

Earth's Future



RESEARCH ARTICLE

10.1029/2018EF001066

Key Points:

- The increase of global permanent surface water area between 1984–1999 and 2000–2015 has caused 30.38 ± 15.51 km³/year increase in evaporation
- The magnitude of this change is comparable to that of annual global evapotranspiration change assuming stationary surface water areas
- Surface water dynamics can lead to considerable changes in evaporation and should not be neglected in future global water budget studies

Supporting Information:

- Supporting Information S1

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Citation:

Zhan, S., Song, C., Wang, J., Sheng, Y., & Quan, J. (2019). A global assessment of terrestrial evapotranspiration increase due to surface water area change. *Earth's Future*, 7, 266–282. <https://doi.org/10.1029/2018EF001066>

Received 4 OCT 2018

Accepted 24 JAN 2019

Accepted article online 4 FEB 2019

Published online 15 MAR 2019

A Global Assessment of Terrestrial Evapotranspiration Increase Due to Surface Water Area Change

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Abstract Surface water, which is changing constantly, is a crucial component in the global water cycle, as it greatly affects the water flux between the land and the atmosphere through evaporation. However, the influences of changing surface water area on the global water budget have largely been neglected. Here we estimate an extra water flux of 30.38 ± 15.51 km³/year omitted in global evaporation calculation caused by a net increase of global surface water area between periods 1984–1999 and 2000–2015. Our estimate is at a similar magnitude to the recent average annual change in global evapotranspiration assuming a stationary surface water area. It is also comparable to the estimated trends in various components of the hydrological cycle such as precipitation, discharge, groundwater depletion, and glacier melting. Our findings suggest that the omission of surface water area changes may cause considerable biases in global evaporation estimation, so an improved understanding of water area dynamics and its atmospheric coupling is crucial to reduce the uncertainty in the estimation of future global water budgets.

Plain Language Summary Past studies have shown that global evapotranspiration has been increasing between the 1980s and 2000 and has been decreasing since 2000. These studies were done assuming surface water body areas (i.e. lakes and rivers) are constant throughout their study periods. However, surface water bodies on earth are changing constantly. Over the past 30 years, more than 90000 km³ of permanent water has disappeared while over 180000 km³ has emerged elsewhere. The conversion between land and water introduces a significant change of evapotranspiration from the earth's surface which has been neglected by past studies. Here, we quantify this change in evapotranspiration caused by such land-water conversion to reduce the uncertainties in the estimation of global evapotranspiration trend. We find an increase in evapotranspiration caused by land-water conversion of 30.38 ± 15.51 km³/yr between 1984–1999 and 2000–2015. The magnitude of this change is comparable to that of annual global evapotranspiration change assuming stationary surface water areas. Thus, surface water dynamics can lead to considerable changes in global evapotranspiration and should not be neglected in future global water budget studies.

1. Introduction

Water comprises a critical component of global/regional hydrological and biogeochemical cycles and is an essential resource for all organisms including humans (Lehner & Döll, 2004; Palmer et al., 2015; Sheng et al., 2016). Both the stocks and flow of water in hydrological cycle components are strongly altered by changing climate and human activities (Song et al., 2014; Wang, Liang, et al., 2014; Wang, Sheng, & Tong, 2014; Wang, Xiao, et al., 2014). In return, they impact the climate system and the available water resources for human society (Oki & Kanae, 2006; Wada et al., 2013). In the past several decades, climate change has intensified the hydrological cycle, with significant implications for ecosystem services and feedback to regional and global climate. Several lines of evidence have been found to support the warming-induced intensification of the water cycle (Huntington, 2006; Jung et al., 2010). Evaporation (E) and evapotranspiration (ET), as a linking mechanism between the land surface and the atmosphere (Mueller et al., 2013), are essential to the water cycle and excellent indicators of the intensity of water cycle. Specifically, about 60% of annual land precipitation is evaporated to the atmosphere, and the figure may exceed 95% in arid climates (Jung et al., 2010; Oki & Kanae, 2006). Knowledge on the temporal changes of ET is crucial for accurately

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estimating global or regional water budgets and better understanding hydrological interactions between the land and the atmosphere.

Evapotranspiration is a function of solar radiation, temperature, wind speed, humidity, atmospheric pressure, and the surrounding environment. To address ET changes and patterns in the hydrological cycle, several alternative global ET data sets have been produced in recent years, with different spatial and temporal resolutions. These data sets include satellite-based estimates, land surface models driven with observation-based forcings, reanalysis data products, estimates based on empirical upscaling of point observations, and atmospheric water balance estimates. Previous studies (Jiménez et al., 2011; Miralles et al., 2011; Mu et al., 2011; Mueller et al., 2011; Weiß & Menzel, 2008) have assessed the spatial patterns of multiyear means and seasonal variations of these data sets and revealed the agreements and differences among these data sets. Studies on temporal variations of ET based on global data sets were conducted by Wang et al. (2010) and Jung et al. (2010) over the periods from 1982 to 2002 and 1982 to 2008, respectively. They both found a tendency of increasing ET for the years 1982 to the late 1990s, which indicates a possible intensification of the hydrological cycle. Jung et al. (2010) further revealed a decline in the period 1998–2008 with a decrease in moisture availability, confirming the cessation of the increasing trend. Another study based on satellite retrievals also confirms the suspension of increasing trend in global land ET after 2000 (Yao et al., 2012).

However, it is important to note that the estimates in these global ET data sets were derived for relatively stationary land areas. They assume that water body areas are constant throughout their study periods. Furthermore, studies of open-water evaporation from surface hydrologic systems, which is considerably different from land ET, were conducted only on some of the large water bodies or hot spot lakes, for example, Caspian Sea and the Great Lakes, as part of some data sets (Jensen, 2010; Renssen et al., 2007). Most lakes, ponds, and wetlands are merely considered as fixed points for the hydrologic processes in many parts of the world (Fisher et al., 2008; Zhang et al., 2010). However, a recent study (Pekel et al., 2016) used three million Landsat satellite images to quantify changes in global surface water between 1984 and 2015. They found permanent surface water has shrunk by about 90,000 km² in the past 32 years, while newly emergent permanent water bodies almost doubled the total lost water area. All continents show a net increase in permanent water, except Oceania. Quantification of the spatiotemporal variations of evaporation caused by the conversion between land and water has long been neglected at the global scale. Given this inventory of global conversion between land and water, it is both feasible and vital to understand and quantify evaporation-induced hydrological flux changes over lakes, reservoirs, and wetlands across various sizes.

The goal of this research is to explore the global water budget estimate biases induced by the omission of evaporation over land-water conversion zones. Such a worldwide quantification is useful for several purposes. In the most recent Intergovernmental Panel on Climate Change (IPCC) sea level budgets (Church et al., 2013), changes in terrestrial water storage driven by the climate have been assumed to be too small to be included. However, recent advances in gravity satellite measurement enabled a quantification of deceleration of sea level rise by 0.71 ± 0.20 mm/year during 2002–2014, contributed by water stored in land due to climate variability (Reager et al., 2016; Wada et al., 2017). This assessment is essential for reducing the uncertainty in terrestrial water budget estimates. Furthermore, the consideration of such evaporation-induced water flux changes can efficiently improve uncertainty estimates on regional or basin-scale hydrologic modeling (Melesse et al., 2009). This study is informative for agricultural and water management communities to estimate future water demands, to make decisions on irrigation regulation and reservoir operations where ET is a crucial factor.

2. Data and Methods

Surface water change over the 1984–2015 period is obtained from the Global Surface Water Database (Pekel et al., 2016; <https://global-surface-water.appspot.com/download>). Specifically, we used the occurrence change intensity data set in the database. We did not use the monthly water data set, which is also available in the Global Surface Water Database, due to the extensive data gaps in Landsat coverage and the noise in the data set. Therefore, our analysis focuses on the changes in permanent water bodies using the occurrence change intensity data set between two time periods: 1984–1999 (P1) and 2000–2015 (P2). Surface water occurrence for a certain month (e.g., July) in a period (e.g., P1) is calculated as the ratio between the number of times a pixel is detected as water in July from 1984 to 1999 and the total number of valid observations in

Table 1
General Information of ET and PET Products Used in This Study

Product	ET coverage	PET coverage	Spatial resolution	Methodology	Source
CSIRO	1984–2012	N/A	0.5 degree	Penman-Monteith Leuning model	Zhang et al., 2016
GLDAS NOAH	1984–2010	1984–2010	0.25 degree	Land surface model	Rodell et al., 2004
GLEAM	1984–2014	1984–2014	0.25 degree	Priestley-Taylor	Martens et al., 2017
Global ET	1984–2013	N/A	8 km	Penman-Monteith	Zhang et al., 2010
MOD16	2000–2014	2000–2014	1 km	Penman-Monteith	Mu et al., 2013

Note. CSIRO = Commonwealth Scientific and Industrial Research Organization; GLDAS NOAH = Global Land Data Assimilation System Noah Land Surface Model; GLEAM = Global Land Evaporation Amsterdam Model; GLOBAL ET = Global Evapotranspiration; MOD16 = Moderate Resolution Imaging Spectroradiometer Global Evapotranspiration Project.

July from 1984 to 1999. The difference in occurrence is calculated for individual pairs of months between the periods of P1 and P2. Occurrence change intensity is the difference in occurrence averaged across all pairs of months in a year and standardized to -1 and 1 . In this study, new surface water (NSW) is defined as water pixels with an occurrence change intensity value greater than 0.9 , and lost surface water (LSW) is defined as water pixels with a value less than -0.9 . Changes between -0.9 and 0.9 are considered as seasonal fluctuations and are not included in the study.

We leveraged various existing data sets to estimate evapotranspiration (ET) and potential ET (PET) during 1984–2015. The analysis focuses only on the regions that experienced conversion between land and water in order to emphasize the contribution of this particular change to terrestrial evaporation. ET/PET changes over permanent land and water areas are not considered. It is assumed that land evaporation can be estimated using ET products and water evaporation can be estimated using PET products. While PET does not equal lake evaporation in some circumstances as lake evaporation is dependent on lake depth, our focus is on the land-water boundary (i.e., where land-water conversion happens) where the water depth is relatively limited. Moreover, our estimation is based on a multiannual timescale (each 15-year period) where lake evaporation changes caused by seasonal variation in the lakes' heat storage are negligible (McMahon et al., 2013; Morton, 1983; Sacks et al., 1994). The change in evaporation caused by the conversion between land and water can thus be quantified as the product of the difference between ET and PET and the changed area.

Specifically, we used five ET products including the monthly global observation-driven Penman-Monteith-Leuning evapotranspiration from the Commonwealth Scientific and Industrial Research Organization (<https://data.csiro.au/dap/landingpage?pid=csiro:17375>), the Global Land Data Assimilation System Noah Land Surface Model (GLDAS NOAH, <https://disc.sci.gsfc.nasa.gov/datasets?keywords=GLDAS>), the Global Land Evaporation Amsterdam Model (GLEAM, <http://gleam.eu>), Global Evapotranspiration (Global ET, http://files.ntsg.umt.edu/data/ET_global_monthly), and Moderate Resolution Imaging Spectroradiometer Global Evapotranspiration Project (MOD16, http://files.ntsg.umt.edu/data/NTSG_Products/MOD16), and three PET products from GLDAS NOAH, GLEAM, and MOD16. The products are chosen based on their temporal coverage and spatial resolution. The spatial resolution has to be finer than the area of drainage basins, which are the spatial units of our analysis. Table 1 describes the characteristics of the different products.

Mean ET and PET for each product are calculated for the two periods according to the surface water occurrence change data set. All data sets are then resampled to the same spatial resolution (i.e., 8 km or 5 arc minutes) and clipped to the same spatial extent, which includes all land surface area except for Greenland and Antarctica. We then averaged the data sets by basins to reduce the influence of spatial resampling and data gaps in large lakes. The basins were primarily derived from the World Wildlife Fund HydroBASINS data set (<http://hydrosheds.org/page/hydrobasins>). For mainland Oceania and High Mountain Asia area, the coarse division was substituted with the drainage basin data from the National Catchment and Stream Environment Database (<http://data.gov.au/dataset/national-catchment-boundaries-v-1-1-4>) and the Global Drainage Basin Database (http://www.cger.nies.go.jp/db/gdbd/gdbd_index_e.html), respectively. We merged neighboring basins that are smaller than 200 km^2 to ensure an adequate number of cells of ET/PET data within a basin. A few large basins (e.g., Caspian Sea basin) were also manually divided into smaller basins for finer assessment. The basin-averaged ET estimations are used to calculate land evapotranspiration, and basin-averaged PET estimations are used to calculate water body evaporation. While the

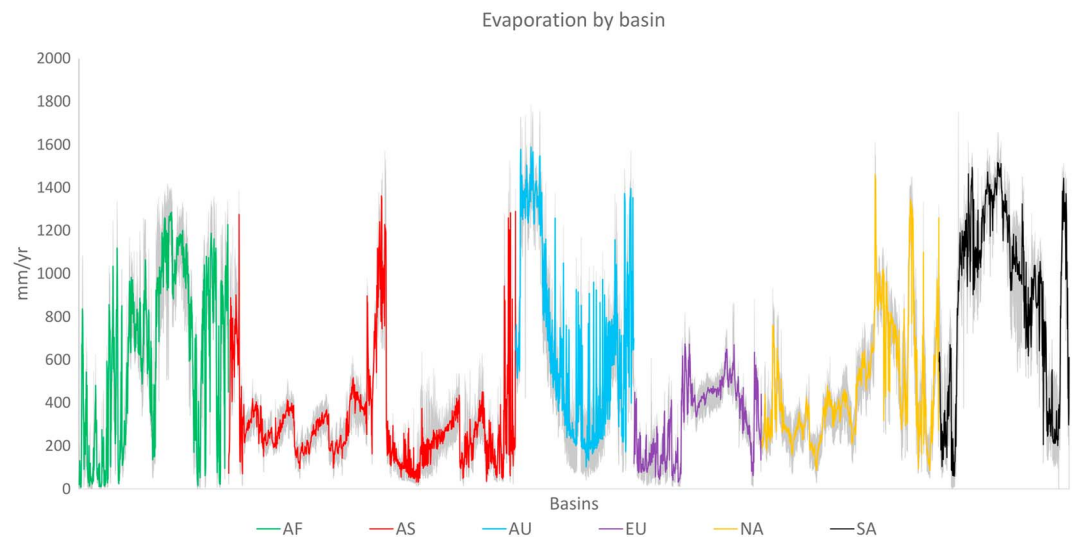


Figure 1. Comparison of the five evapotranspiration products in different continental regions. Color lines illustrate the product means for each of the continents, and the shade illustrates the product range. AF = Africa; AS = Asia; AU = Australia; EU = Europe; NA = North America; SA = South America.

spatial heterogeneity of ET and PET within a basin is not considered, this method fills the data gaps in large water bodies (such as the Great Lakes, the Caspian Sea, the Aral Sea, and Lake Victoria), which are masked by most products, and we included such heterogeneities in the uncertainty assessment.

The ET products agree reasonably well with each other (Figure 1), so we simply averaged the ET estimates for each basin and calculated a standard error from the five products used. However, the PET estimates have large discrepancies among different products (Figure 2). GLDAS NOAH estimates are consistently much higher than GLEAM estimates especially in wetter regions. MOD16 estimates lie in between the other two but are closer to GLDAS NOAH estimates especially in drier regions. We compared the PET products to the results by Weiß and Menzel (2008), which compared the performance of four potential evapotranspiration equations globally and found that GLDAS NOAH and MOD16 overestimated while GLEAM underestimated PET in most regions. We also compiled field-measured or modeled evaporation estimates for over 130 lakes worldwide that are reported in the literature (see Table S1 in the supporting information). The distribution of those lakes is shown in Figure 3. Thirteen lakes have independent field-measured and modeled evaporations (see Table S2). The correlation between field-measured and modeled evaporations for those lakes is over 0.9 (Figure 4). We found that evaporations that are measured only, modeled only, and both combined all have similar correlations with GLDAS NOAH PET (Figures 5 and 6a). Thus, we used all available measurements regardless of method and temporal coverage to assess the quality of the PET products. When multiple measurements for a lake are available, the average for the lake was used. We compared the products to the reported measurements and also found that GLDAS NOAH and MOD16 tend to overestimate PET and GLEAM tends to underestimate (Figure 6). However, it was found that the correlation between GLEAM PET and reported lake surface ET measurements was rather poor. MOD16 has large data gaps in dry and poorly vegetated regions such as Northern Africa, the Arabian Peninsula, and the Tibetan Plateau even after aggregating the estimates by basins. Moreover, MOD16 only covers the period from 2000 to 2014 and was not as well correlated with reported data as GLDAS NOAH. Therefore, we used MOD16 for ET estimates but not for PET estimates. Since the ET products agree well with each other, including MOD16 only in P2 does not affect the results much. GLDAS NOAH is the only product used for PET estimates.

Next, we used a least median of squares regression (Rousseeuw, 1984), which is insensitive to outliers, between GLDAS NOAH PET and the reported lake ET to correct for the biases in GLDAS NOAH estimates (Figure 7). The PET of basins that have lakes with reported measurements was replaced with those reported measurements instead of using the bias-corrected GLDAS NOAH estimates. While these basins only account for 3% of the total number of basins and 18% of the total land surface area, they represent about 24% and 49%

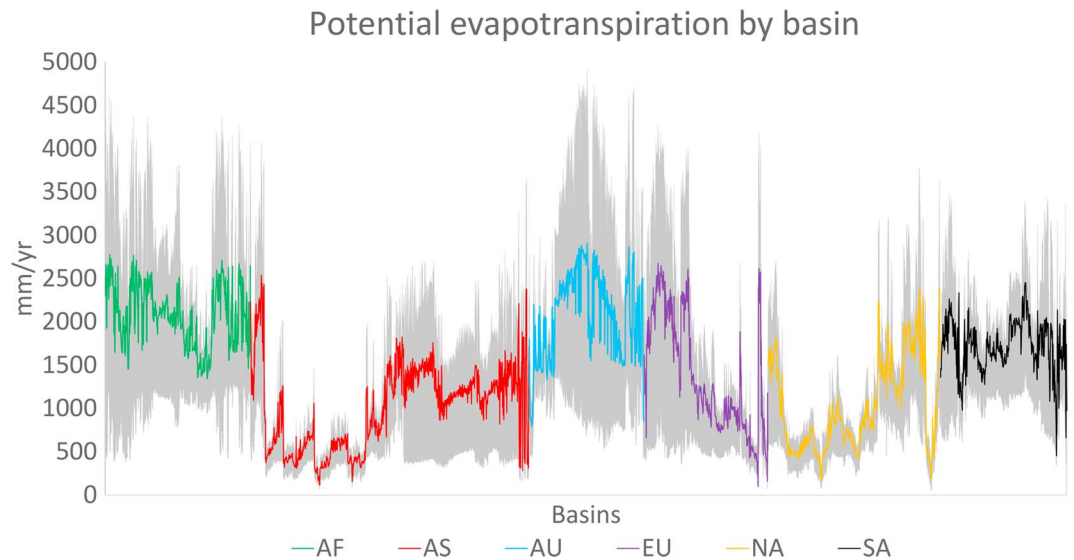


Figure 2. Comparison of the three potential evapotranspiration products in different continental regions. Color lines illustrate the product means for each of the continents, and the shade illustrates the product range. AF = Africa; AS = Asia; AU = Australia; EU = Europe; NA = North America; SA = South America.

of total NSW and LSW worldwide. Thus, we believe that bias correcting the GLDAS NOAH estimates and replacing the PET of selected basins with reported measurements substantially reduces the uncertainty of our evaporation estimates. To further account for the uncertainty induced by various time coverages in our collected lake evaporations, we calculated the root mean square error (RMSE) in the PET bias correction (483.37 mm; Figure 7). This RMSE was combined with the standard errors of ET products for

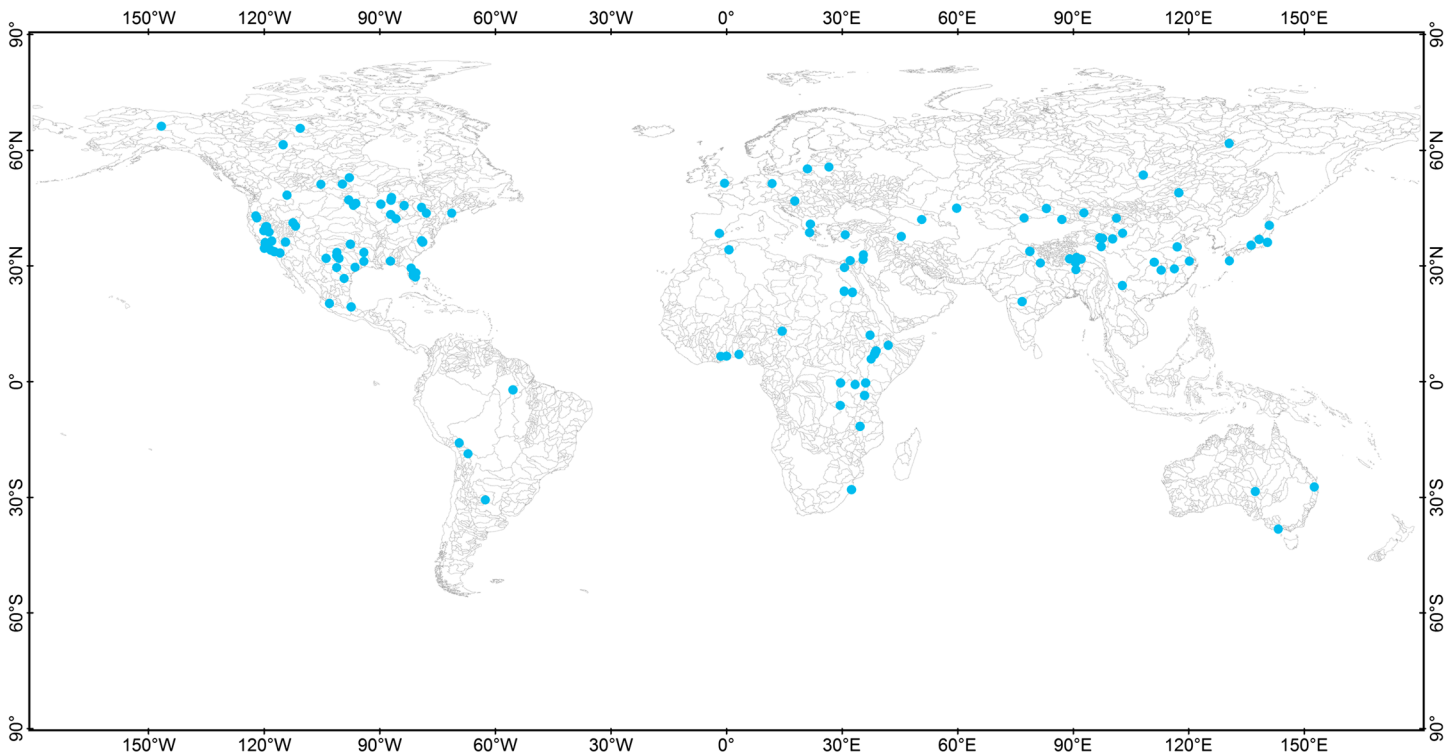


Figure 3. Distribution of lakes and basins with field-measured or modeled evaporations.

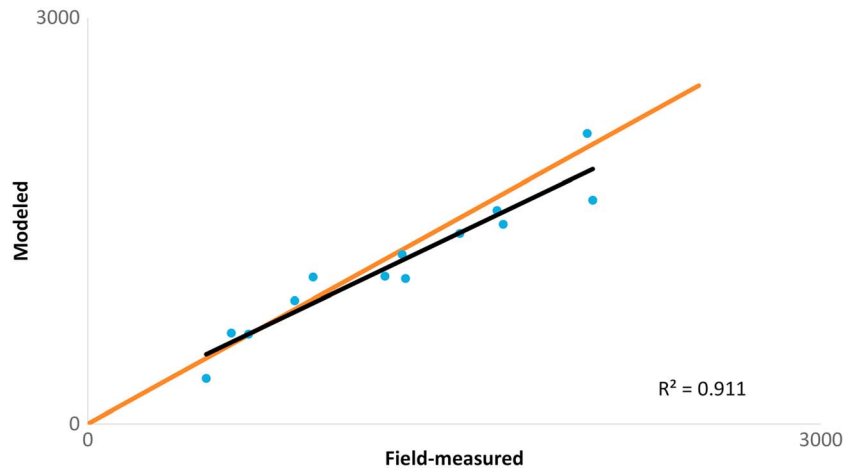


Figure 4. Correlation between independent field-measured and modeled lake evaporations. The orange line represents one-to-one ratio.

each basin (as previously described) to propagate the error bounds of our estimated terrestrial ET change rates.

Finally, we aggregated surface water occurrence change area by basins to obtain the total areas of NSW and LSW during 1984–2015 within each basin. The volume of evaporative change caused by NSW and LSW (ΔV) is the difference between averaged PET and ET during the two 15-year periods (P1 and P2) multiplied by the areas of NSW and LSW, respectively. Thus, the volume of evaporative change over the two periods induced by surface water changes within each basin is calculated as follows:

$$\Delta V = (PET_{P2} - ET_{P1}) \times NSW - (PET_{P1} - ET_{P2}) \times LSW. \#(1)$$

$PET_{P2} - ET_{P1}$ represents the changes in ET when land is converted to water in P2 while $PET_{P1} - ET_{P2}$ represents such change when water is converted to land in P2. NSW and LSW are the total area of new and LSW in a basin, respectively. The equation is applied to each basin, and a positive value indicates a net loss of water to the atmosphere through evaporation.

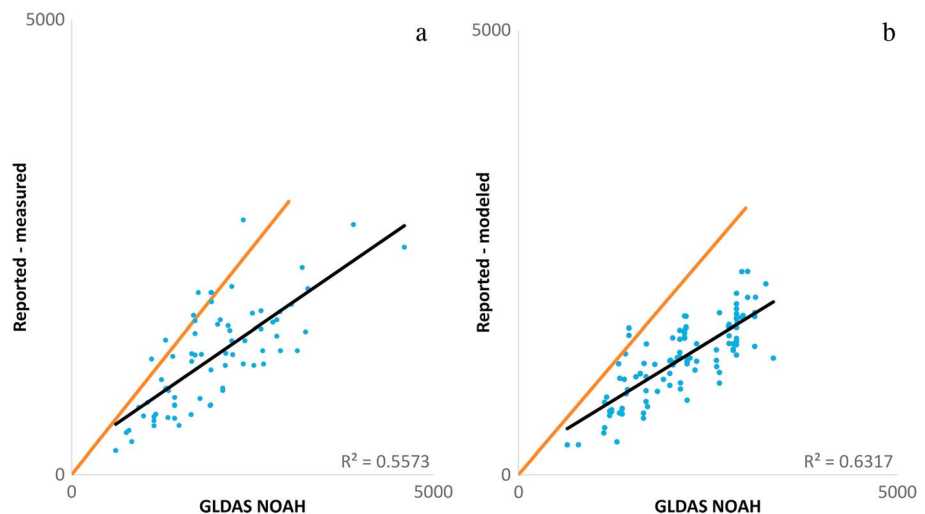


Figure 5. Comparison of the Global Land Data Assimilation System Noah Land Surface Model (GLDAS NOAH) product against measured (a) and modeled (b) evaporation reported in the literature. The orange line represents one-to-one ratio.

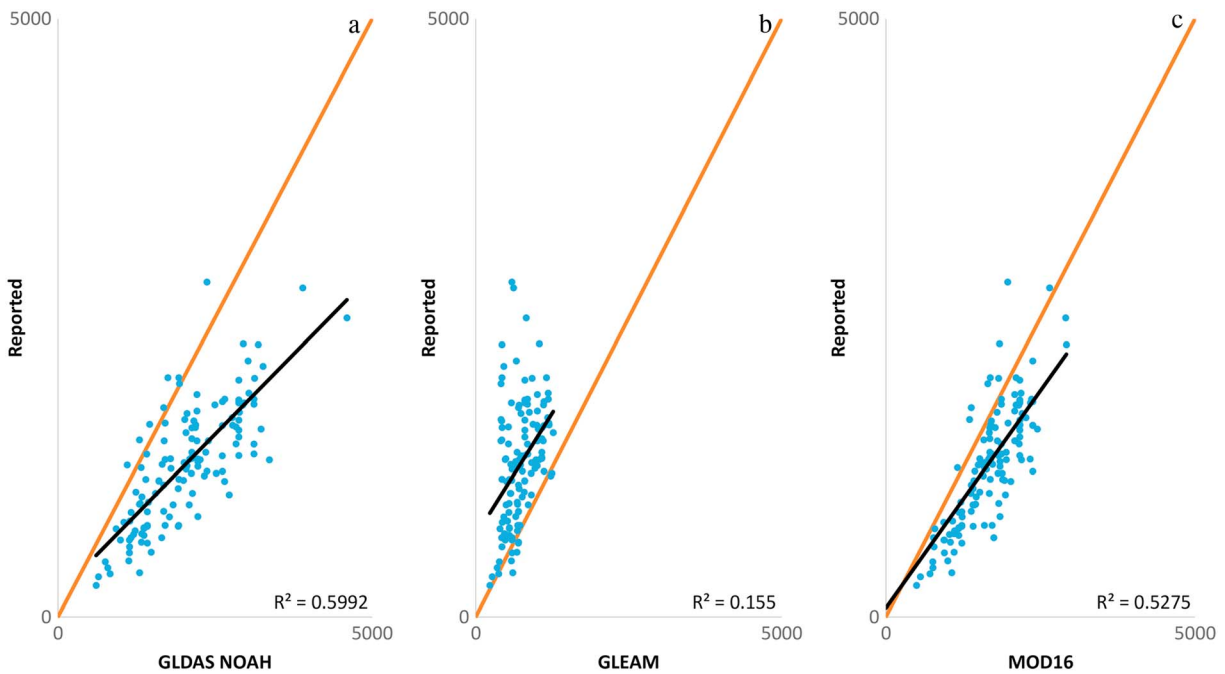


Figure 6. Comparison of potential evapotranspiration products against reported (measured or modeled) lake evapotranspiration measurements. (a) Global Land Data Assimilation System Noah Land Surface Model (GLDAS NOAH) versus reported. (b) Global Land Evaporation Amsterdam Model (GLEAM) versus reported. (c) Moderate Resolution Imaging Spectroradiometer Global Evapotranspiration Project (MOD16) versus reported. The orange line represents one-to-one ratio.

3. Results

3.1. Global Surface Water Changes and Associated Increase in Evaporation

Between 1984–1999 and 2000–2015, the Earth’s surface gained 183,807.2 km² and lost 88,366.8 km² of surface water area with a net gain of 95,440.4 km². The spatial distribution of net surface water area changes by basin is shown in Figure 8. All continents had a positive net change of surface water area. The gain is mostly due to the filling of reservoirs and partly due to climate change while the loss is due to drought and human withdrawal (Pekel et al., 2016). For a detailed discussion of the spatial distribution of NSW and LSW and the cause of changes, the reader is referred to Pekel et al. (2016).

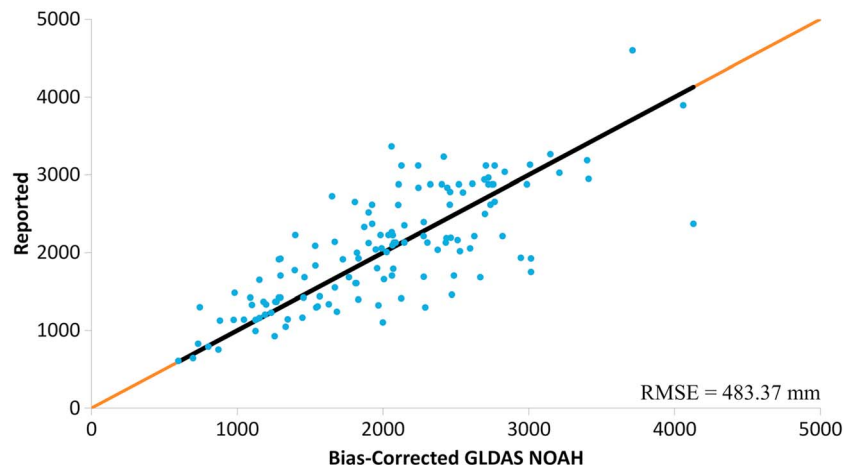


Figure 7. Bias-corrected Global Land Data Assimilation System Noah Land Surface Model (GLDAS NOAH) potential evapotranspiration versus reported lake evapotranspiration from published literature. RMSE = root mean square error.

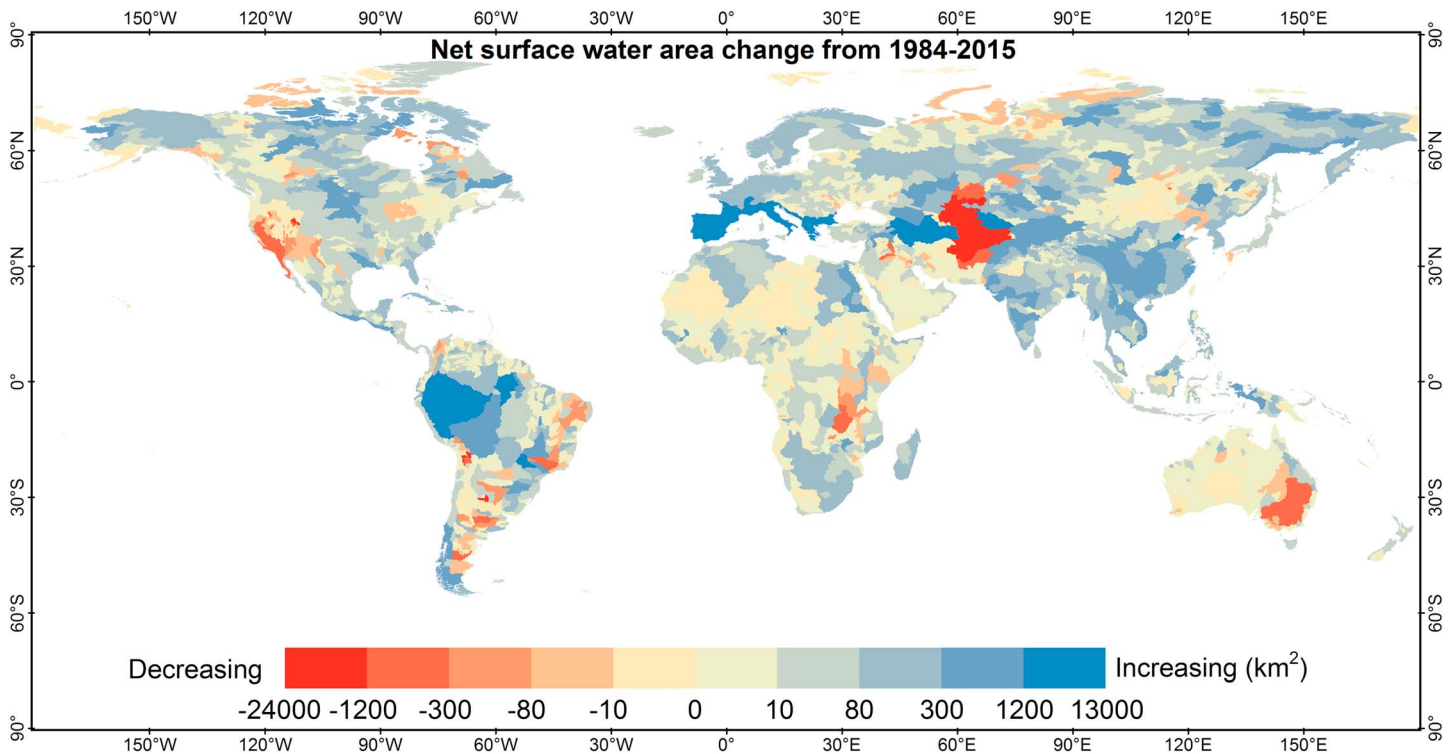


Figure 8. Net surface water area change by basin from 1984 to 2015.

Associated with the global increase in surface water area is the universal net increase in evaporation across all continents. Figure 9 shows evaporation changes caused by the conversion between land and water aggregated by basin. Globally, evaporation increased by $30.38 \pm 15.51 \text{ km}^3/\text{year}$ between 1984–1999 and 2000–2015 (Table 2). If we assume constant ET and PET throughout the period (i.e., using average ET/PET from 1984 to 2015 as opposed to calculating average ET/PET for P1 and P2), the estimate of increased evaporation is $27.86 \pm 15.51 \text{ km}^3/\text{year}$. This suggests that most of the ET change ($\sim 92\%$) was caused by the increase in surface water area while changes in ET/PET over the periods play a minor role (less than $3 \text{ km}^3/\text{year}$ or $\sim 8\%$).

Figure 10 shows the difference between PET and ET by basin. Different evaporation changes given a constant net surface area change can be caused by the difference between a region's PET and ET. If a region's PET is much higher than its ET, a greater proportion of water will be evaporated when land is inundated by water. Similarly, a greater reduction of ET will be observed when water area is converted into land in the same region. Whereas if a region's ET and PET are similar, not much change in evaporation can be observed during land-water conversion. This explains why the net increase in surface area in Africa is only about 40% of that in Europe but they had a similar increase in ET. It can also explain the different ET change between Europe and North America, where both continents have similar increase in surface water area.

3.2. Spatial Distribution of Surface Water Change-Induced Evaporation Change Across the Globe

While all continents experienced evaporation increases, spatial heterogeneity exists within continents (Figure 9). Most regions have an increased evaporation, which is consistent with the net gain of surface water area globally. The increase in evaporation can be largely explained by the construction of dams, coastal flooding, permafrost dynamics (both increase and decrease), and the change of large individual water bodies such as the Caspian Sea, while decreases in evaporation are largely confined to local regions that are mostly affected by droughts and especially the desiccation of the Aral Sea.

The impoundment of water by dams is largely responsible for the increased ET in South America, Africa, and South Asia. According to the Global Reservoir and Dam database (Lehner et al., 2011), South American countries have built 73 dams since 1984 with a total impounded surface water area of

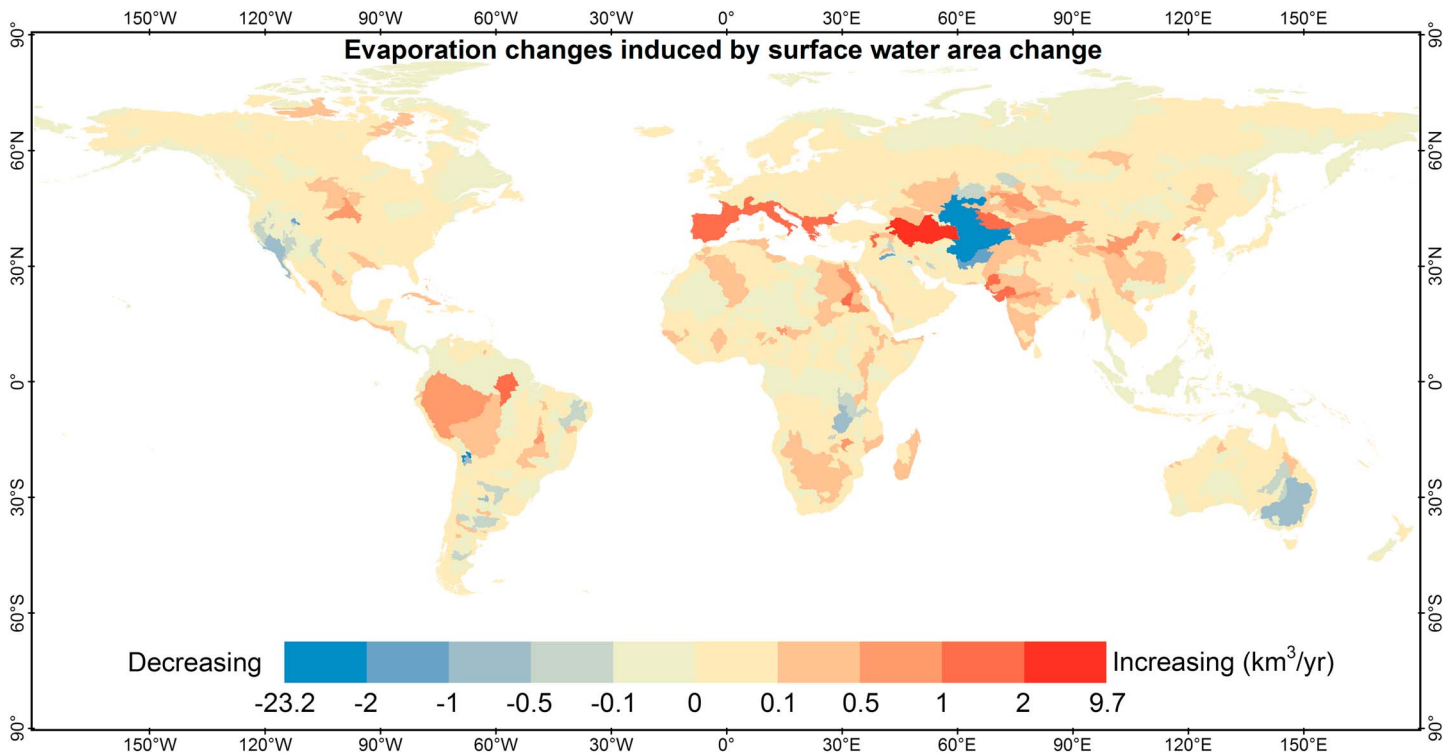


Figure 9. Evaporation changes induced by surface water area change by basin (km^3/year).

15,748 km^2 . The largest contributor is Brazil with 42 dams and 9,638 km^2 of impounded water followed by Venezuela with nine dams and 4,047 km^2 of impounded water. African countries have built 121 dams with 3,879 km^2 of impounded water. South and Southeast Asian countries of India, Thailand, Vietnam, Myanmar, Laos, and Sri Lanka combined have built 63 dams with 3,013 km^2 of impounded water. India is by far the largest contributor in the region with 39 new dams and 1,370 km^2 of impounded water. Note that Global Reservoir and Dam does not include many newly constructed small reservoirs; therefore, the areas here are likely underestimated.

Various coastal regions have seen increases in evaporation. This is partly due to coastal flooding of seawater caused by sea level rise, storm surges, and the retainment of sediment by upstream dams (Jongman et al., 2012; Mentaschi et al., 2018). This can be seen clearly in Louisiana, Florida, and along the coasts of south Asia and China. It is also caused by the expansion of aquaculture (Naylor et al., 2000) especially in major river deltas such as the Nile, the Yangtze, and the Pearl River deltas.

Both increases and decreases of evaporation are observed in the pan-Arctic region. Lakes expand in the ice-rich permafrost through thermomechanical erosion of the surrounding soil and drain through bank

Table 2
Surface Water Changes and Associated Evaporation Changes by Continent

Continent	Total NSW (km^2)	Total LSW (km^2)	Net change (km^2)	Evaporation change rate (km^3/year)	Change caused by land-water conversion (km^3/year)
Africa	12,652.54	3,913.23	8,739.31	12.43 ± 0.92	12.61 ± 0.92
Asia	68,289.75	39,982.94	28,306.81	1.64 ± 13.02	1.03 ± 13.02
Australia	6,477.81	2,749.99	3,727.82	0.80 ± 0.65	0.27 ± 0.65
Europe	29,026.10	7,606.81	21,419.29	12.88 ± 7.44	12.53 ± 7.44
North America	39,292.48	18,729.65	20,562.83	2.04 ± 2.10	1.37 ± 2.10
South America	28,068.53	15,384.23	12,684.30	0.59 ± 3.14	0.06 ± 3.14
Total	183,807.21	88,366.85	95,440.36	30.38 ± 15.51	27.86 ± 15.51

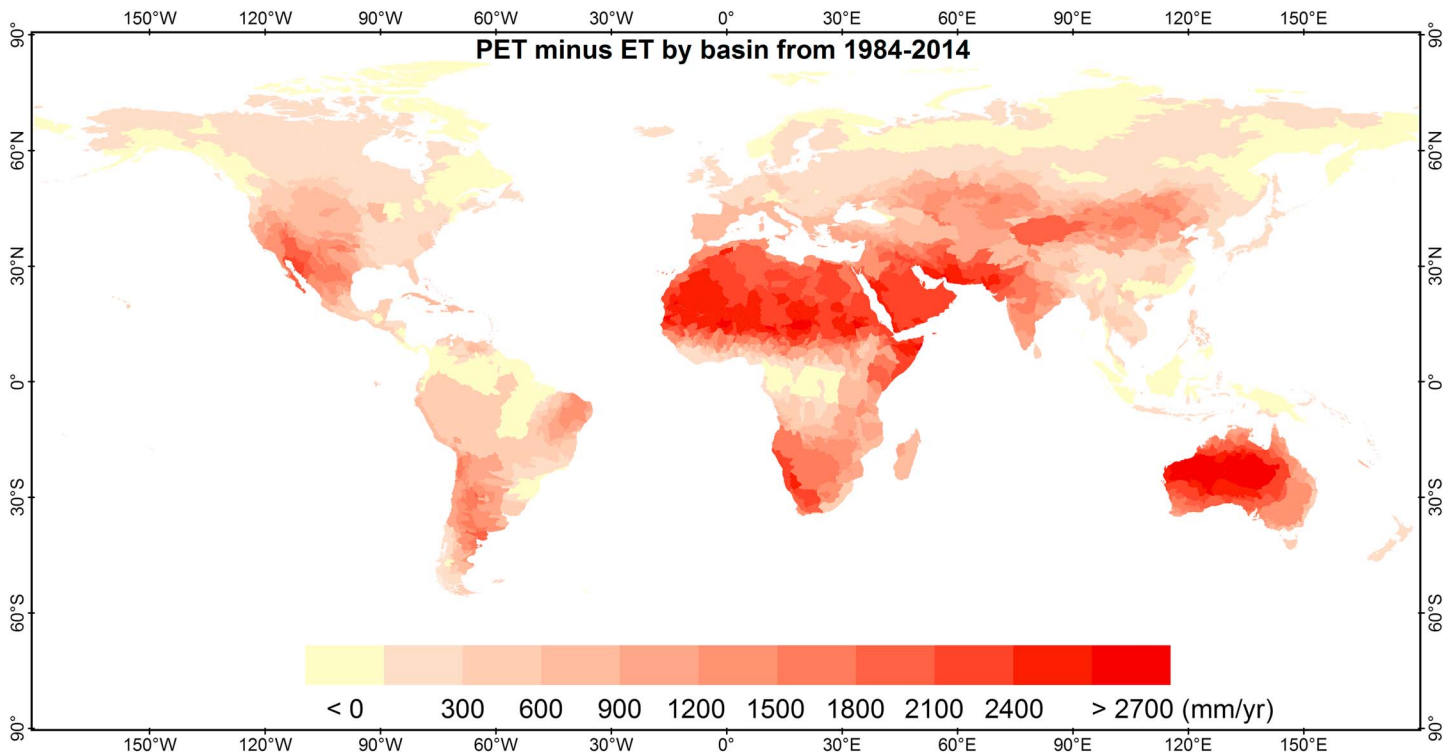


Figure 10. The difference between potential evapotranspiration (PET) and evapotranspiration by basin from 1984 to 2015.

overflow or into the subsurface aquifer when the permafrost underlying the lakes thaws completely (Frohn et al., 2005; Plug & West, 2009; Yoshikawa & Hinzman, 2003). An increase in the abundance and area of lakes in the continuous permafrost regions and a decrease in the discontinuous, isolated, and sporadic permafrost regions have been observed in Siberia (Smith et al., 2005). Thus, the evaporation changes observed across the pan-Arctic are likely the combined result of lake expansion and drainage caused by permafrost dynamics.

Certain local regions have revealed interesting patterns of increasing evaporation as well. For example, the inner Tibetan Plateau has experienced a drastic increase in evaporation as the region gained about 8,000 km² of NSW and lost less than 500 km² of LSW with a net gain of over 7,500 km². The regional evaporation increased by 4.91 ± 0.41 km³/year. This is because the majority of endorheic lakes have experienced expansion due to the wetter climate and increasing glacier meltwater supply (Lutz et al., 2014). Studies based on satellite altimetry and gravimetry measurements also confirmed increasing lake water levels and storages due to more precipitation and more concentrated localized meltwater since the late 1990s (Song et al., 2013, 2014; Yao et al., 2018; Zhang et al., 2017). The rate of warming in the Tibetan Plateau is over 0.4 °C/decade from 1961–2001, which is about double the global rate (Hansen et al., 2010; Xu et al., 2008). The conversion from extremely dry land to water results in significant water loss by evaporation.

The Canadian Prairies have experienced increased evaporation of about 2.5 km³/year. This region is known for wetlands occupying the potholes created by the late Pleistocene glaciation (Johnson et al., 2005). These wetlands provide important ecosystem services and are highly sensitive to climate change and land use change (Conly & Van Der Kamp, 2001). Studies have reported increased precipitation since the 1960s and a higher Palmer Drought Severity Index (higher means wetter) in the 1990s than in the 1980s (Coles et al., 2017; Millett et al., 2009). This may have contributed to the expansion of wetlands and thus increased water body evaporation in the region.

The Caspian Sea has caused the largest increase in evaporation among all basins. The Caspian Sea basin gained over 15,000 km² and lost 1,800 km² of surface water with a net gain of 13,000 km². As a result, the evaporation in the Caspian Sea basin increased by 10.59 ± 8.87 km³/year. Almost all gained surface water

comes from the Kara-Bogaz-Gol Bay, which is connected to the Caspian Sea through a narrow strait. Water in the bay completely depends on the inflow through the strait. A dam was built on the strait in 1980 in order to reduce the outflow from the Caspian Sea and stabilize its decline, and the bay dried up almost entirely by 1984 (Kouraev et al., 2011). After the dam was removed in 1992, the bay restored to a relatively stable extent since 1997.

Despite the overall increasing evaporation, certain regions show clustered patterns of decreased evaporation. Droughts are responsible for the decrease of evaporation in the western United States (MacDonald, 2010) and southeastern Australia (van Dijk et al., 2013). California, which was struck by two droughts from 2007 to 2009 and 2012 to 2016 (Xiao et al., 2017), lost over 1,000 km² of surface water. The Great Salt Lake and Lake Mead lost over 1,800 and 200 km² of surface area, respectively. The western United States combined had about 5.5 km³/year of decrease in evaporation. Southeast Australia experienced the worst drought on record from 2001 to 2009 (van Dijk et al., 2013). This is referred to as the “Millennium Drought” (van Dijk et al., 2013). The region lost over 1,000 km² of surface water during 2000–2015 compared to 1984–1999 and as a result the region had a 1 km³/year of decrease in evaporation.

The Aral Sea has caused the largest decrease in evaporation among all basins. The Aral Sea basin gained 2,400 km² and lost over 26,000 km² of surface water with a net loss of over 23,000 km². As a result, the basin-wide evaporation decreased by 23.18 ± 12.80 km³/year. Micklin et al. (2014) reported a roughly 30,000-km² loss of surface area of the Aral Sea from 1981 to 2010, and Shi et al. (2014) reported a roughly 35,000-km² loss from 1981 to 2013. These numbers suggest that the Aral Sea is likely the single cause for LSW in the basin. The NSW is likely the terminal lakes formed in the deserts due to the drainage of irrigated water (Micklin et al., 2014). The decline of the Aral Sea was mostly due to the diversion of water from the Amu Darya and the Syr Darya for agricultural irrigation (Micklin, 1988; Micklin et al., 2014; Wang et al., 2018). Note that the increased agricultural activities in the Aral Sea basin may have offset some of the evaporation decreases in the basin.

4. Discussions and Conclusions

4.1. Uncertainties of Estimating the Evaporated Water Budgets

According to Pekel et al. (2016), the user's and producer's accuracy of permanent water from different Landsat sensors are both above 98%. However, optical imagery-derived water body data sets underestimate water extent under vegetation cover especially in the rainforests. This effect is not accounted for in the study, which adds some unquantified uncertainties in the changes of water body areas in those regions. Occurrence change intensity cannot be calculated for areas that do not have pairs of months in the two periods. The conversion between land and water body happens at the land-water boundary where the water is shallow. Therefore, the influence of lake depth and thus lake heat storage on evaporation in the transition area can be neglected. There also exists a scale mismatch between the ET/PET products and the land-water conversion zones, which is inherent in the data sets. Using a basin-averaged ET/PET to calculate the evaporation changes in small land-water conversion zones within the basins may lead to some uncertainties in the estimates.

The largest source of uncertainty comes from PET estimates. Unlike ET products, different sources of PET data provide drastically different PET estimates. As discussed earlier, we searched the literature for field measurements of lake surface ET and used them as reference to correct and replace the GLDAS NOAH product. The lakes we collected cover all continents and a wide range of climate conditions. While a few field measurements themselves have noticeable uncertainties, they are much more consistent with each other than the global products. We performed a simple test for the sensitivity of our estimates of evaporation changes to PET estimates in the Aral Sea and the Caspian Sea basins, which are by far the largest contribution of a single basin, using the largest and smallest reported PET from different literature sources. Evaporation from the Aral Sea basin ranged from -25.18 to -20.75 km³/year while the Caspian Sea basin ranged from 9.52 to 11.48 km³/year. These numbers serve as the upper and lower boundaries of the ET estimates as affected by PET products, and the range of the boundaries are less than 20% of their means. Our uncertainty estimates in Table 2 include both the standard errors of ET products and the RMSE of the bias correction for PET products, which can be quite large for continents like Asia and South America. Nevertheless, we provide the first of such global assessment given the limitations in the available data sets.

4.2. Implications to the Future Water Cycle Studies

Jung et al. (2010) estimated a 7.1 mm/year per decade of increased ET during 1982–1997 and a 7.9 mm/year per decade of decrease during 1998–2008. This is equivalent to annual ET increases and decreases of 92.95 and 103.43 km³, respectively. On average, these estimates render a net increasing rate of 1.1 mm/year per decade (14.40 km³/year) in ET during 1982–2008. This rate is based on a constant extent of water bodies. Our calculations reveal a net annual evaporation of 30.38 ± 15.51 km³ upon the changed surface water body areas over the three decades, which has been omitted in conventional estimates. This suggests that a considerable amount of ET change can be caused by surface water dynamics. Most such studies on ET changes are therefore missing a considerable contributor of ET changes by assuming a constant water surface throughout their study period.

In comparison, global precipitation has been increasing at about 1 mm/year per decade (13 km³/year) since 1901 (Smith et al., 2012), and global discharge has been increasing at about 3 mm/year per decade (40 km³/year; Syed et al., 2010). In other components of the water cycle, ice caps and glaciers globally are losing 290 km³/year of equivalent water volume (Gardner et al., 2013); the ice sheets in Greenland and Antarctica are retreating at 142 and 71 km³/year, respectively (Shepherd et al., 2012); the global groundwater is being depleted at an annual rate of 204 km³/year (Wada et al., 2012). These comparisons highlight the importance of understanding long-term land and water transformation, as they may cause a considerable amount of evaporated water flux. Also, changes in sea level rise caused by changes in surface water bodies may not be as inconsequential as the IPCC report has assumed.

Previous studies related to trends in global evapotranspiration have inappropriately omitted this considerable source of evaporation change by assuming constant land and water areas throughout their study periods. This study shows that the noticeable changes of surface water area observed in recent decades may have considerably altered terrestrial surface evaporation rates and led to obvious changes in the surface water budget. Our results are expected to lower the uncertainties in closing the water budgets on both the global and regional scales. This is essential for assessing future water availability and providing water management authorities with insight into future management practices under ongoing climate changes.

Acknowledgments

This study was supported in part by the National Key R & D Program of China (Grants 2018YFD0900804 and 2018YFD1100101) and the Thousand Young Talents Program in China to C. Song and in part by the U.S. Geological Survey (USGS) Landsat Science Team Program Grant G12PC00071, the National Aeronautics and Space Administration (NASA) Terrestrial Hydrology Program under Grant NNX08AE51G, and Surface Water and Ocean Topography (SWOT) Program under Grant NNX16AH85G to Y. Sheng. The authors appreciate two anonymous reviewers and editor for their constructive comments that greatly helped to improve the study. We thank Austin Madson for editing the language of this paper. We also thank the Global Surface Water Database, the Commonwealth Scientific and Industrial Research Organization, the National Aeronautics Space and Administration Goddard Earth Sciences Data Information Services Center, Global Land Evaporation Amsterdam Model, the Numerical Terradynamic Simulation Group at University of Montana, the World Wildlife Fund, the National Catchment and Stream Environment Database, and the Global Drainage Basin Database for making the data sets used in this study publicly available. The source of the data sets can be found in section 2.

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