Amplified warming induced by large-scale application of water-saving techniques

Jing Fu,1 Shaozhong Kang,1∗, Lu Zhang,1 Xiaolin Li,1 Pierre Gentine3 and Jun Niu1

1 Center for Agricultural Water Research in China, China Agricultural University, Beijing 100083, People’s Republic of China
2 CSIRO Land and Water, Canberra, ACT, Australia
3 Department of Earth and Environmental Engineering, Columbia University, New York, NY 10027, United States of America
∗ Author to whom any correspondence should be addressed.
E-mail: kangsz@cau.edu.cn

Keywords: water-saving techniques (WSTs), land management measures, warming effect, regional climate change, threshold, water-scarce regions

Abstract
Large-scale agricultural activities can exacerbate global climate change. In the past three decades, over 5 Mha of cultivated land have been equipped with water-saving techniques (WSTs) in Northwest China to cope with water scarcity. However, the effect of WSTs on local climate and its mechanisms are not yet understood. Here, we have quantified the local climatic effect by comparing temperature and humidity at controlled and irrigated sites before and after the large-scale implementation of WST. Results show that the substantial reduction in irrigation water use has led to an average increase of 0.3 °C in growing-season temperature and reduced relative humidity by 2%. Near-surface air temperature responds nonlinearly to percentage area of WST and a threshold value of 40% is found before any noticeable warming effect over the study area. Moreover, it is found that regions with relatively humid climates respond more significantly to WST. This study reveals the mechanism of WST on near-surface climate and highlights the importance of incorporating this feedback into sustainable water management and land-surface models for assessing the impact of irrigated agriculture on regional climate change.

1. Introduction
The continuous rise in atmospheric concentrations of CO2 and other greenhouse gases (GHGs) has led to significant global warming (Solomon et al 2009, Friedlingstein et al 2010, Jiménez-de-la-Cuesta and Mauritsen 2019). Apart from GHG emission, large-scale anthropogenic activities such as irrigation may have comparable or even stronger impacts on local climate (Bonfils and Lobell 2007, Lobell et al 2009). It is reported that agricultural activities have significantly changed 40% of the Earth’s land surface and are one of the major drivers of global environmental changes in the 20th century (Matson et al 1997, Green et al 2005, Sacks et al 2009, Singh et al 2018). On the other hand, the rapid growth in need for global food production is posing threats to water security. Thus, water-saving techniques (WSTs) aiming to reduce irrigation water is considered one of the most important solutions to water scarcity (Perry et al 2017, Zhou et al 2021), especially in large irrigated areas in arid and semi-arid regions such as the North China Plain, Central Asia and North India. Here we focus on the arid inland region of Northwest China located in the center of the Eurasian continent, with a land area of nearly 2 million km². Large-scale application of WSTs (e.g. drip irrigation under film mulch) have taken place since the 1980s to promote high-efficiency agriculture. As the proportion of water saving irrigation area (WSTA) in the total irrigated area has reached 88%, i.e. 5.16 million ha, the average irrigation water use per unit area (i.e. irrigation water use intensity (IWUI)) over Northwest China has been reduced from 2232 mm yr⁻¹ in the 1980s to 890 mm yr⁻¹ in 2018 (figure 1). While reaching its initial goal to increase agricultural productivity,
WST also caused changes in near-surface climate by affecting land processes such as surface radiation and energy balance.

Land management practices can affect the regional climate, mainly by changing the surface radiation balance, affecting the partitioning of water vapor and sensible heat flux between land surface and the atmosphere (Boucher et al. 2004, Foley et al. 2005, Findell et al. 2017, McDermid et al. 2017). Some of the agricultural practices, including irrigation, double cropping, and crop dusting, are claimed to be climate-effective and can effectively alleviate some of the GHG-induced global warming through evaporative cooling (Lobell et al. 2006, Cook et al. 2015, Hirsch et al. 2017, Thiery et al. 2017, 2020), yet at the expense of increased water use. The increase in humidity caused by large-scale irrigation will increase the maximum wet bulb temperature of the North China Plain by 0.5 °C in RCP scenarios, exacerbating the deadly heatwaves and threatening the outdoor work of local farmers (Kang and Eltahir 2018).

On the other hand, conservation agriculture, which involves crop residue management and no-till farming, appears to generate an increase in air temperature as a result of decreased evapotranspiration due to a combined effect of both higher albedo and higher surface resistance (Gormley-Gallagher et al. 2020).

However, our understanding of the non-negligible roles of different land managements on regional land–atmosphere interactions remains limited, as it exhibits large variability across specific regions (Lobell and Bonfils 2008) and different land use types (Chen et al. 2018). Taking irrigation as an example, the scale of the irrigated land and the change of irrigation methods over time between different regions lead to significant variations in the corresponding changes in land surface characteristics and resulting land–atmosphere feedback. Therefore, it is necessary to explore the mechanisms of specific land management measures on the local climate in order to develop specific adaptive measures to regional climate change. In particular, the variabilities of changing patterns and their driving mechanisms of warming rate remain unexplained (Donat et al. 2017). Studies have shown that the temperature increase in Northwest China in the past few decades has been higher than the average over the whole of China and the globe (Li et al. 2012). We thus test the hypothesis that large-scale application of land management measures (e.g., WSTs), in addition to external factors like geographical location and atmospheric circulation, have resulted in the enhancement of regional warming (Donat et al. 2017). Specifically, the proposed hypothesis is that the application of large-scale WSTs in Northwest China has amplified the warming trend caused by increased GHG concentrations, though it has greatly improved water use productivity.

2. Materials and methods

2.1. Meteorological and irrigation data

We utilize the daily temperature ($T_{\text{mean}}$, $T_{\text{max}}$, $T_{\text{min}}$), precipitation, air pressure and relative humidity data from 75 meteorological stations located in the study area (between $73^\circ 40'\;E \sim 104^\circ 16'\;E$ and $34^\circ 25'\;N \sim 49^\circ 10'\;N$) from the National Meteorological Center. The distribution of meteorological stations is shown in figure 1. The spatial irrigation dataset is the fifth
version of the Global Map of Irrigated Areas (GMIA5) produced by Siebert et al (2015), with a spatial resolution of five arc-minutes. The feasibility of GMIA5 over the study area is tested by comparing it with China’s land use/cover datasets (CLUDs) provided by the Chinese Academy of Sciences and it shows that GMIA5 is able to represent the irrigation situation in Northwest China (table S1 (available online at stacks.iop.org/ERL/17/034018/mmedia)), WSTA and irrigation water intensity data are derived from China Water Resources Statistical Yearbook and Zhou et al (2020). Irrigation water intensity is calculated based on irrigation area and agricultural water consumption.

2.2. Influence of WST on temperature and relative humidity

According to GMIA5, the irrigation fraction (IF) of each meteorological station is extracted based on geographical location. We use the difference between the IRR station (irrigated sites equipped with WST, IF > 50%) and the matched CTL (the adjacent controlled station with IF < 10%) station to indicate the influence of water-saving irrigation on meteorological variables in the study area. The use of the controlled group aims to eliminate the influence of those large-scale background forcings. For details of the IRR and CTL sites, see table 1. The difference in meteorological variables (taking temperature as an example) is calculated as follows:

$$\delta T = \text{Average}(T_{\text{ctl}}) - \text{Average}(T_{\text{wst}})$$

$$= \frac{\sum_{i=1}^{n} (T_{\text{ctl}} - T_{\text{wst}})}{n}$$

(1)

where $\delta T$ represents the average temperature difference of the CTL group and IRR group; $T_{\text{ctl}}$ is the annual mean temperature for irrigated stations; $T_{\text{ctl}}$ is for controlled (nonirrigated) stations; $T_{\text{ctl}}$ is for the $i$th year and $n$ is the number of pairs.

Changes in temperature after the large-scale application of WST:

$$\Delta T_i = \overline{\delta T}_{1965-1991} - \delta T_i$$

(2)

where $\Delta T_i$ represents the warming effect of WST in the $i$th year ($i = 1992, \ldots, 2018$) and $\overline{\delta T}_{1965-1991}$ is the average value of $\delta T$ over 1965–1991. The change point is chosen as 1992 as the result of the Pettitt test based on IWUI. The nonparametric approach developed by Pettitt (1979) was used in this study to determine the occurrence of the change point. This approach detects a significant change in the mean of a time series when the exact time of the change is unknown. The test uses a version of the Mann–Whitney statistic $U_i$, $n$, that verifies if two samples $x_1, \ldots, x_i$ and $x_{i+1}, \ldots, x_n$ are from the same population.

The test statistic counts the number of times a member of the first sample exceeds a member of the second sample. The null hypothesis of Pettit’s test is the absence of a changing point. The method calculates a statistic and the associated probability $p$. If the $p$ value is less than 0.05, a significant change point exists, the time series is divided into two parts at the location of the change point. The Pettitt test has been widely used to detect change points in environmental studies.

2.3. Calculation of potential temperature

Potential temperature is utilized to eliminate errors induced by elevation, which is calculated as follows:

$$\theta = T \left( \frac{P_0}{P} \right)^{R/c_p}$$

(3)

where $T$ is the current absolute temperature, $R$ is the gas constant of air, and $c_p$ is the specific heat capacity at a constant pressure, $R/c_p = 0.286$ for air, $P_0$ is the standard reference pressure, usually taken as 1000 hPa.

### Table 1. Information of IRR (irrigated) and CTL (nonirrigated) gauging stations.

| IRR     | LON   | LAT   | IF (%) |
|---------|-------|-------|--------|
| Tacheng | 83    | 46.73 | 83     |
| Jinghe  | 82.9  | 44.62 | 70     |
| Shihezi | 86.05 | 44.32 | 75     |
| Caijishu| 87.53 | 44.2  | 72     |
| Yingin  | 81.33 | 43.95 | 84     |
| Yanshi  | 86.57 | 42.08 | 87     |
| Baihe  | 81.1  | 41.78 | 84     |
| Luntai  | 84.25 | 41.78 | 89     |
| Shache  | 77.27 | 38.43 | 83     |
| Pishan  | 78.28 | 37.62 | 62     |
| Yutan   | 81.65 | 36.85 | 66     |
| Gaotai  | 99.83 | 39.37 | 64     |
| Wuwei   | 102.67| 37.92 | 57     |

| CTL     | LON   | LAT   | IF (%) |
|---------|-------|-------|--------|
| Alashankou | 82.57 | 45.18 | 0      |
| Alashankou | 82.57 | 45.18 | 0      |
| Kelamayi  | 84.85 | 45.62 | 0      |
| Wurumuqi  | 87.65 | 43.78 | 0      |
| Alashankou | 82.57 | 45.18 | 0      |
| Kuerle    | 86.13 | 41.75 | 4      |
| Kuche     | 82.97 | 41.72 | 5      |
| Kuche     | 82.97 | 41.72 | 5      |
| Bachu     | 78.57 | 39.8  | 5      |
| Bachu     | 78.57 | 39.8  | 5      |
| Minfeng   | 82.72 | 37.07 | 0      |
| Dingxin   | 99.52 | 40.3  | 4      |
| Minqin    | 103.08| 38.63 | 0      |
2.4. The attribution method
To verify the warming effect derived from meteorological stations and investigate the intrinsic biophysical mechanisms, field data from controlled experiments (Tian et al. 2017, Zhao et al. 2021) and an attribution method are employed in this study. The attribution method is derived from the surface energy balance equation based on the theory of Lee et al. (2011) and the assumption that the paired sites (one irrigated with WST and the other with traditional irrigation) receive the same amounts of incoming shortwave and longwave radiation. Derivation of the equation starts from the surface energy balance equation:

\[ R_n = H + LE + G \]  \hspace{1cm} (4)

where \( H \) is sensible heat flux, \( LE \) is latent heat flux, and \( G \) is heat storage in the soil. \( H \) and \( LE \) is calculated as:

\[ H = \rho C_p \left( \frac{T_s - T_a}{r_a} \right) \]  \hspace{1cm} (5)

where \( \rho \) is air density, \( C_p \) is specific heat of air at constant pressure, \( T_s \) is air temperature at a blending height in the atmospheric boundary layer, \( T_a \) is surface temperature, \( r_a \) is aerodynamic resistance and \( \beta \) is Bowen ratio.

\[ LE = \frac{H}{\beta}. \]  \hspace{1cm} (6)

We obtain the solution for \( T_a \) by making use of (7)–(9):

\[ T_a = T_s - f_s(R_n - G) \]  \hspace{1cm} (7)

where \( f_s \) is the energy redistribution factor and is given by:

\[ f_s = \frac{r_a}{\rho C_p (1 + \frac{1}{\beta})}. \]  \hspace{1cm} (8)

We consider the background climate state to be identical between the two stations: the same amounts of incoming shortwave solar radiation and longwave radiation. The net radiation amounts for the two sites are \( R_n \) and \( R_n + \Delta R_n \), respectively. \( \Delta R_n \) is change in net radiation caused by surface albedo changes induced by the application of WST. By differentiating equation (8) and ignoring changes in \( G \) and making use of the solution for \( \Delta T_a \), we obtain the following solution for changes in air temperature \( \Delta T_s \):

\[ \Delta T_s = \left( \frac{\lambda_0}{1 + f} - \frac{\lambda_0}{F} \right) \Delta R_n + \left( \frac{\lambda_0}{(1 + f)^2} - \frac{\lambda_0}{F^2} \right) R_n \Delta f \]  \hspace{1cm} (9)

where \( \lambda_0 = 1/(4\sigma T_s^4) \), the surface temperature sensitivity due to the longwave radiation feedback (Lee et al. 2011), varying from 0.16 K/(W m\(^{-2}\)) to 0.19 K/(W m\(^{-2}\)) over the growing-season temperature range of the study region. \( f \) is energy redistribution factor, which is given by:

\[ f = \frac{\lambda_0 \rho C_p}{\lambda_0} \left( 1 + \frac{1}{\beta} \right) = \frac{\lambda_0}{f_a}. \]  \hspace{1cm} (10)

The change in energy redistribution factor \( \Delta f \) in (9) is calculated as:

\[ \Delta f = -\frac{\rho C_p}{4r_a \sigma T_s^4} \frac{\Delta \beta}{\beta^2}. \]  \hspace{1cm} (11)

Two terms are considered in equation (9) to calculate the WST-induced changes in air temperature: radiative forcing associated with albedo change (\( \Delta R_n \)) and the energy redistribution change associated with Bowen ratio (\( \Delta \beta \)).

\( R_n \) ranges from 115 to 130 W m\(^{-2}\) for growing-season while the averaged \( \Delta R_n \) ranges from –3 to –5 W m\(^{-2}\) d\(^{-1}\) and \( \Delta \beta \) is estimated as –0.17 to –0.25. The aerodynamic resistance \( r_a \) is estimated based on the logarithmic wind profile:

\[ r_a = \frac{\ln \left( \frac{z_{om}}{z_{oh}} \right) \ln \left( \frac{z_{oh}}{z_{oh}} \right)}{K_u} \] (FAO 1998), where \( z_{om} \) and \( z_{oh} \) are lengths estimated from crop height, \( K \) is von Karman’s constant and \( d \) is zero plane displacement height. The temperature change induced by \( r_a \) is ignored because crop heights show no significant difference between crops irrigated with WST and without WST in growing-season average.

3. Results
The average annual IWUI of the study area witnessed a turning point around 1992 after the large-scale application of WST based on the Pettitt test (figure 1(c)). However, though WST has greatly enhanced water productivity in Northwest China, potential negative climatic risks are noticed as IWUI declines. To isolate the influence of WST on local temperature, we first extracted the IF of the grid cell corresponding to each meteorological station and calculated the temperature difference between IRR (sites with IF > 50%) and CTL (sites with IF < 10%) groups and then compared the two periods before and after large-scale application of WST (1965–1991 and 1992–2018, figure S1). The warming trend of air temperature during the period 1992–2018 is 0.028°C yr\(^{-1}\) higher than that during 1965–1991 on average (figure S1(d)) and specifically, the magnitude increases as IF increases, indicating that the warming trend in the study area is related to anthropogenic land management measures. With the large-scale development of WST, the evaporative cooling effect of irrigation on the near-surface climate may be weakened, thus resulting in an exacerbated warming trend in the study area.

3.1. WST-induced amplification of warming
To further prove that the warming trend in the study area is related to the large-scale application of WST,
Figure 2. Seasonal distribution and inter-annual influence of land management on near-surface temperature in Northwest China. ((a)/(b), (c)/(d), (e)/(f)) for mean temperature ($T_{\text{mean}}$), maximum temperature ($T_{\text{max}}$), and minimum temperature ($T_{\text{min}}$), respectively; $\delta T$ represents $T_{\text{ctl}}$ minus $T_{\text{irr}}$; the growing-season temperature difference between controlled and irrigated stations. The time series are split into two stages: before (1965–1991) and after (1992–2018), the large-scale development of WST based on the Pettitt test of regional IWUI.

we use the temporal variation of $\delta T$ (difference in air temperature between CTL and IRR group) to represent the degree of impact of WST on temperature (figure 2). A seasonal pattern can be seen from the intra-annual distribution; the expansion of WST has little effect on the winter $\delta T$, i.e. during a period of weak cultivation, while the magnitude of the temperature difference shows great variability during the growing season (May–September), when local irrigation activities and vegetation growth are vigorous. Due to the effect of irrigation, the temperature during the growth period of IRR sites is lower than that of CTL sites, and it can be seen from figure 2 that the $\delta T$ between the two groups decreases after the large-scale application of WST. Before 1992, the average $\delta T$ caused by irrigation increased at a rate of 0.005 °C yr$^{-1}$, indicating a continued cooling effect of irrigation, but after 1992, the average $\delta T$ started to decrease at a rate of $-0.025$ °C yr$^{-1}$ due to the development of WST. These results indicate that the temperatures of the IRR and CTL sites are getting closer due to a decreased evaporative cooling effect with the expansion of WST. To further eliminate the effect of elevation on $\delta T_{\text{mean}}$, we compare the calculated $\delta T_{\text{mean}}$ with the difference in potential temperature ($\delta \theta$) and found the same changing pattern in most of the regions and little difference in magnitude in the regional averaged trend (figures S2 and S3). Downward trends in $\delta T$ are detected at most sites, with different changing times due to the different times of WST implementation. After the development of large-scale WST, the time series of the difference of various temperature variables ($\delta T_{\text{mean}}$, $\delta T_{\text{max}}$, $\delta T_{\text{min}}$) are highly correlated with the change in IWUI (table 2), which indicates that the large-scale application of WST weakens the evaporative cooling effect of irrigation on hot extremes caused by increased GHG concentration, resulting in an indirect warming effect.

We further calculated the changes in WST-induced temperature change ($\Delta T_a = \delta T_{1965-1991} - \delta T_{1992-2018}$) at each paired site before and after the large-scale application of WST as a function of IF and found that the climatic effect of large-scale WST is positively correlated with IF. At sites with larger

Table 2. Pearson’s correlation coefficient between the time series of climatic differences and IWUI. $\delta T_{\text{mean}}$, $\delta T_{\text{max}}$, and $\delta T_{\text{min}}$ are temperature differences between CTL and IRR groups; $\delta RH$ is difference in relative humidity between IRR and CTL.

| IWUI   | $\Delta T_{\text{mean}}$ | $\Delta T_{\text{max}}$ | $\Delta T_{\text{min}}$ | $\Delta RH$ |
|--------|--------------------------|--------------------------|--------------------------|-------------|
|        | 0.92$^a$                 | 0.90$^b$                 | 0.78$^a$                 | 0.92$^a$    |

$^a$Represents $p < 0.01$.
IF, the warming effect is more obvious, which can explain that the rise in the temperatures is to a certain extent caused by the land management activities (figures 3(a) and S4). On average, the differences in \( \delta T_{\text{mean}}, \delta T_{\text{max}} \) and \( \delta T_{\text{min}} \) decreased by 0.30 °C, 0.45 °C and 0.36 °C, respectively, after 1992, indicating that the effect of large-scale WST on local warming cannot be ignored. The intrinsic biophysical mechanism can be described as follows:

\[
\Delta T_a = \left( \frac{\lambda_0}{1+f} - \frac{\lambda_0}{f} \right) \Delta R_n - \left( \frac{\lambda_0}{(1+f)^2} - \frac{\lambda_0}{f^2} \right) R_n \Delta f
\]

in which the temperature change caused by WST is expressed as the response to changes in net radiation and energy redistribution processes. There are two terms considered in this equation to estimate the WST induced changes in air temperature: radiative forcing associated with albedo change (\( \Delta R_n \)) and the energy redistribution change (\( \Delta f \)) associated with changes in Bowen ratio (the ratio of sensible heat to latent heat). It is shown that calculated \( \Delta T_a \) ranges between 0.29 °C and 0.61 °C and the energy redistribution term plays the dominant role in changing local temperature explains a range of 0.27 °C and 0.59 °C while changes in net radiation slightly amplifies the warming by 0.009 °C and 0.026 °C.

3.2. WST-induced drying effect

By analyzing the timeseries of \( \delta RH \) between IRR and CTL sites, we found that the large-scale development of WST also makes the air drier near the surface. The seasonal variation in \( \delta RH \) is similar to that of \( \delta T \) (figure 4(a)), with a greater change occurring during the growing season, when evapotranspiration is stronger and thus has more impact on both temperature and humidity. Before the development of WST, \( \delta RH \) in the growing season showed an increasing trend. After 1992 when large-scale application of WST began, \( \delta RH \) started to decrease (figure 4(b)) and the average reduction induced by WST is 1.92% (figure 3(a)). This is because after the great reduction in irrigation water consumption per unit area,
less water can be used for evapotranspiration into the atmosphere and, simultaneously, WST will reduce the water vapor flux entering the atmosphere as WST in the study area is usually accompanied by mulching.

Long-term irrigated regions tend to have a higher amount of precipitation than nonirrigated regions, which is one of the memory effects of local climate on irrigation (Adegoke et al. 2003). This study found that after the large-scale implementation of WST, the trend in precipitation difference caused by irrigation has been changed (i.e. δPrep, figure S5). δPrep before the development of WST showed an insignificant increasing trend, yet after that it showed an insignificant decreasing trend. Irrigation will enhance the amount of clouds by the increase of water vapor from moister surface to the air, thereby increasing local precipitation (Segal et al. 1998, Adegoke et al. 2003). In water-constrained areas, soil moisture will directly limit evapotranspiration and thus have a feedback to precipitation via moisture recycling (Guillod et al. 2015), which accounts for the reduced precipitation as a consequence of decreased evapotranspiration by WST compared to previous irrigation conditions.

Furthermore, the difference in aridity index (i.e. the ratio of precipitation and potential evapotranspiration, P/PET) between IRR and CTL sites has also shown a downward trend after the large-scale application of WST (figure 4(c)), which also provides evidence for the drying effect of WST. In arid regions, the feedback between soil moisture and atmospheric aridity is much stronger. Since irrigation water consumption per unit area is decreasing as WST develops, the decrease in ∆(P/PET) suggests the evapotranspiration is decreasing during the growing season following WST implementation.

3.3. Threshold of WST-induced warming and drying effect against WSTA proportion

The percentage of the area implemented with WSTs (WSTA proportion) reached 88% by 2018, with the total area of 5.16 million ha (figure 1). We use the difference in δT and δRH between periods before and after applications of WST (i.e. ∆T and ∆RH) to estimate the WST-induced impacts on meteorological variables for the whole study area (figure 5).

In general, as the proportion of WSTA grows, the amplification of WST on the warming-drying effect becomes stronger. However, the warming and drying effect of WST is not noticeable until a certain threshold is reached. For example, the increasing trend of regional temperature began to exacerbate after the WSTA proportion reached a threshold of 0.37 in Xinjiang, but in Hexi Corridor where it is relatively more humid, the threshold was higher at 0.53, suggesting a nonlinear response as a function of climate. Thus, we investigate the relationship between WSTA proportion thresholds with the aridity index.
Figure 5. Thresholds derived from the relationship between $\Delta T_{ai}$ and WSTA proportion for different regions: $\Delta T_{ai}$ is the change in average temperature difference between the controlled and irrigated sites between the average value of 1965–1991 and the ith year over 1992–2018 ($\Delta T_{ai} = \bar{T}_{1965–1991} - \bar{T}_{i}$). Figures (a)–(d) represent thresholds for Hexi Corridor, South Xinjiang, the whole Xinjiang and Northwest China, respectively; figure (e) shows the relationship between the threshold values and P/PET. $\Delta$ represents changes induced by WST.

3.4. Sensitivity of WST warming-drying effect to background climatic variables

The above findings indicate that the large-scale WST in the arid inland areas of Northwest China has aggravated regional warming and made the near-surface air drier. In order to further explore the relationship between this effect and the distribution of spatial background climatic differences, we compare $\Delta T_a$ for each group of sites with their background climatic variables based on regression analysis (figure 6), and it is found that the warming effect of WST is different for different background climatic variables. It turns out that the warming-drying effect only shows significant correlations with growing season precipitation $P_{gs}$. For every 10 mm increase in $P_{gs}$, the warming effect of WST increases by 0.1 °C and the drying effect decreases by 0.6% (figure 6(b)). Yet no significant associations are detected between the
warming-drying effect and growing-season temperature $T_{gs}$ and diurnal temperature change $D_{gs}$.

4. Discussion and conclusion

The purpose of this study is to quantify the local climatic effects arising from large-scale water management measures, i.e. the implementation of WSTs, which has brought great changes compared to the traditional irrigation methods while significantly improving the irrigation water productivity (Li et al 2017). The results show that the water-saving irrigation techniques (e.g. drip irrigation under mulch) have significantly changed the local climatic conditions: it reduces the evaporative cooling effect of irrigation on GHG-induced warming, and thus indirectly aggravates regional warming in growing-season and it also makes the near-surface air drier. Although irrigation itself still has a cooling effect on near-surface air temperature, it is gradually declining with increasing IWUI.

In climatic studies related to land use change or land management activities, changes in local air temperature are usually attributed to two terms: (a) the radiative forcing associated with albedo change and (b) the energy redistribution associated with roughness change and Bowen ratio (Lee et al 2011). Here, we show that the energy redistribution process plays the dominant role in changing the local near-surface air temperature (figure 3(b)). Changes in net radiation ($R_{n}$), though minor, can slightly amplify the warming effect of Bowen ratio change. The role of $R_{n}$ is limited in our results because a decrease in the absorbance of incoming solar radiation happens only in the initial stage of the growing season and will not cause big changes in the averaged near-surface air temperature over the whole growing season. WST reduces the water consumption of crop-lands and thus changes how the available energy is partitioned on the surface, resulting in the temperature change. At the same time, the increased nighttime temperature can be attributed to widely-used film mulching which prevents the exchange of water and heat fluxes between the soil and near-surface air, increasing the heat storage of soil and thus the soil temperature at night (Qin et al 2018). Field experiments also provide support that drip irrigation, which is the main technique of WST in the study area, will shorten the growth period of crops and reduce soil evaporation, thereby reducing water consumption during the growing season (i.e. evapotranspiration) (Wang et al 2020, Yang et al 2020a). It is intuitively considered that decrease in soil moisture (therefore reduction in evapotranspiration) will result in increased temperature. However, equation (9) suggests that though evapotranspiration is significantly reduced because large-scale mulching reduces the loss of water and energy from the soil to the atmosphere (Ramakrishna et al 2006, Zhou et al 2009, Zhao et al 2021), it is not the direct reason for the increase in near-surface air temperature. Field experiments demonstrated the proportion of energy partitioned into latent heat in the rapid growing season is increased to 0.86 ∼ 0.93 (Tian et al 2017) because the implementation of WST ensured that the absorbed net radiation is prioritized for plant growth, resulting in the decreased Bowen ratio ($\Delta \beta < 0$) compared to the traditional irrigation methods, and this is the main reason for the rising of the air temperature.

In general, conclusions can be drawn from the observational study and biophysical processes that the warming induced by large-scale application of WST has significantly weakened the role of irrigation on mitigating the stress of heat extremes during growing season. At the same time, WST makes the air drier due to the reduced water vapor transport from land to air, which is probably the cause of the decreasing trend of $\delta$Prep after 1992. Yet there is no doubt that precipitation is also affected by atmospheric circulation, so it is necessary to use earth system models to quantify the drying effect caused by such land management measures more accurately in the future.

The warming-drying effect will not appear until the WSTA proportion reaches a certain threshold.
and it has been shown that the climatic effects of changes in underlying surface conditions are closely related to scale (Betts 2000, Khanna et al 2017, Li and Wang 2019). It would not be strong enough to cause observable climatic signals if the ongoing land use or land management activities take place at smaller scale. Therefore, it is necessary to consider the scale issue when considering the response of near-surface climate to terrestrial biophysical processes and the resulting land-atmosphere feedbacks (Lawrence and Vandecar 2015, Khanna et al 2017, Li and Wang 2019). Moreover, the threshold of WSTA proportion in a specific region is dependent on its climatic condition (i.e. P/PET). In the most arid regions, the negative effect of WST appears at earlier stages of its development while the relatively more humid regions respond a bit more slowly. On the other hand, the magnitude of the climatic effects induced by land management measures is also related to the local background climate (Yu et al 2018, Yang et al 2020b). This study analyzed the sensitivity of the observed warming-drying effect of large-scale WST against background climatic variables such as rainfall, temperature and diurnal temperature range in the growing season. Interestingly, though the WSTA proportion threshold is smaller in more arid regions as a result of quicker response to soil moisture variation, the magnitude of the warming-drying effect in such regions is not as large as that in the relatively humid regions (with larger growing-season precipitation): an increased warming-drying effect of WST is detected with the increased growing season precipitation. In the traditionally irrigated fields, a rapid soil moisture increase occurs after a large amount of irrigation water supply, triggering significant changes in local biophysical processes. Yet the effect is weakened when irrigation water is greatly reduced, resulting in decreased turbulent exchange on land surface and weakened sensitivity of land processes to changes in soil moisture in extremely dry regions, which changes the previous pattern of land–atmosphere interactions in such areas. Also, according to the biophysical process represented in equation (9), the contribution of energy redistribution change is magnified because of the inverse relation to decreased $\beta^2$ (squared Bowen ratio) in the relatively humid regions (see equation (11)).

Arid and semi-arid regions, like the North and Northwest China, with severe surface water scarcity and declining terrestrial water storage (Xie et al 2018, Bierkens and Wada 2019), are facing dual pressures from crop production needs and groundwater depletion, which forces the continuing expansion of WST implementation in such areas. Thus, water managers need to have a comprehensive and scientific understanding of the warming-drying effect in order to develop sustainable long-term management plans and make adaptive measures to cope with the eco-environmental effects. Based on these conclusions, a reference for regional water planning can be provided: WST should be developed in areas with a drier climate in future phases of WST development. For example, in the Xinjiang Autonomous Region in Northwest China, more consideration should be given to the development of WST in the south in future planning, but the scale needs to be controlled and other cooperative water resources management measures (such as water transfer projects) are required to prevent the large-scale application of WST from playing a negative role in the land–atmosphere interactions.

The implementation of WST is one of the most important water management measures across major agricultural regions such as North and Northwest China, India, Western US, North Africa and the Middle East. This study shed light on the direct evidence of the warming-drying effect of large-scale WST and shows the importance of considering land management when exploring the impact of large-scale land surface changes on climate. Uncertainties arise from lack of consideration for the cooling effect induced by the continuing expansion of the irrigated area, which may result in the underestimation of the WST warming effect. Besides, only few flux tower datasets are used to verify the result based on meteorological stations in this study. Further validations are needed to test the magnitude of the WST warming effect, including the three aspects: first, more specific data about the WST area around individual stations, rather than merely provincial datasets, need to be collected to improve the accuracy of the analysis. Second, more controlled experiments in the field are needed because the warming effect induced by WST is bound to further affect the growth of crops and microclimate. Lastly, online simulations in earth system models are needed to test the sensitivity of regional or global climatic responses to human water regulations or large-scale water policies. As global warming is posing greater threats to agricultural production throughout the world (Zhao et al 2017), the warming effect induced by WST is bound to further affect the growth of crops and microclimate and the regional water and heat balance. Whether these impacts are conducive to the sustainable development of the region needs to be further explored by earth system models, which will be the key issue and research we will focus on in the next step.

Data availability statement

No new data were created or analyzed in this study.

Acknowledgments

We acknowledge financial support by Chinese National Natural Science Foundation Program (51621061, 91425302) and Discipline Innovative Engineering Plan (111 Program, B14002).
Author contributions

J F carried out the analysis and wrote the manuscript. S K contributed to the analysis and ideas and modified the paper. I C contributed to the analysis, ideas and modified the paper. X. L collected the data and contributed ideas to the analysis. P G contributed ideas and modified the paper. J N contributed to the analysis.

ORCID iDs

Jing Fu https://orcid.org/0000-0002-3746-2685
Pierre Gentine https://orcid.org/0000-0002-0845-8345

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