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Evidence of the Recent Decade Change in Global Fresh Water Discharge and Evapotranspiration Revealed by Reanalysis and Satellite Observations

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Abstract: Variations of global evapotranspiration (*ET*) and fresh water discharge from land to oceans (*D*) are important components of global climate change, but have not been well monitored. In this study, we present an estimate of twenty years (1989 to 2008) variations of global *D* and *ET* derived from satellite remote-sensed measurements and recent reanalysis products, ERA-Interim and CFSR, by using a novel application of the water balance equations separately over land and over oceans. Time series of annual mean global *D* and *ET* from both satellite observations and reanalyses show clear positive and negative trends, respectively, as a result of modest increase of oceanic evaporation (E_o). The inter-annual variations of *D* are similar to the in-situ-based observations, and the negative trend of *ET* supports the previous result that relative humidity has decreased while temperature has increased on land. The results suggest considerable sensitivity of the terrestrial hydrological cycles (e.g., *D* and *ET*) to small changes in precipitation and oceanic evaporation.

Key words: Discharge, evapotranspiration, water cycle, remote sensing, reanalysis

1. Introduction

Global fresh water discharge (*D*) and evapotranspiration (*ET*) are important components of the terrestrial hydrological cycle and also important for ecology, geomorphology and availability of fresh water resources (Oki and Kanae, 2006). Their long-term trends are a key indicator of global climate change. However, global *D* and *ET* are hard to quantify, particularly based on sparse in-situ data. As a result, long-term trends of global *D* and *ET* have not been well documented (Alsdorf and Lettenmaier, 2003). For example, studies based on in-situ gauge measurements and remote sensing reported that the global *D* has increased through the last century (Labat *et al.,* 2004) and the last decade (Syed *et al.,* 2010) possibly due to global warming. In contrast, different evidence based on the similar gauge observations was shown that the global *D* has decreased since 1948 (Dai *et al.,* 2009). This disagreement is possibly due to limitations in the in-situ gauge measurements for estimating the global *D* (Alsdorf and Lettenmaier, 2003). These limitations include: (1) unmonitored surface water flows outside river channels, (2) river gauges are often not located at the farthest downstream point, (3) river gauges are not installed in about 20% of the entire drainage areas, and (4) there are gaps in river gauge data.

Time series of in-situ pan-evaporation measurements exhibit a decreasing trend (Peterson *et al.,* 1995), possibly due to decreasing solar irradiance resulting from increasing cloud cover and aerosol concentration (Roderick and Farquhar, 2002). However, the connection between pan-evaporation and *ET* has not been well established, and thus the trend of pan-evaporation may not be a good indicator of the trend of the global *ET* (Brutsaert and Parlange, 1998). On the other hand, a long-term estimation of global *ET* (1982-2008) based on machine learning algorithm with (limited numbers of) observational data exhibits an increasing trend during 1982-1997 and a relatively weak decreasing trend after 1997 (Jung *et al.,* 2010).

In this study, we estimate the annual mean global *D* and *ET*, and present evidence of their long-term (1989-2008) variations through a novel utilization of the water budget equations and recent state-of-the-art reanalysis products, CFSR (Saha *et al.,* 2010) and ERA-Interim (Simmons *et al.,* 2007), and global satellite data of precipitation and oceanic evaporation.

2. Method

The annual mean global *D* can be estimated using the water balance equation over oceans (Seo *et al.,* 2009):

$$D = \frac{dW_o}{dt} + E_o - P_o \tag{1}$$

where $\frac{dW_o}{dt}$ is the annual oceanic water mass variation, E_o and P_o are annual oceanic evaporation and precipitation, respectively. The water balance equation over oceans is desirable than

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land for this purpose since both satellite-based oceanic evaporation and precipitation data are available (e.g., Yu, 2007). For D in the equation, the oceanic water storage variation is necessary, and it is estimated by the global mean sea level (GMSL) observed by satellite altimeters (available at http://sealevel.colorado.edu) with steric corrections applied (Ishi *et al.,* 2006). Steric correction accounts for ocean density change including thermosteric and halosteric corrections. Because the halosteric data is poorly characterized due to the data sparseness and its effect to the total steric correction is very minor (Ishii *et al.,* 2006), only the thermosteric correction is applied here. The blue line in Fig. 1 shows the oceanic water storage variations from the GMSL observations with the steric correction. Compared to the previous annual global mean of D (Dai and Trenberth, 2002), about 3.7×10^{16} kg yr^{-1}, the amplitude of oceanic water storage variation is very small. In addition its satellite-based estimate period is relatively short compared to our study period (1989-2008), and thus we ignore the term for this study.

Alternatively, the difference between E_o and P_o are evaluated via the atmospheric water balance equations:

$$\int_o \overline{V}\cdot\overline{Q} + \frac{dW_o^a}{dt} = E_o - P_o \tag{2}$$

where $\frac{dW_o^a}{dt}$ is atmospheric water mass variation over oceans and $\overline{Q}$ is the horizontal water flux vector, which is given by,

$$\overline{Q} = \int_{P_o}^{P_S} \frac{q}{g}\overline{V}\,dp \tag{3}$$

in which, q is the specific humidity, g is the gravity acceleration, $\overline{V}$ is the horizontal wind vector, p_s and p_0 is the pressure at the surface and the top of the atmosphere, respectively. In this study, the horizontal water flux vector is estimated using CFSR and ERA-Interim reanalysis products. For D estimate with Eq. (2), the atmospheric water storage variation over oceans is required, and it can be estimated using specific humidity in reanalysis. The red line in Fig. 1 exhibits the atmospheric water storage variations from ERA-Interim, and its amplitude is also negligible. As a result, the D can be evaluated via both ways based on satellite observation of E_o and P_o and divergence of horizontal water flux in reanalysis:

$$D = E_o - P_o = \int_o \overline{V}\cdot\overline{Q} \tag{4}$$

Given the estimated D, the annual mean global ET can be evaluated by the water balance equations over land.

$$ET = P_l - D = \frac{dW_l}{dt} \tag{5}$$

where $\frac{dW_l}{dt}$ and P_l are the annual terrestrial water storage variation and precipitation, respectively. Terrestrial water storage variation has been only observed from GRACE since 2002 (Tapley *et al.,* 2004), but its annual variations during the study period (1989-2008) can be inferred based on GRACE observations and oceanic water storage variations as shown in Fig. 1. GRACE observation shows that oceanic and terrestrial water storage variations are almost the same amplitude with the opposite phases (Chambers, 2006), and hence the annual terrestrial water storage variation from 1989 to 2008 is likely similar amplitude to the blue line in Fig. 1. Consequently, the term is also negligible and the annual global ET is simply:

$$ET = P_l - D \tag{6}$$

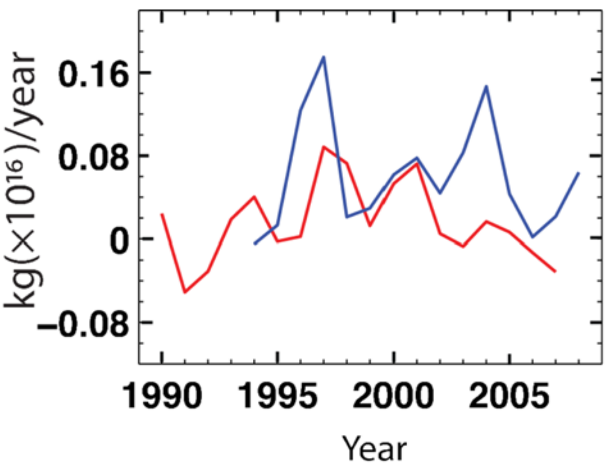

Fig. 1. The water mass variations in the atmosphere (red) and oceans (blue). The atmospheric water mass variations are estimated from ERA-Interim product, and the oceanic water mass variations are evaluated based on global mean sea level data observed by satellite altimeters with steric correction.

3. Results

Since D and ET are linked to other hydrological components as provided by the equations in the 2. Method section, we first examine the annual variations of precipitation and evaporation. Figure 2 shows the time series of annual mean precipitation over both land and oceans and evaporation over oceans from 1989 to 2008 from the satellite data. The precipitation over land (P_l) from GPCP (Adler *et al.,* 2003) and CMAP (Xie and Arkin, 1997) show a systematic bias between them while both show similar increasing trends. The precipitation over oceans (P_o) from GPCP and CMAP also show a systematic bias exhibiting similar year-to-year variations, with some discrepancy during the period between 1995 and 1998. This has been attributed to an artifact in CMAP that derived from adjusting satellite estimates to atoll data (Yin *et al.,* 2004) in 1996. For the P_o from GPCP and CMAP, no statistically significant trend is observed. In contrast, three oceanic evaporation (E_o) products, OAflux (Yu, 2007), HOAPS (Shulz *et al.,* 1997) and J-OFURO (Kubota *et al.,* 2002), all show positive trends which have been hypothesized to result from increases in sea surface temperature (Yu and Weller, 2007) and wind speed (Yu, 2007). As observed in the figure, trends in E_o are steeper than those in P_l and P_o, and thus associated changes in D and ET are expected.

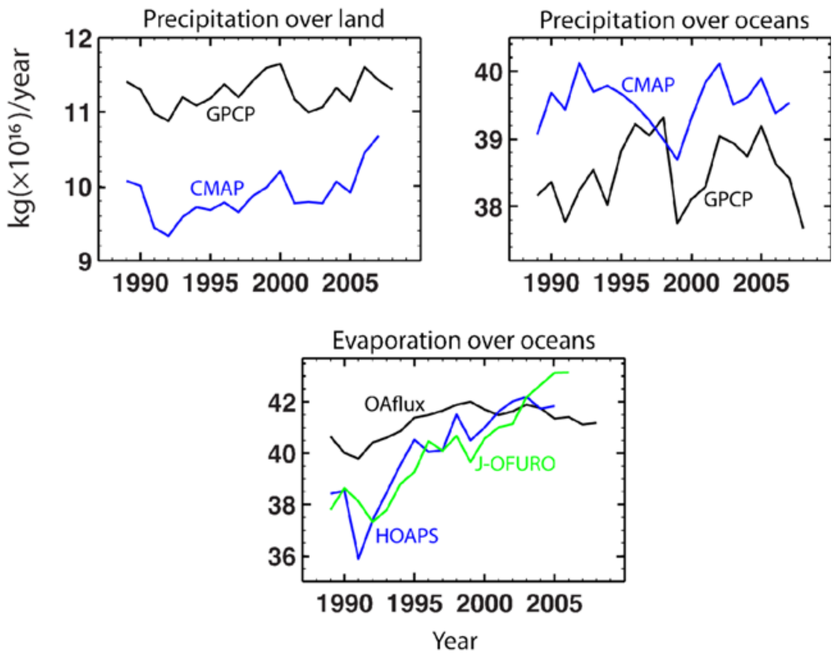

Fig. 2. Precipitation over land (top left panel), precipitation over oceans (top right panel) and evaporation over oceans (bottom panel). Oceanic evaporation show strong secular trends for the last two decades.

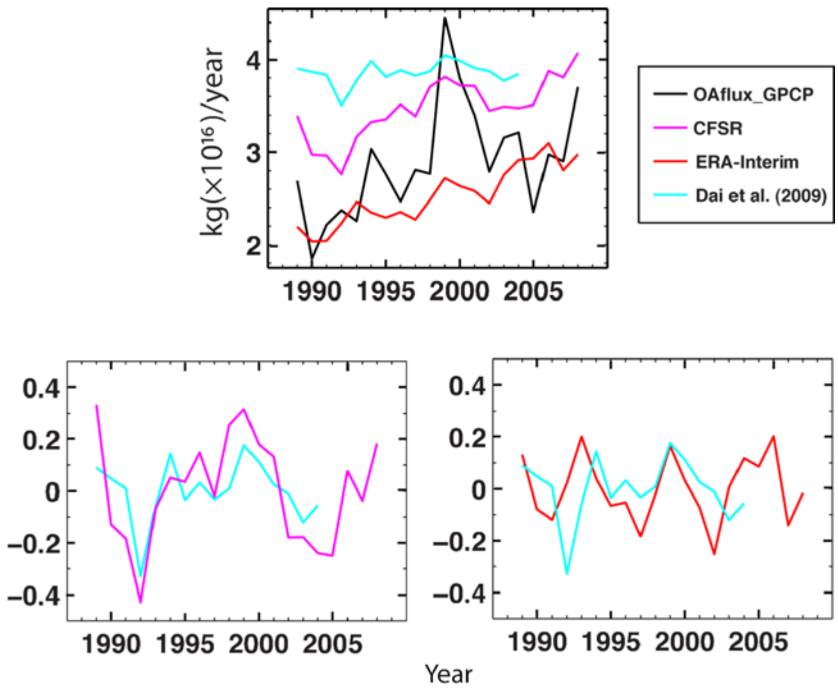

Fig. 3. Top panel: Annual time series of fresh water discharge from land to oceans (D). Clear positive trends are present in D. The black, red, and magenta lines are estimated by OAflux-GPCP, ERA-Interim and CFSR, respectively. In addition, the cyan line is estimated by the in-situ river gauges data combined by the CLM3 simulation (Dai *et al.,* 2009). The cyan line is replotted after digitizing Fig. 9f in Dai *et al*. (2009).
Bottom panel: Comparison in inter-annual variability between the in-situ-based D estimate (cyan line) and reanalysis-based estimates (magenta and red lines for CFSR and ERA-Interim, respectively) after removing means and trends.

The top panel of Fig. 3 shows the time series of annual mean global D derived by the water balance over oceans as shown in Eq. (4) The black line is estimated D based on OAflux_GPCP, and the red and magenta lines represent D using the divergence of the horizontal water flux from the ERA-Interim and the CFSR, respectively. The three estimates all show positive trends while their mean and year-to-year variations differ. The D from other combinations of satellite-based oceanic evaporation and precipitation data all shows steeper positive trends (not shown). In addition, the cyan line exhibits the D estimates based on in-situ river gauge data and a numerical model (Dai *et al.,* 2009) [Community Land Model, version 3, (CLM3)] simulation, and show also an evidence of increasing D, but its trend is not as obvious as the new estimates here.

Mean of the annual global D from the CFSR, 3.27×10^{16} kg yr^{-1}, is greater than those of the OAflux_GPCP and the ERA-Interim by more than 28% but close to the previous in-situ based estimates (Dai *et al.,* 2009), which is about 3.65×10^{16} kg yr^{-1}. It should be noted that the inter-annual variability of D from OAflux_GPCP is likely exaggerated compared to those from ERA_Interim and CFSR because independent observational estimates are not physically constrained, contrast to the case of reanalysis, and thus the presence of errors can lead to physically inconsistent results when combining the observational estimates. In particular, the D from OAflux_GPCP (black) is anomalously large in 1999 and 2000, which is due to the relatively small P_o over oceans during those years while the E_o does not exhibit similar behavior.

While the previous D estimate (Dai *et al.,* 2009) based on in-situ observations combined with the CLM3 simulation does not exhibit a clear trend as shown other estimates, inter-annual variations of D between the in-situ-based estimate and reanalysis-based estimates agree well. The comparisons in inter-annual variability are exhibited in the bottom panels of Fig. 3. Trends and means are removed and residual annual D are shown. The correlation between the magenta line (CFSR) and the cyan line (Dai *et al.,* 2009) is high (0.77). In general, the red line (ERA-Interim) does not agree well with the cyan line before 1994, but the agreement is very good after 1994.

The increasing trend in D found in this study supports a previous estimate (Syed *et al.,* 2010). The previous study, on the other hand, also claimed that the trend is superposed by two different sub-trends separated by two periods, from 1994 to 1999 and from 1999 to 2006. The first and the second trends were 29.04×10^{14} kg yr^{-2} and -7.56×10^{14} kg yr^{-2}, respectively. The anomalous large positive trend for the first period (which indicates that D increased almost double in 5 years) and the negative trend in the second period were due to the abnormally large D in 1999 that is also observed here in the black line in Fig. 3. However, based on other D estimates from both reanalyses and in-situ observations in Fig. 3., the large D in 1999 is not present and thus the upward and downward trends are not observed. As discussed before, it is suspicious that the large D in 1999 is due to the amplified error from the subtraction of OAflux and GPCP products. Thus, more studies are necessary to further examine the reason for this large D in 1999.

Based on the D estimates, the annual ET is evaluated via the water balance equation over land (see Eq. (6)). In Fig. 4, the black, red and magenta lines are the ET estimates based on OAflux_GPCP, ERA_Interim and CFSR, respectively. In this case, we use GPCP for the P_l. All three estimates show negative trends while their means and inter-annual variations are different. When CMAP used for P_l, we found the similar negative trends (not shown). Similar to the D time series, the ET estimate based on OAflux_GPCP exhibit larger inter-annual variations than those based on ERA_Interim and CFSR. Mean of the annual global ET based on the CFSR, 7.99×10^{16} kg yr^{-1}, is similar to the previous estimate (Trenberth *et al.,* 2007), 7.30×10^{16} kg yr^{-1}.

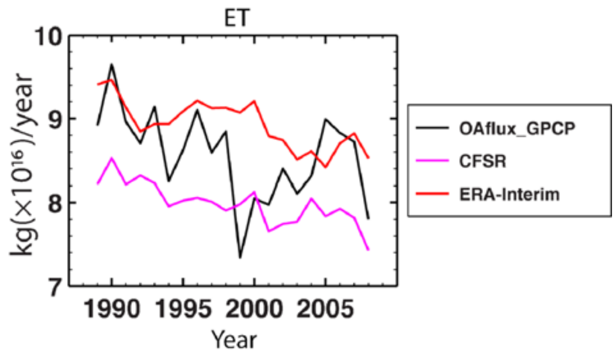

Fig. 4. Annual time series of evapotranspiration (*ET*). Clear negative trends are present in *ET*. The black line is estimated by OAflux and GPCP, the red line is estimated by ERA-Interim and GPCP, and the magenta line is estimated by CFSR and GPCP.

4. Conclusions and discussions

In this study, we have showed evidence of increasing trend in D and decreasing trend ET for the last two decades (1989-2008) using satellite-based data and reanalysis products with a novel approach of water balance equation over land and oceans. The previous D estimate based on the in-situ observation also exhibits a positive trend and very similar year-to-year variations to the new D estimates, particularly from reanalyses. Even though the D and ET estimates based on remote sensing (OAflux and GPCP) and reanalyses (ERA-Interim and CFSR) show different annual means and inter-annual variability, both independent estimates show similar positive D and negative ET trends. The secular trends in D and ET are mainly associated with the increase of E_o while long-term trends in P_o and P_l appear to be relatively small. E_o (OAflux) increased about 1.27×10^{16} kg yr^{-1} over the study period, from 1989 to 2008, at a rate of 6.71×10^{14} kg yr^{-2}. P_o and P_l from GPCP increased about 0.28×10^{16} kg yr^{-1} and 0.19×10^{16} kg yr^{-1}, at a rate of 1.49×10^{14} kg yr^{-2} and 1.01×10^{14} kg yr^{-2}, respectively, during the same period. The increments of oceanic evaporation (E_o) and global precipitations (P_o and P_l) are minor compared to their 20-year means. However, the relative variations of the D and ET are much larger. For example, the D and ET estimates derived from CFSR increased 25.38% and decreased −8.01%, respectively. This result indicates that small changes of precipitation and oceanic evaporation have a significant impact on terrestrial hydrological cycles such as D and ET. On the other hand, this increment of D has little affected the global means sea level as shown in Fig. 1 because oceans mass has been balanced between $E_o - P_o$ and D.

The trend discrepancy in D between the previous in-situ-based estimate (Dai *et al.,* 2009) and the current new estimates may be due to the following reasons: limitations of the river gauge-based estimate that requires numerical simulations on statistical inference to account for missing data gaps, unmonitored areas, and converting station data often observed hundreds of kilometers from the river mouth into the river mouth flow. In addition, as noted above, the gauge observations are not able to measure groundwater discharge and may underestimate river discharge in case of flooding. On the other hand, the larger upward trend in D estimated here may be overestimated due to spurious variations in reanalyses and remote sensing data as the observing system changes (Trenberth *et al.,* 2011). For example, when HOAPS and J-OFURO are used, the trends in D (not shown) are much steeper than those when OAflux, ERA-Interim and CFSR are used, indicating uncertainties of trend in D estimated from remote sensing and reanalysis data.

The ET trend difference between the previous study (Jung *et al.,* 2010) and this study is much more apparent than the D trend difference. Jung *et al*. (2010) showed that ET increased from 1982 to 1997 and decreased after 1997, while our study indicates that ET decreased from 1989 to 2008. Similar to the D trend estimate, our ET trend estimate is also vulnerable to variations of observing system. For example, our ET trend estimate may be overestimated. On the other hand, some limitations also exist for the ET trend estimate by Jung *et al.* (2010). For example, because the ET estimate in Jung *et al.* (2010) was based on model based training algorithm with observational data, its accuracy heavily relied on the in-situ data used such as FLUXNET data. The uncertainties of the FLUXNET data for the purpose of the long-term global ET estimate are well known: (1) The numbers of the FLUXNET data is very limited before late 1990's (there were less than 100 FLUXNET tower sites only in North America and Europe by 1997). (2) Most FLUXNET towers are located in the low latitudes (FLUXNET, 2010). Therefore, future studies using both in-situ and remote sensing observations are needed for the long-term trends of D and ET.

Although differences exist in estimates of D and ET between previous studies (Dai *et al.,* 2009; Jung *et al.,* 2010) and current study, these studies all confirm that D increased and ET decreased during the recent decades. One of the possible explanations for the trends in D and ET is changes in the temporal characteristics of precipitation (Karl and Knight 1998). Given the same amount of precipitation over a given time period, increasing heavy rain events would generate higher D and lower ET compared to steadier lighter rain (Trenberth *et al.,* 2003). If this explanation turns out to be true, the societal impact with regard to the variations of D and ET would be significant, since heavy rain events would imply less fresh water availability and higher risk of flooding. In addition, the consequence of decreases in ET restrains cooling through evaporation and drives increasing temperature over land (Trenberth *et al.,* 2003). This scenario can support the previous finding that relative humidity decreased while temperature increased at 2-m height over land (Simmons *et al.,* 2010).

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