耶鲁大学-南京信息工程大学大气环境中心
Yale-NUIST Center on Atmospheric Environment

The experimental investigation of kinetic fractionation of open-water evaporation over large and small water bodies

Wei Xiao[1], Xuhui Lee[1,2], Yongbo Hu[1], Shoudong Liu[1], Wei Wang[1], Xuefa Wen[3], Chengyu Xie[1]

1 Yale-NUIST Center on Atmospheric Environment, Nanjing University of Information Science and Technology, Nanjing, Jiangsu, China

2 School of Forestry and Environmental Studies, Yale University, New Haven, Connecticut, USA

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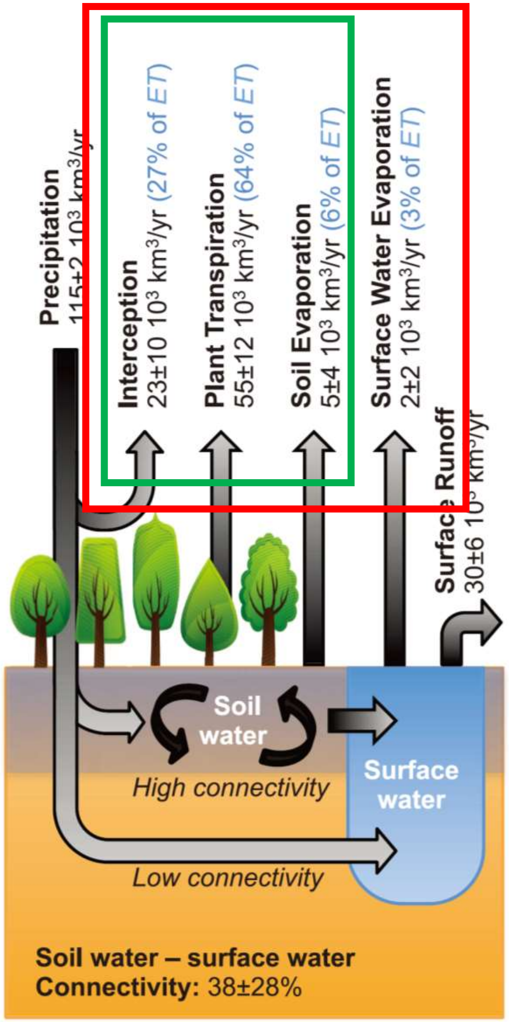
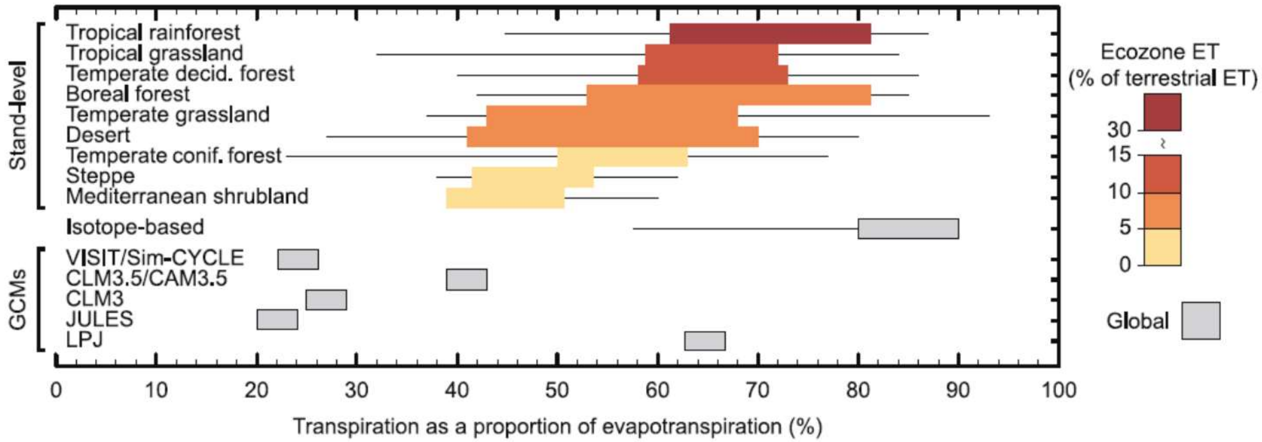
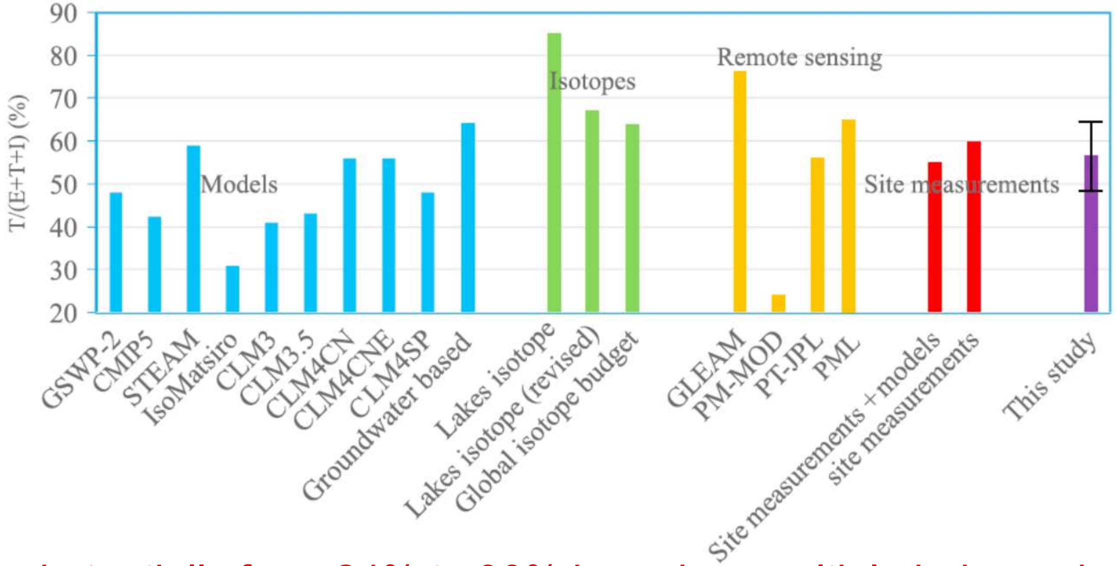
Transpiration as a proportion of evapotranspiration







Globally, *T/ET* reported previously varies substantially from 24% to 90% based on multiple independent sources.

(Schlesinger & Jasechko 2014; Wei et al. 2017)

Isotopic mass balance model & Craig-Gordon model

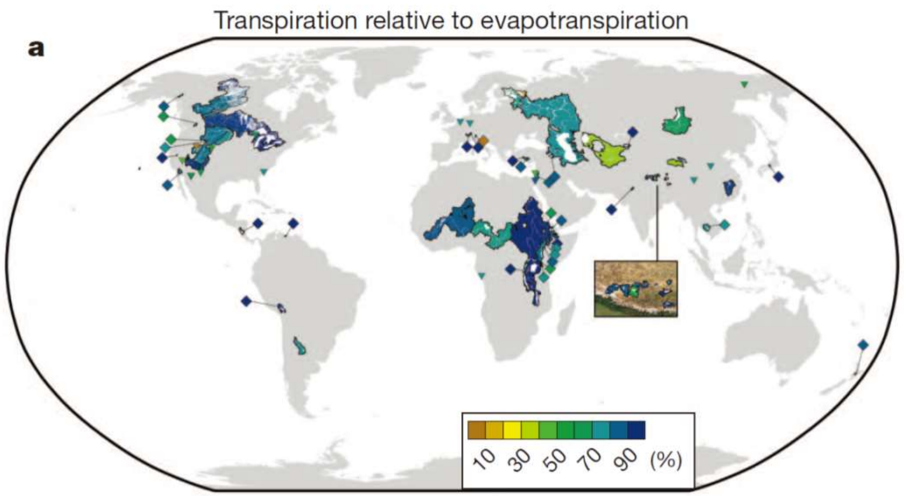
The tracer applications are based on the premise that the $^{18}O/^{16}O$ or D/H ratio of open-water evaporation (δ_E) can be calculated from environmental conditions.

Isotopic mass balance model

$$I = xP + E + T + Q$$

$$\delta_I I = \delta_P xP + \delta_E E + \delta_T T + \delta_Q Q$$

$$T = \frac{I(\delta_I - \delta_E) - Q(\delta_Q - \delta_E) - xP(\delta_P - \delta_E)}{\delta_T - \delta_E}$$



The Craig-Gordon model

$$\delta_E = \frac{\alpha_{eq}^{-1}\delta_L - h\delta_V - \varepsilon_{eq} - (1-h)\varepsilon_k}{1 - h + 10^{-3}(1-h)\varepsilon_k}$$

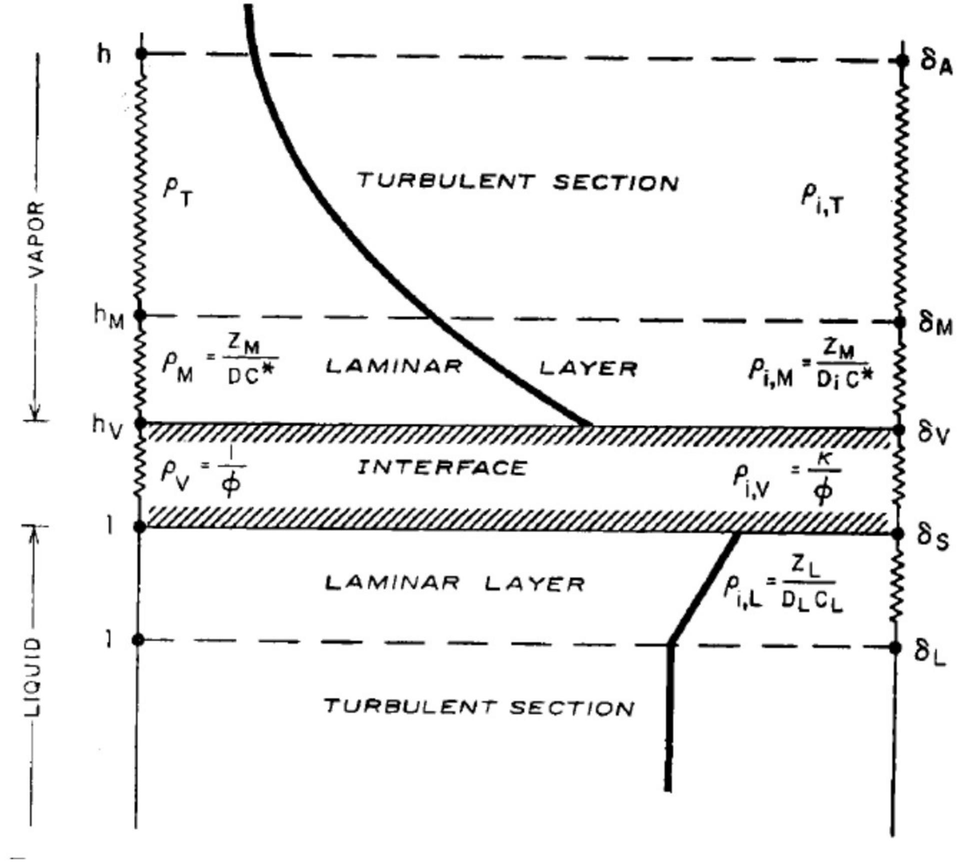
Kinetic fractionation factor

$$\varepsilon_K = n\left(1 - \frac{D_i}{D}\right) \times 10^3$$

(Craig & Gordon 1965; Jasechko et al. 2013)

Kinetic fractionation factor

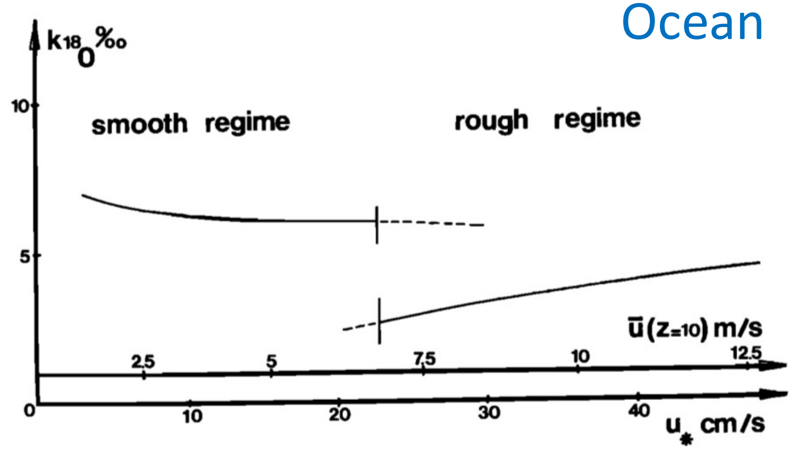
The kinetic effect, an important part of the overall evaporative fractionation against $H_2^{18}O$ and HDO, has been a subject of debate for more than half a century.



$$\varepsilon_K = n\left(1 - \frac{D_i}{D}\right) \times 10^3$$

Lake	For $H_2^{18}O$	$\varepsilon_k = 14.2‰$
$n = 0.5$	For HDO	$\varepsilon_k = 12.5‰$

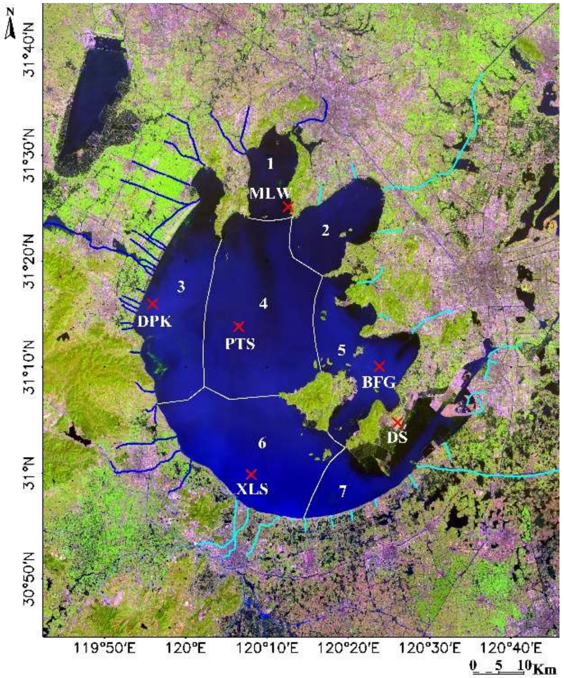
Ocean



(Craig & Gordon, 1965; Gonfiantini 1986; Merlivat & Jouzel, 1979)

Objectives

- We report the results of an experimental determination of $\delta^{18}O_E$ of open-water evaporation.
- We aim to determine which of the two kinetic factors (LK versus OS) is more appropriate for describing the isotopic processes over large lake, fish pond and evaporation pans.
- We also discuss the implication of the kinetic effect for the determination of lake evaporation using the isotope mass balance principle.



Lake Taihu
(area 2400 km²)

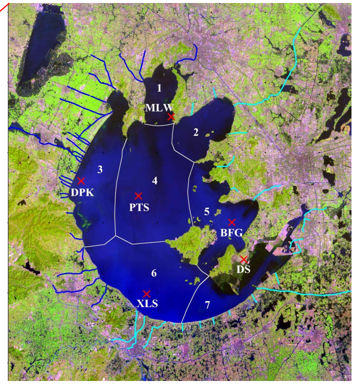
Fish pond
(area 6912 m²)

Big evaporation
pan (0.28 m²)

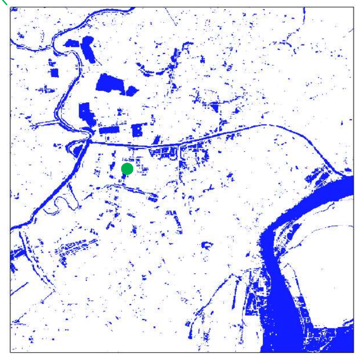
Small evaporation
pan (0.03 m²)

Experimental sites

Lake Taihu



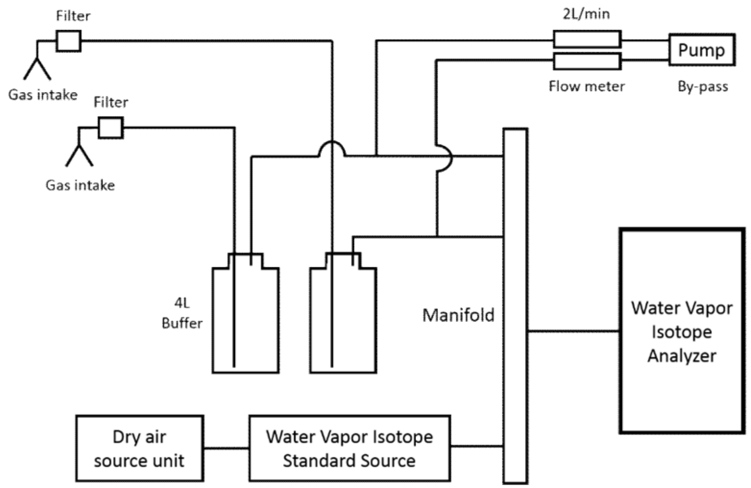
Fish ponds



In-situ measurement of isotopes over Lake Taihu

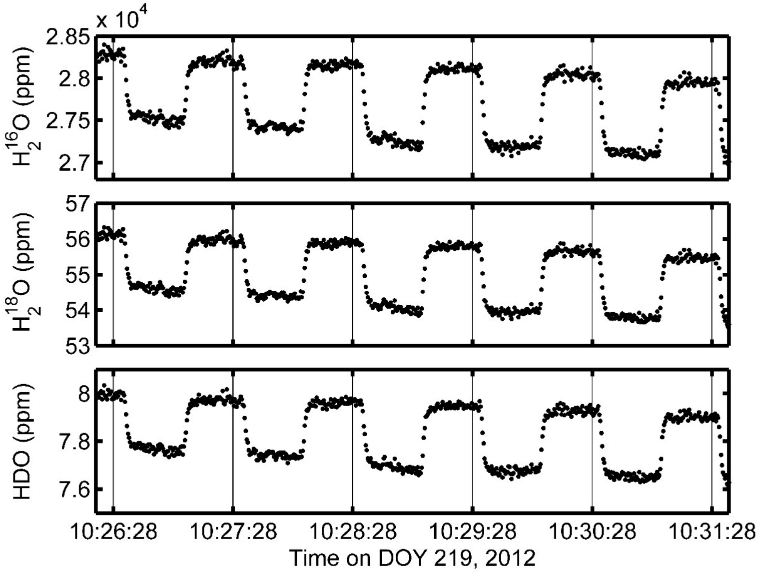
The gradient-diffusion method

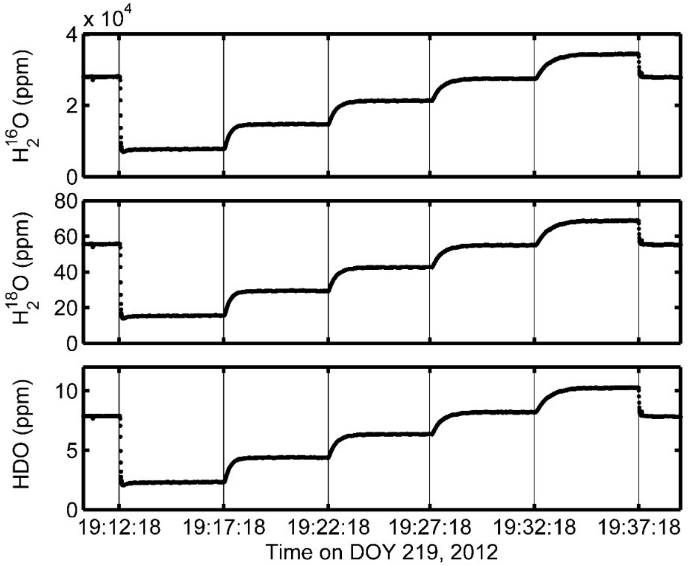
$$R_E = R_s \cdot \frac{x_{s,2} - x_{s,1}}{x'_{s,2} - x'_{s,1}} \cdot \frac{x'_{a,2} - x'_{a,1}}{x_{a,2} - x_{a,1}}$$

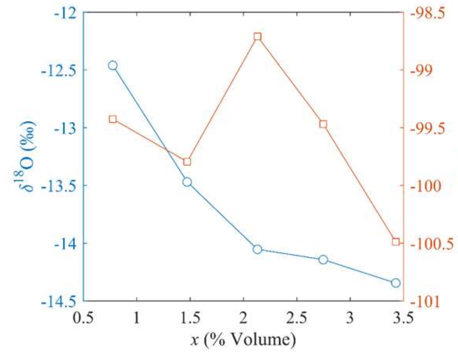


(Lee et al. 2007; Xiao et al. 2017)

Step changes in the H_2O, $H_2{}^{18}O$ and HDO mixing ratios in response to valve switching and during a calibration cycle



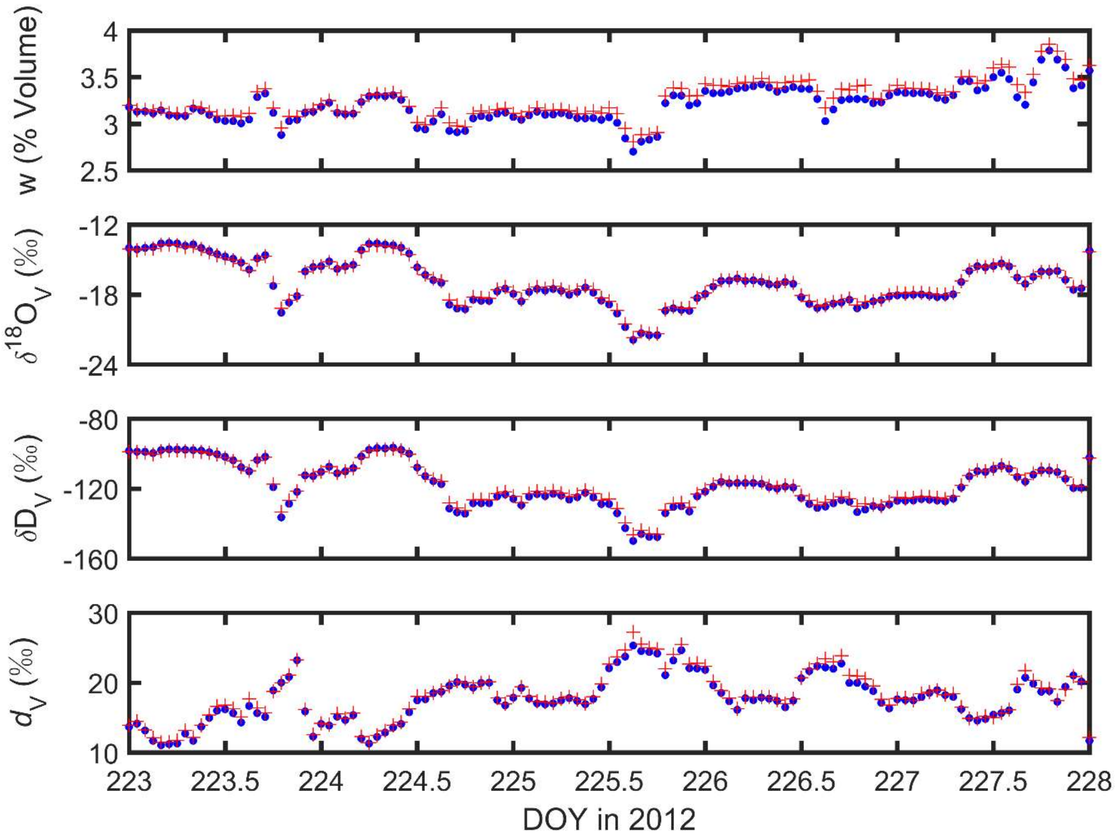




When measuring the ambient air, the manifold switched between the two intakes every 30 s. The measurement approached steady state in less than 10 s after each switching.

To eliminate the effect of non-linearity and signal drift, we calibrated the analyzer every 3 h against 5 water vapor standards of identical isotopic compositions that bracketed the ambient humidity.

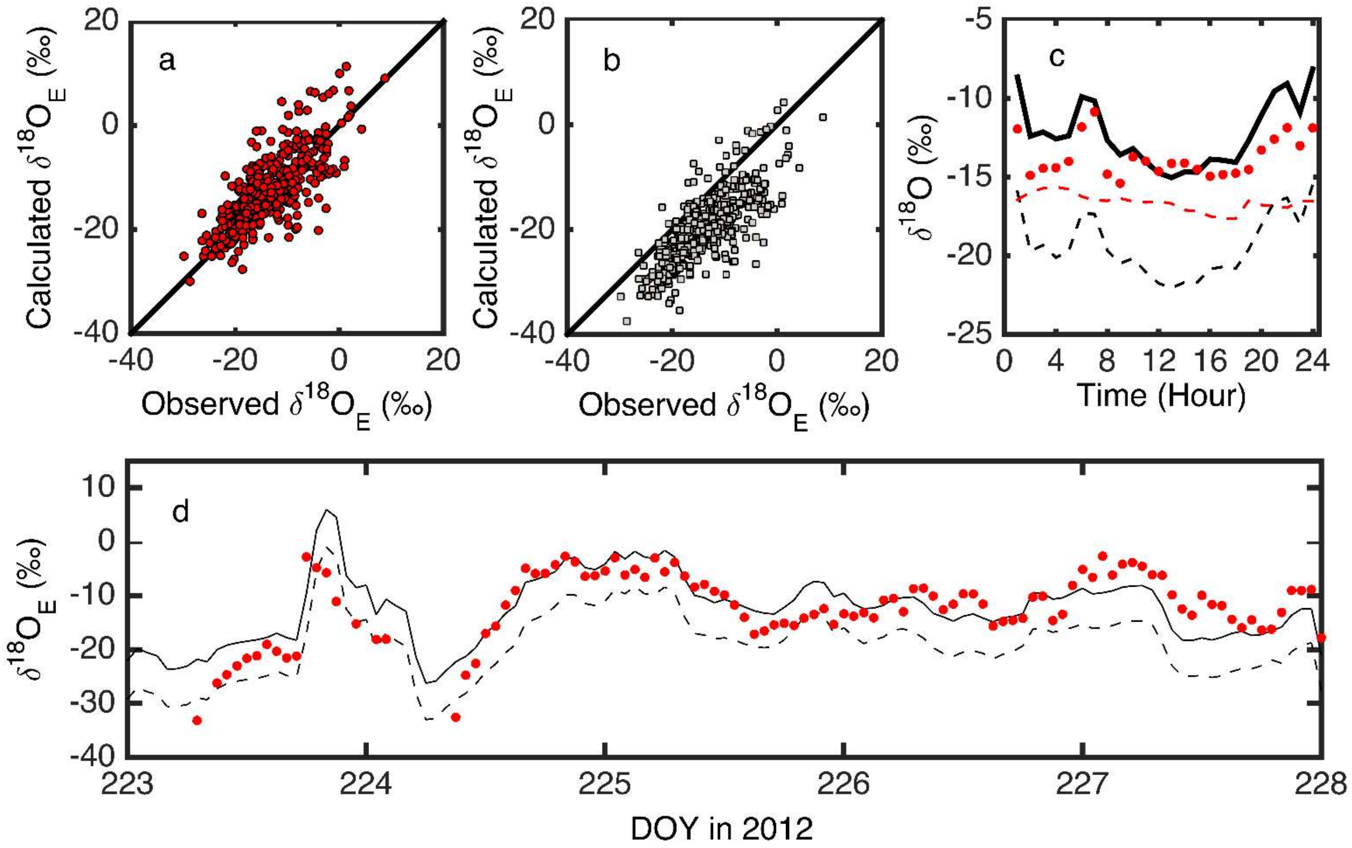
Time series of the water vapor mixing ratio, δD_V, $\delta^{18}O_V$ and d_V



(blue dots, at 3.5 m height; red crosses, at 1.1 m height)

Evidence for a weak kinetic effect

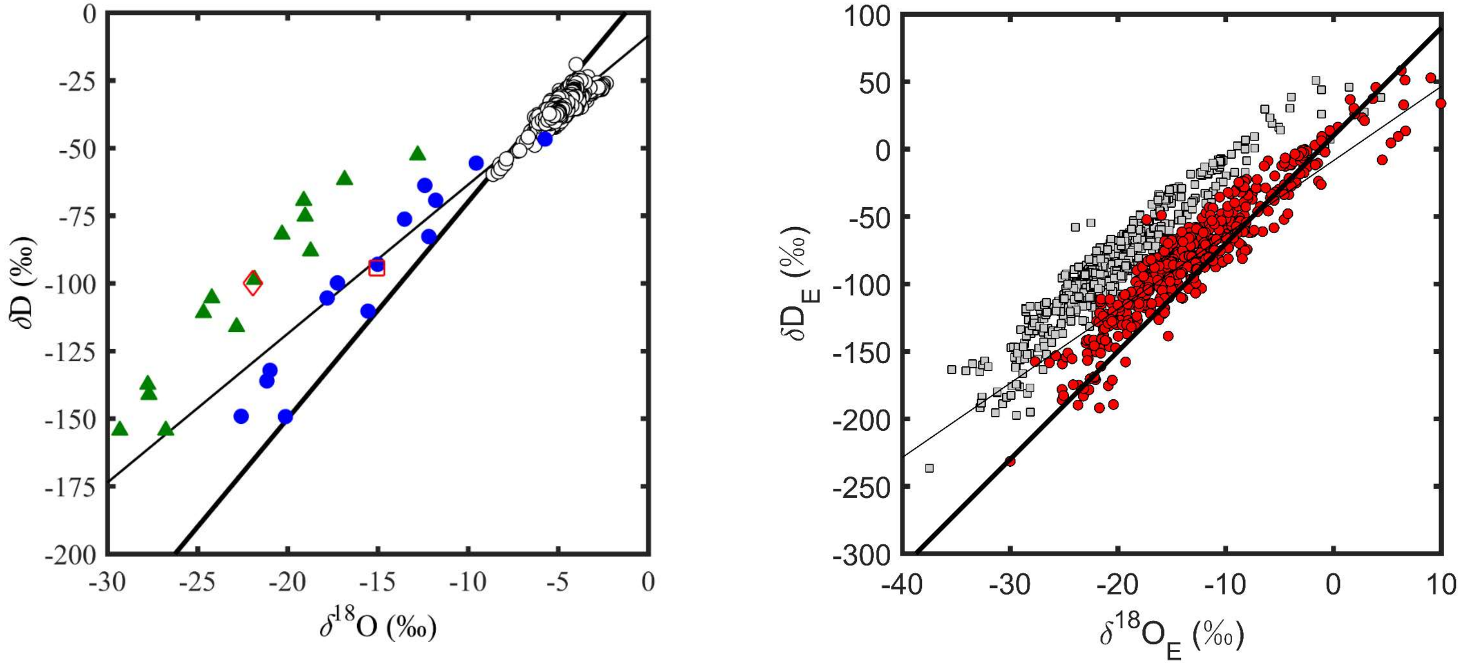
$H_2{}^{18}O$ isotopic composition of evaporation at Lake Taihu under open fetch conditions.



Our results show a much weaker kinetic effect than suggested by the kinetic factor ε_k adopted in some previous studies of lake hydrology (14.2 ‰).

Evidence for a weak kinetic effect

Comparison of the Craig-Gordon model calculation with the local evaporation line.
Mass balance requires that the evaporation delta values be on the LEL defined by the lake water delta values.

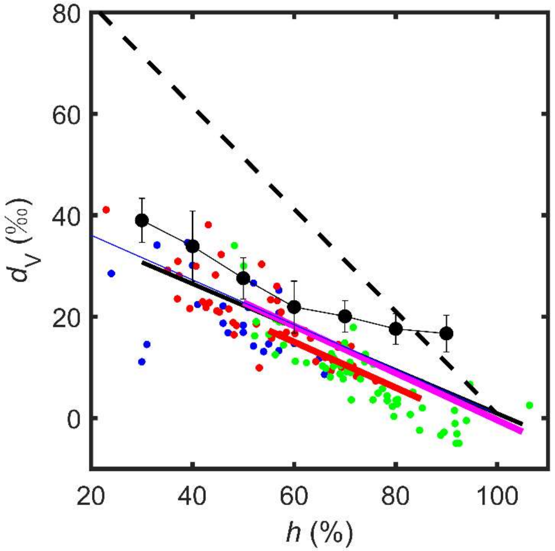


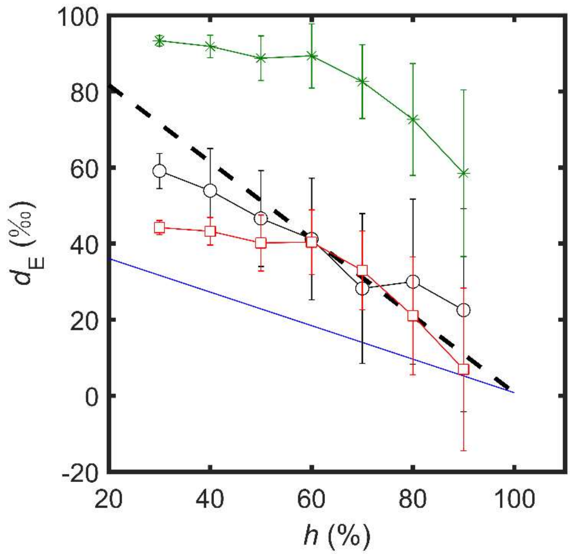
Evidence for a weak kinetic effect is also seen in the HDO – $H_2{}^{18}O$ relationship.

Evidence for a weak kinetic effect

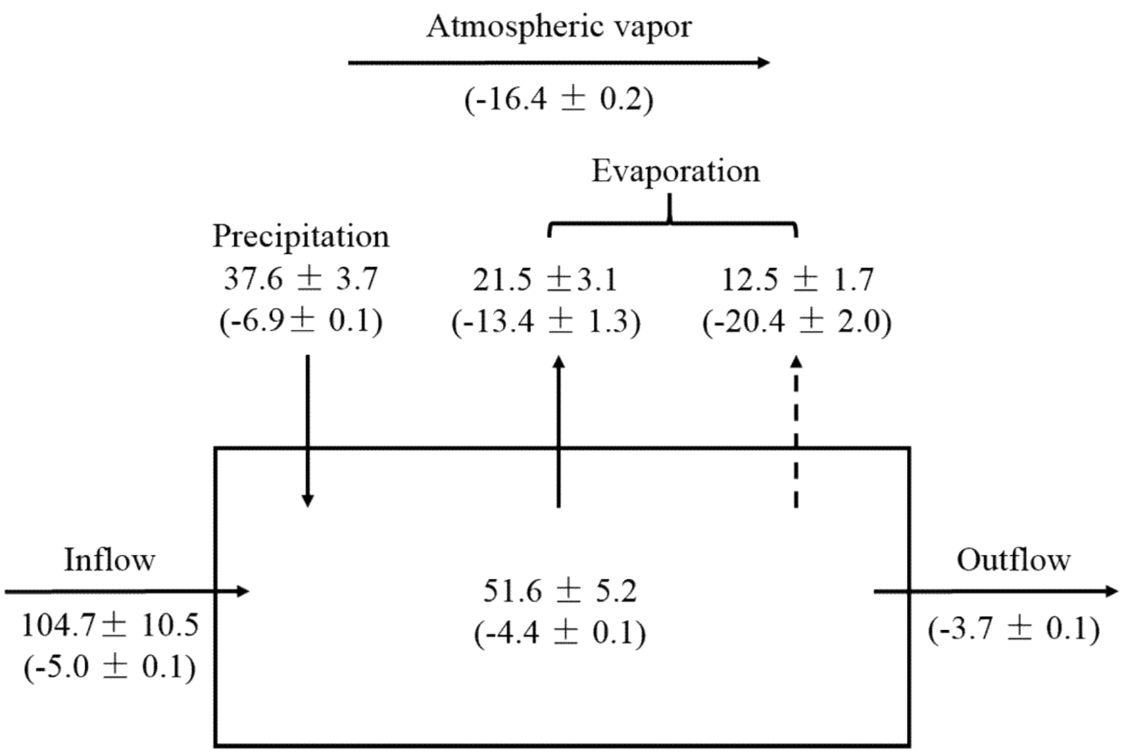
Deuterium excess of atmospheric vapor and open-water versus relative humidity referenced to water surface temperature

$$d_V = d_E = d_L + (8\varepsilon_k - \varepsilon_k^D) - (8\varepsilon_k - \varepsilon_k^D)h$$





Evidence for a weak kinetic effect



Annual evaporation

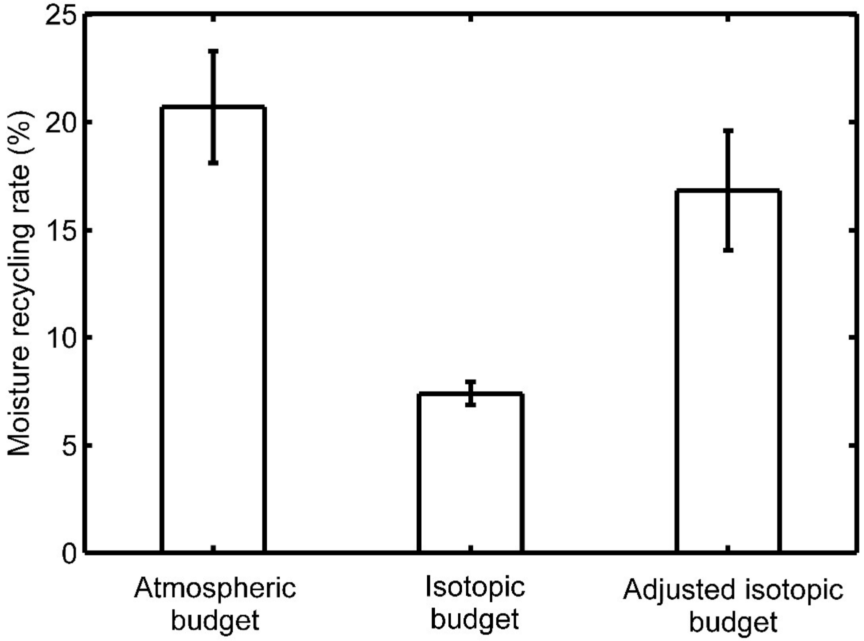
The OS e_k: **897** mm y^{-1}
The LK e_k: **520** mm y^{-1}
EC system: **863** mm y^{-1}

The annual evaporation rate of Lake Taihu is 520 mm if the LK ε_k is used in the isotopic mass balance analysis and increases by 72% to 897 mm if the OS ε_k is used.

The latter assessment is in better agreement with an independent eddy covariance observation.

Sensitivity analysis on the kinetic factor – Moisture recycling

Moisture recycling, or the fractional contribution of locally evaporated water vapor from lake surfaces to the atmospheric water vapor.



$$f_r = (d_s - d_a)/(d_E - d_a) \qquad d_E - d_a \approx \frac{d_w - d_a}{1 - h} + 107 \times \theta$$

(Bryan et al. 2015; Bowen et al. 2012; Gat et al. 1994)

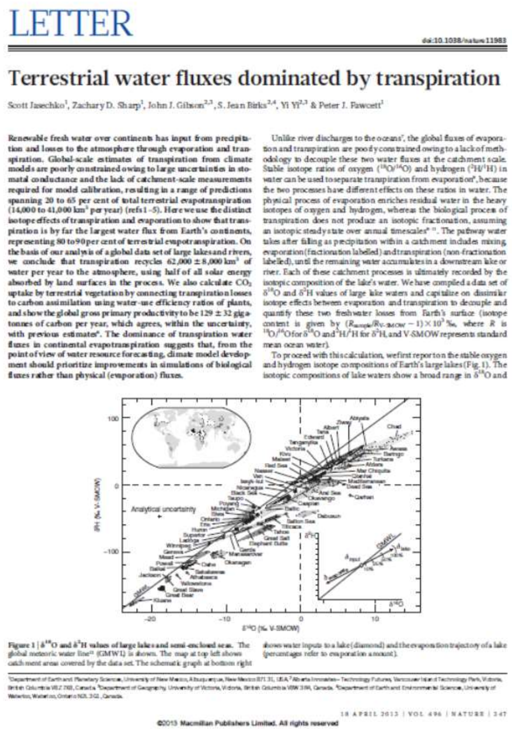
Sensitivity on kinetic factor – E/ET

An inaccurate ε_k will result in errors in calculating the fraction of lake-water and soil evaporation contribution to the land water flux to the atmosphere.

E/ET
The LK ε_k: **10-20%**.
The OS ε_k: **~30%**

In much better agreement with ecosystem-scale observations

An implicit assumption is that the kinetic factor of lake evaporation can be used to describe isotopic effects of soil evaporation.


LETTER

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Terrestrial water fluxes dominated by transpiration

Scott Jasechko[1], Zachary D. Sharp[1], John J. Gibson[2,3], S. Jean Birks[2,4], Yi Yi[2,3] & Peter J. Fawcett[1]

Renewable fresh water over continents has input from precipitation and losses to the atmosphere through evaporation and transpiration. Global-scale estimates of transpiration from climate models are poorly constrained owing to large uncertainties in stomatal conductance and the lack of catchment-scale measurements required for model calibration, resulting in a range of predictions spanning 20 to 65 per cent of total terrestrial evapotranspiration (14,000 to 41,000 km^3 per year) (refs 1–5). Here we use the distinct isotope effects of transpiration and evaporation to show that transpiration is by far the largest water flux from Earth's continents, representing 80 to 90 per cent of terrestrial evapotranspiration. On the basis of our analysis of a global data set of large lakes and rivers, we conclude that transpiration recycles 62,000 ± 8,000 km^3 of water per year to the atmosphere, using half of all solar energy absorbed by land surfaces in the process. We also calculate CO_2 uptake by terrestrial vegetation by connecting transpiration losses to carbon assimilation using water-use efficiency ratios of plants, and show the global gross primary productivity to be 129 ± 32 gigatonnes of carbon per year, which agrees, within the uncertainty, with previous estimates[6]. The dominance of transpiration water fluxes in continental evapotranspiration suggests that, from the point of view of water resource forecasting, climate model development should prioritize improvements in simulations of biological fluxes rather than physical (evaporation) fluxes.

Unlike river discharges to the oceans[7], the global fluxes of evaporation and transpiration are poorly constrained owing to a lack of methodology to decouple these two water fluxes at the catchment scale. Stable isotope ratios of oxygen ($^{18}O/^{16}O$) and hydrogen ($^2H/^1H$) in water can be used to separate transpiration from evaporation[8], because the two processes have different effects on these ratios in water. The physical process of evaporation enriches residual water in the heavy isotopes of oxygen and hydrogen, whereas the biological process of transpiration does not produce an isotopic fractionation, assuming an isotopic steady state over annual timescales[9–11]. The pathway water takes after falling as precipitation within a catchment includes mixing, evaporation (fractionation labelled) and transpiration (non-fractionation labelled), until the remaining water accumulates in a downstream lake or river. Each of these catchment processes is ultimately recorded by the isotopic composition of the lake's water. We have compiled a data set of $\delta^{18}O$ and δ^2H values of large lake waters and capitalize on dissimilar isotope effects between evaporation and transpiration to decouple and quantify these two freshwater losses from Earth's surface (isotope content is given by $(R_{sample}/R_{V\text{-}SMOW} - 1) \times 10^3$ ‰, where R is $^{18}O/^{16}O$ for $\delta^{18}O$ and $^2H/^1H$ for δ^2H, and V-SMOW represents standard mean ocean water).

To proceed with this calculation, we first report on the stable oxygen and hydrogen isotope compositions of Earth's large lakes (Fig. 1). The isotopic compositions of lake waters show a broad range in $\delta^{18}O$ and

Figure 1 | $\delta^{18}O$ and δ^2H values of large lakes and semi-enclosed seas. The global meteoric water line[12] (GMWL) is shown. The map at top left shows catchment areas covered by the data set. The schematic graph at bottom right shows water inputs to a lake (diamond) and the evaporation trajectory of a lake (percentages refer to evaporation amount).

[1]Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131, USA. [2]Alberta Innovates – Technology Futures, Vancouver Island Technology Park, Victoria, British Columbia V8Z 7X8, Canada. [3]Department of Geography, University of Victoria, Victoria, British Columbia V8W 3R4, Canada. [4]Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada.

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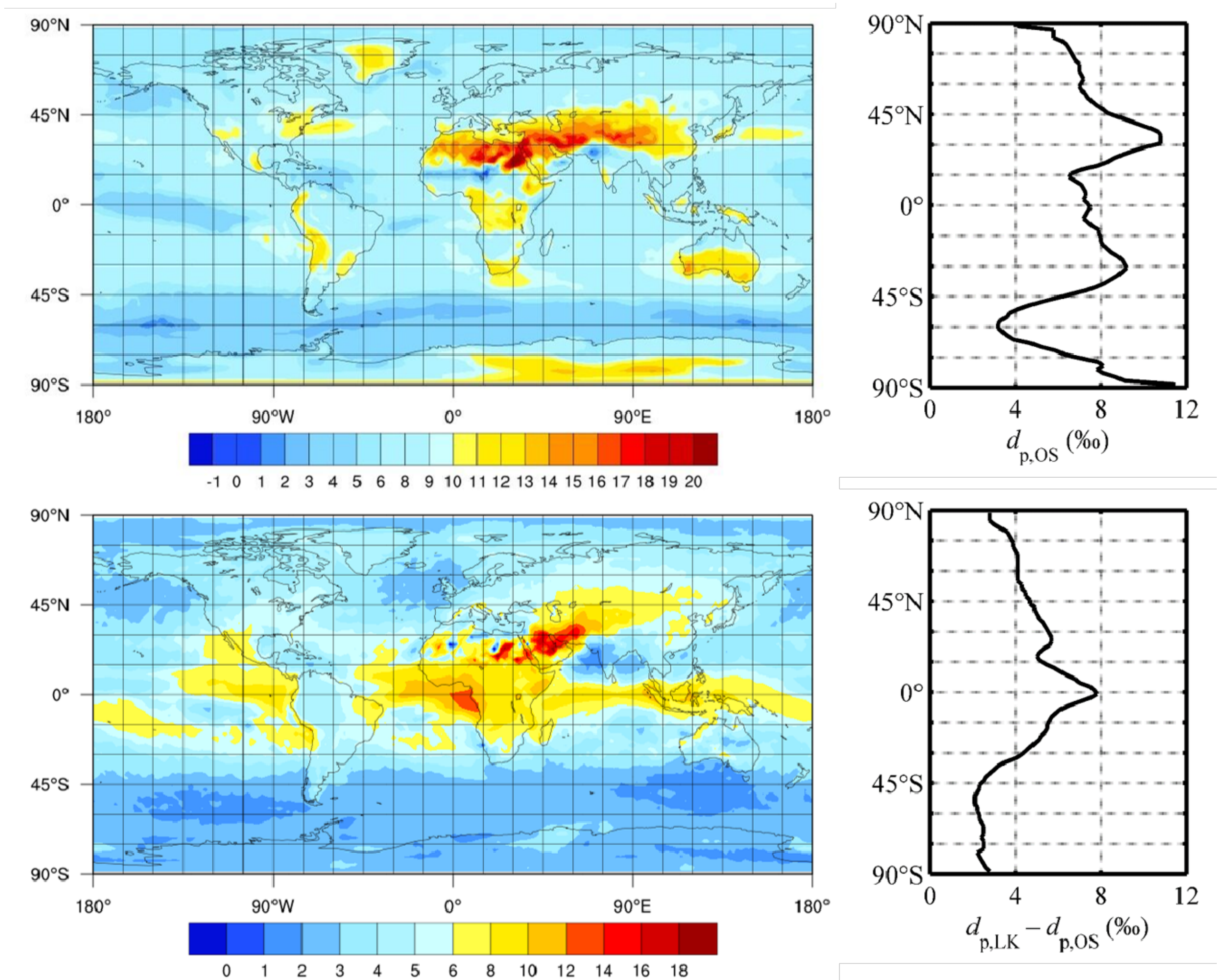
(Jasechko et al. 2013)

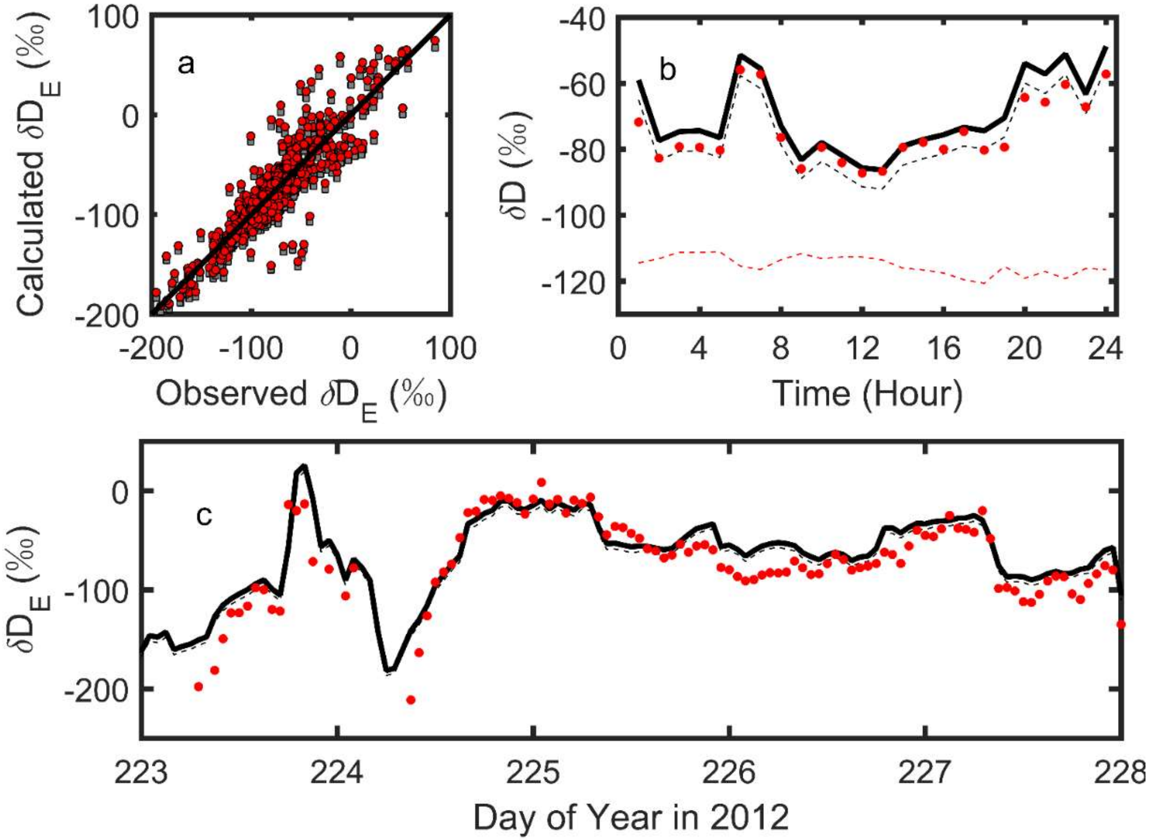
Sensitivity analysis on the kinetic factor –precipitation deuterium excess

ECHAM5-wiso



HDO as a tracer

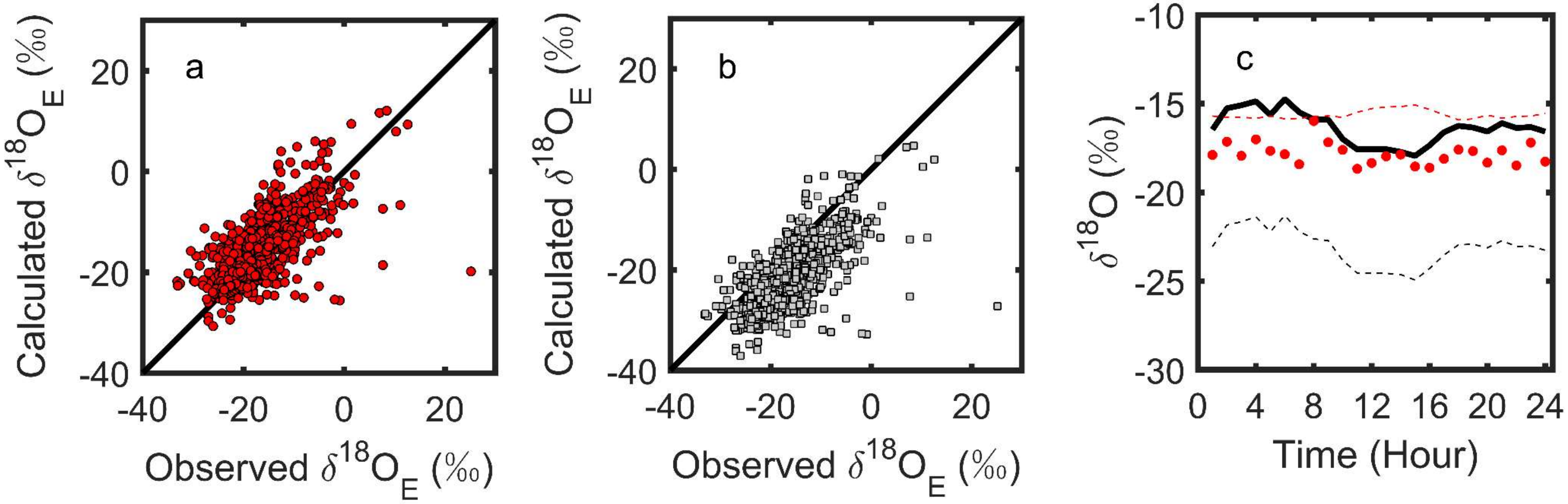
HDO isotopic composition of evaporation at Lake Taihu in open fetch conditions.



The low sensitivity to the kinetic fractionation against HDO suggested that HDO may be a better tracer than $H_2^{18}O$ isotope for the mass balance approach to study lake evaporation.

Large lakes versus small lakes

$H_2^{18}O$ isotopic composition of Lake Taihu evaporation in short fetch conditions (wind directions 315 – 135°).

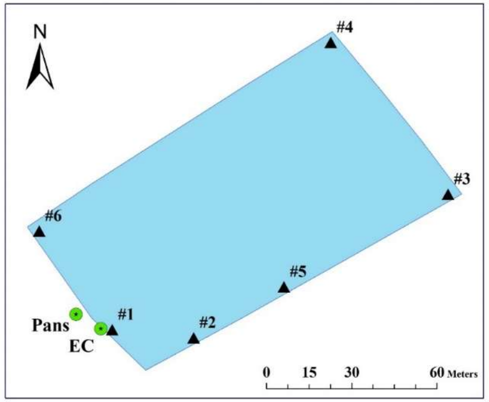


The effective ε_k was not very sensitive to fetch.

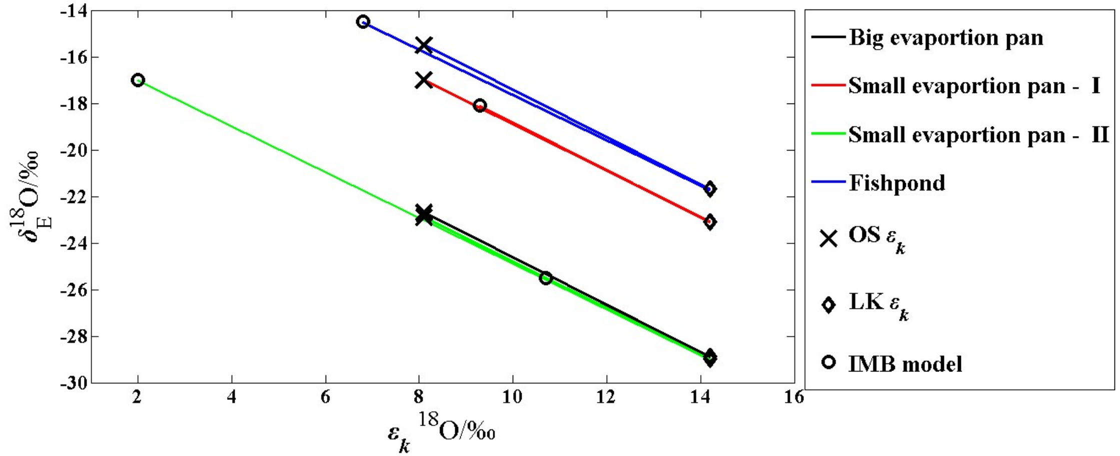
An open question is whether the results reported here for a large lake can be extended to small lakes.

Experiments on fish pond and evaporation pans

Fish pond



Evaporation pans



Preliminary results over small water bodies indicated that the LK ε_k was also biased high for fish pond and evaporation pans.

Summary

- The success of the OS ε_k at Lake Taihu implies that atmospheric turbulence plays similar roles in gaseous diffusion in the lake and the marine environment.
- A higher ε_k would lead to a greater amount of $H_2{}^{18}O$ accumulated in lakes.
- The isotopic mass balance calculations using the weak ε_k point to a much stronger role of lake evaporation in the terrestrial hydrological cycle than indicated by previous studies.
- Preliminary results over small water bodies indicated that the LK ε_k was also biased high for fish pond and evaporation pans.

Conference on Stable Isotopic Ecology

第四届全国稳定同位素生态学学术研讨会

暨中国生态学学会稳定同位素生态专业委员会2017年学术年会

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地　　点：南 京 (Nanjing)

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