Environmental Research Letters

LETTER

Substantial decline in atmospheric aridity due to irrigation in India

Anukesh Krishnankutty Ambika and Vimal Mishra

1 Earth Sciences, Indian Institute of Technology (IIT) Gandhinagar, India
2 Civil Engineering, Indian Institute of Technology (IIT) Gandhinagar, India
E-mail: vmishra@iitgn.ac.in

Keywords: irrigation, atmospheric aridity, soil moisture, vapor pressure deficit

Abstract

Compound extremes of soil moisture (SM) drought and high vapor pressure deficit (atmospheric aridity) are disastrous for natural and social systems. Despite a significant expansion in irrigated area in India, the role of irrigation on SM and atmospheric aridity is not examined. We used observations, reanalysis datasets, and high-resolution simulations from the Weather Research and Forecasting (WRF) model to show that irrigation significantly modulates SM and atmospheric aridity in India. The Indo-Gangetic Plain, which is one of the most intensively irrigated regions in the world, experienced significant ($P$-value = 0.03) cooling (~0.8 °C) and an increase in solar-induced chlorophyll fluorescence during the crop growing season (November–February). Atmospheric aridity has significantly ($P$-value = 0.0002) declined (~1.38 kPa) while SM (1.6 m$^3$ m$^{-3}$) and relative humidity (RH) (2.0%) have increased over the Indo-Gangetic Plain during 1979–2018. We conducted high-resolution simulations using the WRF model to examine the role of irrigation on atmospheric aridity. Irrigation strongly modulates SM drought and atmospheric aridity by increasing latent heat and RH and reducing sensible heat. Our findings have implications as irrigation can influence compound extremes of SM drought and atmospheric aridity. Climate models need to incorporate the influence of irrigation for reliable projections in the intensively irrigated regions.

1. Introduction

Agriculture is the largest water consumption sector and accounts for more than 70% of all water withdrawn globally (Siebert et al 2005). Use of a large amount of water in irrigated agriculture caused water scarcity in some regions and resulted in altered water budget (Oki et al 2001, Shah et al 2019). Irrigated area has significantly increased globally to sustain the food demands of the growing population. In India, a massive irrigation expansion has taken place after the Green revolution in the 1970s due to the significant rise in the number of groundwater wells (Mishra et al 2018). India has the largest irrigated area in the world, with more than 57 million ha irrigated through surface and groundwater sources (Siebert et al 2005, Ambika and Mishra 2019). Moreover, the irrigated area in India has increased by threefold between 1950 and 2013 (Alauddin and Quiggin 2008, Ambika et al 2016). Irrigation expansion in India has played a tremendous role in improving the socio-economic condition of the population and ensuring food security (Narayanaamoorthy 2011, Chen et al 2019). For instance, irrigation contributed to more than 13% increase in wheat yield between 1970 and 2000 in India (Zaveri and Lobell 2019).

Irrigation has considerably influenced vegetation greening in India and China (Chen et al 2019). Irrigation and other human land-use practices (e.g. fertilizer application) contributed to greening and expansion in agricultural regions across the globe but more dominantly in India (Asoka and Mishra 2015, Chen et al 2019, Piao et al 2019). Previous studies (Im et al 2014, Marcella and Eltahir 2014, Alter et al 2015, Thiery et al 2017, Ambika and Mishra 2019, Kang and Eltahir 2019, Shah et al 2019) examined the influence of irrigation on climate, energy and water budgets. A significant expansion in irrigation modulated the hydrological cycle (Piao et al 2019). Lo and Famiglietti (2013) reported that irrigation in California results in increased evapotranspiration and moisture transport, which strengthens the
water cycle in the Southwestern United States. Also, irrigation enhances cloud cover and precipitation in many regions while causing a reduction in the monsoon precipitation in Asia (Cook et al 2015). Thiery et al (2020) showed that irrigation expansion had dampened anthropogenic warming influence on hot days and day-time summer temperature. The cooling in land surface temperature due to irrigation is linked with the increased evapotranspiration (Ambika and Mishra 2019, Li and Xiao 2019). For instance, irrigation results in increased latent heat while reduced sensible heat (Kueppers et al 2007, Lobell et al 2008, Pei et al 2016, Thiery et al 2017, Yao et al 2017, Shah et al 2019). Not only the energy partitioning over land, but irrigation can also have a substantial influence on precipitation, cloud formation, and planetary boundary layer dynamics (Im et al 2014, Alter et al 2015).

Irrigation can considerably modulate the land–atmospheric coupling affecting weather and climate extremes (Lu et al 2017). Land–atmospheric coupling plays an essential role in the water and energy cycles and in improving the predictability of weather and climate (Chen et al 2001, Los et al 2001, Koster et al 2004). Feedbacks between soil moisture (SM), air temperature, and precipitation affect mean and extremes associated with weather and climate (Betts et al 1996, Pielke et al 1999). For instance, during heatwaves anomalously, high land–atmospheric coupling exists in the areas that have SM deficit and high atmospheric water demands (Miralles et al 2012). Miralles et al (2014) reported that SM deficit and land–atmospheric interactions played an essential role in the mega heatwaves that occurred in Europe. Lu et al (2017) reported that irrigation resulted in a significant decline in the land–atmospheric coupling strength in the Midwestern United States. Similarly, Badger and Dirmeyer (2015) showed that irrigation reduced land–atmospheric coupling strength in Amazon. Since irrigation affects the land–atmospheric coupling (Seneviratne et al 2010), it modulates moisture availability on land and atmosphere. However, the role of irrigation on atmospheric aridity over in India has not been examined.

Changes in SM and atmospheric aridity by irrigation have implications. For instance, SM is a limiting factor for ecosystem carbon uptake as net primary productivity declines due to prolonged SM deficit (Green et al 2019), which can be further amplified by the land–atmosphere feedback (Zhou et al 2019a). Notwithstanding the profound implications of irrigation in modulating SM and atmospheric aridity, previous studies (Ambika and Mishra 2019, Yang et al 2019, Thiery et al 2020) did not consider the influence of irrigation on the land–atmospheric coupling. We conduct high-resolution simulations using the Weather Research and Forecasting (WRF) model forced with European Centre for Medium-Range Weather Forecasts Reanalysis (ERA-5) (Dee et al 2011) as a boundary condition for irrigation-on and irrigation-off scenarios for the 1979–2018 period. We aim to examine the influence of irrigation on SM and atmospheric aridity in India using ERA-5 reanalysis and WRF simulations with irrigation on and off scenarios.

2. Data and methods

2.1. Datasets

We obtained the static irrigated area map from the Food and Agriculture Organization (FAO; Siebert et al 2013, 2015a). The irrigated area from FAO was updated recently and provided the irrigation extent of 2013. FAO irrigated area maps may differ from the actual area under irrigation due to the unaccounted cropping pattern and irrigated secondary crops (Ajaz et al 2019). The application of FAO irrigated area maps is more common in the climate and land surface model simulations as the dataset provides fractional information of the irrigated area in each grid (Ambika et al 2016). The datasets used in our study primarily cover the Indian landmass (Latitude: 5–40° N; Longitude: 65–110° E). We used the FAO version 5.0 irrigated area map that is available at a resolution of 0.083° (∼8–9 km approximately). We resampled the irrigated area from FAO to make it consistent with the WRF resolution (0.25°). The historic irrigation fraction (Historical Irrigation Datasets–HID; Siebert et al 2015a, 2015b) was used to evaluate the fractional increase in the irrigated area over a selected period. The HID is the newly developed irrigation map which represents the area equipped for irrigation (AEI) spanning for the period 1900–2015. HID maps are available at five arcmin resolution and use sub-national level statistics with different area extent of pasture and cropland (Siebert et al 2015a).

Land surface temperature (LST) at 4 km spatial resolution was obtained from National Oceanic and Atmospheric Administration (NOAA) Star Centre for Satellite Application and Research (NSTAR) from 1982 to 2018 (Yu et al 2017). We obtained solar-induced chlorophyll fluorescence (SIF, Li and Xiao 2019) for the 2000–2016 period, which represents plant photosynthetic activity (Jonard et al 2020). We examined the observed changes in LST and SIF during the crop growing season (November–February). Irrigation water use during the major crop growing season (November–March) is higher in comparison to the other seasons over the Indo-Gangetic Plain (Huang et al 2018). Therefore, we estimated the role of irrigation on atmospheric aridity during the growing season in India.

We estimated changes in leaf area index (LAI), normalized difference vegetation index (NDVI), and fraction of absorbed photosynthetic active radiation (FPAR) obtained from NOAA’s advanced very-high-resolution radiometer (AVHRR) satellite dataset (Loveland et al 2000). The net and gross primary
productivity (GPP) were obtained from the gross and dry matter products (GDMP and DMP) of Copernicus Global Land Operations Vegetation and Energy (CGLOPS-1; Buchhorn et al. 2017) for the 1999–2018 period. The DMP and GDMP were adequately scaled to estimate net primary productivity (NPP) and GPP for the growing period. We calculated the autotrophic respiration (AR), which is the contribution of CO₂ resired by plant roots (Bond-Lamberty et al. 2004). AR was estimated using the difference between GPP and NPP. The changes in the selected variables were estimated after interpolating them to 0.25° using nonparametric Mann–Kendall trend test (Mann 1945) and Sen's (Sen 1968) slope method. The growing season LAI is considered as a proxy of vegetation health (Chen et al. 2019, Wang et al. 2019). Daily gridded precipitation was obtained from the India Meteorological Department (IMD), which is available at 0.25° (Pai et al. 2014). ERA-5 reanalysis data (Dee et al. 2011) was obtained from the Copernicus climate data storage. ERA-5 dataset is available at 31 km spatial resolution and hourly temporal
resolution. We used hourly ERA-5 data of air temperature, relative humidity (RH), and SM to derive hourly VPD for the 1979–2018 period. Daily VPD was calculated using the methodology based on Ficklin and Novick (2017). We used the difference between saturation and actual vapor pressures for estimating the VPD from the ERA-5 reanalysis data. The saturation and actual vapor pressures were calculated based on the method given in Allen et al. (1998). The RH used for the estimation of actual vapor pressure was obtained using the Teten's formula (Teten 1930) with the parameters based on saturation over water (Buck 1981).

2.2. WRF simulations

The WRF 4.0 is a non-hydrostatic compressible model (Chen et al 2011). The WRF is a state-of-the-art weather forecasting tool used for operational forecast, real-time prediction, regional climate, and coupled-model application (Skamarock and Klemp 2019). The WRF multi-scheme mesoscale process was designed for numerical weather prediction; however, the model can be used for weather prediction and to understand regional climate dynamics (Chen et al 2011). The WRF can simulate regional and local scale hydrometeorological processes by dynamically linking land surface process, planetary boundary

Figure 2. Changes in VPD, RH, and SM during the growing period. (a) and (b) Changes in VPD for the period 1979–2018, (c)–(f) same as (a) and (b) but for RH, and SM, respectively. SM depth of 30 cm was considered for the analysis. VPD, RH, and SM were obtained from ERA-5 reanalysis. The changes were estimated using a nonparametric Mann–Kendall test. (b), (d) and (f) Changes estimated for the Indo-Gangetic Plain. The p-value less than 0.05 shows statistically significant change at 5% significance level.
Figure 3. Modulation of SM and atmospheric aridity by irrigation. (a) Standardized soil moisture index (SSI) estimated using 30 cm soil moisture based on the control (irrigation-off) simulation of WRF for the period 1980–2018 in Indo-Gangetic Plain, (b) anomaly composite of the three droughts for (a) surface temperature at 2 m, (c) SM, (d) VPD, (e) RH under the control simulation. (f)–(i) same as (b)–(e) but for the irrigation-on scenario. WRF simulations were conducted using the ERA-5 as boundary condition.

layer, cumulus development, advection of atmospheric moisture, and feedback from the energy and radiation budget at the surface layer (Sridhar 2013). The model follows a terrain-following hybrid-sigma vertical pressure coordinate system that extends from the surface to 50 hPa with constant pressure at the top (Harding and Snyder 2012).

We conducted simulations using WRF version 4.0 with ERA-5 reanalysis as the boundary condition for 1979–2018 period. The WRF simulations were conducted with the irrigation on and off scenarios to examine the influence of irrigation on SM and atmospheric aridity. The irrigation-on scenario represents the addition of required water to the soil in agricultural regions. Under the irrigation-off scenario, the model does not provide additional water to the soil. Our WRF simulations used the NOAH land surface model to simulate latent heat, sensible heat, and land surface temperature (Mitchell 2005). Terrestrial radiation processes in WRF are estimated using the Rapid Radiative transfer Model (RRTMG) scheme (Iacono et al 2008). We adopted the Kain–Fritsch (KF) scheme (Kain 2004) for convective parameterization to achieve a realistic pattern and extent of precipitation (Qian et al 2013). Also, we used Mellor–Yamada–Janjic (MYJ) scheme for the planetary boundary physical mechanism (Janjić 1994). Surface variables including 2 m temperature, 10 meter wind, mean sea level pressure, sea surface temperature, land surface temperature, snow density, snow depth, soil temperature at different levels, surface pressure, and volumetric soil water from ERA-5 were used to conduct the control (irrigation-off) simulations at 0.25° spatial resolution. Moreover, we used pressure level variables, which include specific humidity (SH), 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 from ERA-5. The irrigation scheme implemented in the WRF model starts applying water when
the root-zone SM falls below the field capacity (Kain 2004, Qian et al 2013, Yang et al 2019). More details on the irrigation scheme can be obtained from the previous studies (Ozdogan et al 2010, Yang et al 2019).

The WRF simulations in control (no-irrigation) scenarios were compared with ERA-5 datasets. We estimated the standardized SM index (SSI, Xu et al 2018) using the WRF simulated SM under the irrigation on and off scenarios to evaluate drought condition for the 1979–2018 period. We compared SH, air temperature, and VPD from the WRF simulations against the ERA-5 reanalysis under the control scenarios. Moreover, we examined the role of irrigation on atmospheric aridity (VPD) and drought using WRF simulations.

3. Results and discussion

3.1. Influence of irrigation on land surface temperature and vegetation growth

The net irrigated area has significantly increased in India after the 1950s (figures S1(a) and (b) are available online at stacks.iop.org/ERL/15/124060/mmedia). The Indo-Gangetic Plain is one of the most extensively irrigated regions in India (figure S1(a)). The Indo-Gangetic Plain witnessed changes in LST and vegetation growth during the past few decades (figure 1(a)), which might be partly contributed by the irrigation expansion (figures 1 and S1). We found that LST has considerably (0.4–1.7 °C) declined during the growing season over the Indo-Gangetic Plain and in other parts of India (figure 1(b)). This significant cooling of 0.8 °C (P-value = 0.03) over the Indo-Gangetic Plain in satellite-based LST is associated with the irrigation expansion (Cook et al 2011, 2015, Thiery et al 2017, Ambika and Mishra 2019).

On the other hand, a substantial increase in SIF was found over the Indo-Gangetic Plain and in different regions of India during 2000–2018 (Asoka and Mishra 2015, Chen et al 2019). For instance, SIF averaged over the Indo-Gangetic Plain has increased (change = 2.81 mW m\(^{-2}\) nm\(^{-1}\) sr\(^{-1}\); here SIF unit is the radiance of a surface per unit wavelength) significantly (P-value = 0.00001) during 2000–2016 period (figure 1(e)). Greening in vegetation (Asoka and Mishra 2015, Chen et al 2019) and cooling in LST (Ambika and Mishra 2019) show the influence of irrigation over the intensively irrigated Indo-Gangetic Plain (figures 1(b) and (c)).

Next, we estimated the changes in NDVI, LAI, and FPAR during the 1982–2018 period (figure S2). We found a greening trend across India (figure S2). However, the increase in NDVI, LAI, and FPAR was more prominent and significant (P-value = 0.0001) over the Indo-Gangetic Plain during the 1982–2018 period (figure S2). This significant rise in greening over the Indo-Gangetic Plain can be partly attributed to the increase in an irrigated area in the region (Ambika et al 2016, Ambika and Mishra 2019, Thiery et al 2020) (figure S1(b)). Other human land management practices (e.g. fertilizer application, improved seed varieties) can also contribute to greening over the Indo-Gangetic Plain (Schmidhuber and Tubiello 2007, Brown and Funk 2008). In addition to greening trend, we examined the changes in GPP and NPP, and AR during the recent period (2000–2018) based on the availability of the satellite datasets. GPP, NPP, and AR have significantly (P-value < 0.05) increased over the Indo-Gangetic Plain (figure S3). Greening trends and an increase in the GPP and NPP further confirmed the potential role of irrigation over the Indo-Gangetic Plain. However, the land surface cooling due to irrigation is attributed to an increase in evapotranspiration (Shah et al 2019) and latent heat flux (Seneviratne et al 2010). Besides, greening and increase in NPP indicate the modulation of SM deficit due to irrigation (Ozdogan 2011).

3.2. Changes in atmospheric aridity and SM

Low SM and high atmospheric vapor pressure deficit (VPD) are considered as the two main stressors on ecosystem productivity during drought (Zhou et al 2019b). VPD is a measure of atmospheric aridity and drives evapotranspiration (Zhou et al 2019a). We estimated changes in VPD, RH, and SM from ERA-5 reanalysis for 1979–2018 period (figure 2). We find that the intensive irrigation over the Indo-Gangetic Plain has resulted in cooling and greening (figure 1). VPD from ERA-5 reanalysis has significantly (P-value = 0.00002) declined (~1.38 kPa) during the growing season over the Indo-Gangetic Plain for 1979–2018 period (figures 2(a) and (b)). The decline in atmospheric aridity and the increase in vegetation health can be attributed to increased soil moisture (figures 2(c) and (d)). In addition, during irrigation, the near-surface temperature is expected to be cooler and moist static energy is higher near the middle to low boundary layer (Qian et al 2013). Moreover, RH in the irrigated regions is higher than the non-irrigated regions (Qian et al 2013). We find an increase in RH from ERA-5 during the growing season across India, which can be attributed to irrigation and the warming climate (Sherwood and Huber 2010, Fischer and Knutti 2013) (figure 2(c)). However, the increase (2.05%) in RH over the Indo-Gangetic Plain was more prominent (P-value = 0.0052). As expected, SM over the Indo-Gangetic Plain has significantly (P-value < 0.05) increased (1.63 m\(^3\) m\(^{-2}\)) during 1979–2018, indicating the potential role of increased irrigation in the region (figures 2(e) and (f)).

Our analysis based on ERA-5 reanalysis shows that irrigation over the Indo-Gangetic Plain modulates both SM and atmospheric aridity by increasing RH. The increase in RH is due to increased evapotranspiration and latent heat flux (Seneviratne et al 2010, Zhou et al 2019a). Since ERA-5 reanalysis assimilates observations, it partly captures the influence of irrigation on land and atmospheric processes (Zohaib and
Choi 2020). Our results show that VPD–RH (correlation = −0.95) and VPD–SM (correlation = −0.84) are negatively correlated over the Indo-Gangetic Plain (figure S4) indicating that increased soil moisture due to irrigation results in increased RH (Kueppers et al. 2007), which in turn, reduces atmospheric aridity. Since precipitation during the growing season is not sufficient to meet the crop water requirements, irrigation plays a vital role in food production over the Indo-Gangetic Plain (figure S5). The estimated anomaly composites of VPD, RH, and SM show a reduction in atmospheric aridity and an increase in RH and SM during drought over the Indo-Gangetic Plain (figure S6). Since LAI is negatively associated with atmospheric aridity while positively related to RH (figure S7), decreased VPD and increased RH have supported greening in India.

A significant increase in VPD stimulates high evaporative demand, reduces SM, and results in enhanced heating and drying in the lower level atmosphere (Lansu et al. 2020). However, increased SM due to irrigation in the Indo-Gangetic Plain alleviates exacerbation of atmospheric aridity during droughts (Cook et al. 2011, Thierry et al. 2017, 2020). Atmospheric circulation plays a substantial role in VPD–SM coupling through blocking (Pfahl et al. 2015, Rodrigues and Woollings 2017), tropospheric warming, and subsidence (Helama et al. 2009). Our results based on ERA-5 reanalysis show that irrigation influences land–atmospheric interaction and modulates SM drought and atmospheric aridity. Moreover, modulation in SM by irrigation can influence atmospheric circulation (Koster et al. 2016, Zhou et al. 2019a).

3.3. Modulation of SM drought and atmospheric aridity by irrigation
Irrigation considerably influenced greening and cooling during the growing season over the Indo-Gangetic Plain, as shown by the satellite-based observations (figures 1, 2 and S2, S3). Moreover, ERA-5 reanalysis showed a substantial increase in SM while a decline in atmospheric aridity in the region during 1979–2018. We used WRF simulations for causal attribution of the land–atmospheric feedback to further diagnose the role of irrigation on soil drought and atmospheric aridity (figure 3). The WRF simulations for the control (irrigation-off) and irrigation-on scenarios were conducted using ERA-5 reanalysis as a boundary condition. The control simulations from the WRF model capture the spatial variability in SH, air temperature, and VPD reasonably well for the 1979–2018 period (figure S8).

We estimated SSI (Xu et al. 2018) using the root-zone (30 cm) SM to examine the role of irrigation during droughts (figure 3(a)). The three major growing season droughts that occurred in 1980, 1988, and 1995 were identified to examine the role of irrigation using the WRF simulations (figure 3(a)). Positive surface temperature (∼1 K)
A K Ambika and V Mishra

Figure 5. Role of irrigation on energy partitioning over the land surface. (a) Difference in latent heat between irrigation on and off (irrigation–no irrigation) scenarios during the growing period for 1979–2018, (b) same as (a) but for sensible heat, (c) same as (a) but for net radiation, (d) same as (a) but for Bowen ratio, and (e)–(h) is kernel density function for (a)–(d) for the grids in the Indo-Gangetic Plain. 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 irrigation was estimated using the WRF simulations for the 1979–2018 period using ERA-5 as boundary conditions.

and VPD (∼0.4 kPa) anomalies persist during the growing season drought across north India under control (no-irrigation) simulations (figures 3(b), (d) and S9). Increased atmospheric aridity depletes soil moisture (∼−0.1 m³ m⁻³), leading to low RH (5–10%) under the growing season droughts (figures 3(c) and (e)). We used WRF simulations with the irrigation-on scenario to examine the modulation of soil drought and atmospheric aridity by irrigation. Consistent with the satellite observations and ERA-5 reanalysis, irrigation cools down the increased land surface temperature caused by droughts (figure 3(f)). Similarly, irrigation during the growing season enhances SM and RH over the Indo-Gangetic Plain (figures 3(g) and (i)). Due to increased SM and RH, the atmospheric aridity declines during the growing season droughts (figure 3(h)). Moreover, irrigation during droughts results in increased sea level pressure and reduced planetary boundary layer (figure S10). These results further show the modulation of soil drought and atmospheric aridity due to irrigation, which plays a crucial role in triggering short- or long-term droughts (Zhou et al 2019a, Pendergrass et al 2020).

Next, we examined the role of irrigation in alleviating the growing season atmospheric aridity and SM drought using WRF simulations for irrigation-on and off scenarios during 1979–2018 (figure 4). We estimated the difference in VPD, SM, SH, and 2 m air temperature under the irrigation-on and irrigation-off (irrigation-on–irrigation-off) scenarios (figure 4). The difference in climatological mean VPD, SM, surface temperature, and SH for the growing season showed a considerable influence of irrigation across India depending on the irrigated area fraction (figure 4). However, we noted a more prominent influence of irrigation over the Indo-Gangetic Plain (figure 4(a)). The difference in the irrigation-on and off scenarios from the WRF showed the cooling of air temperature (0.5–1.0 °C), increase in SM (0.7–1.0 m³ m⁻³) and SH, and a reduction in atmospheric aridity (0.3–0.5 kPa) (figures 4(a)–(d)).

We analyzed the surface energy budget from the WRF simulations under irrigation on and off scenarios to understand the physical mechanism behind the modulation of soil moisture drought and atmospheric aridity by irrigation (figures 5 and S11). Irrigation causes an increase in latent heat flux (Marcella and Eltahir 2014), reduction in sensible heat flux (figures 5 and S11). Increase in latent heat is compensated by the decrease in sensible heat, leading to cooling (figure 5(d)). Irrigation alters the partitioning of energy budget over the land. For instance, Bowen’s ratio, which is the ratio of sensible and latent heat flux, declines significantly (p < 0.05, figures 5(d) and (h)) due to irrigation. Therefore, the cooling over the Indo-Gangetic Plain can be attributed to changes in the land surface energy budget (figures 5(e) and (f)), which results in reduced sensible heat flux (figure S11). The increased evapotranspiration and
humidity cause reduced atmospheric aridity (VPD). Atmospheric aridity is reduced by the increase in moist-enthalpy in the lower atmosphere due to the reduction in planetary boundary layer height (figures S10 and S11) (Gentine et al 2013). Overall, we found that irrigation over the Indo-Gangetic Plain modulates SM drought and atmospheric aridity through the partitioning of the land surface energy budget.

4. Summary and conclusions

A large abstraction of groundwater for irrigation and changes in precipitation resulted in a rapid decline in groundwater storage in the Indo-Gangetic Plain (Rodell et al 2009, Tiwari et al 2009, Asoka et al 2017, 2018). Irrigation contributes to a significant increase in greening, GPP, NPP indicated the potential role of irrigation on vegetation growth in the last few decades in India (Asoka and Mishra 2015, Chen et al 2019). However, irrigation over the Indo-Gangetic Plain resulted in significant cooling, increased SM, and reduced atmospheric aridity during 1979–2018. Simulations conducted using WRF showed that irrigation considerably modulates surface temperature, VPD, and SM during the droughts. Therefore, the decline in primary productivity (Ciais et al 2005, Zhao and Running 2010) due to SM deficit and increased atmospheric aridity can be partly managed by irrigation. Irrigation changes the land surface energy budget and land–atmospheric coupling, which are the primary drivers of modulation of SM drought and atmospheric aridity. Compound extremes of concurrent SM drought and atmospheric aridity can be disastrous for natural and social systems, which can be exacerbated by land–atmospheric feedbacks (Zhou et al 2019a). Our results show that irrigation can modulate SM drought and atmospheric aridity, therefore, can reduce the risk of compound extremes of low SM and high VPD. Since a majority of global climate models do not explicitly represent irrigation for the future projections of climate (Puma and Cook 2010, Cook et al 2015), primary production (Zhao and Running 2010), and carbon sequestration, the important role of irrigation on temperature, primary productivity, SM drought, and atmospheric aridity is not well represented.

Acknowledgments

Authors acknowledge the data availability from the ERA-5 reanalysis. All the datasets used in this study can be obtained with a reasonable request to the corresponding author. The work was partly funded by the Ministry of Earth Sciences.

ORCID iDs

Anukesh Krishnankutty Ambika https://orcid.org/0000-0002-7791-499X

Vimal Mishra https://orcid.org/0000-0002-3046-6296

References

Ajaz A, Karimi P, Cai X, De Frature C and Akhter M S 2019 Statistical data collection methodologies of irrigated areas and their limitations: a review IRRIG. DRAIN. 68 702–13
Alaudin M and Quiggin J 2008 Agricultural intensification, irrigation and the environment in South Asia: issues and policy options Ecol. Econ. 65 111–24
Allen R G, Pereira L S, Raes D and Smith M 1998 Crop evapotranspiration—guidelines for computing crop water requirements—FAO Irrigation and drainage paper 56 Fao Rome 300 D05109 (https://www.sccourt.org/complex/105CV049053/volume3/1726168e_5xAGWAxk.pdf)
Alter R E, Im E S and Eltahir E A B 2015 Rainfall consistently enhanced around the Geiza scheme in East Africa due to irrigation Nat. Geosci. 8 763–7
Ambika A K and Mishra V 2019 Observational evidence of irrigation influence on vegetation health and land surface temperature in India Geophys. Res. Lett. 46 13441–13451
Ambika A K, Wardlow B and Mishra V 2016 Remotely sensed high resolution irrigated area mapping in India for 2000–2015 Sci. Data 3 1–14
Asoka A, Gleeson T, Wada Y and Mishra V 2017 Relative contribution of monsoon precipitation and pumping to changes in groundwater storage in India Nat. Geosci. 10 109
Asoka A and Mishra V 2015 Prediction of vegetation anomalies to improve food security and water management in India Geophys. Res. Lett. 42 5290–8
Asoka A, Wada Y, Fishman R and Mishra V 2018 Strong linkage between precipitation intensity and monsoon season groundwater recharge in India Geophys. Res. Lett. 45 5336–44
Badger A M and Dirmeyer P A 2015 Climate response to Amazon forest replacement by heterogeneous crop cover HydroL. Earth Syst. Sci. 19 4547–4557
Betts A K, Ball J H, Beljaars A C M, Miller M J and Viterbo P A 1996 The land surface-atmosphere interaction: a review based on observational and global modeling perspectives J. Geophys. Res. Atmos. 101 7299–23
Bond-Lamberty B, Wang C and Gower S T 2004 A global relationship between the heterotrophic and autotrophic components of soil respiration Glob. Change Biol. 10 1756–66
Brown M E and Funk C C 2008 Food security under climate change 319 580–581
Buchhorn M, Smets B, Bertels L, Lesiv M and Tsindibazar N 2017 Copernicus land global operations ‘Vegetation and Energy’ CGLIOPS-1. Product user manual (https://icdc.cen.uni-hamburg.de/fileadmin/user_upload/icdc_Dokumente/COPERNICUS_LAND/CGLIOPS1_PUM_LAI1km-V2_11.33.pdf)
Buck A L 1981 New equations for computing vapor pressure and enhancement factor J. Appl. Meteorol. 20 1527–32
Chen C, Park T, Wang X, Piao S, Xu B, Chaturvedi R K, Fuchis R, Brovkin V, Ciais P and Fensholt R 2019 China and India lead in greening of the world through land-use management Nat. Sustain. 2 122–9
Chen F, Kusaka H, Bornstein R, Ching I, Grimmond C S B, Grossman-Clarke S, Lorian T, Manning K W, Martilli A and Miao S 2011 The integrated WRF/urban modelling system: development, evaluation, and applications to urban environmental problems Int. J. Climatol. 31 273–88
Chen F, Warner T T and Manning K 2001 Sensitivity of orographic moist convection to landscape variability: a study of the Buffalo Creek, Colorado, flash flood case of 1996 J. Atmos. Sci. 58 3204–23
Ciais P, Reichstein M, Viovy N, Granier A, Ogée J, Allard V, Aubinet M, Buchmann N, Bernhofer C and Carrara A 2005
Europe-wide reduction in primary productivity caused by the heat and drought in 2003 Nature 437 529–33
Cook B, Puma M J and Krakauer N Y 2011 Irrigation induced surface cooling in the context of modern and increased greenhouse gas forcing Clim. Dyn. 37 1587–600
Cook B I, Shukla S P, Puma M J and Nazarenko L S 2015 Irrigation as an historical climate forcing Clim. Dyn. 44 1715–30
Dee D P, Uppala S M, Simmons A J, Berrisford P, Poli P, Kobayashi S, Andrae U, Balmaseda M A, Balsamo G and Bauer D P 2011 The ERA-Interim reanalysis: configuration and performance of the data assimilation system Q. J. R. Meteorol. Soc. 137 553–97
Ficklin D L and Novick K A 2017 Historic and projected changes in vapor pressure deficit suggest a continental-scale drying of the United States atmosphere J. Geophys. Res. Atmos. 122 79
Fischer E M and Knutti R 2013 Robust projections of combined humidity and temperature extremes Nat. Clim. Change 3 126–30
Gentine P, Holtslag A M, D’Andrea F and Ek M 2013 Surface and atmospheric controls on the onset of moist convection over land J. Hydrometeorol. 14 1443–62
Green J K, Seneviratne S I, Berg A M, Findell K L, Hageman S, Lawrence D M and Gentine P 2019 Large influence of soil moisture on long-term terrestrial carbon uptake Nature 565 476–9
Harding K J and Snyder P K 2012 Modeling the atmospheric response to irrigation in the great plains Part I: general impacts on precipitation and the energy budget J. Hydrometeorol. 13 1667–86
Helama S, Meriläinen J and Tuomenvirta H 2009 Multicentennial megadrought in northern Europe coincided with a global El Niño–Southern oscillation drought pattern during the medieval climate anomaly Geogly 37 175–8
Huang Z, Hejazi M, Li X, Tang Q, Vernon C, Leng G, Liu Y, Dole P, Eisner S and Gerten D 2018 Reconstruction of global gridded monthly sectoral water withdrawals for 1971–2010 and analysis of their spatiotemporal patterns Hydrofl. Eart Syst. Sci. 22 2117–33
Iacono M J, Delamer J S, Mlawer E J, Shephard M W, Clough S A and Collins W D 2008 Radiative forcing by long-lived greenhouse gases: calculations with the AER radiative transfer models J. Geophys. Res. Atmos. 113 D13103
Im E-S, Marcella M P and Eltahir E A B 2014 Impact of potential large-scale irrigation on the African monsoon and its dependence on location of irrigated area J. Clim. 27 994–1009
Janjic Z I 1994 The step-mountain eta coordinate model: further developments of the convection, viscous sublayer, and turbulence closure schemes Mon. Weather Rev. 122 927–45
Jonard F, De Canni S, Brüggemann N, Gentine P, Gianiotti D J S, Lobet G, Miralles D G, Montzka C, Pagan B R and Rascher U 2020 Value of sun-induced chlorophyll fluorescence derived from AGRS. Res. Lett. 2117–33
Kain J S 2004 The Kain–Fritsch convective parameterization: an update J. Appl. Meteorol. 43 170–81
Kang S and Eltahir E A B 2019 Impact of irrigation on regional climate over Eastern China Geophys. Res. Lett. 46 5499–505
Koster R D, Chang Y, Wang H and Schubert S D 2016 Impacts of local soil moisture anomalies on the atmospheric circulation and on remote surface meteorological fields during boreal summer: a comprehensive analysis over North America J. Clim. 29 745–64
Koster R D, Dirmeyer P A, Guo Z, Bonan G, Chan E, Cox P, Gordon C T, Kanse S, Kowalczyk E and Lawrence D 2004 Regions of strong coupling between soil moisture and precipitation Science 305 1138–40
Kueppers L M, Snyder M A and Sloan L C 2007 Irrigation cooling effect: regional climate forcing by land-use change Geophys. Res. Lett. 34 L03705
Lansu E M, van Heerwaarden C C, Stegehuis W P and Teuling A J 2020 Atmospheric aridity and apparent soil moisture drought in European forest during heat waves Geophys. Res. Lett. 47 e2020GL087091
Li X and Xiao J 2019 A global, 0.05-degree product of solar-induced chlorophyll fluorescence derived from OCO-2, MODIS, and reanalysis data Remote Sens. 11 517
Lo M and Famiglietti J S 2013 Irrigation in California’s central valley: droughts of the southwestern US water cycle Geophys. Res. Lett. 40 301–6
Lobell D B, Bonfils C J, Kueppers L M and Snyder M A 2008 Irrigation cooling effect on temperature and heat index extremes Geophys. Res. Lett. 35 1–5
Los S O, Collatz G J, Bounoua L, Sellers P J and Tucker C J 2001 Global interannual variations in sea surface temperature and land surface vegetation, air temperature, and precipitation J. Clim. 14 1535–49
Lovald T R, Reed B C, Brown J F, Olenh D O, Zhu Z, Yang L and Merchant J W 2000 Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data Int. J. Remote Sens. 21 1303–30
Lu Y, Harding K and Kueppers L 2017 Irrigation effects on land–atmosphere coupling strength in the United States J. Clim. 30 3671–83
Mann H B 1945 Nonparametric tests against trend Econom. J. Econom. Soc. 13 245–59
Marcella M P and Eltahir E A B 2014 Introducing an irrigation scheme to a regional climate model: a case study over West Africa J. Clim. 27 5708–23
Miralles D G, Teuling A J, Van Heerwaarden C C and de Arellano J V G 2014 Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation Nat. Geosci. 7 345
Miralles D G, Van Den Berg M J, Teuling A J and De Jeu R A M 2012 Soil moisture–temperature coupling: a multiscale observational analysis Geophys. Res. Lett. 39 L21707
Mishra V, Shah R, Azhar S, Shah H, Modi P and Kumar R 2018 Reconstruction of droughts in India using multiple land-surface models (1951–2015) Hydrol. Earth Syst. Sci. 22 2269–84
Mitchell K 2005 The community Noah land–surface model (LSM) User’s Guide. Recover. from ftp://ftp.ncep.noaa.noaa.gov/mmb/gep/ldas/noahslm/ver_2_7
Narayanoomathy A 2011 Development and composition of irrigation in India: temporal trends and regional patterns Irrig. Drain 60 431–45
Oki T, Agata Y, Kanae S, Sarushashi T, Yang D and Musiaka K 2001 Global assessment of current water resources using total runoff integrating pathways Hydrofl. Sci. J. 46 983–45
Ozdogan M 2011 Exploring the potential contribution of irrigation to global agricultural primary productivity Global Biog. Cycles 25 GB3016
Ozdogan M, Rodel M, Beaudoin H K and Toll D L 2010 Simulating the effects of irrigation over the United States in a land surface model based on satellite-derived agricultural data J. Hydrometeorol. 11 171–84
Pai D S, Srivastava L, Rajeevan M, Sreebhi O P, Sarthab N S and Mukhopadhay B 2014 Development of a new high spatial resolution (0.25 × 0.25) long period (1901–2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region Mqauam 65 1–18
Pei L, Moore N, Zhong S, Kendall A D, Gao Z and Hyndman D W 2016 Effects of irrigation on summer precipitation over the United States J. Clim. 29 3541–58
Pendergrass A G, Meehl G A, Pulwarty R, Hobins M, Hoell A, Aghakouchak A, Bonfils C J W, Gallant A J E, Hoering M and Hofmann D 2020 Flash droughts present a new challenge for seasonal-to-seasonal prediction Nat. Clim. Change 10 191–9
Pfahl S, Schwierz C, Croci-Marspoli M, Grams C M and Wernli H 2015 Importance of latent heat release in ascending air streams for atmospheric blocking Nat. Geosci. 8 610–4
Piao S, Wang X, Park T, Chen C, Lian X, He Y, Bjerke J W, Chen A, Ciais P and Temmermink H 2019 Characteristics, drivers and feedbacks of global greening Nat. Rev. Earth Environ. 1 1–14

Pieček R A, Walko R L, Steyaert I T, Vidale P L, Liston G E, Lyons W A and Chase T N 1999 The influence of anthropogenic landscape changes on weather in south Florida Mon. Weather Rev. 127 1663–73

Puma M J and Cook B I 2010 Effects of irrigation on global climate during the 20th century J. Geophys. Res. Atmos. 115 D16120

Qian Y, Huang M, Yang B and Berg L K 2013 A modeling study of irrigation effects on surface fluxes and land–air–cloud interactions in the Southern Great Plains J. Hydrometeorol. 14 700–21

Rodell M, Velicogna I and Famiglietti J S 2009 Satellite-based estimates of groundwater depletion in India Nature 460 999

Rodrigues R R and Woodings T 2017 Impact of atmospheric blocking on South America in austral summer J. Clim. 30 1821–37

Schmidhuber J and Tubiello F N 2007 Global food security under climate change Proc. Natl Acad. Sci. 104 19703–8

Sen P K 1968 Estimates of the regression coefficient based on Kendall’s tau J. Am. Stat. Assoc. 63 1379–89

Seneviratne S I, Corti T, Davin E L, Hirschi M, Jaeger E B, Lehner I, Orlowsky B and Teuling A J 2010 Investigating soil moisture–climate interactions in a changing climate: a review Earth-Sci. Rev. 99 125–61

Shah H L, Zhou T, Huang M and Mishra V 2019 Strong influence of irrigation on water budget and land surface temperature in Indian sub-continental river basins J. Geophys. Res. Atmos. 124 11220–41

Yu Y, Liu Y, Liu F and Wang Q 2017 Temporal trends of surface urban heat islands and associated determinants in major Chinese cities Sci. Total Environ. 609 742–54

Sridhar V 2013 Tracking the influence of irrigation on land surface fluxes and boundary layer climatology J. Contemp. Water Res. Educ. 152 79–93

Tetens O 1930 Uber einige meteorologische Begriffe Z. Geophys. 6 297–309

Thiery W, Davin E L, Lawrence D M, Hirsch A L, Hauser M and Seneviratne S I 2017 Present-day irrigation mitigates heat extremes J. Geophys. Res. Atmos. 122 1403–22

Thiery W, Visser A J, Fischer E M, Hauser M, Hirsch A L, Lawrence D M, Lejeune Q, Davin E L and Seneviratne S I 2020 Warming of hot extremes alleviated by expanding irrigation Nat. Commun. 11 1–7

Tiwari V M, Wahr J and Swenson S 2009 Dwindling groundwater resources in northern India, from satellite gravity observations Geophys. Res. Lett. 36 L18401

Wang L, Chang Q, Li F, Yan L, Huang Y, Wang Q and Luo L 2019 Effects of growth stage development on paddy rice leaf area index prediction models Remote Sens. 11 361

Xu Y, Wang L, Ross K W, Liu C and Berry K 2018 Standardized soil moisture index for drought monitoring based on soil moisture active passive observations and 36 years of North American land data assimilation system data: a case study in the Southeast United States Remote Sens. 10 301

Yang Z, Qian Y, Liu Y, Berg L, Hu H, Dominguez F, Yang B, Feng Z, Gustafsson J W I and Huang M 2019 Irrigation impact on water and energy cycle during dry years over the united states using convection-permitting WRF and a dynamical recycling model J. Geophys. Res. Atmos. 124 11220–41

Yao R, Wang L, Huang X, Niu Z, Liu F and Wang Q 2017

Zaveri E and Lobell D B 2019 The role of irrigation in changing climate during the 20th century J. Geophys. Res. Atmos. 124 11220–41

Zhao M and Running S W 2010 Drought-induced reduction in global terrestrial net primary production from 2000 through 2009 Science 329 940–3

Zhou S, Park Williams A, Berg A M, Cook B I, Zhang Y, Hagemann S, Lorenz R, Seneviratne S I and Gentine P 2019a Land–atmosphere feedbacks exacerbate concurrent soil drought and atmospheric aridity Proc. Natl Acad. Sci. USA 116 18848–53

Zhou S, Zhang Y, Williams A P and Gentine P 2019b Projected increases in intensity, frequency, and terrestrial carbon costs of compound drought and aridity events Sci. Adv. 5 eaau5740

Zohaib M and Choi M 2020 Satellite-based global-scale irrigation water use and its contemporary trends Sci. Total Environ. 714 136719