as in the AMIP experiment[22] of CMIP6, which means that only atmospheric and land models are activated. Sea surface temperatures and sea ice concentrations are prescribed consistent with observations. Other forcings, including land use, land cover, volcanic aerosols, solar variability, greenhouse gas concentrations and anthropogenic aerosols, are transient and prescribed from historical data. We recommend using the LUH2 transient irrigation extent data[23], but alternative data sources could be used. The simulation period is from 1^{st} January 1901 to 31 December 2015. The experiment consists of two ensembles, and for every ensemble, at least 3 members are recommended. Modelling teams are free to choose their own spatial resolution and model settings. This study uses the results from six ESMs, varying in spatial and temporal resolution and number of ensemble members. More details are in Table S2.

1.3 Supplementary Note 3: Other moist-heat metrics

Apparent temperature (AT) is a "feel-like" temperature perceived by human bodies, considering the impacts of temperature, radiation, humidity, and wind speed[24]. The AT used in this study ignores the impact of sunlight to detect the thermal comfort of an adult walking outdoors in the shade[25]. AT is calculated as

$$\mathrm{AT} = T_{\mathrm{C}} + \frac{3.3e_{\mathrm{RH}}}{1000} - 0.7u_{10\ \mathrm{m}} - 4,$$

where u_{10m} is the wind speed at 10-meter height (m s^{-1}), T_C is the temperature at 2-meter height (°C), e_{RH} (Pa) is the vapour pressure calculated based on relative humidity (RH) and saturated vapour pressure (e_s in Pa):

$$e_{\mathrm{RH}} = \mathrm{RH}e_{\mathrm{s}},$$

AT prediction is provided by the Australian Bureau of Meteorology and the National Weather Service of the United States.

The Temperature Humidity Index for Comfort (THIC) is also a comfort algorithm used for quantifying livestock's comfort[26]. The original calibration is specifically used for pigs, which is calculated as follows:

$$\mathrm{THIC} = 0.72T_{\mathrm{w}} + 0.72T_{\mathrm{C}} + 40.6$$

where T_w is the wet bulb temperature (°C).
Considering that it is not easy to approach the maximum cooling impacts, another two metrics, T_{s65} and T_{s80}, in which 65 % or 80 % of the swamp coolers are approached, respectively, are developed.

$$T_{\mathrm{s}} = T_{\mathrm{C}} - \frac{\eta}{100}\left(T_{\mathrm{C}} - T_{\mathrm{w}}\right)$$

where η can be 65 or 80, according to which metric we want to calculate. We use the same thresholds of T_w for them in this study.

The only metric derived from the physiology algorithm in this study is the Temperature Humidity Index for Physiology (THIP), which is calculated as:

$$\mathrm{THIP} = 0.63T_{\mathrm{w}} + 1.17T_{\mathrm{C}} + 32$$

THIP and THIC are both for livestock[27], and the equations we use in this study are specifically for pigs. For THIC and THIP, 75-78 means alert, 79-83 means dangerous, and 84+ means very dangerous.

Discomfort Index (DI) was developed firstly as an air conditioner calibration[28], and the Israeli Defense Force used it to make decisions about heat stress[29]. It is calculated as the average value of T_w and T_C:

$$\mathrm{DI} = 0.5T_\mathrm{w} + 0.5T_\mathrm{C}$$

For DI, we use a series of thresholds: 21-24 means <50 % of people feel discomfort, 24-27 means >50 % of people feel comfort, 27 - 29 means most of the people feel discomfort, and 29-32 and >32 mean severe stress and emergency, respectively[30].

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