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Key Points:
- Human water use alters the continental sink for atmospheric water across watersheds
- Atmospheric feedbacks induced by human water use contribute to drying at the watershed scale over Europe
- Integrated modeling systems are required to quantify anthropogenic impacts on the water cycle through groundwater-to-atmosphere feedbacks

Supporting Information:
- Supporting Information S1

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Human Water Use Impacts on the Strength of the Continental Sink for Atmospheric Water

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Abstract In the hydrologic cycle, continental landmasses constitute a sink for atmospheric moisture as annual terrestrial precipitation commonly exceeds evapotranspiration. Simultaneously, humans intervene in the hydrologic cycle and pump groundwater to sustain, for example, drinking water and food production. Here we use a coupled groundwater-to-atmosphere modeling platform, set up over the European continent, to study the influence of groundwater pumping and irrigation on the net atmospheric moisture import of the continental landmasses, which defines the strength of the continental sink. Water use scenarios are constructed to account for uncertainties of atmospheric feedback during the heatwave year 2003. We find that human water use induces groundwater-to-atmosphere feedback, which potentially weaken the continental sink over arid watersheds in southern Europe. This feedback is linked to groundwater storage, which suggests that atmospheric feedbacks to human water use may contribute to drying of watersheds, thereby raising water resources and socio-economic concerns beyond local sustainability considerations.

Plain Language Summary In the global water cycle, the land receives more water through precipitation than it loses through evaporation and transpiration from plants over long time periods, leading to continental runoff of the continental river systems. Especially during dry periods, humans intervene in this natural hydrologic cycle by pumping groundwater and irrigation for agriculture to maintain drinking water and food supply. The impact of this human intervention on the water cycle including the atmosphere is not yet fully understood. Previous studies neglect the full feedback pathway from the bedrock to the atmosphere, thereby ignoring the fact that human water use may influence precipitation, which can in turn affect water resources. In this study, we use a modeling system that simulates the full terrestrial water cycle by incorporating groundwater dynamics in a regional climate model. We analyze how human water use affects the balance between precipitation and evaporation during the heatwave in 2003 over Europe, and we find that these changes are the main driver for drying of watersheds in southern Europe. These results suggest that human water use has impacts beyond the local scale via atmospheric processes, which is not yet considered in climate change and water resource assessment studies.

1. Introduction

Groundwater sustains ecosystems and simultaneously secures global water and food supply via, for example, groundwater abstraction and irrigation (Taylor et al., 2013; Wada et al., 2012). Groundwater pumping significantly contributes to declining water tables in aquifers and watersheds around the world (Famiglietti, 2014; Long et al., 2013; Rodell et al., 2009; Scanlon et al., 2012). Previous studies also indicated that the effect of human water use (HWU) on the terrestrial hydrology is comparable to climate change effects at the regional scale (Ferguson & Maxwell, 2012) and may already exceed sustainability at the global scale (Jaramillo & Destouni, 2015).

Irrigation may decrease land surface temperatures through increasing evapotranspiration (ET) and associated surface cooling (Kueppers et al., 2008; Lobell et al., 2009) and mitigate heat extremes (Thiery et al., 2017), thereby potentially counteracting warming effects due to climate change (Hirsch et al., 2017).

Simultaneously, groundwater depletion may limit future irrigation water and hence increase the heatwave risk (Lu & Kueppers, 2015). Via ET, HWU may also impact precipitation (P) at different spatial scales and contribute to sea level rise (Wada et al., 2016). Previous studies linked observed P changes over the continental United States to the development of groundwater pumping and an intensification of irrigation during the last century (Alter et al., 2015; DeAngelis et al., 2010; Moore & Rojstaczer, 2001). Simulations indicated that irrigation can either increase P but also inhibit P initiation locally (Barnston & Schickedanz, 1984; Douglas et al., 2009; Pei et al., 2016), and beyond the local impact, may also affect terrestrial P in remote regions through changes of the atmospheric moisture transport (de Vrese et al., 2016). These precipitation feedbacks can in turn impact river flow at remote locations (Wang-Erlandsson et al., 2017) and affect water resource governance (Keys et al., 2017). Consequently, the impacts of HWU on water resources may impact sustainability especially during dry and hot summers (such as the European heatwave in 2003) in which water demands increase significantly (e.g., van der Velde et al., 2010) and land-atmosphere feedback are expected to be strongest (Ferranti and Viterbo, 2006; Fischer et al., 2007; Miralles et al., 2014). While such feedbacks cannot be easily unraveled using observations (e.g., Karl & Trenberth, 2003; Turner et al., 2007), recent progress in Earth system modeling allows to perform sensitivity studies in order to identify potential feedback pathways.

However, previous atmospheric impact studies applying regional climate models assume an unlimited supply of water at the land surface to mimic irrigation or use simplified hydrologic models, which do not close the terrestrial hydrologic cycle from groundwater into the atmosphere (Nazemi & Wheater, 2015; Wada et al., 2017). Thus, the connection of groundwater with the land surface energy balance and atmospheric processes has not been taken into account explicitly (Anyah et al., 2008; Gilbert et al., 2017), and their impact on subsurface water storages is not considered. In turn, hydrologic studies including groundwater processes are just beginning to emerge at the continental scale (Bierkens et al., 2015; Maxwell & Condon, 2016; Maxwell et al., 2014) and still neglect atmospheric feedbacks to HWU.

In this study, we perform a sensitivity study by applying a mass and energy conservative groundwater-to-atmosphere modeling platform in an ensemble approach, unifying the atmospheric and hydrologic paradigms. We study how HWU, here considered as groundwater abstraction and irrigation, may alter the strength of the continental moisture sink. The analysis covers different spatial and temporal scales across European watersheds during the European heatwave in 2003. While this heatwave was an extreme event in the recent past, droughts and heatwaves are expected to increase in the future (e.g., Beniston, 2004; Beniston & Stephenson, 2004; Perkins et al., 2012), being tightly coupled to the projected water demand, as indicated by, e.g., Schewe et al. (2014) and Wada et al. (2013). Yet the full impacts of HWU during extended dry periods remain poorly understood constituting a challenge for water security and water resource vulnerability (Oki & Kanae, 2006**;** Vörösmarty et al., 2000).

2. Methods

The integrated Terrestrial Systems Modeling Platform (TerrSysMP; Shrestha et al., 2014; Gasper et al., 2014) is used to perform this sensitivity study. TerrSysMP consists of the atmospheric model COSMO (Baldauf et al., 2011; Doms & Schättler, 2002), the Community Land Model (Oleson et al., 2008), and the surface-subsurface model ParFlow (Jones & Woodward, 2001; Kollet & Maxwell, 2006), coupled through OASIS3-MCT (Valcke, 2013). TerrSysMP accounts for fully coupled atmospheric and land surface-subsurface hydrologic processes and incorporates a realistic representation of groundwater dynamics, the hydraulic connection to surface water, and two-way feedbacks with atmospheric processes. The platform has already been set up over the European CORDEX domain at 0.11° resolution (Keune et al., 2016), and only small modifications to the setup are made (supporting information). In this study, we incorporate HWU as groundwater abstraction and irrigation in the surface-subsurface flow model of TerrSysMP (the Modeling System Section in the supporting information). In order to account for uncertainty of the land-atmosphere feedbacks and precipitation initiation, four HWU scenarios are constructed and results are based on the comparison of the HWU ensemble to a natural reference model run (NAT) covering the heatwave year 2003 over the European continent. Here, the natural reference run is representative of an undisturbed water cycle without groundwater pumping and irrigation. The HWU scenarios are based on realistic estimates of daily groundwater abstraction for industrial, domestic, and agricultural use, as well as irrigation (HWU1, Wada et al., 2012; Wada et al., 2016), and HWU2, Siebert et al., 2010; Siebert & Döll, 2010; Figures S2–S4). In addition, two water use schedules are applied for

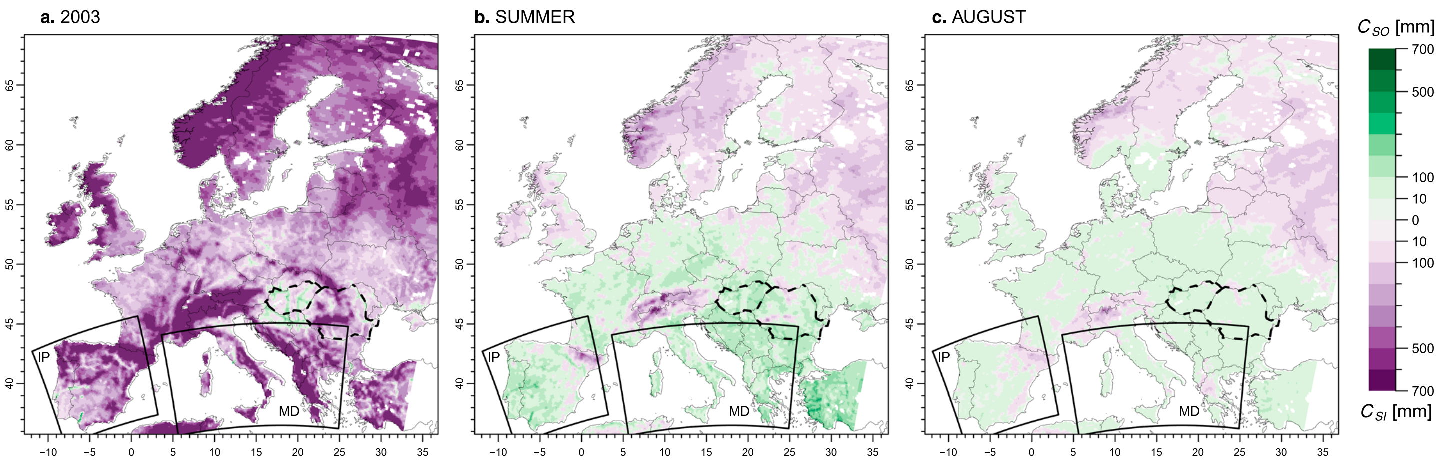

Figure 1. Strength of the natural continental sink-source. Continental sink-source relationship for atmospheric moisture simulated with NAT over (a) the full year 2003, (b) summer: June-July-August (JJA) 2003, and (c) the heatwave month August 2003. The purple shaded areas indicate that the land is a net sink for atmospheric moisture (C_{SI}: P $>$ ET, div(Q) $<$ 0); the green shaded areas indicate that the land is a net source of moisture to the atmosphere (C_{SO}: ET $>$ P, div(Q) $>$ 0). The boxes indicate the PRUDENCE regions Iberian Peninsula (IP) and Mediterranean (MD). Hungary and Romania, in which the Pannonian Plain and the Transylvanian Plateau are located, are highlighted by thicker dashed lines.

each data set (HWU1-1 and HWU2-1: daytime water use; HWU1-2 and HWU2-2: nighttime water use). In order to keep the large-scale atmospheric circulation as close as possible to the driving ERA-Interim reanalysis, we apply the spectral nudging approach (von Storch et al., 2000) for the horizontal wind components above the planetary boundary layer. This technique arrives at precipitation events closer to reality also reducing biases (supporting information). Simulations start from a multiyear spin-up of the hydrological compartments of TerrSysMP.

This set of simulations is used to examine groundwater-to-atmosphere feedbacks of HWU on the strength of the continental moisture sink, measured by the atmospheric divergence div(Q). We define the continental sink of moisture as $C_{SI} = -\text{div}(Q)$ = P-ET, if P exceeds ET, P $>$ ET. Vice versa, the continent is a net source of water to the atmosphere, $C_{SO} = \text{div}(Q)$ = ET-P, if ET exceeds P, ET $>$ P. Subsequently, we identify the impact of this change of the continental sink on continental drying as simulated by changes in the subsurface storage S and runoff R (Figure S1). A detailed description of the land-atmosphere water balance and the analyzed differences induced by HWU is provided in the supporting information.

3. Results and Discussion

3.1. Water Use Impacts on the Continental Sink

At the annual time scale and in the natural hydrologic cycle, most of the continental landmasses are a net sink of water as precipitation exceeds ET (C_{SI} in Figure 1a). Hence the atmosphere is a net importer of water for the continent, which is well known (Gimeno et al., 2012). However, there exists spatial and temporal variability depending on atmospheric dynamics, land cover, and groundwater dynamics. Regions and entire watersheds can also be a net source of moisture to the atmosphere seasonally and for warm summer months (C_{SO} in Figures 1b and 1c), but also for the full year in areas with strong groundwater convergence, such as the Pannonian Plain and the Transylvanian Plateau (Figure 1a). In those cases, the atmosphere exports more water of continental origin to other regions, increasing the potential for precipitation recycling (Brubaker et al., 1993; Gimeno et al., 2012; Keys et al., 2016).

HWU perturbs the natural land and atmospheric water balances and may amplify or attenuate the continental sink of water in a consistent manner through systematic differences in div(Q) by changes of evapotranspiration (ΔET) and precipitation (ΔP) (supporting information). All simulations in this study indicate a decrease of the net sink of moisture, C_{SI}, with respect to the natural reference simulation for the entire continent caused by HWU (between 0.7 and 3.2 mm/year; Table S1). This decrease in C_{SI} on the order of ~1 mm/year is small, and the relatively large range of differences indicates high uncertainty. However, the sign of the

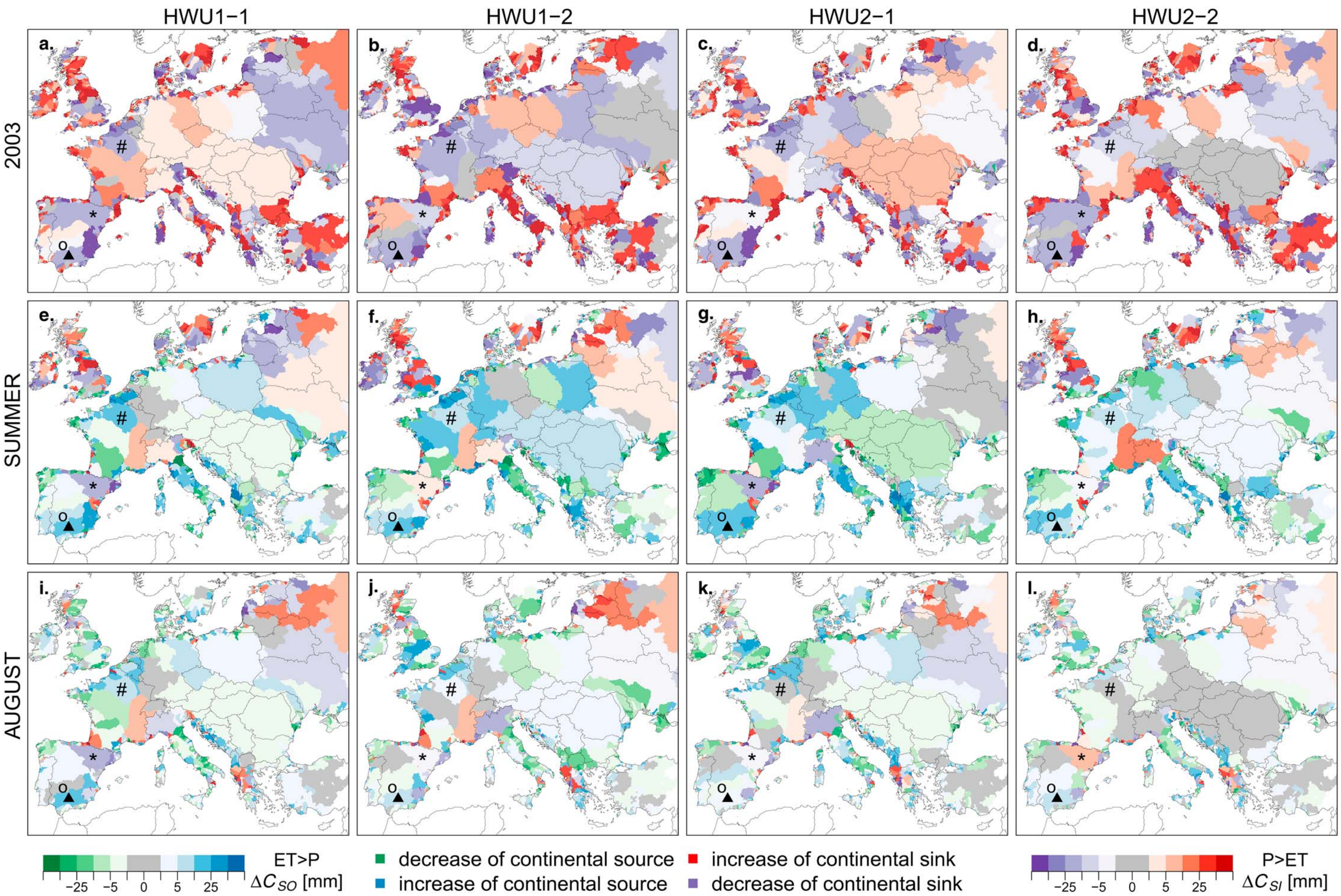

Figure 2. Human water use-induced alteration of the continental moisture sink. Mean human water use-induced increase or decrease of the continental source or sink of moisture for atmospheric water, compared to the natural reference run (i.e., HWU-NAT) over European watersheds for all water use scenarios along the columns: (a, e, and i) HWU1-1, (b, f, and j) HWU1-2, (c, g, and k) HWU2-1, and (d, h, and l) HWU2-2, over the full year 2003 (a–d), summer 2003 (JJA, e–h), and August 2003 (i–l). The watersheds Ebro (*), Guadalquivir (Δ), Guadiana (o), and Seine (#) are marked.

signal is consistent and its magnitude is comparable to previous studies, which focused on the influence of groundwater pumping on sea level rise (Konikow & Kendy, 2005; Wada et al., 2016). Inspecting the terrestrial feedback of moisture transport, we observe a systematic spatial and temporal redistribution of water due to HWU. Our results indicate that HWU consistently alters the annual continental sink C_{SI} of atmospheric moisture over the most arid watersheds in southern Europe (Figure 2). Regionally, irrigation and pumping and resulting groundwater-to-atmosphere feedbacks lead to a decrease of C_{SI} ranging from 2.6 to 7.8 mm/year (depending on the water use scenario and relative to a natural sink of 456 mm/year) over the Iberian Peninsula, of which the Guadalquivir basin shows the largest decrease ranging from 13.2 to 19.2 mm/year (with $C_{SI(NAT)}$ = 251 mm/year). France also shows a decrease in C_{SI} for 3 out of the 4 water use scenarios ranging from 1.7 to 12.3 mm/year (with $C_{SI(NAT)}$ = 374 mm/year), where the Seine basin shows the largest consistent decrease in C_{SI} as a result of decreased precipitation (Figure S7). A net increase in C_{SI} is simulated over the Mediterranean (by 0.7 to 12.3 mm/year, with $C_{SI(NAT)}$ = 493 mm/year), but a large number of small watersheds also experience a precipitation deficit (Figure S7) accompanied by an increase in ET (Figure S8). This indicates the spatial contrast in the Mediterranean climate regimes, which are influenced by the Apennines mountains in the western regions of the Italian Peninsula and the Mediterranean suboceanic climate in the east.

The simulated feedback and sensitivities to HWU and soil moisture perturbations are strongest in summer (Wei et al., 2016), which is the main season for irrigation and pumping (Figure S4). In summer, HWU can increase the continental source, C_{SO}, by more than 25 mm for the managed basins in the Southern parts of the Iberian Peninsula (Figures 2e–2l). While the southern regions of the Iberian Peninsula are characterized by an increasing export of atmospheric moisture, mainly through increased ET as a result of irrigation (Figures S2 and S3 and S8), the northern regions (i.e., Ebro and Douro) act as both, attenuated sinks or attenuated sources driven by the uncertainty of the precipitation response in August (Figures 2i–2l and S7). At the daily time scale, HWU may even turn an entire watershed from a natural sink to a human-induced source of moisture to the atmosphere (Figure S6).

Thus, the continental sink of the two most intensively water managed regions in Europe (Figures S2 and S3) appears to be altered systematically by HWU, and the consequences strongly depend on the atmospheric feedback processes. Many arid watersheds in southern Europe import less atmospheric moisture influencing continental freshwater storage through complex feedback pathways, thereby raising water resources and sustainability concerns. These sustainability concerns are addressed in a section below.

3.2. Consistency Across Space and Time Scales

While the ensemble simulations in this study show large variability and, hence, large uncertainty of the atmospheric feedback to relatively small perturbations of soil moisture by HWU, with respect to magnitude and position, all water use scenarios show considerable consistency of the simulated feedback across various space and time scales. Figure 3 shows $\Delta(\mathrm{div}(Q))$ from HWU1 and HWU2 along the x and y axes, respectively. Increased percentages of regions, watersheds, and grid points falling in the upper right and lower left quadrant of Figure 3 indicate consistency between the water use scenario simulations and a systematic feedback signal. Deviations from the 1:1 line illustrate the large variability of the simulated feedbacks, which are expected due to the natural chaotic dynamics of the terrestrial system and the high nonlinearity of the feedbacks. Local feedbacks at the grid point scale exhibit large spatial variability for all water use scenarios with similar spatial patterns (Figure S5) but indicate a consistent feedback signal (approximately 69% for the year and 74% for summer). This variability may be caused by differences in the irrigation and groundwater abstraction rates and in the location between the different water use data sets, as well as less-pronounced atmospheric feedbacks during nighttime water use. The results show that uncertainty decreases and consistency increases with increasing watershed size (Figure 3b). Moreover, small-scale perturbations can also trigger consistent changes in the hydrologic cycle at the regional scale (Figures 3a and 3b). Our simulations indicate a consistent alteration of the hydrologic cycle for the Iberian Peninsula and the Mediterranean for all water use scenarios, with an increase of the continental sink over the Mediterranean and a decrease of the continental sink over the Iberian Peninsula. Simulated feedback for other regions are uncertain, including central Europe, France, eastern Europe, and the Alps (Figure 3a), which were less irrigated and experienced less groundwater pumping in 2003 compared to southern Europe (Figures S2 and S3; Wada et al., 2014).

Moreover, inspection of Figure 3 along the columns reveals that consistency increases between the water use scenarios toward summer and single summer months and is strongest in the summer season and the heatwave month of August (Figures 3g–3l). Interestingly, the precipitation feedback often exceed the ET feedbacks due to nonlinear interacting processes, yet indicate a stronger consistency for August 2003 (Figures S7 and S8). Here all water use scenarios show that HWU triggers convection and lead to a simulated increase in precipitation in Southern France and parts of mid-Europe (Figure S7), thereby potentially alleviating water stress and consequently the heatwave, as shown in other irrigation-based studies (Thiery et al., 2017).

3.3. Impact on Continental Water Resources

Systematic changes in the continental sink-source relationship for atmospheric water due to HWU are contributing to changes of continental freshwater storage and discharge through complex feedback pathways; that is, HWU can lead to a decrease of continental freshwater storage through an increase of ET, a decrease of precipitation, an increase of discharge, and their combination, respectively (a detailed description of the land-atmosphere water balance is provided in the supporting information). These feedbacks can be identified and quantified from our simulation results constituting a major advantage of the integrated groundwater-to-atmosphere modeling approach. We find a clear inverse relationship between the atmospheric feedback on the change of the continental moisture sink ΔC_{SI} and the subsurface water storage changes ΔS, as illustrated in Figure 4; that is, a decrease of the continental sink for atmospheric moisture leads directly to a decrease in continental freshwater storage. Note that ΔS was calculated over the full subsurface column

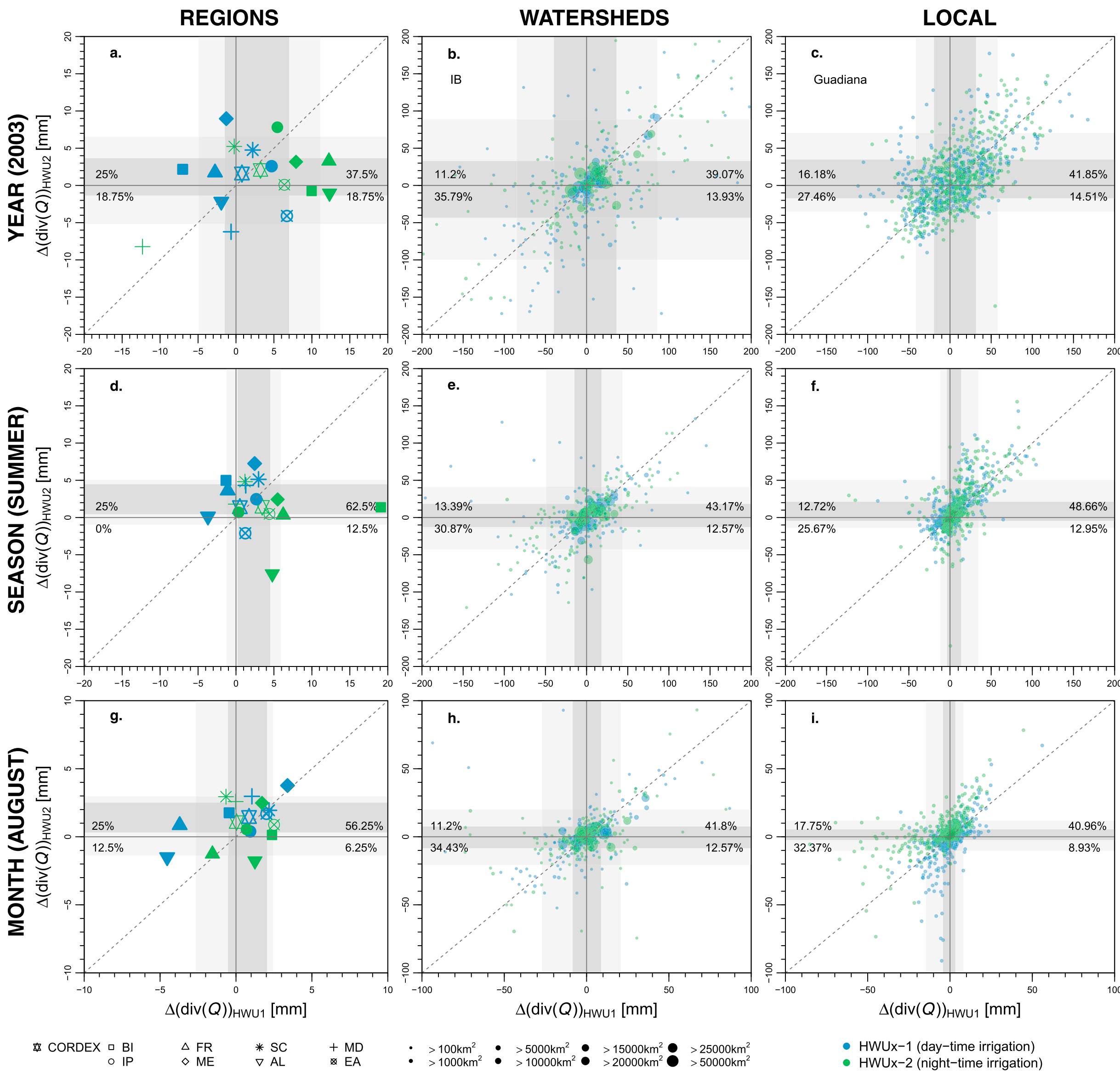

Figure 3. (a–l) Consistency between the water use scenarios (HWU1 and HWU2) induced feedbacks of atmospheric divergence across spatial and temporal scales. Consistency of Δ(div(*Q*)) over a range of spatial and temporal scales: from year to season to month (along the rows) and from PRUDENCE regions to watersheds to grid points (along the columns). Figures 3b, 3e, and 3h illustrate exemplarily the consistency of watersheds over the Iberian Peninsula. Figures 3c, 3f, and 3l illustrate the grid point scale feedback in the Guadiana basin. The grey shaded areas show the 10, 25, 75, and 90% quantiles, respectively. The blue (green) points indicate simulations using daytime (nighttime) water use. In Figures 3b, 3e, and 3h, the size of the symbols is commensurate with the watershed size. The symbols indicate the PRUDENCE regions British Islands (BI), France (FR), Scandinavia (SC), Mediterranean (MD), Iberian Peninsula (IP), Mid-Europe (ME), Alps (AL), and eastern Europe (EA). Note that the scales of each subplot are different. The consistency between the water use scenarios is indicated by the percentages in the lower left and upper right quadrant.

from the bottom of the aquifer to the land surface including the variably saturated zone. Thus, while ΔS over some watersheds may be small, localized groundwater storage changes may still be relevant due to transient effects. Approximately 46% of all watersheds plotting in the lower left quadrant of Figure 4a experience a decrease in the strength of the continental sink, while about 36% of all watersheds plotting in the upper right quadrant experience an increase. Figures 4b and 4c show the upper right and lower left quadrant, respectively, in double logarithmic scale for better inspection. Watersheds close to the 1:1 line are of particular interest and raise socio-economic concerns related to water resource sustainability, as increased atmospheric moisture demand induced by HWU is entirely met by a decrease in terrestrial water storages. Moreover, our results indicate that the large watersheds with a deep water table over the Iberian

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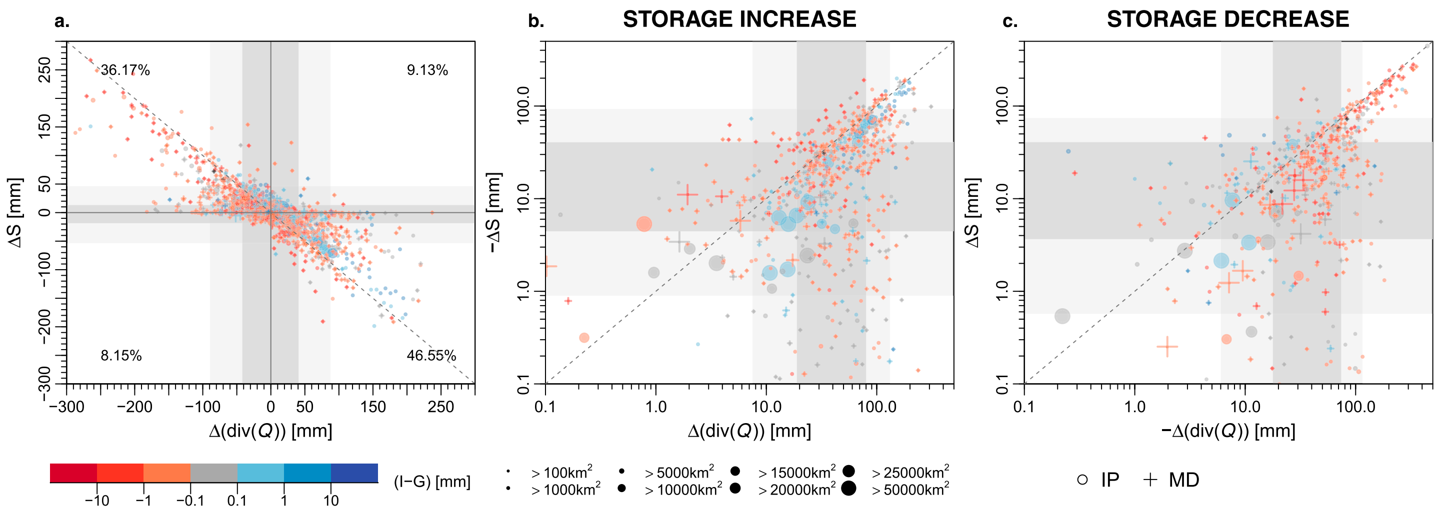

Figure 4. (a–c) Relationship between human water use-induced atmospheric feedback and soil drying. Annual subsurface water storage changes as a function of changes in the continental sink C_{SI} for all watersheds and all water use scenarios over the Iberian Peninsula and the Mediterranean. The $\Delta S < 0$ indicates a subsurface storage decline with respect to the natural simulation NAT over the full year 2003. The grey shaded areas indicate the 10, 25, 75, and 90% quantiles, respectively. The colors indicate the net human water use as the difference between irrigation (I) and groundwater abstraction (G). Panel a displays the entire range, while panel b (c) shows the relation where an increase (decrease) of the continental sink leads to an increase (decrease) of the subsurface water storage. All units are mm per unit watershed area. The size of the symbols is commensurate with the watershed size.

Peninsula and the Mediterranean region are most likely to suffer a water table decline due to HWU and the integrated atmospheric feedbacks (Figures 4c and S9 and S10), thereby emphasizing sustainability concerns. Watersheds plotting above and below the 1:1 line respond to changes in the continental sink by changes in groundwater divergence $\Delta \mathrm{div}(Q_g)$ (including cross-watershed flow) and continental discharge ΔR (supporting information). Figure 4 illustrates that in most cases, the terrestrial water storage change ΔS is determined by the atmospheric feedbacks ΔC_{SI} to HWU, rather than the net effect of groundwater pumping and irrigation.

4. Conclusions

The simulations in this study show that HWU alters the atmospheric moisture transport and the strength of the continental sink-source for atmospheric water, and hence leads to nonlocal effects beyond the watershed scale. Our analyses indicate consistent impacts for watersheds in southern Europe, in which HWU-induced feedbacks decrease the strength of the continental sink for atmospheric moisture, C_{SI}, constituting that the main contribution to terrestrial water storage declines for a large number of watersheds. The Iberian Peninsula and the Mediterranean encompass the most intensively water managed regions in Europe and show the strongest, consistent alteration of C_{SI} in our simulations during the European heatwave in 2003. However, uncertainty remains for large parts of Europe indicating that even small rates of local HWU in a relatively water-rich region may have an impact on moisture transport and terrestrial hydrology, ultimately contributing to the uncertainty of climate change signals (Allen et al., 2002). These findings suggest that the effect of a decreasing continental moisture sink potentially amplifies water scarcity in regions of strong groundwater abstraction and irrigation, possibly leading to increasing drought and heatwave frequency, strength, and duration. Thus, the simulation results do not corroborate that HWU counteracts an intensification of the hydrologic cycle through climate change effects. This study confirms that HWU is a significant source of uncertainty in global and regional climate simulations not taken into account in current climate model intercomparison and also impact studies (Jaramillo & Destouni, 2015). Unfortunately, observations of the terrestrial system are prohibitively scarce and error prone especially with regard to the subsurface hydrology to perform this type of study at the continental scale based on measurements. However, in future, available observations must be merged with models via data assimilation approaches to obtain a best estimate of the current state of the water cycle under HWU conditions. We presented the sensitivity of a fully coupled bedrock-to-atmosphere system for an extreme and dry year. While this might be an upper estimate of the atmospheric feedbacks to HWU under current conditions, the effect might aggravate under global change with increasing occurrence of droughts and heatwaves (Beniston & Stephenson, 2004).

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