

Responses to the Referee's Comments

ID: HESS-2016-87-RC2

We would like to thank the editor's decision regarding the revision of our manuscript. We are greatly thankful for the insightful and constructive comments from the anonymous reviewer. We have carefully studied them and revised the manuscript accordingly. This document contains our specific responses to the comments.

Responses to Anonymous Referee #2's Comments:

1. First, the research aimed to examine factors controlling net primary productivity (NPP) change and its feedbacks to the atmosphere, but the actual design was largely made to address the first part of the objective. More efforts on the second part would help bridge a knowledge gap and would definitely add values to the entire work.

Response: We rewrote the 3.1 & 3.3 parts according to the reviewer's comment.

3.1 Spatiotemporal variations in global terrestrial NPP and their effects on ET

The spatial patterns of global NPP from 2000 to 2014 showed a steadily decreasing trend from the equator to the Arctic and Antarctic (Fig. 1c). Overall, the inter-annual series of NPP increased moderately at a rate of 0.06 PgC/yr^2 over the past 15 years, and also shows different changes in the Northern and Southern Hemispheres. While NPP in most parts of the NH increased (Fig. 1a), it decreased in most parts of the SH (Fig. 1b). Specifically, in the NH, 64% of vegetated land area experienced increased NPP, including large areas of North America, Western Europe, India, and eastern China. Regions with decreased NPP include Eastern Europe and higher latitudes of central and west Asia. In the SH, decreased NPP accounted for about 60.3% of vegetated land area, mainly concentrated in South America, South Africa, and western Australia. Furthermore, in the equatorial regions, Amazon rainforests had significantly decreased NPP, whereas African rainforests experienced an increasing trend (Fig. 1c). Because tropical rainforest NPP accounts for a large proportion of global NPP, decreases in SH NPP partially counteracted increases in NH NPP.

When we combined global LUCC characteristics, the results showed that shrubland has the greatest potential increasing trend of NPP ($16.5 \text{ gC/m}^2/\text{yr}$) compared to other biomes, followed by grassland ($12.5 \text{ gC/m}^2/\text{yr}$). This may be related to the expansion of woody vegetation over the past 15 years. In the Arctic tundra (Hughes et al., 2006)

and lower latitudes in arid environments (Chen et al., 2014), experimental studies provided clear evidence that climate warming is sufficient to account for the expansion of shrubs and graminoids.

Changes in vegetation albedo and emissivity exert feedback on climate, which is especially obvious in ET (Field et al., 2007). The viability of vegetation cover can substantially modulate available surface energy and partition that energy into sensible and latent heat fluxes (Matsui et al., 2005). Vegetation changes can affect water and energy cycles in the land-atmosphere circulation by changing the physical characteristics of the land surface. For instance, the albedo of vegetation is less than that of bare soil, enabling it to absorb more energy and thus increase ET. Moreover, canopy height can change land surface roughness and affect the energy and momentum between land and air transport, and leaves promote ET through direct evaporation either from precipitation or transpiration interception from water uptake by roots.

Increased vegetation productivity and climate change may promote multi-decadal rises of global land ET (Zhang et al., 2015). Vegetation generally promotes land-atmosphere water exchange via transpiration through a biological process, changing soil moisture conditions and affecting the land-atmosphere feedback. The average mean of estimated global annual ET is 518.6 mm/yr, with an inter-annual trend of 0.46 mm/yr². Figures 1a and 1b show that the spatiotemporal changes of global ET are consistent with NPP variations, especially in the NH. Furthermore, where their association is less than that in the NH, NPP and ET in the SH have much higher variability. The spatial inconsistency in the SH mainly occurred near the equator, e.g., southern African rainforests (Figs. 1b & 1d). These regions have high values of average annual precipitation and stronger variability of precipitation than elsewhere, causing greater changes to ET and its components (land-surface evaporation, canopy evaporation, and transpiration). In places where the inter-annual variability of NPP is small, the ET component of land-surface evaporation increases. In contrast, in areas with large inter-annual variability of NPP, such as shrubland and grass-dominant regions, the ET components of land-surface evaporation decline and transpiration increases.

3.3 Continued effects of NPP on evapotranspiration likely to exacerbate regional droughts

With respect to the impact of drought on the world's ecosystems, studies have been limited regarding the contribution of vegetation and terrestrial water cycle components to drought variations (Falloon et al., 2012; Teuling et al., 2013). However, the present lack of high-quality and long-term records of actual ET limits the forecasting of drought under climate change circumstances.

Drought indices are pointing to an increased risk of drought in the present century. We used potential evapotranspiration (PET) as a surrogate measure of atmospheric moisture demand. PET is defined as the maximum quantity of water capable of being evaporated from soil and transpired from vegetation, whereas ET is the actual evaporation from water and soil, as well as transpiration from vegetation. Penman (1948) stated that ET had a proportional relationship with PET, and Bouchet (1963) hypothesized that a complementary feedback mechanism exists between ET and PET in water-limited regions. Overall, our investigation indicate that there is a proportional relationship between ET and PET in humid regions and a complementary one in arid regions (Fig. 1d and Fig. 4a). In PET, the combined impacts of temperature, solar radiation, vapor pressure and wind speed (Zhang et al., 2015) interact with NPP (Fig. 4b). Over the past 15 years, global PET showed an increasing trend of 1.72 mm/yr^2 , while global P increased at a rate of 0.84 mm/yr^2 . However, precipitation increases cannot offset evaporative demand, indicating a potential moisture deficit for water supplies constrained by ET. In other words, P is mostly being lost to ET rather than being allocated to other components of the energy and water cycles (Zhang et al., 2015).

Various factors, including vegetation, affect the intensity and spatial variation of drought. Vegetation generally promotes land-atmosphere water exchange via transpiration, changing soil moisture conditions and affecting the land-atmosphere feedback. Water vapor via transpiration can lead to increased regional atmospheric humidity over the short term, but preserve less water in the soil. This, in turn, accelerates reductions in soil moisture caused by warming and provides a negative feedback. Vegetation growth causes increased soil moisture evaporation, thus reducing the amount of soil water storage. Once vegetation suffers persistent drought, the vegetation biomass will rapidly decline and further intensify the drought. Thus, decreasing soil moisture tends to decrease net terrestrial radiation at the surface through increasing land-surface temperatures. If low levels of soil moisture persist for long enough, reductions in vegetation cover and vigor can occur. As land-surface

temperatures rise, increases in precipitation are insufficient to offset increases in evaporative demand, indicating a potential moisture deficit for water supplies constrained by ET. This leads to soil water loss and reduced vegetation growth, along with higher risk of drought (Meng et al., 2014; Zhang et al., 2015). Soil moisture is an important sensor for measuring superficial wetness and dryness levels, and generally reflects the dryness and wetness of climate. Figure 5 illustrates the world-wide decrease in soil moisture of four layers (0-10, 10-40, 40-100, and 100-200 cm). With precipitation being the most direct factor affecting soil moisture, temperature and solar radiation may cause soil moisture loss through ET. Available soil moisture is defined as the amount of water a plant can access in its root zone. Thus, spatial and temporal variations in soil moisture are closely related to vegetation growth (Davis and Pelsor, 2001; Yang et al., 2010).

2. Second, the authors need to be aware that from statistical perspective, correlation and causation are two related but distinct concepts. Correlation refers to how closely two sets of information or data are related, while causation means the act or process of causing that is often referred to as “cause and effect”. Correlation may imply causation but in some cases, such a relation may not be true. Adding some more physical or theoretical explanation of the statistical relationship would help understand the causation.

Response: Table 1 and its description in the text are the correlations between NPP and four climatic variables (temperature, precipitation, net radiation and PDSI) for over both hemispheres. We have not made the quantitative association/correlation between NPP and ET. We just wanted to show that: Land actual evapotranspiration (ET) changes are positively with net primary production changes, especially in the Northern Hemisphere. Under the context of past warmest 15 years, the slightly increased inter-annual series of NPP and climate change promote decadal rises of global land ET. According to the reviewer’s comment, we corrected several sentences that seem strong statement that NPP is the cause for the change of ET. Meanwhile, we added some more physical or theoretical explanation.

e.g. 3.1 & 3.3 (Please see the response of comment 1)

3.2 Controlling factors for NPP variations

Water, temperature, and radiation interact to impose complex and varying limitations

on vegetation activities in different parts of the world. To understand why NPP variations in the Northern and Southern Hemispheres respond differently to different climates, we first estimated the spatial trends of climatic control factors and then analyzed the complex multiple climatic constraints to plant growth. A comprehensive interpretation of interactive climatic controls on plant productivity showed that water, temperature, and radiation are the key factors affecting vegetation growth. Globally, growth was most strongly limited by water availability on 40% of the Earth's vegetated surface, while temperature limitations exerted the main controlling influence on 33% of the surface, and radiation on 27% (Nemani et al., 2003).

From 2000 to 2014, overall trends of average annual temperature ($0.007\text{ }^{\circ}\text{C}/\text{yr}^2$) and precipitation ($0.84\text{ mm}/\text{yr}^2$) experienced world-wide increases while showing different temporal change patterns (Figs. 2a & 2b). Eastern Europe, South America, southern Africa and western Australia experienced warming combined with decreased precipitation (warm-dry trend), whereas southeast North America, western Europe, east Russia, and African rainforests experienced warming combined with increased precipitation (warm-wet trend). Meanwhile, net radiation (Rn) increased in the equatorial tropics and arid regions in Northwestern China, but decreased in the Arctic and Antarctic (Fig. 2c). The Palmer Drought Severity Index (PDSI) is a widely-used index that correlates with soil moisture during warm seasons (Dai et al., 2004; 2013). Generally, a lower PDSI implies a drier climate. Global PDSI decreased at a rate of $0.04/\text{yr}^2$ from 2000 to 2014, suggesting an increased risk of drought in the 21st century. The spatial trend of PDSI shows that the eastern and northern coasts of North America, along with the African continent, Eurasia and southern South America, exhibited obvious drought trends in 2000-2014. Northern China, parts of Mongolia, and western Russia near Lake Baikal also experienced a drying trend (Fig. 2d). Warming-induced drying resulted from increased ET and was most prevalent over mid-high latitudes in the NH. Drought develops with periods of low-accumulated precipitation and is exacerbated by high temperatures.

We analyzed partial correlations between NPP and temperature (T), precipitation (P), Net radiation (Rn) and PDSI during growing seasons to determine their respective contributions across different regions (Fig. 3, Table 1). The climate changes during 2000-2014 have made precipitation, temperature, and radiation somewhat beneficial to plant growth. In the NH, climate changes have eased multiple climatic constraints

to plant growth through earlier springs, but the continuous warming may offset these benefits.

In high latitudes of the NH ($>47.5^{\circ}\text{N}$), temperature has a positive correlation with NPP ($R=0.6$). Significant warming generally lengthens growing seasons for vegetation and promotes plant growth in tundra regions, so the recent warming in this region has increased NPP (Fig. 3a). For northern mid and low latitudes ($<47.5^{\circ}\text{N}$), where large areas are classified as having an arid climate, vegetation is short-rooted. NPP has a significant negative correlation with P ($R=0.7$, $p<0.05$) (Fig. 3b) and is also correlated to R_n (Fig. 3c). In areas of high elevation such as the Tibetan plateau (which is similar to high latitudes), temperature is the dominant control factor in vegetation growth.

Equatorial Amazon rainforests experienced significantly decreased NPP, whereas African rainforests exhibited an increasing trend. These changes in equatorial regions are mainly related to the warming in the Amazon along with increasing precipitation in African rainforests. High temperatures caused higher rates of ET, generally reducing soil water availability for vegetation in the Amazon.

In the SH, we noted a significant correlation ($r =0.7$, $p<0.05$) between NPP and PDSI (Fig. 3d). The warming trend induced a much higher evaporative demand and led to a drying trend, except for the afore-mentioned increased precipitation in African rainforests. The PDSI in African rainforests also showed a slight increasing trend. A high T-value can increase both vapour pressure deficiency and moisture deficit and lead to a dryer environment. The general drought event across the SH, which was induced by extreme heat and a precipitation deficit, has resulted in a net water availability reduction, ultimately reducing NPP. Hence, warming-associated drying directly caused the significant decreasing trend of NPP in the SH.

3. Last, I understand English is not the mother language for these authors, and they must have made substantial efforts in polishing the English for the current submission. But there are still some small errors in English usage and grammar throughout the entire manuscript. These small errors collectively undermine the scholarly quality of this article. These authors are urged to find someone with competent English to edit the text.

Response: We carefully modified the grammar and sentence structure with the assistance of native English-speaking editors.

4. *The abstract is too long and is not quite coherent. It needs to be better organized and written. Although the findings are present, it is not clear why these authors conducted this research, what would be the objectives, and what methods they have used.*

Response: We have rewritten the abstract.

Abstract. The Earth has experienced a dramatic increase in global climate warming since 2000, which has significantly influenced the global water cycle and vegetation activities. Despite these radical changes, there is little observational evidence to demonstrate the effects of vegetation variations on climate in different global geographical units. A few studies focused on feedback relating to the inter-annual variability of vegetation on the physical processes of atmosphere-land surfaces, especially with regards to evapotranspiration. Overall, the global inter-annual series of net primary production (NPP) slightly increased in 2000-2014 at a rate of 0.06 PgC/yr². More than 64% of vegetated land in the Northern Hemisphere (NH) showed increased NPP (at a rate of 0.13 PgC/yr²), while 60.3% of vegetated land in the Southern Hemisphere (SH) showed a decreasing trend (at a rate of -0.18 PgC/yr²). Temperature was the dominant control factor for vegetation growth in high latitudes in the NH, net radiation and precipitation were the main factors affecting NPP in the mid latitudes, and warming-associated large-scale drying trends led to decreases in NPP in the SH.

Vegetation productivity influences albedo and emissivity, both of which regulate evapotranspiration (ET). Changes in actual ET correlate positively with changes in NPP, especially in the NH, where increased vegetation productivity and climate change have promoted sharp rises in terrestrial ET (0.61 mm/yr²). At the same time, anomalous dry conditions have caused a reduction in vegetation productivity and a near cessation of terrestrial ET growth in the SH (0.41 mm/yr²). Although water vapor via vegetation transpiration can lead to increased regional atmospheric humidity over a short time span, it also preserves less water in the soil. This, in turn, accelerates reductions in soil moisture caused by warming and triggers negative feedback. Drought indices, along with precipitation-minus-evaporation calculations, point to an increased risk of drought in the 21st century.

5. *Key words should include a term for the geographical area*

Response: Journal of *Hydrol. Earth Syst. Sci.* looks probably no keywords.

6. *Introduction: The literature review could be more coherent with specific methods and critical issues (e.g. temporal and spatial scales) targeted. Also additional context would help justify the three specific objectives targeted.*

Response: We have rewritten the Introduction.

Introduction

Organizations such as the Intergovernmental Panel on Climate Change (IPCC) and the World Meteorological Organization (WMO) have reported that the past decade was the warmest on record. Global warming indicates a general acceleration or intensification of the global hydrological cycle and thus an alteration in the process of evapotranspiration (ET) (Wentz et al., 2007; Douville et al., 2013), with implications for the response and mutual feedback of ecosystem services (Jung et al., 2010; Davie et al., 2013). Most of the recent research in this area has analyzed the impacts of climate change on vegetation activities, although some of the research on the feedback of terrestrial ecosystems to climate change has centered on the ecosystems' potential role as carbon sources (Field et al., 2007). Only a few studies focused on feedback relating to the inter-annual variability of vegetation on the physical processes of land surfaces and climate systems (Zhi et al., 2009), especially with regards to ET.

Terrestrial net primary production (NPP) can be defined as the amount of photosynthetically fixed carbon available to the first heterotrophic level in an ecosystem, and links terrestrial biota with atmospheric systems (Beer et al., 2010). Numerous ecosystem models have attempted to estimate terrestrial NPP, owing to its importance for ecological and social systems, both regionally and globally (Chen et al., 2012; Potter et al., 2012; Pan et al., 2014). From 1982 to 1999, climatic changes enhanced plant growth globally, especially in the northern mid and high latitudes (Nemani, 2003); this was followed, in 2000-2009, by a drought-induced reduction in global NPP (Zhao and Running, 2010). Gang et al. (2015) projected the dynamics of NPP in response to future anticipated climate changes in the 2030s, 2050s and 2070s, and found that global NPP would show an increasing trend. In particular, NPP at high latitudes in the Northern Hemisphere (NH) would likely be more sensitive to future climate change. The interaction of water, temperature, and radiation has imposed complex and varying limitations on vegetation activities in different regions of the world. However, clear data on spatiotemporal variations and attributes in global terrestrial NPP within the context of high variability warming are still lacking.

Meanwhile, several studies have indicated that climate constraints (e.g., increasing temperatures and solar radiation) are relaxing (Nemani et al., 2003).

A recent study suggested that vegetation productivity influences albedo and emissivity, which then strongly regulate global climate (Chapin et al., 2011). This is especially obvious in evapotranspiration (ET), which is a central process in the climate system and a nexus of the water, energy and carbon cycles. Hence, it plays a pivotal role in maintaining the water and heat balance. Shen and colleagues (2015) reported that, in contrast to the Arctic region (i.e., positive feedback to warming), increased vegetation activity may attenuate daytime warming by enhancing actual ET as a cooling process on the Tibetan Plateau. Zhang et al. (2015) investigated how climate change and recent vegetation greening promote multi-decadal rises of global ET, while an anomalous drought between 2000 and 2009 led to reduced vegetation productivity in the Southern Hemisphere (SH) (Zhao and Running, 2010). However, little observational evidence exists to demonstrate vegetation feedback on climate across different global geographical units.

Investigating factors that control changes in NPP and its feedback effects could provide important clues to the underlying mechanisms and complex interactions between ecosystems and climate systems (Tian et al., 2000; 2012). Having a clear understanding of the land's biophysical feedback to the atmosphere is crucial if we are to simulate regional climate accurately. In our study, we investigated the following three major points of interest: 1) whether the high volatility temperature of the past decade continued to increase NPP, or if different climate constraints were at play; 2) why NPP variations in the Northern and Southern Hemispheres respond differently to climate changes; and 3) what the spatiotemporal variation of NPP is, and what its effects are on ET.

7. Data and Methodology

Data: For each dataset, supply a brief description including the source. How did you resample and reclassify them? Methods: The authors used the NPP datasets from MODIS, and it does not set here is no need to have a lengthy discussion on the algorithms (Equations 1-7) used by NASA in a methodology section. This section should focus on the specific methods developed by these authors.

Response: We clarified the source for each dataset in the “2.1 Data”, meanwhile deleted the unnecessary algorithm details from “2.2 Methods”.

2.1 Data

The monthly grid data of the temperature and precipitation series from 2000-2014, with a spatial resolution of 0.5 degrees, were collected from the Climatic Research Unit (<http://www.cru.uea.ac.uk/data/>). The radiation and soil moisture data series was issued by the Global Land Data Assimilation System (GLDAS-1), with a spatial resolution of 0.25 degrees (http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=GLDAS025_M). The depths of the four soil layers are: 0-10 cm, 10-40 cm, 40-100 cm, and 100-200 cm. The quality of the GLDAS data set was assessed against available observations from multiple sources (Zhang et al., 2008; Chen et al., 2013).

The monthly data of the Palmer Drought Severity Index (PDSI), with a spatial resolution of 2.5 degrees, was available at <http://www.cgd.ucar.edu/cas/catalog/limind/pdsi.html>. As an indicator of land-surface moisture conditions, PDSI has been widely used for the routine monitoring and assessment of global and regional drought conditions. The global dry areas were defined as $PDSI < -3.0$, while the wet areas were defined as $PDSI > +3.0$ (Dai et al., 2004).

We used the Global Land Cover Characterization data from the International Geosphere-Biosphere Program (IGBP) in 2000 (<http://edc2.usgs.gov/glcc/glcc.php>), along with MODIS in 2000 and 2013 (<http://modis.gsfc.nasa.gov/data/dataproduct/mod12.php>). From these data, a routinely integrated classification of land use/cover change (LUCC) characteristics was obtained based on the feature fusion processes.

The global 1-km MODIS NPP datasets (2000-2014) are from MOD17. NPP estimations are typically model-based and biogeochemical, and are generated from a larger set of simulated C fluxes between the atmosphere and terrestrial ecosystems (Ito et al., 2011). A better agreement of MODIS and terrestrial NPP estimates allows the use of MODIS in large-scale estimates (Neumann et al., 2015).

The MODIS evapotranspiration datasets (2000-2014) from MOD16 are estimated using Mu and colleagues' (2011) improved ET algorithm over Mu et al.'s (2007) previous paper. Based on the energy-balance theory and the Penman-Monteith equation, the required MODIS data inputs for the ET algorithms include daily meteorology (temperature, actual vapor pressure, and incoming solar radiation) remotely-sensed land cover, FPAR/LAI, and albedo (Friedl et al., 2010; Myneni et al., 2002). We unified the spatiotemporal resolution of these data from different sources, based on re-sampling (nearest neighbor interpolation) and re-classification techniques.

2.2 Methods

Trend analysis. To further discern the trends of yearly NPP and ET, we examined linear trend estimations on a per-pixel basis to establish a linear regression relationship between variables and time.

Partial correlation analysis. This method is used to describe the relationship between two variables while taking away the effects of several other variables. The partial correlation of x_1 and x_2 is adjusted for a third variable y (at a significance level of 0.05 by t-Test):

$$r_{x_1x_2 \cdot y} = \frac{r_{x_1x_2} - r_{x_1y}r_{x_2y}}{\sqrt{(1 - r_{x_1y}^2)(1 - r_{x_2y}^2)}} \quad (1)$$

8. Results and Analyses

Statistical correlation and causation are related but different concepts. See my general comments. Need to check some sentences with strong statements (of causation).

Response: Thanks for the reviewer's comment. Please see the response to the comment 2.

9. Table 1: remove "over". The heading for Column 4 is not correct. Please double check this.

Response: We corrected the table 1 in the revision.

Table 1. Correlations between NPP and climatic variables for both hemispheres

Zones	NPP trend PgC yr ⁻²	T trend °C yr ⁻²	P trend mm yr ⁻²	Rn trend W m ⁻² yr ⁻²	PDSI trend yr ⁻²
NH high latitudes (>47.5 °N)	y=0.02x+30.51	y=0.021x-5.75 R= 0.60*	y=0.104x+46.58 R=0.29	y=-5.21x+453.6 R=0.45	y=-0.005x+0.23 R=0.44
NH mid/low latitudes (<47.5 °N)	y=0.07x+45.68	y=0.009x+18.3 R= -0.17	y=0.341x+76.8 R= 0.70**	y=3.239x+105.9 R=0.50	y=0.006x-0.46 R=0.56
South Hemisphere	y=-0.18x+78.37	y=0.010x+21.6 R= -0.53	y=0.074x+116.8 R=0.37	y=2.455x+129.4 R=0.43	y=-0.042x+0.33 R= 0.70**

10. Figures (changes in both captions and map legends)

Figure 1: use "Temporospatial". Which year of C and D for? Legends (C and D): remove "trend"

Response: We updated Figure 1 according to the reviewer's comments.

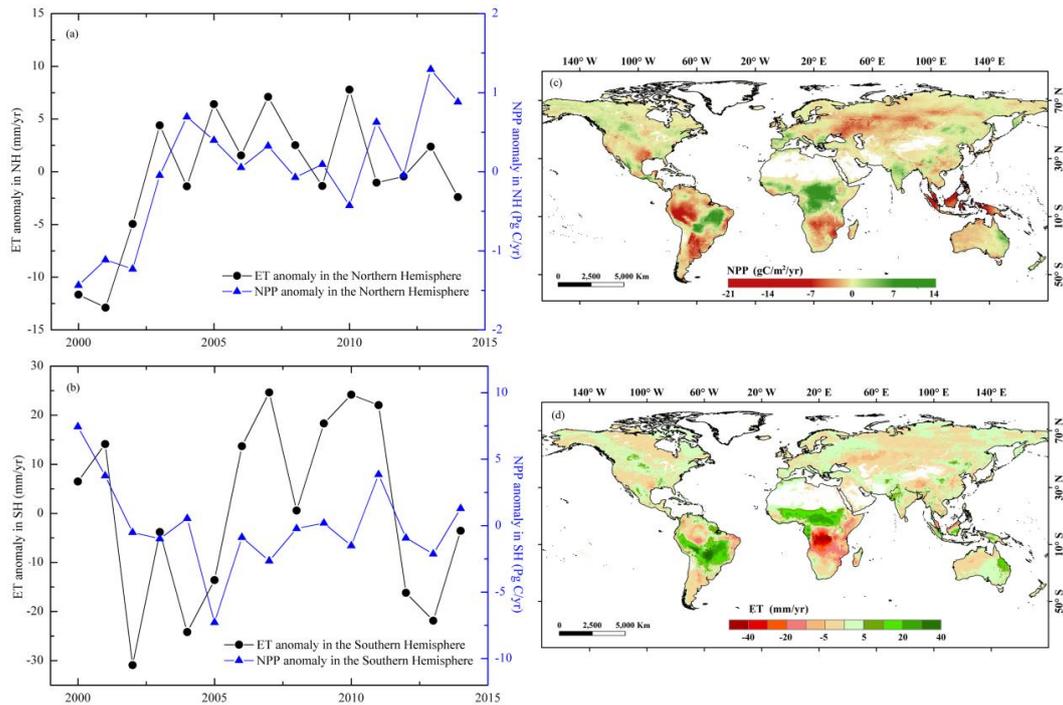


Fig. 1. Temporospatial variations in global terrestrial NPP and ET from 2000-2014. (a) Inter-annual variations of NPP and ET in the Northern Hemisphere (NH). (b) Inter-annual variations of NPP and ET in the Southern Hemisphere (SH). (c) Spatial pattern of NPP trend from 2000-2014. (d) Spatial pattern of ET trend from 2000-2014.

11. Figure 2: remove “trend” in the legend

Response: We updated Figure 2 according to the reviewer’s comments.

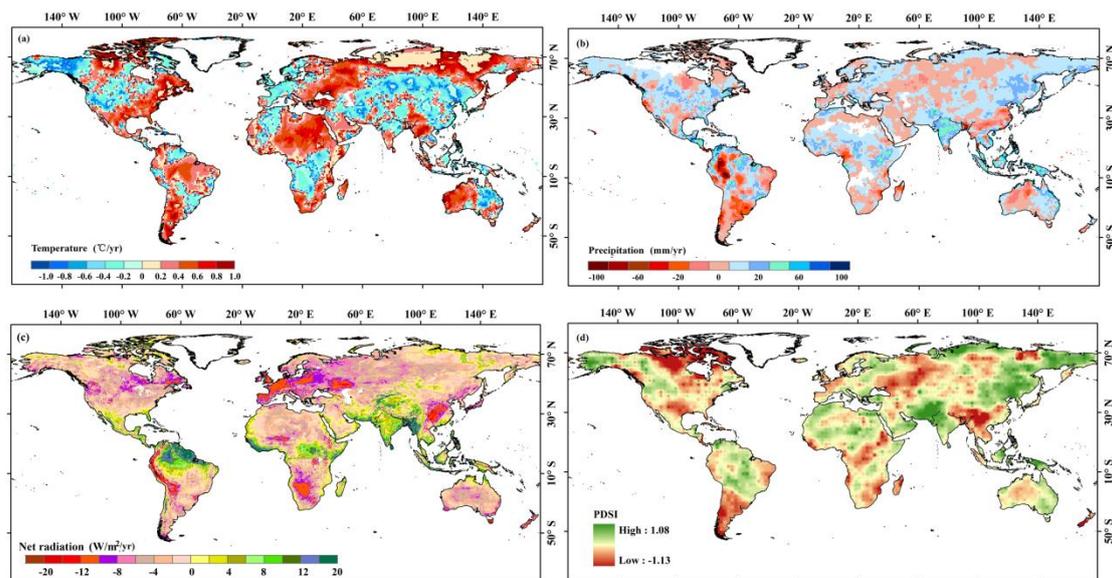


Fig. 2. Trends of air temperature (T), precipitation (P), net radiation (Rn) and Palmer Drought Severity Index (PDSI) from 2000-2014.

12. Figure 3: add “or” in front of (d)

Response: We corrected the caption according to the reviewer’s comments.

Fig. 3. Partial correlations between NPP and (a) Temperature, (b) Precipitation, (c) Net radiation, or (d) PDSI in growing season

Figure 4: add a map to show NPP (should be (a)). Also remove “trend” in the legend.

Response: We have removed “trend” in the legend. Because of the NPP has already showed in the figure 1(c), here probably does not need to appear again.

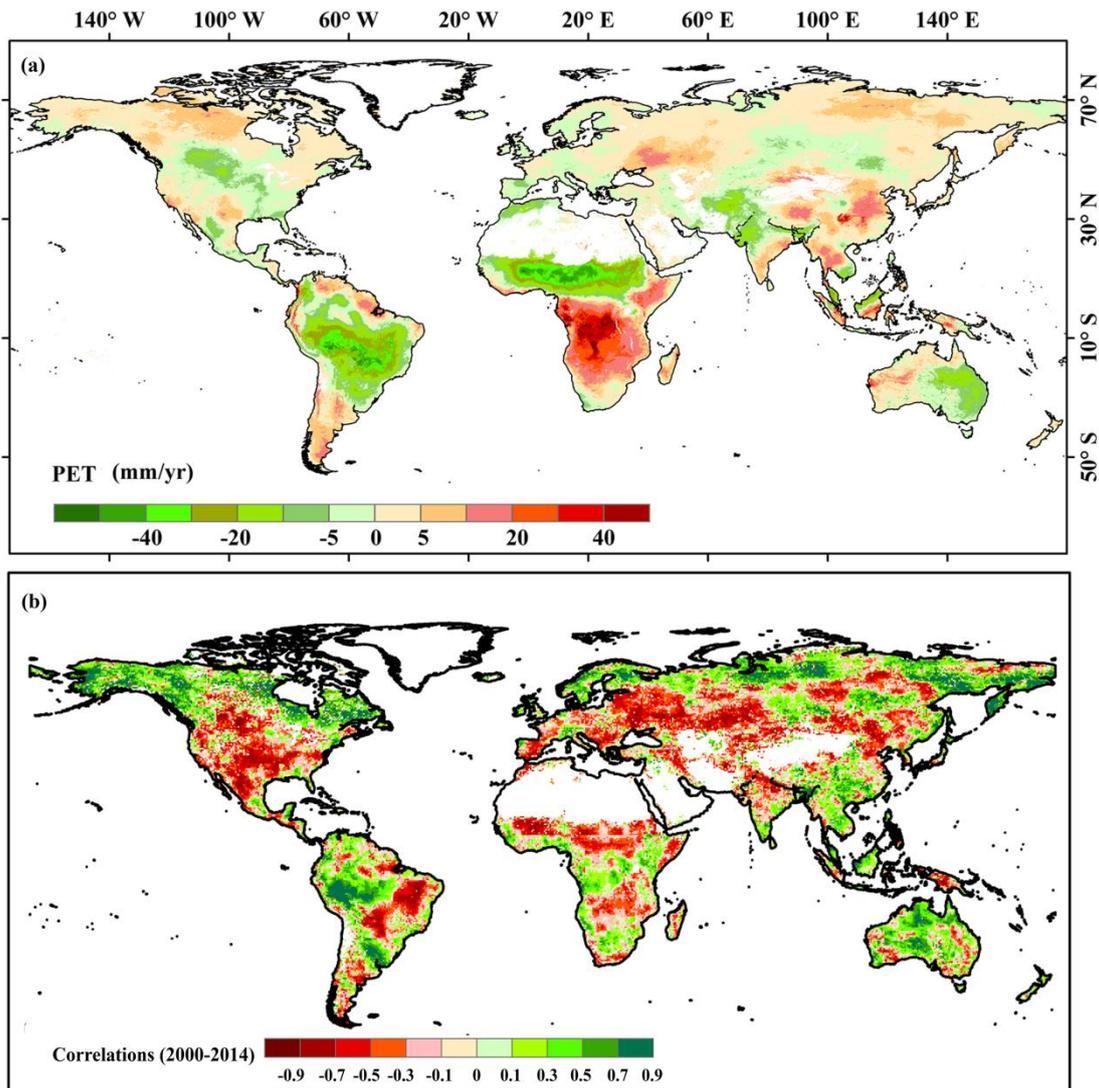


Fig. 4. (a) Spatial pattern of PET trend. (b) Partial correlations between NPP and PET.

Figure 5: Remove “trend” in the legend. Change the title into “—in layers with different depths.”

Response: We updated the Figure 5 according to the reviewer’s comments.

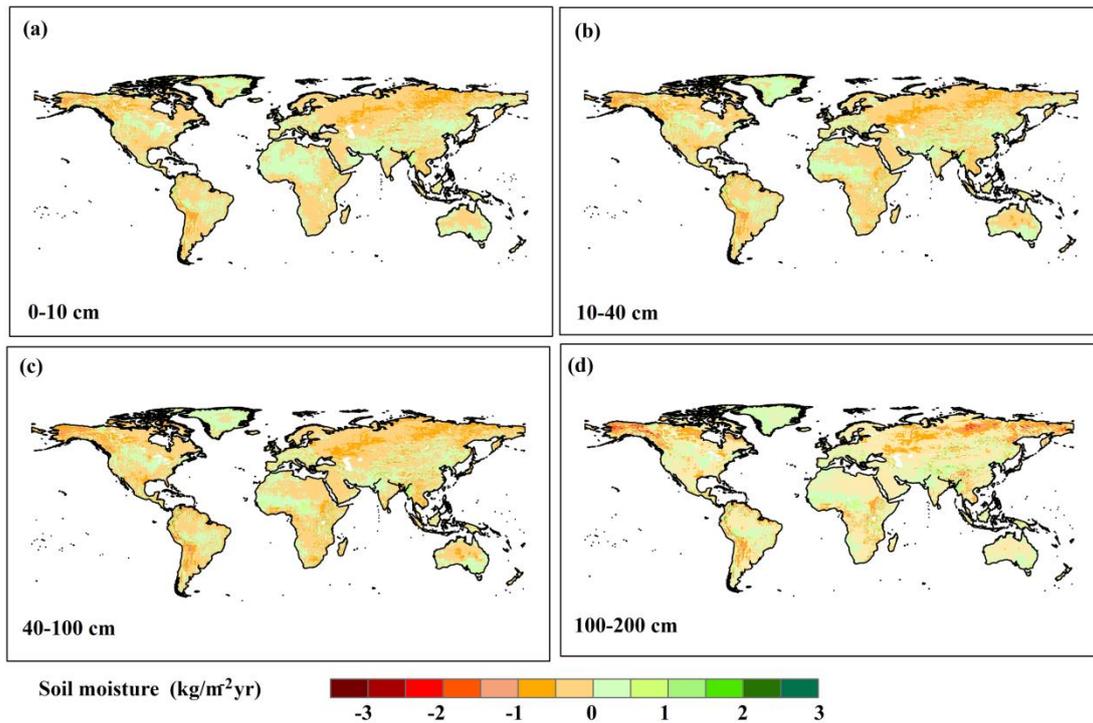


Fig. 5. Trends of soil moisture -in layers with different depths in 2000-2014.