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Key Points:

- Groundwater-atmosphere nexus heavily depends on model resolution and is accelerated at convection-permitting scales
- Convection-permitting simulations with groundwater effectively mitigates summer warm and dry biases in central United States
- The amount of water transported from shallow water tables to plant root zones is nearly identical to the increased amount of precipitation

Supporting Information:

- Supporting Information S1

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The Importance of Scale-Dependent Groundwater Processes in Land-Atmosphere Interactions Over the Central United States

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Abstract This study explores the impacts of groundwater processes on the simulated land-surface water balance and hydrometeorology. Observations are compared to multiscale Weather Research and Forecasting (WRF) simulations of three summer seasons: 2012, 2013, and 2014. Results show that a grid spacing of 3 km or smaller is necessary to capture small-scale river and stream networks and associated shallow water tables, which supplies additional root-zone water double that of simulations with 9-km and 27-km grid spacing and is critical to replenishing the depleted vegetation root zones and leads to 150 mm more evapotranspiration. Including groundwater processes in convection-permitting models is effective to reduce: (1) 2-m temperature warm biases from 5–6 to 2–3 °C and (2) the low precipitation bias by half. The additional groundwater supply to active soil flux in convection-permitting simulations with groundwater for June-August is nearly translated into the same amount of increased precipitation in the domain investigated.

Plain Language Summary Groundwater plays an important role in land-atmosphere interactions. This study explores the impacts of groundwater processes on the model simulated land-surface water balance and hydrometeorology. Observations are compared to multiscale Weather Research and Forecasting model simulations of summer seasons for three years: 2012, 2013, and 2014. Results show that high-resolution modeling (with a grid spacing of 3 km or smaller) is necessary to capture small-scale river and stream networks and associated shallow water tables, and supply crop and plant root-zone water double that of low-resolution simulations, which is critical to replenishing the depleted vegetation root zones and leads to 150 mm more evapotranspiration. Including groundwater processes in high-resolution models is effective to reduce: (1) 2-m temperature warm biases from 5–6 to 2–3 °C and (2) the low precipitation bias by half. The additional groundwater supply to active soil flux in high-resolution simulations with groundwater for June-August is nearly translated into the same amount of increased precipitation in the domain investigated.

1. Introduction

Groundwater (GW) can play an important role in the water balance of the land/atmosphere interface (Keune et al., 2016; Liang & Xie, 2003; Martínez-de la Torre & Miguez-Macho, 2019; Maxwell et al., 2007, 2011; Miguez-Macho & Fan, 2012; Zeng et al., 2017; Zipper et al., 2019; Zou et al., 2014). However, its role in weather and climate models has often been ignored due to the complexity of including a reasonable representation in the land-surface model employed. The development of GW models (Maxwell et al., 2007; Wang et al., 2020) and especially the recent work by Miguez-Macho et al. (2007) has provided a GW parameterization that helps overcome this challenge. This is important as climate model simulations and weather forecasts over the midcontinental midlatitude regions of the world often contain a warm and dry bias that has been notoriously difficult to reduce, especially in the central United States (U.S.) (Cheruy et al., 2014; Klein et al., 2006; Liu et al., 2017; Mueller & Seneviratne, 2014). These climate and weather models often did not include the representation of groundwater, and thus one of the plausible causes of the warm and dry bias may be the absent or inadequate representation of groundwater processes, and in particular of the key role of groundwater as transpiration source in dry periods wherever the water table is sufficiently shallow.

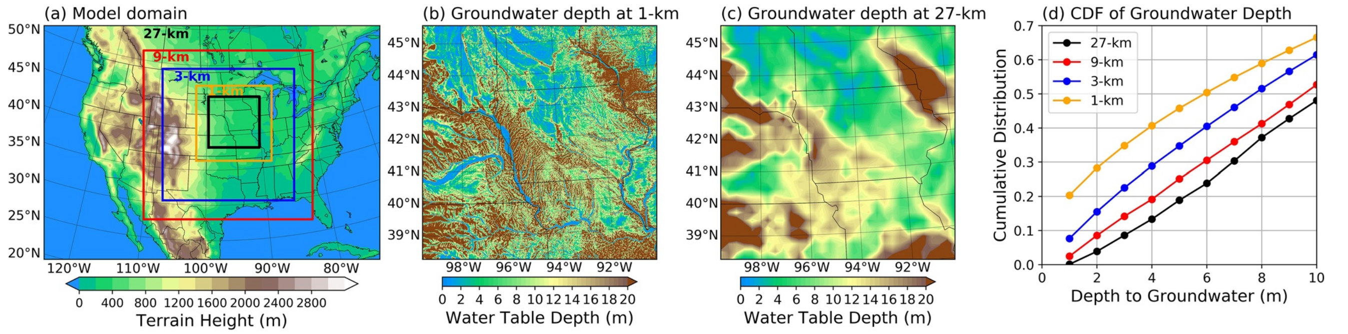

Figure 1. (a) Model domain boundaries for 27-km, 9-km, 3-km, and 1-km grid spacing. The inner black rectangle represents the analysis domain with a significant portion of shallow water tables; (b) and (c) water-table depth at 1 and 27 km; (d) cumulative distribution of grid points as function of depth to groundwater (m) for 27-km, 9-km, 3-km, and 1-km grid spacing.

The representation of land-atmosphere interactions in climate models has been identified as one important factor contributing to the outstanding warm and dry bias over the central U.S. (Cheruy et al., 2014; Klein et al., 2006; Liu et al., 2017; Mueller & Seneviratne, 2014), which is known for a strong soil moisture-precipitation feedback (Dirmeyer et al., 2009;Koster et al., 2004; Trier et al., 2004, 2008). A deficit in summer soil moisture content (i.e., drier soil) decreases the surface evapotranspiration and hence water vapor transported from vegetation and crop root zones to the atmosphere, modifies the thermal structures of the atmospheric boundary layer, and reduces the formation of clouds and precipitation. Groundwater-atmosphere interactions provide a pathway to replenish the upper-layer soil moisture and increase soil and vegetation evaporation, hence reducing the surface air temperature and potentially increasing precipitation. Barlage et al. (2015) showed that including groundwater-atmosphere interactions can mitigate warm and dry biases. For example, a reduction of 1–2 °C in central U.S. summer temperature by considering the interactive groundwater parameterization in the Noah multiphysics (Noah-MP) land model in a 6-month Weather Research and Forecasting (WRF) regional climate simulation with 30-km grid spacing.

However, modeled groundwater-atmosphere interactions depend on the model spatial resolution that impacts the ability of representing fine-scale natures of the local hillslope gradients driving the groundwater convergence that yields shallow water-table depths in valleys. For instance, for the central U.S. domain in which the WRF model produced significant summer warm and dry bias (Liu et al., 2017) shown in Figure 1a, the 1-km grid-spacing model (Figure 1b) resolves more small-scale river and stream networks and associated shallow water tables along riparian zones than the 27-km model (Figure 1c). In fact, the former captures about 284% more grid points of water-table depth <4 m (critical for recharging the vegetation and crop root zones) than the latter (Figure 1d). Figures S1 and S2 also demonstrate the modeling scale-dependence on representing the lateral flow with high-resolution grid spacing, and the 1-km grid-spacing simulation clearly demonstrates details and more significant water replenishment in areas near river valleys. Given such a substantial difference in representing shallow water tables in models with different resolutions, this paper, for the first time, explores the role of scale-dependent groundwater processes. The main objective of this study is to investigate the importance of scale-dependent groundwater processes on the water balance near the land surface and on the simulated temperature and precipitation biases using observations and multiscale WRF model simulations.

2. Method

Our convection-permitting (using 4-km grid spacing) 13-years-long WRF simulations of the climate of the continental U.S. (Liu et al., 2017, called CONUS1 hereafter) reveled a significant high temperature bias (up to 6 °C) and low precipitation bias over the central U.S. in July and August. Prior to July, CONUS1 simulations produced precipitation in this region mainly through the formation of Mesoscale Convective Systems (MCSs) that propagated from west to east in good agreement with the radar observations (Prein et al., 2017). However, in July and August, hardly any MCSs formed. A potential clue to this behavior was that most MCSs in May and June were forced by large scale frontal passages and other synoptic disturbances, while in

July and August MCSs were weakly forced by local mesoscale circulations, which are highly related to local and regional convective instabilities and thermal gradients that are heavily modulated by soil moisture and temperature (Dirmeyer et al., 2009;Koster et al., 2004; Trier et al., 2004, 2008).

To isolate the problem, WRF simulations were conducted over a subdomain (shown in Figure 1) of the continental U.S. A nested approach was used with an outer domain at 27 km grid spacing (black rectangular outline in Figure 1), a first nest with a grid spacing of 9 km, a second nest at 3-km grid spacing, and a final inner nest at 1 km. Fifty-one vertical levels were used and the physical parameterizations were the same as Liu et al. (2017) CONUS1 simulation: the Thompson aerosol-aware microphysics (Thompson & Eidhammer, 2014), the YSU planetary boundary layer (Hong et al., 2006), the rapid radiative transfer model (RRTMG, Iacono et al., 2008), and the Noah-MP land-surface model (Niu et al., 2011). The 27-km, 9-km, and 3-km grid spacing used the scale-aware Kain-Fritsch convection scheme (Kain & Fritsch, 1993), which produces insignificant convective precipitation at 3-km. The GW (i.e., including groundwater representation) simulations with various grid spacings were conducted using the 3D groundwater scheme of Miguez-Macho et al. (2007) within Noah-MP, which extends the soil columns to the water table, connecting groundwater to the top-soil. The model considers the vertical transport of water through capillary rise from shallow water tables to plant root zones and calculates groundwater-river exchange and lateral flow from cell to cell using Darcy's law. Only unconfined aquifers are represented. Our recent work showed that this GW scheme, when applied at 4-km grid spacing, was able to reasonably capture the seasonal evolution of water-table depth and the timing of recharge processes (Zhang et al., 2020).

By contrast, the NOGW simulations were conducted with a 1D free drainage approach, which implies water drained out from the active 2-m soil column and no upward transport of water. These multiscale WRF simulations were designed to investigate the individual and combined effects of including the GW dynamics and model horizontal resolution on the summer warm and dry bias. To evaluate the robustness of the results to various climate regimes, we tested a dry year (2012), a normal moisture year (2013), and a wet year (2014). Since the warm, dry bias occurred in the summertime, we focused our simulations on the period of April to September for each of the chosen years, and analyzed the simulation results after a 1-month spin-up. Initial conditions for water-table depth are taken from the equilibrium water-table depth calculations in Fan et al. (2013) and represent the mean hydrological state of the region. All averages are computed for the black boundary in Figure 1a.

3. Results

3.1. Impact of GW on Temperature and Precipitation Biases

Figure 2 shows the impact of using the GW model (Miguez-Macho et al., 2007) on the 2-m temperature bias based on the evaluation against METAR observations for WRF simulations with four different grid spacings. All NOGW simulations suffer from substantial temperature bias (>4 °C in most areas, 4-month average from May to August), and merely increasing the model resolution to 1-km grid spacing does not reduce such warm biases. Simulations with GW do not meaningfully alter temperature bias with 27-km and 9-km grid spacings, but significantly reduce warm biases from 5–6 to 2–3 °C with 3 km and especially with 1-km grid spacings. Such a remarkable scale-dependent warm-bias reduction is most evident in the third row of Figure 2, which shows the difference between simulations with GW and without GW scheme. A greater bias reduction is achieved over much of the central U.S. when the model horizontal grid spacing is 3 km or less.

The bar charts at the bottom of Figure 2 show the monthly averaged 2-m temperature bias for each summer month of 2012. The GW simulations at horizontal grid spacing of 3 km or less reduce the temperature bias by approximately half compared to the respective NOGW simulations for all summer months. This implies the dominant GW impact on mitigating the temperature bias throughout the summer months in this region occurs at fine scales.

Similar, but to a lesser degree, reduction in temperature biases is evident for the 2013 (normal) and 2014 (wet) years as shown in Table S1 in the simulations using grid spacing <9 km. Moreover, it is noteworthy that the domain-averaged 2-m temperature bias in the 1-km simulation with GW is significantly reduced to <1 °C, except for July and August of the dry year 2012.

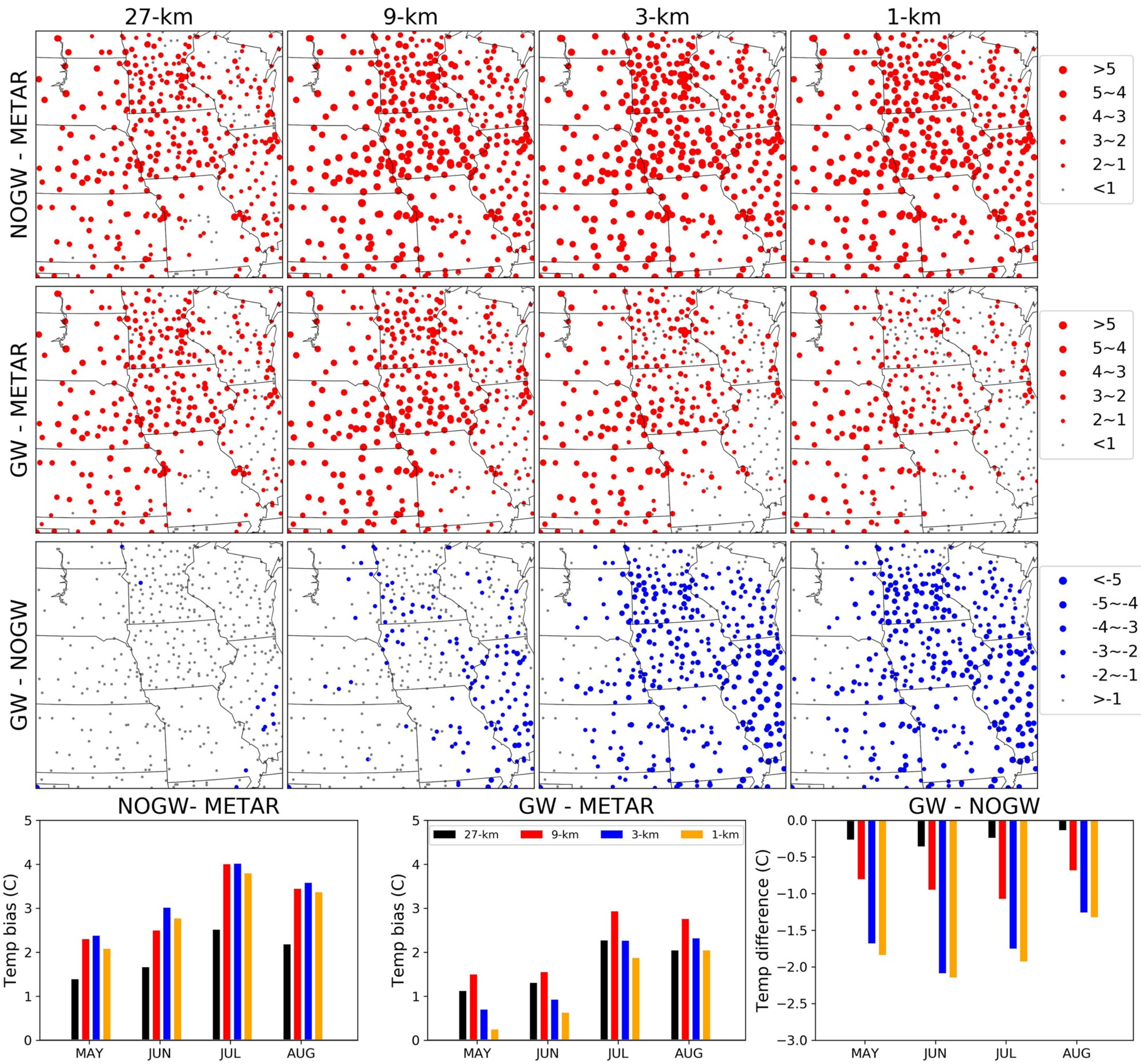

Figure 2. Spatial distribution of May–August 2012 averaged 2-m temperature bias (°C) of WRF simulations with 27-km, 9-km, 3-km, and 1-km grid spacing. The first three rows represent simulations with the groundwater scheme (GW), without the groundwater scheme (NOGW) and differences between these two simulations (GW-NOGW). The bottom row presents domain-average and monthly averaged 2-m temperature bias of 27-km, 9-km, 3-km, and 1-km WRF simulations for May–August 2012. The hourly surface weather METAR observations are available at https://catalog.data.gov/dataset/metar-data-access. WRF, Weather Research and Forecasting.

As shown in Figure 3, NOGW simulations produce low precipitation biases (up to 150 mm/month deficit) over this domain. Note that the NOGW simulation with 27-km grid spacing has a less severe dry bias compared to its counterparts with finer model resolution, which is most likely due to the fact that in the 27-km WRF simulation, the scale-dependent convection parametrization was much more active than in the other three grid spacings. More precipitation and cloudiness in the 27-km simulation may be the reason for its smaller warm biases shown in Figure 2 compared to other NOGW simulations. Again, increasing the model grid spacing from 9 to 1 km without the GW scheme does not substantially modify the low precipitation biases.

While not as obvious as the temperature bias reduction shown above, regional precipitation is also enhanced with increasing model resolution when the groundwater model is included. This is most evident

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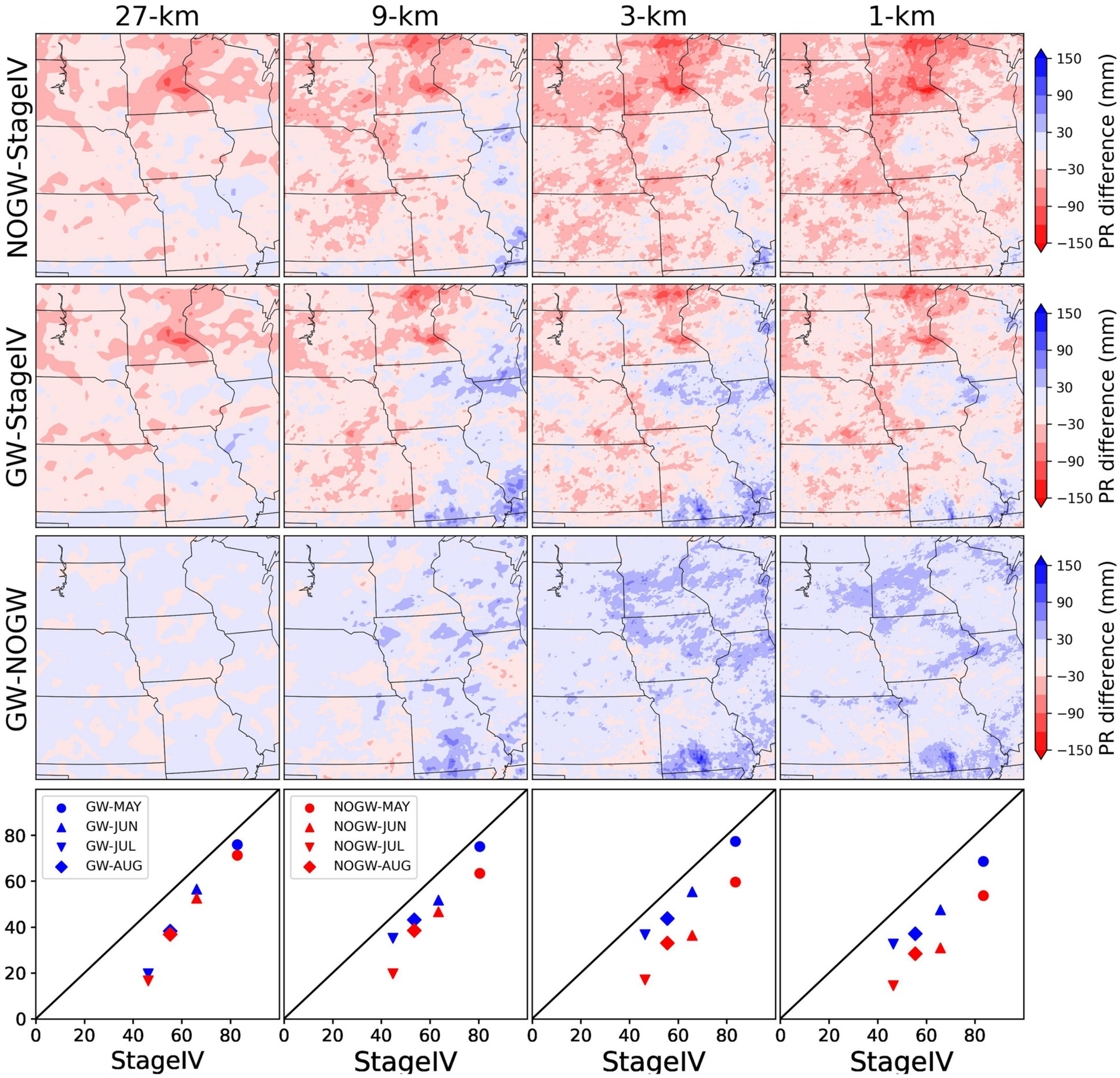


Figure 3. Spatial distribution of May–August 2012 average precipitation bias (mm), verified against Stage IV observations, for WRF simulations with 27-km, 9-km, 3-km, and 1-km grid spacing. The three rows represent simulations with the groundwater scheme (GW), without the groundwater scheme (NOGW), and differences between these two simulations (GW-NOGW). The bottom scatter plots present domain-averaged precipitation bias of 27-km, 9-km, 3-km, and 1-km WRF simulations for May, June, July, and August 2012. WRF, Weather Research and Forecasting.

in the bottom scatter plot in Figure 3, which compares the observed monthly precipitation to the model estimated precipitation. The improvement in simulated precipitation with the inclusion of GW (blue data points) as compared to simulation without GW (red data points) is clearly manifested at model grid spacing <9 km. Moreover, Table S2 shows that the reduction in the low precipitation biases by incorporating the GW physics in WRF occurs not only for the dry year 2012 but also for the normal and moist water years of 2013 and 2014. Again, simulations with grid spacing 9 and 3 km demonstrate more significant GW impact than those with coarser resolution, and are able to reduce precipitation bias by about half throughout summer months and for all three years investigated.

3.2. Impact of GW on Surface Water Cycle

The chief reason for including the GW physics is to produce a realistic water table pattern (Miguez-Macho et al., 2007) with shallow water tables in areas of poor drainage or lateral flow convergence. These shallow water tables, through capillary rise, as well as the lateral transport of aquifer water from neighboring model grid points, are able to replenish the depleted soil moisture in the vegetation and crop root zones as the growing season proceeds. As shown in Figure 4a, the recharge is always positive (i.e., losing water from active soil column to water table below through gravitational drainage) in simulations without GW, thus the model is not able to replenish the soil moisture used for evapotranspiration due to water-demanding plant and crop growth (Figure 4c). Starkly contrasted to simulations without GW, water is transported from the groundwater to plant and crop root zones in the simulations with GW. Coarser grid-spacing simulations only capture the regional scale groundwater pattern, with shallow water tables only in large flatter areas with slow drainage. However, simulations with 3-km or less grid spacing in which local topographic resolve better gradients-driving lateral GW flow convergence zones (Figures S1 and S2) than simulations with coarser resolutions, shallow water tables in valleys emerge, and the net upward water transport over the domain starts earlier in the season and moves more total water. Simulations with 3-km or less grid spacing produce at least the double amount of negative recharge than simulations with coarser resolution (50–60 mm vs. 10–20 mm), in a general agreement with the temperature and precipitation bias results shown earlier.

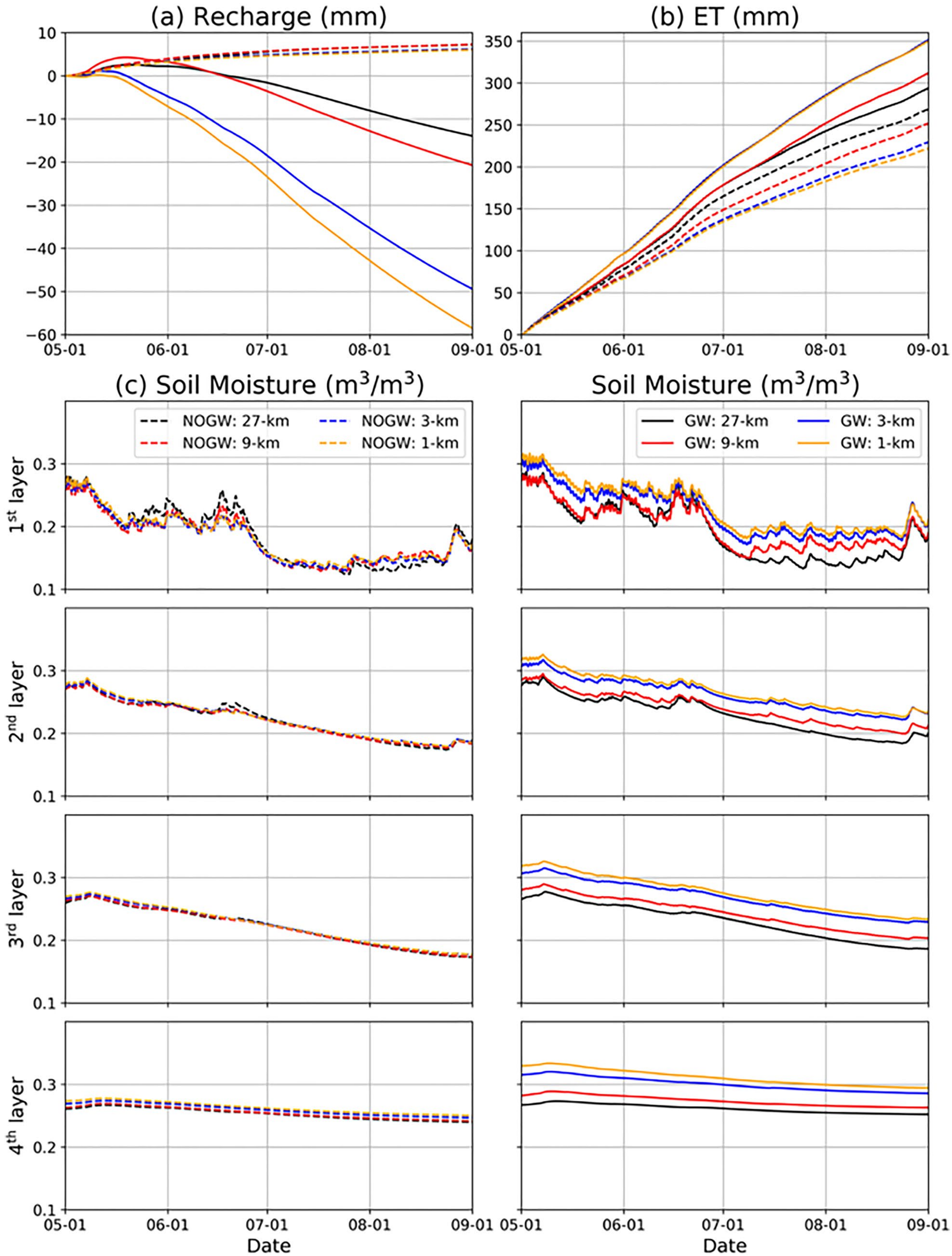
Consequently, simulations without GW produce much lower evapotranspiration than those with GW for all model horizontal resolutions (Figure 4b), and their differences increase with increasing model resolutions. Moreover, compared to the monthly evapotranspiration estimated from the 1-km Moderate Resolution Imaging Spectroradiometer (MODIS) data (see Table S3), NOGW simulations significantly underestimate the surface evapotranspiration throughout the summer months for all three years investigated, especially for the climatically dry year 2012. The higher evapotranspiration for the GW simulations despite the relatively lower temperature is likely due to the additional soil moisture available due to the replenishment from the water table below (Figure 4c).

A comparison of the evolution of soil moisture during the growing season between simulations with and without GW confirms the critical role of groundwater replenishment of root-zone soil moisture in the central U.S. (Figure 4c). It is clear that without groundwater supply the root-zone soil moisture in June and July quickly approaches or is below the wilting point, so that plant and crop evapotranspiration ceases. It is noteworthy that the root-zone soil moisture increased most at horizontal grid spacings 3 km or less, and was significantly lower at grid spacings of 9 and 27 km.

These results strongly suggest that the inclusion of a GW scheme can help alleviate the warm and dry bias in the central U.S. and that the lack of replenishment of the soil moisture from the water table below the active soil column may be the primary cause for the warm and dry bias observed in the Liu et al. (2017) 13-years WRF convection-permitting simulations.

Having examined individual components, we shall now discuss the integrated impact of GW on the surface water cycle. As shown in Figure 5, in simulations with finer grid spacing (1 and 3 km) the groundwater supply (negative recharge) is about 20 mm/month in the peak growing season (June and July), which is about double the amount from coarser model resolutions. Note that, compared to simulations without GW, this additional 20 mm only increases the soil moisture by about 5 mm in June and July. This is not surprising, because a large portion of this groundwater source is used to increase evapotranspiration. For instance, 1-km and 3-km simulations with GW produce about 35 mm more evapotranspiration than their counterpart without GW in June and July.

More interesting and important, the additional groundwater supply (∼20 mm) in 1-km and 3-km GW simulations are nearly translated into the same amount of precipitation increase in this domain, illustrating the importance of recycling of precipitation and the role of additional water vapor in enhancing convective activities in the central U.S. (e.g., Prein et al., 2017; Trenberth et al., 2003).


(a) Recharge (mm)
(b) ET (mm)
(c) Soil Moisture (m³/m³)
Soil Moisture (m³/m³)
NOGW: 27-km
NOGW: 9-km
NOGW: 3-km
NOGW: 1-km
GW: 27-km
GW: 9-km
GW: 3-km
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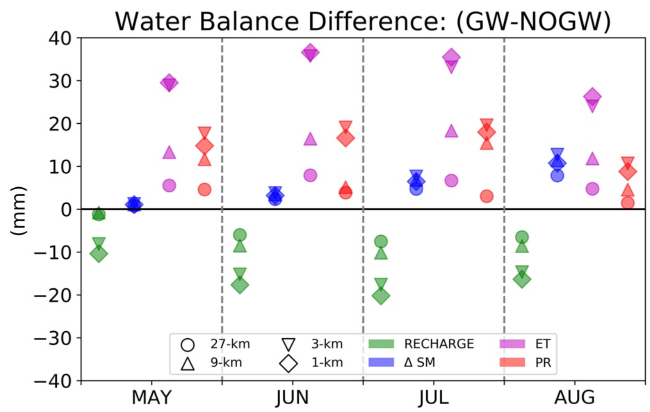

Figure 5. May–August 2012 monthly water balance difference (mm) between GW and NOGW simulations (GW-NOGW) in recharge, Δsoil moisture (change in 2-m soil moisture storage), evapotranspiration (ET), and precipitation (PR), across months and four grid spacing. GW, groundwater scheme.

4. Summary and Discussions

This study investigates, using observations and multiscale WRF model simulations, the role of representing groundwater processes across different scales on the water balance near the land surface and on the simulated temperature and precipitation biases. Compelling evidence is provided that the summertime warm and dry bias manifested in many climate and weather models over relatively flat midcontinental regions such as the central U.S. is partially a result of the lack of proper representation of groundwater-atmosphere interactions in those models. An investigation of model horizontal resolution highlights that a grid spacing of 3 km or less is necessary to capture small-scale river valleys and stream networks and associated shallow water tables and lateral-flow water fluxes and allow for meaningful interactions among GW, evapotranspiration, surface temperature, and precipitation. Indeed, only simulations with 1-km and 3-km grid spacing capture water tables shallower than 1 m and water-convergence zones along riparian regions of the domain, slow down drainage of directly feeding transpiration needs via upward capillary fluxes, and hence supply double the recharge water amount (50–60 mm throughout the growing season) than those with 9-km and 27-km grid spacing.

The additional water source is critical to replenishing the depleted vegetation and crop root zones during the growing season. As a result, the evapotranspiration in 1-km and 3-km simulations with GW is about 150 mm higher than their counterparts without GW, and agrees better with observations, especially in July and August. Including the groundwater model is effective at reducing the summertime 2-m temperature warm biases from 5–6 to 2–3 °C in simulations with 3-km or less grid spacing. The increase in the boundary-layer moisture appears to be significant enough to modify convective activities and enhance regional precipitation in the simulations that include groundwater at horizontal resolutions higher than 3–4 km. GW simulations with 3-km or less grid spacing are able to reduce the precipitation dry bias by half.

Moreover, the additional recharge amount (~20 mm) in 1-km and 3-km simulations with GW is nearly translated into the same amount of precipitation increase in this domain, highlighting the importance of recycling of precipitation and the role of additional water vapor in enhancing convective activities in the central U.S. This study illustrates the necessity to include the interactions among subsurface, surface, and the atmosphere, especially at convection-permitting scales, where these interactions seem to amplify. The central U.S. includes a significant irrigated land (e.g., in western Corn Belt) where the irrigated water impacts evaporation and precipitation. The impacts of the coupling between groundwater and irrigation through groundwater pumping on evaporation, partitioning between soil evaporation and plant evapotranspiration (e.g., Chang et al., 2018), and regional precipitation recycling (e.g., Trenberth et al., 2003) need future research. Understanding the physical mechanisms through which the increased boundary-layer water vapor modifies the regional precipitation is beyond the scope of the current study and warrants further investigation.

Data Availability Statement

METAR observations are available at: https://rda.ucar.edu/datasets/ds461.0/; MODIS evaporation data are available at: https://modis.gsfc.nasa.gov/data/dataprod/mod16.php; Stage IV data are available at: https://www.emc.ncep.noaa.gov/mmb/ylin/pcpanl/stage4/. Model data used in this study are available at the public repository: https://osf.io/t2brd/?view_only=8bf3115513ec42c1827daf106a6930b7.

Figure 4. (a) Domain-averaged accumulated recharge to the water table (mm) leaving the 2-m active soil column from May 1 to September 1, 2012, for four WRF simulations with different horizontal resolutions. Negative slope implies upwards water transport from water table to the active 2-m soil column; (b) same as (a) but for accumulated ET (mm), (c) domain-averaged volumetric soil moisture (m^3/m^3) for simulations with and without GW at different resolutions at first soil layer (0–10 cm below the surface), second layer soil moisture (10–40 cm), third soil layer (40–100 cm), and fourth soil layer (100–200 cm). WRF, Weather Research and Forecasting; GW, groundwater scheme; ET, evapotranspiration.

Acknowledgments

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