GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L13404, doi:10.1029/2011GL047929, 2011

Recent changes in pan-evaporation dynamics in China

Xiaomang Liu,[1,2] Yuzhou Luo,[2] Dan Zhang,[1] Minghua Zhang,[2] and Changming Liu[1]

Received 25 April 2011; revised 20 May 2011; accepted 24 May 2011; published 6 July 2011.

[1] Pan-evaporation (E_{pan}) as the indicator of atmospheric evaporative demand has decreased worldwide with climate change in the last decades, which is called "Pan Evaporation Paradox". This study investigates the recent changes in E_{pan} dynamics in China using the observed E_{pan} records for the period 1960–2007. The records show that E_{pan} decreased in China from 1960 to 1991 by -5.4 mm yr^{-2}. The attribution results show that the significant decreases ($P < 0.001$) in wind speed and solar radiation offset the effect of increasing air temperature and led to the decrease in E_{pan}. However, the observed E_{pan} has increased since 1992 by 7.9 mm yr^{-2}. From 1992 to 2007, the amplitude of increase in air temperature rose seriously, while the amplitude of decrease in wind speed declined and solar radiation even increased insignificantly ($P > 0.1$). The results show that increasing air temperature dominated the change in E_{pan}, which offset the effect of wind speed and led to the increase in E_{pan}. **Citation:** Liu, X., Y. Luo, D. Zhang, M. Zhang, and C. Liu (2011), Recent changes in pan-evaporation dynamics in China, *Geophys. Res. Lett.*, *38*, L13404, doi:10.1029/2011GL047929.

1. Introduction

[2] Decreases in pan-evaporation (E_{pan}) over the last decades have been reported in many regions of the world associated with climate change [e.g., *Peterson et al.*, 1995; *Roderick and Farquhar*, 2002; *Liu et al.*, 2004]. The decrease in E_{pan} associated with the increasing near-surface air temperatures is called "Pan Evaporation Paradox" [*Brutsaert and Parlange*, 1998]. Various interpretations have been presented to explain the "Paradox" in different regions. As E_{pan} is an integrated effect of climate variables, increases in air temperature should lead to increases in E_{pan}. However, this effect could be offset by decreases in vapor pressure deficit, wind speed and solar radiation which lead to decreasing rates of E_{pan}. Therefore, observed decreases in solar radiation and/or wind speed are considered the causing factors of decreasing $\mathrm{E_{pan}}$ in different regions of the world [e.g., *Roderick et al.*, 2009a, 2009b]. Recently, the decrease in wind speed is widely considered as the dominant factor contributing to the decreases in E_{pan} [e.g., *Rayner*, 2007; *Roderick et al.*, 2007; *Zheng et al.*, 2009].

[3] Decreases in E_{pan} from the 1950s to around 2000 were also reported in China, and decreases in solar radiation and wind speed were considered the driving forces [e.g., *Liu et al.*, 2004, 2010]. However, most of the E_{pan} time series ended in 2001 and those studies focused on trend estimation directly, while analysis on the abrupt change in E_{pan} was not available. In addition, nationwide quantitative attribution of changes in E_{pan} to climate variables was also not available in the literature. In this study, the updated data (1960 to 2007) from the weather station network in China were used and the abrupt changes in E_{pan} were analyzed nationwide. Attribution analysis was performed using the Penman-Monteith formulation to quantify the contributions of climate variables to overall trends in E_{pan}. Our results focus on the recent changes and attribution of E_{pan} dynamics in China.

2. Data and Methods

2.1. Data

[4] Monthly meteorological records of 518 national meteorological stations from 1960 to 2007 from the National Climatic Centre (NCC) of China Meteorological Administration (CMA) were used in the study (Figure 1). Crop reference evapotranspiration was calculated based on the mean values of daily maximum, minimum and air temperatures ($T_{\max}$, $T_{\min}$, T_a) at 2 m height, wind speed measured at 10 m height, vapor pressure (VP) at 2 m height and sunshine duration [*Allen et al.*, 1998]. Wind speed was adjusted to 2 m height (U) using *Allen et al.*'s [1998] wind profile relationship. Solar radiation (R_s) was available at 51 stations. E_{pan} was measured using a metal pan, 20 cm in diameter and 10 cm high, installed 70 cm above the ground on a wooden platform. The pan was filled to 2 cm, or sometimes 3 cm, depending on local daily evaporative rates [*McVicar et al.*, 2007].

2.2. Methods

[5] The rank-based non-parametric Mann–Kendall statistical test [*Mann*, 1945; *Kendall*, 1975] has been commonly used for trend detection due to its robustness for non-normally distributed data, which are frequently encountered in hydro-climatic time-series. Assuming normal distribution at the significant level of $P = 0.05$, a positive Mann-Kendal statistics Z larger than 1.96 indicates an significant increasing trend, while a negative Z lower than -1.96 indicates a significant decreasing trend. Critical Z values of ±1.64, ±2.58 and ±3.29 were used for the probabilities of P = 0.1, 0.01 and 0.001, respectively. Spatially, China is divided into eight climatic regions (Figure 1), which are generally consistent with those defined by *Liu et al.* [2004]. Nationwide and regional averages of E_{pan} and climate variables were first calculated. Temporal trends and change points of the average E_{pan} and climate variables were then quantified by the linear regression and *Pettitt*'s [1979] test, respectively.

[6] The differentiation equation method [*Zheng et al.*, 2009] was used to attribute the change in E_{pan}. It is widely accepted that there exists a good linear relationship

---

[1] Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China.

[2] Department of Land, Air and Water Resources, University of California, Davis, California, USA.

0094-8276/11/2011GL047929

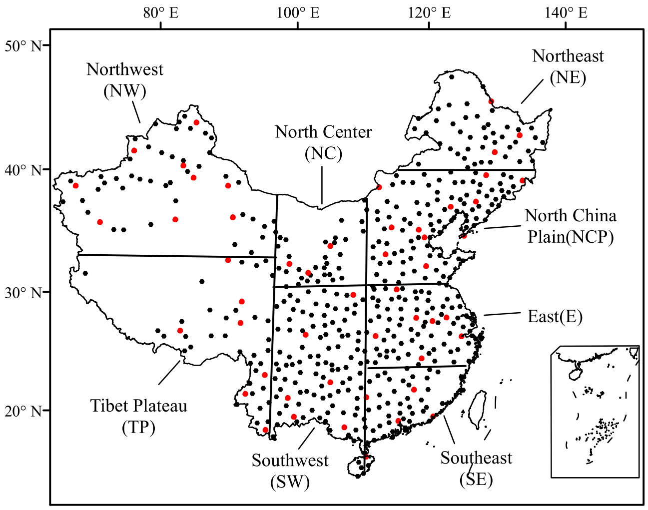

Figure 1. The spatial distribution of the 518 meteorological stations in China. The red circles indicate the 51 stations which have observed solar radiation data. Regional abbreviates are provided in the figure. The latitudes to define the 8 regions are about 44°N, 36°N, 35°N and 28°N from North to South respectively and the longitude are 100°E and 110°E from West to East respectively.

between E_{pan} and reference evapotranspiration (ET_{ref}), expressed as:

$$E_{pan} = K_p \times ET_{ref} + K_c \tag{1}$$

where K_p and K_c are regression coefficients. ET_{ref} is the crop reference evapotranspiration of a hypothetical surface estimated by the Penman-Monteith formula [*Allen et al.*, 1998]. The calculating processes and results of ET_{ref} and R_s are summarized in Text S1, Table S1, and Figure S1 of the auxiliary material.[1] Following the Penman-Monteith formula, contributions of changes in climate factors to ET_{ref} trend can be approximately estimated as the following [*Zheng et al.*, 2009]:

$$\frac{dET_{ref}}{dt} = \frac{\partial ET_{ref}}{\partial R_s}\frac{dR_s}{dt} + \frac{\partial ET_{ref}}{\partial T_a}\frac{dT_a}{dt} + \frac{\partial ET_{ref}}{\partial U}\frac{dU}{dt} + \frac{\partial ET_{ref}}{\partial VP}\frac{dVP}{dt} + \delta \tag{2}$$

where δ is the error item. The detailed formulas and calculating results of differential items are summarized in Text S1 and Tables S2 and S3 of the auxiliary material. With the relationship between E_{pan} and ET_{ref} shown in equation (1), the contributions of climate factors to the long-term trend in E_{pan} can be expressed as:

$$\frac{dE_{pan}}{dt} = K_p\frac{\partial ET_{ref}}{\partial R_s}\frac{dR_s}{dt} + K_p\frac{\partial ET_{ref}}{\partial T_a}\frac{dT_a}{dt} + K_p\frac{\partial ET_{ref}}{\partial U}\frac{dU}{dt} + K_p\frac{\partial ET_{ref}}{\partial VP}\frac{dVP}{dt} + \varepsilon \tag{3a}$$

or simplified as:

$$C\_E_{pan} = C\_(R_s) + C\_(T_{mean}) + C\_(U) + C\_(VP) + \varepsilon \tag{3b}$$

where C_E_{pan} is the calculated long-term trend in E_{pan}. $C\_(R_s)$, $C\_(T_a)$, $C\_(U)$ and $C\_(VP)$ are individual contributions to the long-term trend in E_{pan} due to the change in R_s, T_a, U and VP respectively. ε is the error item between C_E_{pan} and observed E_{pan} trend (O_E_{pan}).

3. Results

3.1. E_{pan} Trend

[7] Figure 2a shows the variation of annual E_{pan} for nationwide average from 1960 to 2007. A change point for E_{pan} series was identified around the year 1992. E_{pan} decreased significantly ($P < 0.001$) at -5.4 mm yr^{-2} from 1960 to 1991, while E_{pan} increased significantly ($P < 0.001$) at 7.9 mm yr^{-2} from 1992 to 2007. For all the eight climatic regions, change points of annual E_{pan} series were observed in early 1990s. The regional variations of E_{pan} and climate

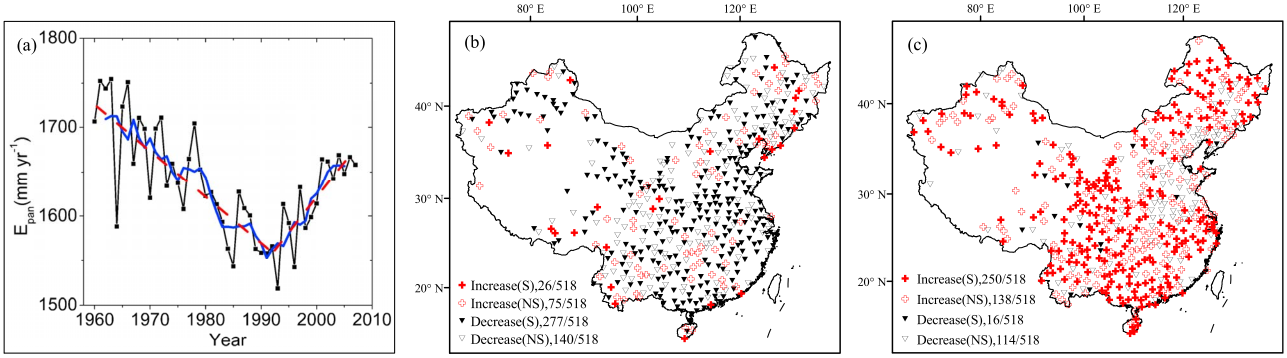

Figure 2. (a) Variation of annual E_{pan} for nationwide average from 1960 to 2007. The blue line shows the five year moving average and the red dotted lines are the linear trends fitted to corresponding periods. Trends in annual E_{pan} for the 518 meteorological stations in China during the periods (b) 1960 to the early 1990s and (c) the early 1990s to 2007 (E_{pan} trends for the stations were calculated before and after the change points of the corresponding climatic regions). S and NS in the figure legend indicate significance and insignificance at P = 0.05, respectively. The numbers given after S or NS indicate the number of stations out of 518 stations in these categories.

---

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL047929.

Table 1. Contributions of Climate Factors to the Trends in Annual E_{pan} in the Eight Climatic Regions and the Whole China[a]

	CALC					OBS		
Region	$C\_(T_a)$	$C\_(U)$	$C\_(VP)$	$C\_(R_S)$	C_E_{pan}	O_E_{pan}	ε	$\rho(\varepsilon)$(%)
The Period: 1960 to the Early 1990s (Change Date Subtracts 1 Year)								
Nation(92)	1.3	−3.5	−0.1	−2.7	−5.0	−5.4	0.4	−7
NW(94)	1.8	−7.5	−1.6	−0.8	−8.2	−7.7	−0.6	7
NC(91)	2.2	−7.3	−0.1	−1.5	−6.6	−7.2	0.6	−8
NE(93)	3.1	−4.3	−0.9	−0.9	−3.0	−3.3	0.3	−10
NCP(92)	2.1	−5.6	−0.4	−2.6	−6.4	−7.2	0.8	−11
TP(92)	0.7	−3.2	−0.7	0.0	−3.2	−3.6	0.4	−12
SE(95)	0.7	−1.6	0.3	−4.0	−4.6	−4.1	−0.4	10
E(92)	−0.7	−2.2	1.0	−5.1	−7.0	−6.6	−0.4	6
SW(92)	0.0	−0.8	0.1	−3.8	−4.5	−4.9	0.4	−8
The Period: The Early 1990s (Change Date) to 2007								
Nation(92)	7.4	−2.0	1.7	0.2	7.2	7.9	−0.7	−9
NW(94)	6.1	3.2	1.5	−0.9	9.8	9.5	0.4	4
NC(91)	8.7	−3.4	1.2	1.3	7.8	9.3	−1.5	−16
NE(93)	2.1	−4.3	6.5	1.4	5.7	6.7	−0.9	−14
NCP(92)	9.2	−4.4	0.3	−1.5	3.7	4.0	−0.4	−9
TP(92)	5.9	−0.8	−1.3	1.9	5.7	5.4	0.4	7
SE(95)	5.4	−1.7	4.4	3.5	11.6	12.8	−1.2	−9
E(92)	6.8	−1.5	1.3	−0.9	5.7	6.5	−0.8	−12
SW(92)	5.2	−0.6	0.0	2.9	7.5	6.8	0.8	11

[a] The numbers in brackets after regional names mean the change dates of each region. OBS: observed trends; CALC: calculated trends by equation (3); the unit is given in mm yr^{-2}. ε and $\rho(\varepsilon)$ mean error and relative error to observed trends, respectively. See Figure 1 for descriptions of climatic regions.

factors are summarized in Table S4 and Figure S2 of the auxiliary material. Annual E_{pan} in all the eight regions decreased before early 1990s and increased since then. E_{pan} trends for the 518 stations were calculated before and after the corresponding regional change points. As shown in Figures 2b and 2c, annual E_{pan} in most stations decreased from 1960 to the early 1990s and increased from the early 1990s to 2007.

3.2. E_{pan} Attribution

[8] The contributions of changes in climate factors to the long-term trend in annual E_{pan} were estimated by equation (3) at all the stations. The calculated E_{pan} trends (C_E_{pan}) fit well with the observed E_{pan} trends (O_E_{pan}) for the 518 stations with $R^2 = 0.93$ and 0.91 before and after the early 1990s respectively (see Figure S3 of the auxiliary material). For the country average, the overall relative errors between C_E_{pan} and O_E_{pan} were −7% and −9% for the two periods, respectively (Table 1). For the eight climatic regions, the maximum relative error from 1960 to the early 1990s was −12% which occurred in the Tibet Plateau. The maximum relative error from the early 1990s to 2007 was −16% which occurred in the North Center. The good agreement between C_E_{pan} and O_E_{pan} suggested that it was reasonable to use equation (3) to estimate contributions of individual climate factors to the long-term trend in E_{pan}.

[9] Table 1 shows the contribution of each climate factor to the trend in annual E_{pan}. For the nationwide average, from 1960 to 1991, T_a increased significantly ($P < 0.05$) at 0.011°C yr^{-1}, and the increases in T_a should have led to an increase in E_{pan} at 1.3 mm yr^{-2}. However, both U and R_S decreased significantly ($P < 0.001$) at −0.012 m s^{-1} yr^{-1} and −0.023 MJ m^{-2} day^{-1} yr^{-1} respectively, and decreases in U and R_S should have led to a decrease in E_{pan} at −3.5 mm yr^{-2} and −2.7 mm yr^{-2}, respectively. VP increased insignificantly ($P > 0.1$) and led to a decrease in E_{pan} at −0.1 mm yr^{-2}. The combined effects of the four climate factors resulted in a decrease in E_{pan} at −5.0 mm yr^{-2}, and the absolute and relative error compared to O_E_{pan} was 0.4 mm yr^{-2} and −7%, respectively. It is clear that the increasing T_a had a positive effect on E_{pan}, but the effect had been offset by decreasing U and R_S.

[10] From 1992 to 2007, T_a increased significantly ($P < 0.01$) with a much larger amplitude of 0.064°C yr^{-1} and the increases in T_a should have led to an increase in E_{pan} at 7.4 mm yr^{-2}. Meanwhile, U decreased with a smaller rate of −0.007 m s^{-1} yr^{-1} ($P < 0.05$), while VP decreased insignificantly and R_S increased insignificantly ($P > 0.1$). Decrease in U should have led to a decrease in E_{pan} at −2.0 mm yr^{-2}, while increase in R_S and decrease in VP should have led to an increase in E_{pan} at 0.2 and 1.7 mm yr^{-2} respectively. The combined effects of the four climate factors resulted in an increase in E_{pan} at 7.2 mm yr^{-2}, and the absolute and relative error compared to O_E_{pan} was −0.7 mm yr^{-2} and −9%, respectively. Decreasing U could not offset the effects of increasing T_a, and E_{pan} increased since 1992.

[11] For the eight climatic regions, from 1960 to the early 1990s, decreases in U dominated the decreases in E_{pan} in the northern and central parts of China such as Northwest, North Center, Northeast, North China Plain and Tibet Plateau, while decreases in R_S dominated the decreases in E_{pan} in the southern part of China such as Southeast, East, and Southwest. From the early 1990s to 2007, increases in T_a dominated the increases in E_{pan} in all the climatic regions except Northeast, where significant decrease ($P < 0.05$) in VP dominated the increase in E_{pan}.

4. Discussion

[12] The differentiation equation method based on the Penman-Monteith formula was used to quantify the contribution of climate variables to overall trends in E_{pan}. The errors between C_E_{pan} and O_E_{pan} could come from the

assumption of differential equations (equation (3)). The four climate factors impacted each other and they were not totally independent. However, the differential equations assumed that they were independent. In addition, the majority of errors between C_E_{pan} and O_E_{pan} were negative (Table 1), which partly because the four climate factors could not completely capture the changes in E_{pan}. Other factors such as aerosol and dust etc. could also impact the radiation and further impact the evaporation process.

[13] Serious decrease in U contributed to the decrease in E_{pan} from 1960 to the early 1990s in the northern and central parts of China. Such results were also found in the United States [*Hobbins*, 2004] and Australia [e.g., *Rayner*, 2007; *Roderick et al.*, 2007; *McVicar et al.*, 2008; *Donohue et al.*, 2010]. Meanwhile, U decreased at -0.012 m s^{-1} yr^{-1} for China average, which is almost identical to the trends reported in Australia [*Roderick et al.*, 2007] and many Northern Hemisphere countries [*Vautard et al.*, 2010]. The dominant factor in the E_{pan} trend had regional differences, despite U being the dominant factor for nationwide average. The amplitude of decrease in R_S in the southern part of China was larger than that in the northern and central part of China, and decrease in R_S played a more important role in the decrease in E_{pan} in southern part of China. *Xu et al.* [2006] also found that decrease in E_{pan} in Yangtze River catchment (located in the southern part of China) was mainly caused by the decrease in R_S and to a lesser extent by the decrease in U.

[14] Globally, the observed increase in T_a rose dramatically since the 1990s and the warmest 11 years from 1850 all occurred between 1995 and 2007 [*World Meteorological Organization*, 2007]. For China average, the annual increase in T_a was 0.064°C yr^{-1} from 1992 to 2007, about six times higher than that of 0.011°C yr^{-1} from 1960 to 1991. Effect of sharply increasing T_a dominated the changes in E_{pan} and led to the reversal of E_{pan} trends. In addition, the impacts of increasing T_a led to increase in E_{pan} can be partitioned in to two components, aerodynamic component and radiative component (see Text S1 of the auxiliary material). Increasing T_a led to 5.6 mm yr^{-2} increase in aerodynamic component and 1.8 mm yr^{-2} increase in radiative component from 1992 to 2007. Increasing T_a were impacting aerodynamic component more than radiative component of E_{pan}.

5. Conclusion

[15] The recent changes in E_{pan} dynamics in China were investigated based on measurements at 518 stations. Annual E_{pan} for the China average decreased significantly ($P < 0.001$) at -5.4 mm yr^{-2} from 1960 to 1991 and increased significantly ($P < 0.001$) at 7.9 mm yr^{-2} from 1992 to 2007. The increasing T_a had a positive effect on E_{pan}, but the effect had been offset by decreasing U and R_S from 1960 to 1991. Since 1992, serious increases in T_a dominated the changes in E_{pan} and led to the increase in E_{pan}. Regionally, change points of annual E_{pan} series were observed in the early 1990s for all the eight climatic regions. Decreasing U dominated the decreases in E_{pan} in the northern and central parts of China, while decreasing R_S dominated the decreases in E_{pan} in the southern part of China from 1960 to the early 1990s. Increasing T_a dominated the increases in E_{pan} in all the climatic regions except Northeast, where decrease in VP dominated the increase in E_{pan} from the early 1990s to 2007.

[16] **Acknowledgments.** This research was supported by the National Basic Research Program of China (2010CB428406) and Natural Science Foundation of China (40971023). We thank the two anonymous reviewers for their constructive comments.

[17] The Editor thanks two anonymous reviewers for their assistance evaluating this paper.

References

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith (1998), Crop evapotranspiration: Guidelines for computing crop requirements, *Irrig. Drain. Pap. 56*, Food and Agric. Organ. of the U. N., Rome.

Brutsaert, W., and M. B. Parlange (1998), Hydrologic cycle explains the evaporation paradox, *Nature*, *396*, 30, doi:10.1038/23845.

Donohue, R. J., T. R. McVicar, and M. L. Roderick (2010), Assessing the ability of potential evaporation formulations to capture the dynamics in evaporative demand within a changing climate, *J. Hydrol.*, *386*, 186–197, doi:10.1016/j.jhydrol.2010.03.020.

Hobbins, M. T. (2004), Regional evapotranspiration and pan evaporation: Complementary interactions and long-term trends across the conterminous United States, Ph.D. thesis, Colo. State Univ., Fort Collins.

Kendall, M. G. (1975), *Rank Correlation Measures*, Charles Griffin, London.

Liu, B. H., M. Xu, M. Henderson, and W. G. Gong (2004), A spatial analysis of pan evaporation trends in China, 1955–2000, *J. Geophys. Res.*, *109*, D15102, doi:10.1029/2004JD004511.

Liu, M., Y. Shen, Y. Zeng, and C. Liu (2010), Trend in pan evaporation and its attribution over the past 50 years in China, *J. Geogr. Sci.*, *20*(4), 557–568, doi:10.1007/s11442-010-0557-3.

Mann, H. B. (1945), Non-parametric tests against trend, *Econometrica*, *13*, 245–259, doi:10.2307/1907187.

McVicar, T. R., et al. (2007), Spatially distributing monthly reference evapotranspiration and pan evaporation considering topographic influences, *J. Hydrol.*, *338*, 196–220, doi:10.1016/j.jhydrol.2007.02.018.

McVicar, T. R., T. G. Van Niel, L. T. Li, M. L. Roderick, D. P. Rayner, L. Ricciardulli, and R. J. Donohue (2008), Wind speed climatology and trends for Australia, 1975–2006: Capturing the stilling phenomenon and comparison with near-surface reanalysis output, *Geophys. Res. Lett.*, *35*, L20403, doi:10.1029/2008GL035627.

Peterson, T. C., V. S. Golubev, and P. Y. Groisman (1995), Evaporation losing its strength, *Nature*, *377*, 687–688, doi:10.1038/377687b0.

Pettitt, A. N. (1979), A non-parametric approach to the change point problem, *Appl. Stat.*, *28*, 126–135, doi:10.2307/2346729.

Rayner, D. (2007), Wind run changes are the dominant factor affecting pan evaporation trends in Australia, *J. Clim.*, *20*(14), 3379–3394, doi:10.1175/JCLI4181.1.

Roderick, M. L., and G. D. Farquhar (2002), The cause of decreased pan evaporation over the past 50 years, *Science*, *298*, 1410–1411.

Roderick, M. L., L. D. Rotstayn, G. D. Farquhar, and M. T. Hobbins (2007), On the attribution of changing pan evaporation, *Geophys. Res. Lett.*, *34*, L17403, doi:10.1029/2007GL031166.

Roderick, M. L., M. T. Hobbins, and G. D. Farquhar (2009a), Pan evaporation trends and the terrestrial water balance. I. Principles and observations, *Geogr. Compass*, *3*(2), 746–760, doi:10.1111/j.1749-8198.2008.00213.x.

Roderick, M. L., M. T. Hobbins, and G. D. Farquhar (2009b), Pan evaporation trends and the terrestrial water balance. II. Energy balance and interpretation, *Geogr. Compass*, *3*(2), 761–780, doi:10.1111/j.1749-8198.2008.00214.x.

Vautard, R., J. Cattiaux, P. Yiou, J.-N. Thépaut, and P. Ciais (2010), Northern Hemisphere atmospheric stilling partly attributed to an increase in surface roughness, *Nat. Geosci.*, *3*, 756–761, doi:10.1038/ngeo979.

World Meteorological Organization (2007), Top 11 warmest years on record have all been in last 13 years [online], *Sci. Daily*, 13 Dec. [Available at http://www.sciencedaily.com/releases/2007/12/071213101419.htm.]

Xu, C. Y., L. B. Gong, T. Jiang, D. L. Chen, and V. P. Sigh (2006), Analysis of spatial distribution and temporal trend of reference evapotranspiration and pan evaporation in Changjing (Yangtze River) catchment, *J. Hydrol.*, *327*, 81–93, doi:10.1016/j.jhydrol.2005.11.029.

Zheng, H., X. Liu, C. Liu, X. Dai, and R. Zhu (2009), Assessing the contribution to pan evaporation trends in Haihe River Basin, China, *J. Geophys. Res.*, *114*, D24105, doi:10.1029/2009JD012203.

C. Liu, X. Liu, and D. Zhang, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China.

Y. Luo and M. Zhang, Department of Land, Air and Water Resources, University of California, One Shield Ave., Davis, CA 95616, USA. (mhzhang@ucdavis.edu)