Spatiotemporal patterns of evapotranspiration in response to multiple environmental factors simulated by the Community Land Model

Xiaoying Shi, Jiafu Mao, Peter E Thornton and Maoyi Huang

1 Climate Change Science Institute/Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
2 Pacific Northwest National Laboratory, Richland, WA 99352, USA

E-mail: shix@ornl.gov

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Abstract

Spatiotemporal patterns of evapotranspiration (ET) over the period from 1982 to 2008 are investigated and attributed to multiple environmental factors using the Community Land Model version 4 (CLM4). Our results show that CLM4 captures the spatial distribution and interannual variability of ET well when compared to observation-based estimates. We find that climate dominates the predicted variability in ET. Elevated atmospheric CO$_2$ concentration also plays an important role in modulating the trend of predicted ET over most land areas, and replaces climate to function as the dominant factor controlling ET changes over the North America, South America and Asia regions. Compared to the effect of climate and CO$_2$ concentration, the roles of other factors such as nitrogen deposition, land use change and aerosol deposition are less pronounced and regionally dependent. The aerosol deposition contribution is the third most important factor for trends of ET over Europe, while it has the smallest impact over other regions. As ET is a dominant component of the terrestrial water cycle, our results suggest that environmental factors like elevated CO$_2$, nitrogen and aerosol depositions, and land use change, in addition to climate, could have significant impact on future projections of water resources and water cycle dynamics at global and regional scales.

Keywords: evapotranspiration (ET), Community Land Model (CLM), model tree ensembles (MTE)

1. Introduction

Evapotranspiration (ET), or water transferred from the land surface to the atmosphere, is an essential process in the climate system that links water, energy and carbon cycles (Nachabe et al. 2005, Alton et al. 2009, Jung et al. 2010, Wang and Dickinson 2012). ET over land is the second largest component (after precipitation) of the terrestrial water cycle at the global scale and returns about 60% of precipitation falling on land back to the atmosphere on an annual basis (L’vovich and White 1990, Oki and Kanae 2006, Lettenmaier and Famiglietti 2006). It is expected that the hydrological cycle will be intensified under climate change (Huntington 2006) with varied impacts on ET. Physically and physiologically, ET is driven not only by climatic factors, such as precipitation, temperature, wind speed, surface humidity, and solar radiation, but also is modulated by changes in environmental factors such as the atmospheric CO$_2$
The atmospheric CO₂ concentration affects the hydrological cycle mainly in two ways: (1) the physiological effect where plants regulate the opening and closing of their stomata in response to changes in CO₂ concentration and (2) the structural effect where the increase in CO₂ concentration leads to enhanced vegetation growth, thus changing plant structure and increasing the leaf area index (Piao et al. 2007, Felzer et al. 2009, Shi et al. 2011).

Hence, the purpose of this study is to quantify the possible control variability of ET at different time scales. However, made to improve our understanding of the factors that ET are still poorly quantified (Wang and Dickinson 2012).

Methods

2.1. Model description

Version 4 of the CLM, used in this study, succeeds CLM 3.5 (Oleson et al. 2008) with revised runoff generation and snow parameterizations, organic soil, a 50 m deep ground column for energy budget calculations, a 3.82 m deep soil column overlaid with a groundwater aquifer for hydrologic calculations, and an updated distribution of plant functional types (Oleson et al. 2010, Lawrence et al. 2011). The fully prognostic carbon and nitrogen dynamics of the terrestrial biogeochemistry model Biome-BGC (version 4.1.2) (Thornton and Rosenbloom 2005, Thornton et al. 2002) have also been merged to CLM4. The resulting model, CLM4, includes prognostic carbon and nitrogen pools and fluxes in vegetation, litter, and soil organic matter (Thornton and Zimmermann 2007, Thornton et al. 2009). Thus, CLM4 can modulate transpiration and canopy evaporation through prognostic leaf and stem area, which influences ET. The hydrology scheme includes a revised ground evaporation parameterization that accounts for the stability of near-surface air as modified by the vegetation canopy and a litter layer. The snow parameterization incorporates the snow and ice aerosol radiation model, which includes aerosol deposition, grain-size dependent snow aging, and vertically resolved snowpack heating (Lawrence et al. 2011).

2.2. Simulation setup

Global simulations were conducted using CLM4 driven by the 111-year (1901–2010) observation-constrained half-degree CRUNCEP dataset (http://dods.extra.cea.fr/data/p529nio/cruncep/readme.htm), including temperature, precipitation, specific humidity, solar radiation, wind speed, pressure and long wave radiation at a 6 h time step. The CRUNCEP is a combination of the CRU TS.3.2.0.5°C monthly climatology covering the period 1901–2010 (http://badc.nerc.ac.uk/view/badc.nerc.ac.uk_ATOM_dataent_1256223773328276) and the 2.5°C NCEP2 reanalysis data beginning in 1948 and available in near real time (Kanamitsu et al. 2002, Mao et al. 2012a, 2012b). Consistent with the climate forcing, the spatial resolution of the CLM4 simulations is 0.5°, with a temporal resolution of 30 min. The simulations were spun up to equilibrium under environmental conditions (i.e., atmospheric CO₂, nitrogen deposition, land use and land cover change, and aerosol deposition, to trends and variability in ET over the period of 1982–2008).

2.3. Transient simulations

Global simulations were conducted using CLM4 driven by the 111-year (1901–2010) observation-constrained half-degree CRUNCEP dataset (http://dods.extra.cea.fr/data/p529nio/cruncep/readme.htm), including temperature, precipitation, specific humidity, solar radiation, wind speed, pressure and long wave radiation at a 6 h time step. The CRUNCEP is a combination of the CRU TS.3.2.0.5°C monthly climatology covering the period 1901–2010 (http://badc.nerc.ac.uk/view/badc.nerc.ac.uk_ATOM_dataent_1256223773328276) and the 2.5°C NCEP2 reanalysis data beginning in 1948 and available in near real time (Kanamitsu et al. 2002, Mao et al. 2012a, 2012b). Consistent with the climate forcing, the spatial resolution of the CLM4 simulations is 0.5°, with a temporal resolution of 30 min. The simulations were spun up to equilibrium under environmental conditions (i.e., atmospheric CO₂, nitrogen deposition, land use and land cover change, and aerosol deposition, to trends and variability in ET over the period of 1982–2008).
together with the other transient environmental driving dataset for the period 1901–2009. Annual land use change and harvest area were derived from the University of New Hampshire version 1 Land-Use History A (LUHa.v1) historical dataset based on that of Hurtt et al (2006) for 1850–2005, and from the RCP4.5 scenario of AR5 for the period 2006–2009, respectively. Effects of rotational wood harvest, conversion of natural vegetation to agriculture or pasture, and abandonment of managed lands are included in the land use change term (Shi et al 2011). The details of the atmospheric CO$_2$ concentration and nitrogen deposition are similar to Shi et al (2011). The aerosol deposition data include eight particle species: hydrophilic black carbon, hydrophobic black carbon, hydrophilic organic carbon, hydrophobic organic carbon, and four species of mineral dust. In our simulations, the aerosol deposition rates are prescribed according to rates obtained from a transient 1850–2009 CAM-chem simulation with interactive chemistry (Lawrence et al 2011).

In order to assess the relative contributions of climate, increasing atmospheric CO$_2$ concentration, nitrogen deposition, land use and land cover change, and aerosol deposition, we performed seven simulations in this study. In simulation S1 (i.e., the control simulation), we repeated the 20-year subset of climate drivers (1901–1920) for the entire period 1850–2009, and kept atmospheric CO$_2$ concentration, nitrogen deposition, land use change, and aerosol deposition constant at their 1850 values. In simulations S2–S5, we used the same subset of transient climate, and varied one of the four remaining factors while holding the other three constant at their 1850 values (i.e., CO$_2$, nitrogen deposition, land use change and aerosol deposition are varied in S2, S3, S4 and S5 simulations, respectively). In the S6 simulation (hereafter CLIM simulation), historical transient climate from CRUNCEP was applied after 1900 and the other factors were held at their 1850 values. Finally, in simulation S7 (hereafter ALL simulation), we allowed all factors (climate, CO$_2$, nitrogen deposition, land use change and aerosol deposition) to vary throughout the fully transient simulation. The effect of each individual non-climate factor is calculated by subtracting S2, S3, S4 and S5 from simulation S1 (hereafter referred to CO$_2$, NDEP, LUC and AERO, respectively).

To evaluate our simulations, we used the global land ET data derived from the FLUXNET network of eddy covariance towers using the model tree ensembles (MTE) approach (Jung et al 2010). The FLUXNET-MTE up-scaling provides monthly ET at 0.5° spatial resolution over the period 1982–2008, allowing comparison with CLM4 results without need for spatial interpolation or regridding. As with observation-based ET data, only the model simulations from 1982 to 2008 were selected and analyzed.

3. Results

3.1. Spatial patterns of ET

To provide some credibility for the model predicted ET changes, we first compare the CLM4 simulated globally averaged and spatial patterns of ET with observation-based FLUXNET-MTE product. Global mean ET as predicted by CLM4 is 639 mm yr$^{-1}$ for the period 1982–2008, compared to FLUXNET-MTE estimation of 574 mm yr$^{-1}$. Figure 1 shows the spatial distributions of land annual mean ET over the study period for ALL simulation, FLUXNET-MTE and the difference between them. It can be seen that CLM4 captures the global distribution of ET well (figures 1(a) and (b)), but CLM4 predicted ET is higher than FLUXNET-MTE over the tropics (figure 1(c)), which is the major contribution to the higher value of CLM4 simulated globally averaged ET when compared to MET product.

3.2. Interannual variation in ET

Both the CLM4 modeled ET in simulation ALL (including all forcing factors) and the observation-based FLUXNET-MTE product show significant interannual variability between 1982 and 2008 (figure 2(a)). The interannual variability of ET due to the combined effects of all the forcing factors is consistent with the observation-based ET data ($R = 0.65$, $P < 0.005$). On average, the simulated global land area mean ET from simulation ALL demonstrates a significant positive trend with the rate of $0.60 \pm 0.14$ mm yr$^{-2}$, slightly higher than the trend of $0.47 \pm 0.12$ mm yr$^{-2}$ for the observation-based ET over the study period 1982–2008, but both at high confidence levels with p-values less than 5%. Jung et al (2010) also have reported that ET shows a declining trend for the subset time period of 1998–2008. However, our predicted ET trend does not follow that decreasing trend as the MTE product does. We have separated the effect of each individual factor for climate, increasing atmospheric CO$_2$ concentration, nitrogen deposition, land use and land cover change, and aerosol deposition. The results show that ET predictions from the individual factor simulations also demonstrate substantial interannual fluctuation over the study period (figure 2(b)). We will attribute the effect of each individual factor to the ET trends in section 3.3.

Simulation ALL captures regional-scale interannual variability in ET over major continents when compared to the FLUXNET-MTE product, with the exception of South America (figure 3). CLM4 can reproduce more than 50% variance over three continents (North America, Africa and Australia), and 25% variance over the other continents (Europe and Asia). While, CLM4 fails to captures the variance of South America.

3.3. Factor contributing to the global and continental ET trends

For the period 1982–2008, globally averaged increasing trends of CRUNCEP climate forcings over land in precipitation, temperature, specific humidity, shortwave radiation, and long wave radiation are significant. Wind speed also shows an increasing rate but the trend is not significant. In contrast, surface pressure shows an insignificant decreasing trend over the study period. Other forcing factors, such as atmospheric CO$_2$ and aerosol deposition show significant increasing trends, while nitrogen deposition shows insignificant increasing trend
Figure 1. Spatial distribution of annual ET (mm d\(^{-1}\)) for 1982–2008: (a) from CLM4, (b) from MTE and (c) the difference between the CLM4 and MTE (i.e., CLM4–MTE).

Figure 2. Change in global annual ET anomalies from 1982–2008. (a) Comparison of global ET between FLUXNET-MTE by Jung et al (2010) and that predicted in simulation ALL, including climate, atmospheric CO\(_2\), nitrogen deposition, land use and land cover change, and aerosol deposition. (b) Interannual variability and trend in modeled global ET resulting from the effects of climate change (simulation CLIM), increased atmospheric CO\(_2\) (simulation CO\(_2\)), nitrogen deposition (simulation, NDEP), land use change (simulation LUC), aerosol deposition (simulation, AERO), and the combined effect of all the factors (simulation ALL), respectively.
We investigated the relative contributions of major environmental driving factors to global and continental-level ET. For global land, historical climate variation generates a significant increasing ET trend, with a rate 0.78 mm yr$^{-2}$, while the CO$_2$-only simulation produces a decreasing trend ($-0.20$ mm yr$^{-2}$). Nitrogen deposition generates an increase in ET of 0.02 mm yr$^{-2}$, and land use change results in a decrease of 0.001 mm yr$^{-2}$. Aerosol deposition does not exert any significant effects for global land ET. Figure 4 shows that climate is the strongest driving factor, and rising CO$_2$ concentration is the second most important for trends in ET over global land, or regionally over Europe, Africa and Australia, while nitrogen deposition, land use change

(table 1). It should be noted that all these statistics are global land values over the period of 1982–2008, and that regional and different temporal features may vary.

Figure 3. The time evolution of anomalies in continental-level annual ET.
and aerosol deposition have smaller but varying effects. Rising atmospheric CO$_2$ concentration is the primary driving factor for simulated trends in ET over North America, South America and Asia, followed by climate, with nitrogen deposition, land use change and aerosol deposition again having small and variable effects. The effect of nitrogen deposition is twice that for land use change over North America, while the impacts from land use change are higher than nitrogen deposition over Africa and Australia, and impacts of those two factors are comparable over Europe, Asia and South America. Contributions from aerosol deposition are small for all regions except for Europe (−0.06 mm yr$^{-2}$), where the aerosol deposition contribution is the third most important factor for trends of ET. This result is consistent with Lawrence et al (2011) who showed that the CLM4 snow model generates darkening of the snow surface in areas that receive large amounts of black carbon and/or dust deposition (e.g., central and eastern Europe), with indirect effects on ET through modulating the timing of snowmelt.

There is a clear disparity in global-scale ET trends between our climate-only simulation (CLIM) and the observation-based MTE product (figure 4), which suggests that ET change driven by climate alone is not sufficient to account for the total trend in MTE ET. Because the MTE product is based on flux observations, it implicitly includes the influence of rising CO$_2$, anthropogenic nitrogen deposition, and other non-climate forcing factors. Our all factor simulation (ALL) has a global-scale trend closer to the MTE product, with rising CO$_2$ indicated as the most important factor modifying the influence of climate. We see that this pattern also holds for several sub-regions (South America, Africa, and Australia), but that in several other regions our ALL simulation is worse than CLIM, when compared to MTE (North America, Europe, and Asia, figure 4).

3.4. Spatial patterns of trends in ET

The general agreement of the spatial distribution between the modeled ET from the simulation driven by all factors (ALL) and observation-based estimates by Jung et al (2010) is evident as seen in figure 1, suggesting that it is useful to explore the spatial patterns of changes in ET. Figure 5 displays the spatial distribution of trends in modeled and observation-based ET, and CRUNCEP precipitation over the 27-year study period. The ET trend from all factor simulation ALL (figure 5(a)) follows the spatial distribution of precipitation in general (figure 5(h)), and has similar spatial patterns compared to observation-based MTE data (figure 5(b)). However there are some notable differences between the modeled and MTE ET over Europe, China, southeastern North America and southeastern Africa. As discussed earlier, the MTE ET product relies heavily on FLUXNET observations and is subject to uncertainty rooted from the limited spatial and temporal coverage of flux towers, which made it an imperfect metric for measuring model performance. In addition, MTE ET dataset does not explicitly take into account the other environmental factors, such as CO$_2$ concentration, nitrogen deposition, land use and land cover change, and aerosol deposition.

The spatial pattern of ET trends in climate-only simulation CLIM follows the pattern from all factors simulation ALL very well, suggesting that the increasing trend of ET over the past 27 years is induced mainly by the changes in mean climate, as well as by its variability (figure 5(c)). Nitrogen deposition enhances the upward trends in ET over most parts of the global land (figure 5(e)), which is consistent with a previous study examining the influence of single forcing factors on river flow (Shi et al 2011). In contrast, elevated atmospheric CO$_2$ concentration exerts significant decreasing trends in ET over almost global land surface (figure 5(d)), a result in agreement with previous studies (Cramer et al 2001, Betts et al 2007, Felzer et al 2009, Alkama et al 2010, Shi et al 2011). The land use change generates inhomogeneous trends over most portions of global land, but induces upward trends over high latitude regions of the Northern Hemisphere, southeastern China and western parts of Australia (figure 5(f)). Piao et al (2007) also have reported that land use change plays an important role in controlling regional runoff values. Aerosol deposition enhances ET over low latitude areas and Southern Hemisphere, while decreases ET over middle and high latitude regions of Northern Hemisphere (figure 5(g)).

3.5. Sensitivity of ET to climate change

To clarify the relationship of ET to climate variability, correlation coefficients between ET and climatic variables are

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**Table 1. Changing trends of different driving factors for CLM4 simulations of the study period 1982–2008. (Climatic factor includes precipitation, temperature, specific humidity, short wave radiation, long wave radiation, wind speed and surface pressure, other forcing includes atmospheric CO$_2$ concentration, nitrogen deposition and aerosol deposition.)**

| Variables          | Changing trends (mean ± SD) | $P$ values |
|--------------------|-----------------------------|------------|
| Climate            |                             |            |
| Precipitation      | 1.460 ± 0.365 (mm yr$^{-2}$) | <0.005     |
| Temperature        | 0.034 ± 0.004 (K yr$^{-1}$)   | <0.005     |
| Specific humidity  | 0.011 ± 0.002 (g kg$^{-1}$ yr$^{-1}$) | <0.005 |
| Short wave radiation | 0.033 ± 0.010 (W m$^{-2}$ yr$^{-1}$) | <0.005 |
| Long wave radiation | 0.100 ± 0.029 (W m$^{-2}$ yr$^{-1}$) | <0.005 |
| Wind speed         | 0.002 ± 0.004 (cm s$^{-1}$ yr$^{-1}$) | 0.670    |
| Surface pressure   | −0.613 ± 0.386 (Pa yr$^{-1}$) | 0.125     |
| Others             |                             |            |
| CO$_2$             | 1.672 ± 0.030 (ppmv yr$^{-1}$) | <0.005 |
| Nitrogen deposition | 0.0004 ± 0.0003 (g N m$^{-2}$ yr$^{-2}$) | 0.159 |
| Aerosol deposition | 0.038 ± 0.042 (g m$^{-2}$ yr$^{-2}$) | <0.005 |

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calculated (table 2). Modeled ET has a significant positive correlation with precipitation in all regions and globally, while observation-based MTE ET shows significant positive relationship only for Australia, Africa and globally. It is noticeable that the correlation between ET and precipitation is higher over dry regions (e.g., Australia), in which the
ET processes are controlled by water availability in the root zone or shallow surface. CLM4 ET has significant positive connection with temperature globally and over Europe and Africa, while MTE ET has significant positive correlation with temperature globally and for all regions except Australia. Both CLM4 and MTE ET have significant negative correlation with temperature over Australia, where high temperature is generally associated with drought conditions. Modeled ET shows significant positive correlation with specific humidity globally and over Europe, Asia and Africa, while MTE ET shows significant positive correlation globally and over all continents except Australia. Both CLM4 and MTE ET show significant positive correlation with long wave radiation for global and continental scale except over South America. There are few significant correlations between either CLM4 or MTE ET and shortwave radiation or wind speed, although both CLM4 and MTE approaches have a significant negative correlation with shortwave radiation over Australia, which might be related to drought effect. We also calculated the correlation coefficients of CLM4 predicted net radiation and ET, but not for MTE dataset because of lacking the observed net radiation data. The result shows that there are significant positive relationship between CLM4 predicted net radiation and ET for global land, Africa, Austria, North America (the correlation coefficient is 0.50, 0.78, 0.73 and 0.78, respectively), while there are not significant relationships over Asia, Europe and South America (the correlation coefficient is 0.33, 0.44, and 0.12, respectively). The only region where either approach shows a significant correlation between ET and surface pressure is

**Figure 5.** Spatial distribution of modeled and observation-based ET and precipitation trends (mm/day/27 yr) over the period 1982–2008 (a) all factors; (b) observation-based MTE data; (c) climate only; (d) CO\(_2\); (e) nitrogen deposition; (f) land use change; (g) aerosol deposition; (h) CRUNCEP precipitation. Stipples mean the trends are statistically significant at the 5% level based on 2-side Student’s test.
CLM4 all factor simulation (ALL) predicted ET is helpful in assessing the uncertainty in CLM4 (2011). Correlations between annual mean climatic variables and ET (Prec: precipitation, Temp: temperature, SH: specific humidity, LWR: long wave radiation, SWR: short wave radiation, Wind: wind speed, Psrf: surface pressure). These seven variables are from CLM4 climate forcing data, CRUNCEP, while the net radiation (NetR) is from CLM4 output. Bold values represent trends with significance (P < 0.05).

| Period       | Methods | Global   | N-America | Europe   | Asia     | S-America | Africa   | Australia |
|--------------|---------|----------|-----------|----------|----------|-----------|----------|-----------|
| 1982–2008    | CLM     | 0.60 ± 0.14 | −0.09 ± 0.26 | 0.14 ± 0.27 | −0.02 ± 0.19 | −0.04 ± 0.28 | 1.87 ± 0.39 | 0.57 ± 0.90 |
| 1982–2008    | MTE     | 0.47 ± 0.12 | 0.14 ± 0.16 | 0.60 ± 0.11 | 0.57 ± 0.13 | 0.01 ± 0.20 | 1.04 ± 0.24 | 0.30 ± 0.62 |
| 1983–2006    | ZHA10   | 0.72 ± 0.21 | 1.12 ± 0.32 | 1.24 ± 0.30 | −0.74 ± 0.22 | 3.21 ± 1.00 | 1.22 ± 0.38 | −0.46 ± 0.39 |
| 1982–2009    | ZENG12  | 1.10 ± 0.20 | 0.56 ± 0.22 | 0.96 ± 0.21 | 0.87 ± 0.28 | 1.84 ± 0.56 | 1.50 ± 0.30 | 0.48 ± 0.49 |

Europe, with CLM4 predicting a negative relationship, while MTE shows a positive relationship. The spatial distribution of correlation coefficients between modeled ET from all factor simulation ALL and observation-based ET and selected climatic variables also demonstrates that the modeled ET has significant positive correlation with precipitation (figure 6(a)), while the observation-based ET tends to highly correlate with temperature and specific humidity (figures 6(d) and (f)). This could be related to the fact that the MTE ET dataset is biased for energy-limited regions (i.e., humid regions), such as limited coverage of FLUXNET sites over the tropics. Both modeled and observation-based ET show significant positive relationship with long wave radiation over most global land areas (figures 6(g) and (h)).

4. Discussion

4.1. The uncertainty of ET estimation

Comparison to other global- and continental-scale estimates of ET is helpful in assessing the uncertainty in CLM4 predictions. CLM4 all factor simulation (ALL) predicted globally averaged ET is 639 mm yr⁻¹ for the period 1982–2008, compared to FLUXNET-MTE estimation of 574 mm yr⁻¹. Both numbers are comparable to Zeng et al. (2012), who reported the globally averaged land ET at 604 mm yr⁻¹ with a range of 558–650 mm yr⁻¹. Mueller et al. (2011) compared 30 global observation-based ET datasets and the modeled ET from 11 coupled global climate models of the IPCC Fourth Assessment Report and concluded that the global mean annual ET of the 41 datasets ranged from 511 to 650 mm yr⁻¹, with an average value of 580 mm yr⁻¹.

Table 3 shows the global- and continental-scale ET trends from our all factor simulation ALL, MTE estimates, and two other data sources: one from Zhang et al. (2010) (hereafter ZHA10), and the other from Zeng et al. (2012) (hereafter ZENG12). Both MTE and ZHA10 estimated ET by up-scaling local eddy covariance flux measurements from global FLUXNET network, through integration with gridded satellite FPAR (or NDVI) and climate data. MTE used Global Precipitation Climatology Center (GPCC) precipitation and temperature from CRU while ZHA10 used NCEP precipitation and temperature. ZENG12 was estimated by using a simple regression approach using temperature and precipitation from CRU and NDVI data from NOAA/AVHRR. Both our simulations and the three studies agree that there is a significant increasing trend in ET globally and over Africa. Over Europe, all the other three studies show significant upward trends in ET, while CLM4 shows an insignificant increasing trend. CLM4 predicts insignificant decreasing trends in ET over North America and South America, while the other three methods estimate significant increasing trends. Over Asia, CLM4 demonstrates an insignificant downward trend, while ZHA10 shows a
significant decreasing trend, and MTE and ZENG12 show significant upward trends in ET. Both CLM4 and the MTE and ZENG12 estimate insignificant increasing trends in ET over Australia, while ZHA10 estimates an insignificant decreasing trend.

It should be noted that our predicted ET from the all factor simulation ALL considers not only climate change, but also the rising atmospheric CO$_2$ concentration, nitrogen deposition, land use and land cover change and aerosol deposition. However, ET of MTE, ZHA10 and ZENG12 do not explicitly take into account these other environmental factors. It has been shown in recent years that the effect of rising atmospheric CO$_2$ concentration on the water cycle is very important (Gedney et al 2006, Piao et al 2007, Shi et al 2011). Figure 4 clearly shows that the ET trend should change from negative to positive if we exclude the effect of CO$_2$ from our all factor simulation ALL over North America, Asia and South America, confirming that the rising atmospheric CO$_2$ concentration is very crucial for land ET. Piao et al (2007) and Shi et al (2011) have reported that it is necessary to consider the effect of land use change on the hydrological cycle, and Felzer et al (2009) and Shi et al (2011) have demonstrated that nitrogen limitation is another factor controlling the water balance of ecosystems. Zeng et al (2012) have noted that excluding the effects of rising atmospheric CO$_2$ concentration, land use change and humidity on the estimation of ET, introduced uncertainty for their dataset.

The variation among these independent methods for estimation of global and regional trends in ET highlights the need for continued and expanded collection of ET.
observations for validation. The advantage of the modeling approach capable of quantifying ET over large areas and field experiments capable of providing accurate local-scale ET estimates with process-level understanding could serve as constraints for improving models and reducing uncertainty in ET estimate, respectively, making collaborative efforts between field scientists and modelers essential, especially in data-poor regions.

4.2. The uncertainty of our prediction

This study investigates the relative contributions of multiple environmental factors on temporal and spatial variability in ET during 1982–2008. Although this relatively comprehensive analysis is intended to quantify the factorial contributions to the changing rate of ET, it is also important to recognize the uncertainties that are inherent in such a study. First, our simulations do not consider some possible disturbances (except for fire) or environmental factors that may influence the terrestrial ecosystem water cycle, for example ozone pollution (Felzer et al. 2009), or irrigation (Doll 2002, Gordon et al. 2005), all of which might influence regional and global trends of ET. Further studies are still needed to quantify the effects of these factors on ET. Second, uncertainties induced by model structure, parameters, and the driving data remain to be evaluated.

5. Conclusions

In this study, the process-based model CLM4 is used to explore the relative importance of changes in climate, atmospheric CO$_2$ concentration, nitrogen deposition, land use change and aerosol deposition on spatial and temporal variations in ET at global and continental scales during the period 1982–2008. Our model results suggest that the changing rates in ET at global and continental scales have been mainly a consequence of climate and rising CO$_2$ concentration during the study period. The relative roles of nitrogen deposition, land use change and aerosol deposition are small and variable by region. Our simulated results not only provide insights for large-scale field experiments, but also highlight the importance of biosphere feedbacks and anthropogenic influence on hydrological cycle (Gedney et al. 2006, Piao et al. 2007). The roles of non-climate factors, such as the rising atmospheric CO$_2$ concentration, nitrogen deposition (Shi et al. 2011), land use change (Piao et al. 2007, Shi et al. 2011) and aerosol deposition should not be ignored when project future changes in water cycle and climate.

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References

Alkama R, Kageyama M and Ramstein G 2010 Relative contributions of climate change, stomatal closure, and leaf area index changes to 20th and 21st century runoff change: a modelling approach using the organizing carbon and hydrology in dynamic ecosystems (ORCHIDEE) land surface model J. Geophys. Res. 115 D17112

Alton P, Fisher R, Los S and Williams M 2009 Simulations of global evapotranspiration using semiempirical and mechanistic schemes of plant hydrology Glob. Biogeoch. Cycles 23 GB4023

Betts R, Boucher O, Collins M, Cox P, Falloon P, Gedney N, Hemming D, Huntingford C, Jones C and Sexton D 2007 Projected increase in continental runoff due to plant responses to increasing carbon dioxide Nature 448 1037–41

Cao L, Govindasamy B, Caldeira K, Nemani R and Ban-Weiss G 2010 Importance of carbon dioxide physiological forcing to future climate change Proc. Natl Acad. Sci. USA 107 9513–8

Cramer W, Bondeau A, Woodward F, Prentice I, Betts R, Brovkin V, Cox P, Fisher V, Foley J and Friend A 2001 Global response of terrestrial ecosystem structure and function to CO$_2$ and climate change: results from six dynamic global vegetation models Glob. Change Biol. 7 357–73

Doll P 2002 Impact of climate change and variability on irrigation requirements: a global perspective Clim. Change 54 269–93

Felzer B, Cronin T, Melillo J, Kicklighter D and Schlosser C 2009 Importance of carbon–nitrogen interactions and ozone on ecosystem hydrology during the 21st century J. Geophys. Res. 114 G01020

Flanner M G, Zender C J, Randerson J T and Rasch P J 2006 Linking snowpack microphysics and albedo evolution J. Geophys. Res. 111 D12208

Gedney N, Cox P, Betts R, Boucher O, Huntingford C and Stott P 2006 Detection of a direct carbon dioxide effect in continental river runoff records Nature 439 835–8

Gopalakrishnan R, Bala G, Jayaraman M, Cao L, Nemani R and Ravindranath N H 2011 Sensitivity of terrestrial water and energy budgets to CO$_2$-physiological forcing: an investigation using an offline land model Environ. Res. Lett. 6 044013

Gordon L J, Steffen W, Jonsson B F, Folke C, Falkenmark M and Johannessen A 2005 Human modifications of global water vapor flows from the land surface Proc. Natl Acad. Sci. USA 102 7612–7

Huntington T 2006 Evidence for intensification of the global water cycle: review and synthesis J. Hydrolg. 319 83–95

Hurt G, Froliking S, Fearon M, Moore B, Shevlakova E, Malyshiev S, Pacala S and Houghton R 2006 The underpinnings of land use history: three centuries of global gridded land use transitions, wood harvest activity, and resulting secondary lands Glob. Change Biol. 12 1208–29

Jung M et al 2010 Recent decline in the global land evapotranspiration trend due to limited moisture supply Nature 467 951–4

Kanamitsu M, Ebisuzaki W, Woollen J, Yang S-K, Hnilo J, Fiorino M and Potter G L 2002 NCEP–DOE AMIP-II Reanalysis (R-2) Bull. Am. Meteorol. Soc. 83 1631–43

Lawrence D M et al 2011 Parameterization improvements and functional and structural advances in version 4 of the Community Land Model J. Adv. Model. Earth Syst. 3 1–27

Lettenmaier D P and Famiglietti J S 2006 Hydrology: water from on high Nature 444 562–3

L’vovich M I and White G F 1990 Use and transformation of terrestrial water systems The Earth as Transformed by Human
Action: Global and Regional Changes in the Biosphere over the Past 300 Years ed B L Turner, W C Clark, R W Kates, J F Richards, J T Mathews and W B Meyer (Cambridge: Cambridge University Press with Clark University) pp 235–52
Mao J, Shi X, Thornton P E, Piao S and Wang X 2012a Causes of spring vegetation growth trends in the northern mid-high latitudes from 1982 to 2004 Environ. Res. Lett. 7 014010
Mao J, Thornton P E, Shi X, Zhao M and Post W M 2012b Remote sensing evaluation of CLM4 GPP for the period 2000–09 J. Clim. 25 5327–42
Mueller B et al 2011 Evaluation of global observations-based evapotranspiration datasets and IPCC AR4 simulations Geophys. Res. Lett. 38 L06402
Nachabe M, Shah N, Ross M and Vomacka J 2005 Evapotranspiration of two vegetation covers in a shallow water table environment Soil Sci. Soc. Am. J. 69 492–9
Oki T and Kanae S 2006 Global hydrological cycles and world water resources Science 313 1068–72
Oleson K et al 2010 Technical description of version 4.0 of the Community Land Model (CLM) NCAR Tech. Note NCAR/TN-4781STR p 257
Oleson K, Niu G, Yang Z, Lawrence D, Thornton P E, Lawrence P, Stöckli R, Dickinson R, Bonan G and Levis S 2008 Improvements to the community land model and their impact on the hydrological cycle J. Geophys. Res. 113 G01021
Piao S, Friedlingstein P, Ciais P, de Noblet-Ducoudré N, Labat D and Zaehle S 2007 Changes in climate and land use have a larger direct impact than rising CO2 on global river runoff trends Proc. Natl Acad. Sci. 104 15242–7
Roderick M L and Farquhar G D 2002 The cause of decreased pan evaporation over the last 50 years Science 298 1410–1
Shi X, Mao J, Thornton P E, Hoffman F M and Post W M 2011 The impact of climate, CO2, nitrogen deposition and land use change on simulated contemporary global river flow Geophys. Res. Lett. 38 L08704
Thornton P E, Doney S, Lindsay K, Moore J K, Mahowald N, Randerson J T, Fung I, Lamarque J F, Feddema JJ and Lee Y H 2009 Carbon–nitrogen interactions regulate climate–carbon cycle feedbacks: results from an atmosphere–ocean general circulation model Biogeosciences 6 2099–120
Thornton P E, Law B, Ghol H, Clark K, Falge E, Ellsworth D, Goldstein A, Monson R, Hollinger D and Falk M 2002 Modeling and measuring the effects of disturbance history and climate on carbon and water budgets in evergreen needleleaf forests Agric. Forest Meteorol. 113 185–222
Thornton P E and Rosenbloom N 2005 Ecosystem model spin-up: estimating steady state conditions in a coupled terrestrial carbon and nitrogen cycle model Ecol. Modelling 189 25–48
Thornton P E and Zimmermann N 2007 An improved canopy integration scheme for a land surface model with prognostic canopy structure J. Clim. 20 3902–23
Wang K C and Dickinson R E 2012 A review of global terrestrial evapotranspiration: observation, modeling, climatology, and climatic variability Rev. Geophys. 50 RG2005
Zeng Z, Piao S, Lin X, Yin G, Peng S, Ciais P and Myneni R B 2012 Global evapotranspiration over the past three decades: estimation based on the water balance equation combined with empirical models Environ. Res. Lett. 7 014026
Zhang K, Kimball J S, Nemani R R and Running S W 2010 A continuous satellite-derived global record of land surface evapotranspiration from 1983 to 2006 Water Resour. Res. 46 W09522