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

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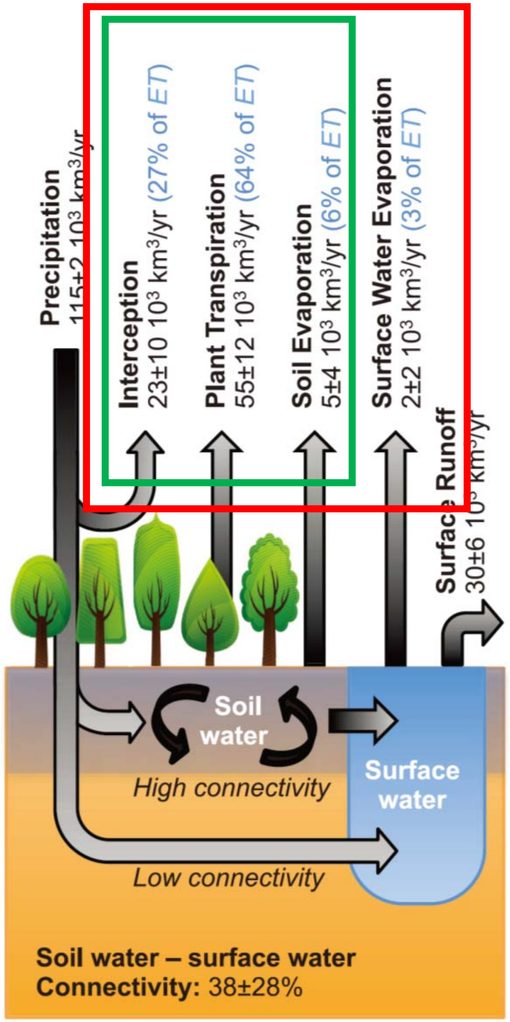
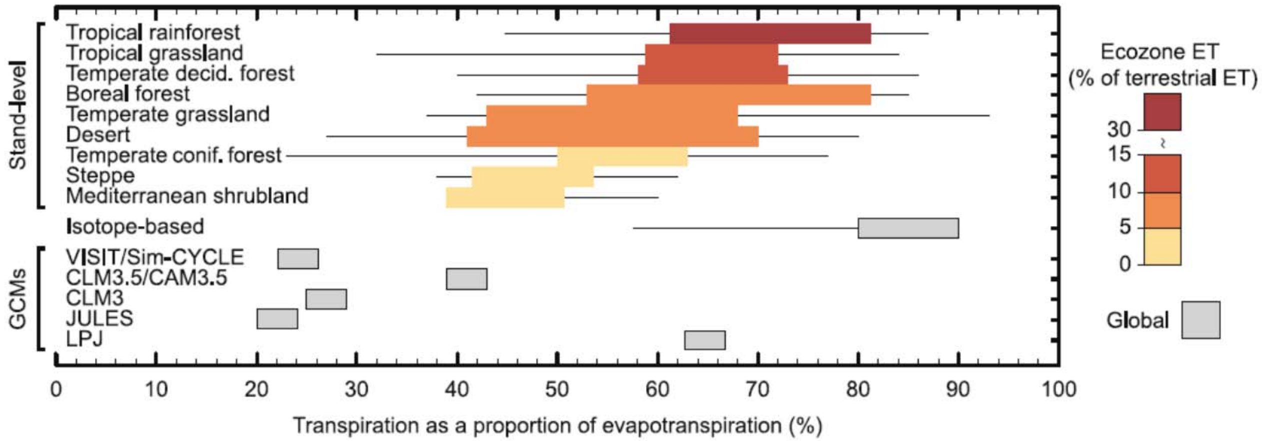
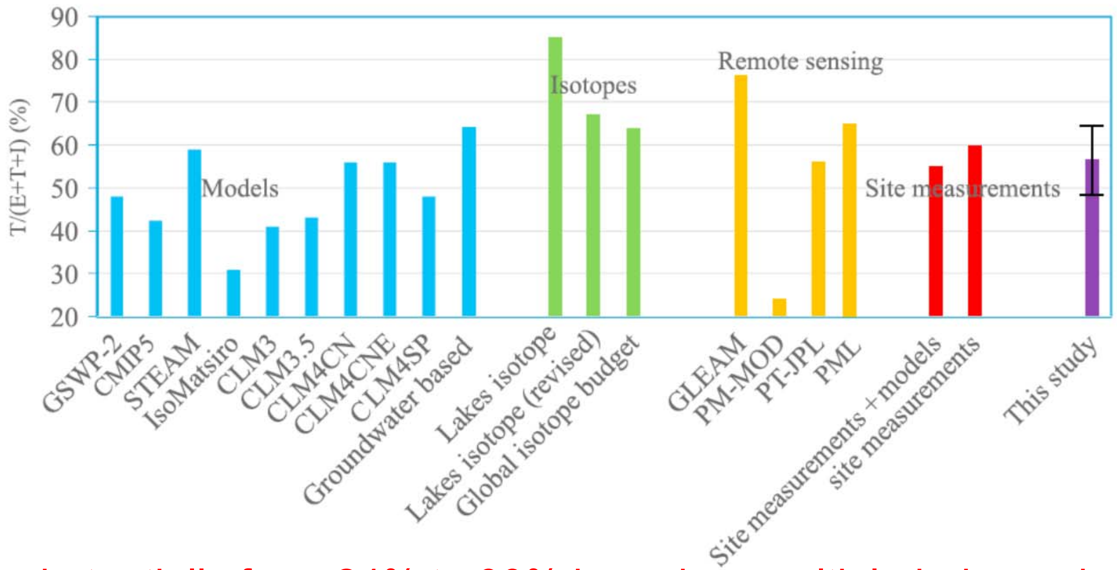
Joint conference of AsiaFlux Workshop 2017 and the 15th Anniversary Celebration of ChinaFLUX
August 17-19, 2017 Beijing, China

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

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

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

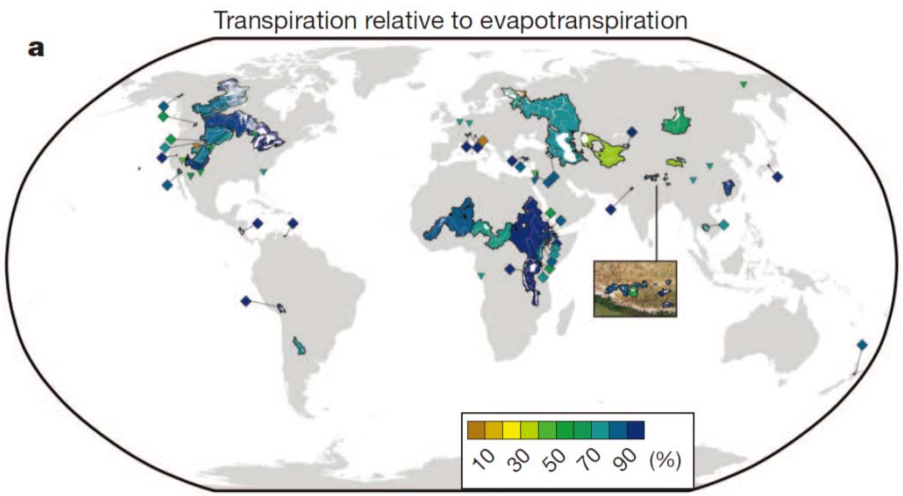
$$T = \frac{I(\delta_I - \delta_E) - Q(\delta_Q - \delta_E) - xP(\delta_P - \delta_E)}{\delta_T - \delta_E}$$

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

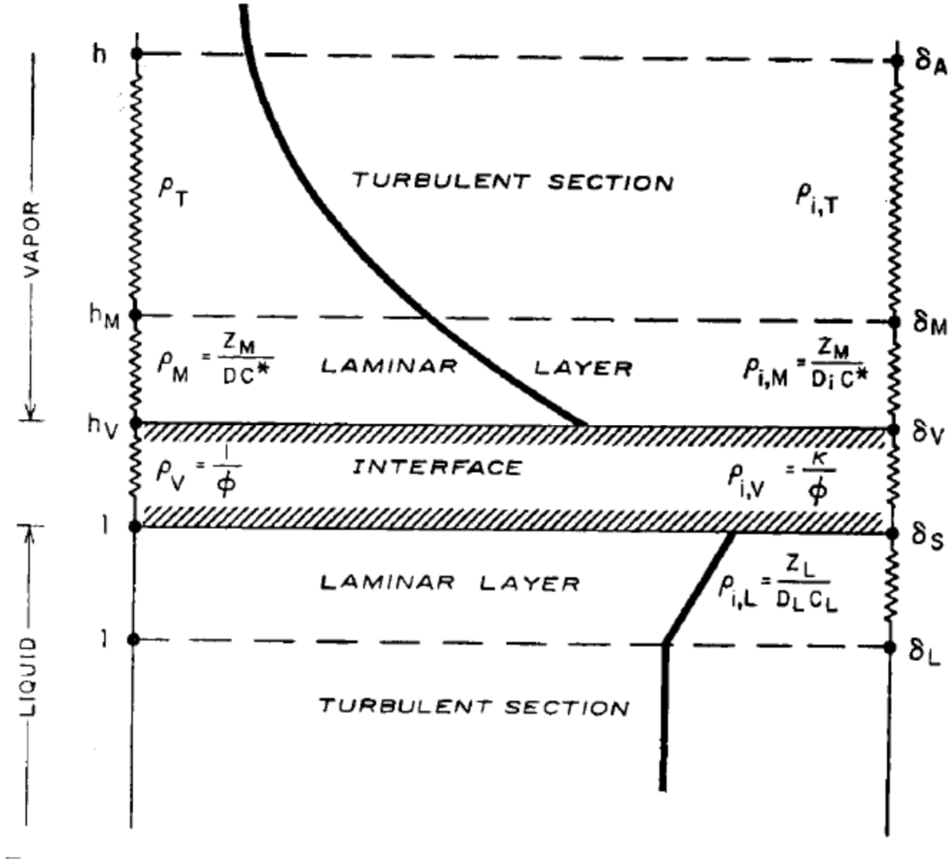
$$\varepsilon_K = n\left(1 - \frac{D_i}{D}\right) \times 10^3$$



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

Kinetic fractionation factor

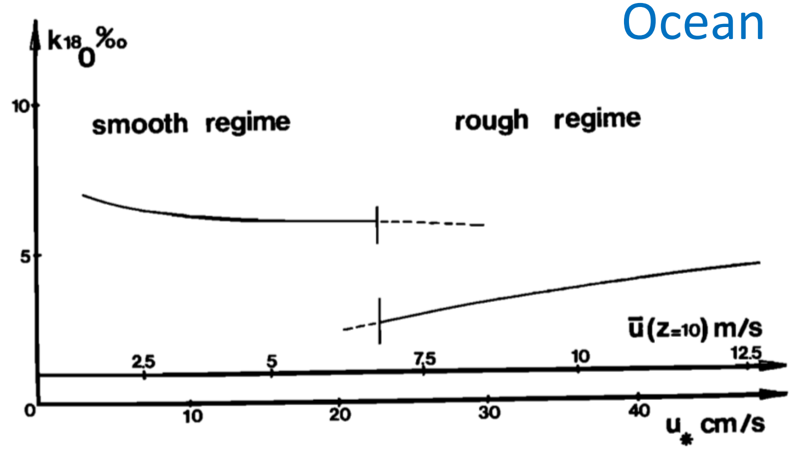
The kinetic effect, an important part of the overall evaporative fractionation against $H_2{}^{18}O$ and HDO, has been a subject of debate for more than half a century.



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

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

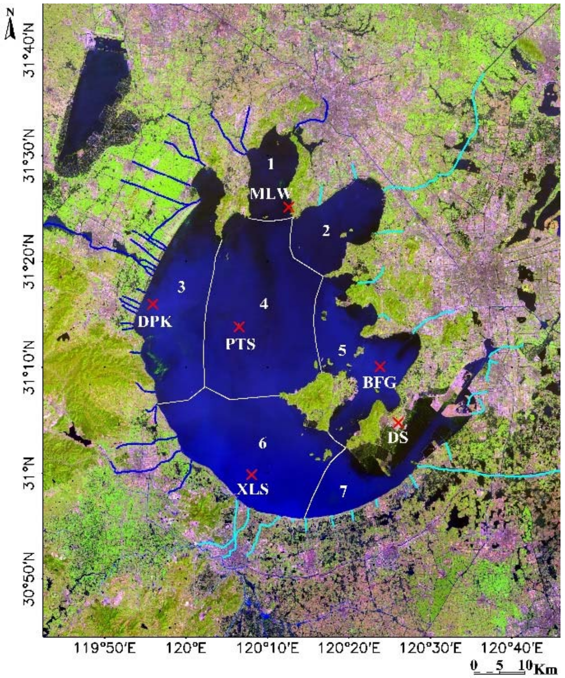
Ocean



(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 km^2)

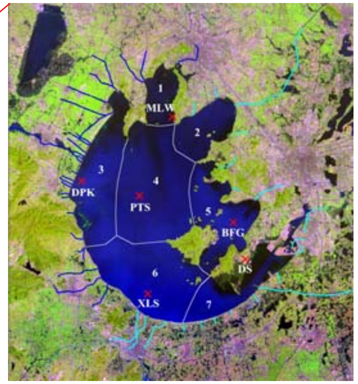
Fish pond
(area 6912 m^2)

Big evaporation pan (0.28 m^2)

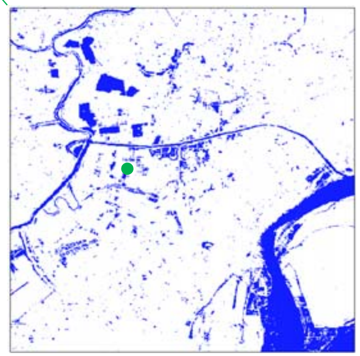
Small evaporation pan (0.03 m^2)

Experimental sites

Lake Taihu



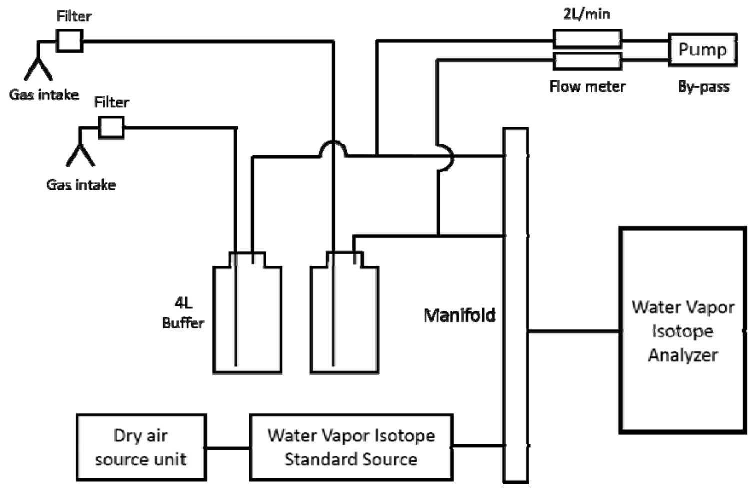
Fish ponds

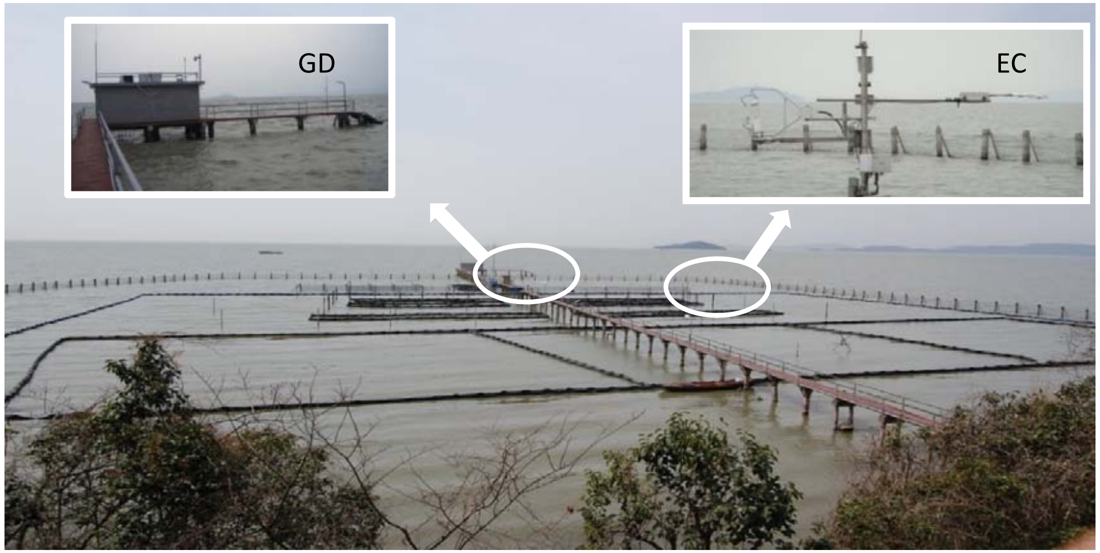


In-situ measurement of isotopes over Lake Taihu

The gradient-diffusion method

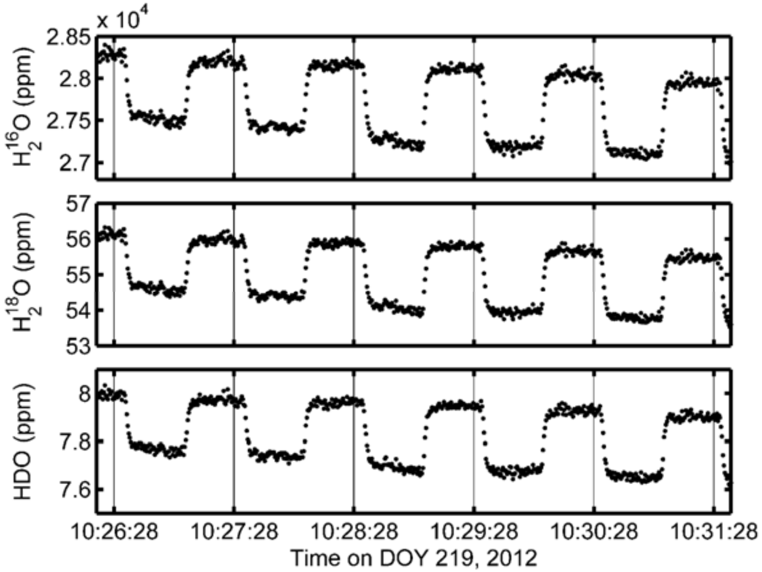
$$R_E = R_s \cdot \frac{x_{s,2} - x_{s,1}}{x'_{s,2} - x'_{s,1}} \cdot \frac{x'_{a,2} - x'_{a,1}}{x_{a,2} - x_{a,1}}$$

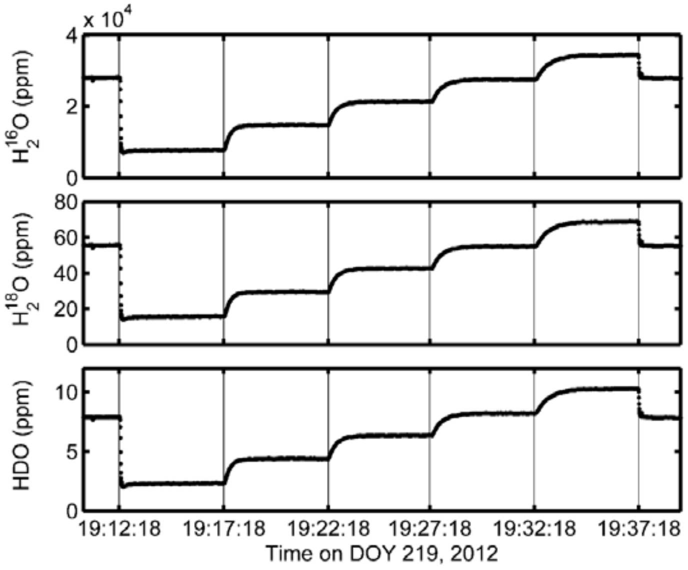


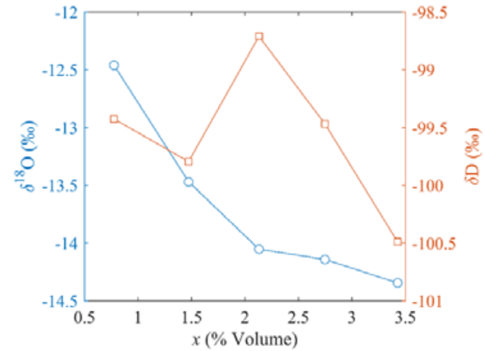


(Lee et al. 2007; Xiao et al. 2017)

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



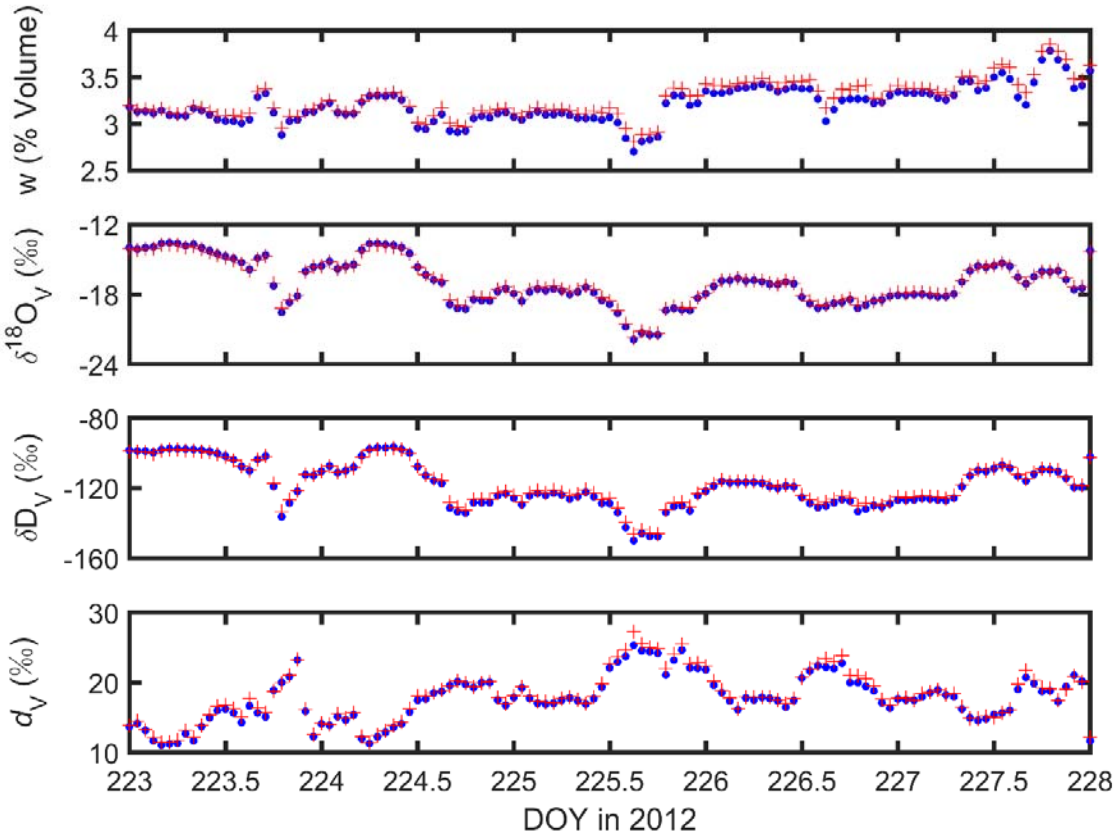




When measuring the ambient air, the manifold switched between the two intakes every 30 s. The measurement approached steady state in less than 10 s after each switching.

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.

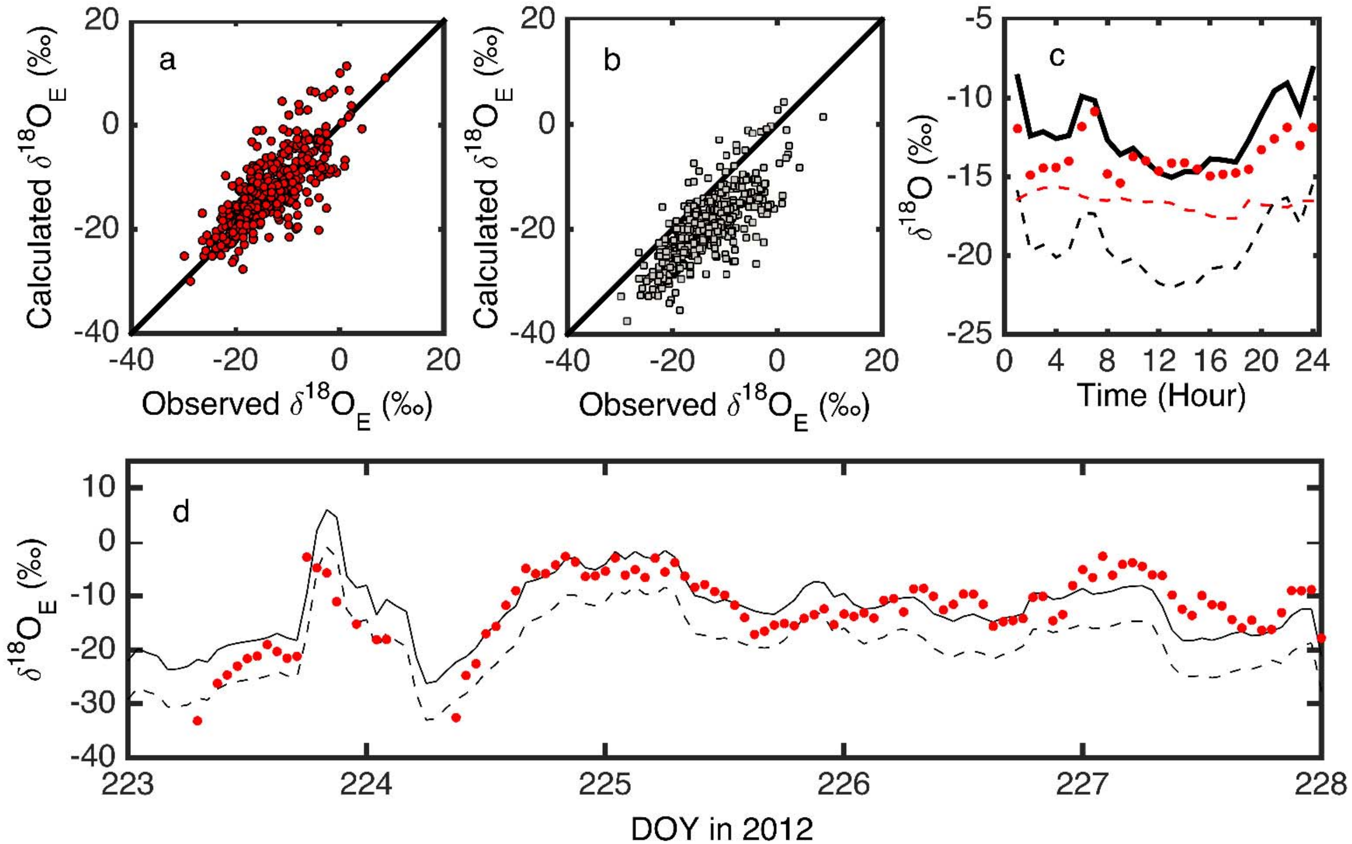
Time series of the water vapor mixing ratio, δD_V, $\delta^{18}O_V$ and d_V



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

Evidence for a weak kinetic effect

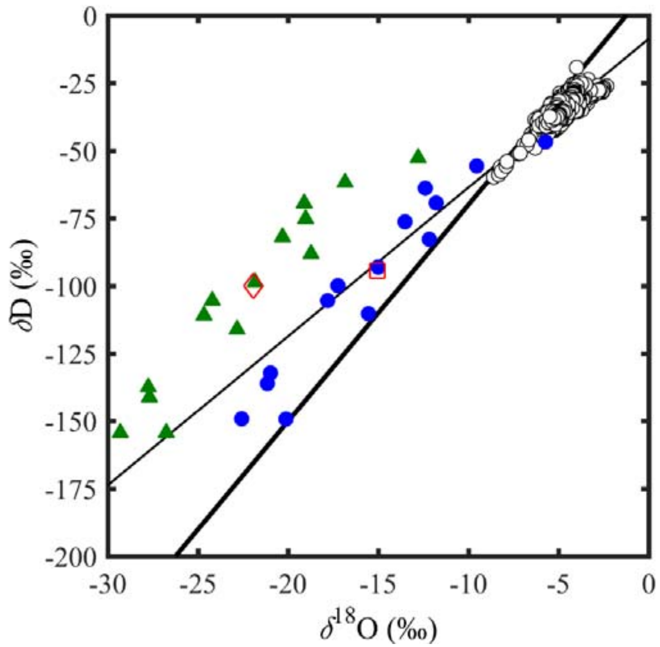
$H_2{}^{18}O$ isotopic composition of evaporation at Lake Taihu under open fetch conditions.

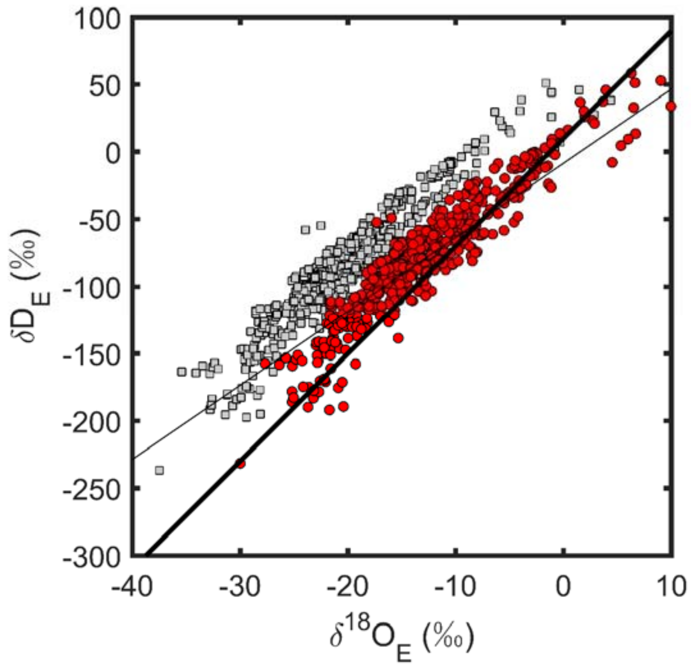


Our results show a much weaker kinetic effect than suggested by the kinetic factor ε_k adopted in some previous studies of lake hydrology (14.2 ‰).

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.



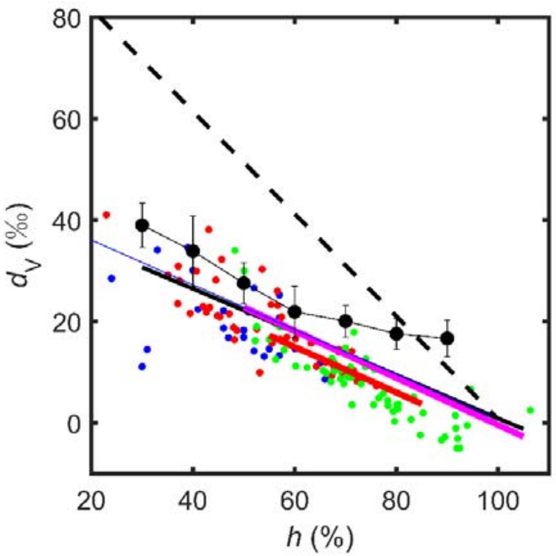


Evidence for a weak kinetic effect is also seen in the HDO – $H_2{}^{18}O$ relationship.

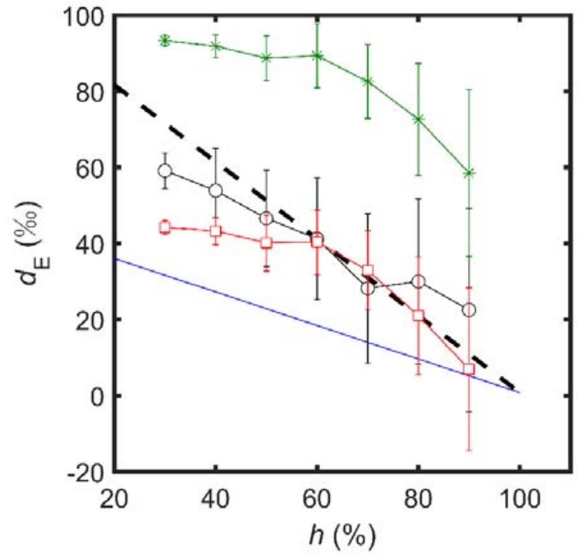
Evidence for a weak kinetic effect

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

$$d_{\mathrm{V}} = d_{\mathrm{E}} = d_{\mathrm{L}} + (8\varepsilon_k - \varepsilon_{\mathrm{k}}^{\mathrm{D}}) - (8\varepsilon_k - \varepsilon_{\mathrm{k}}^{\mathrm{D}})h$$

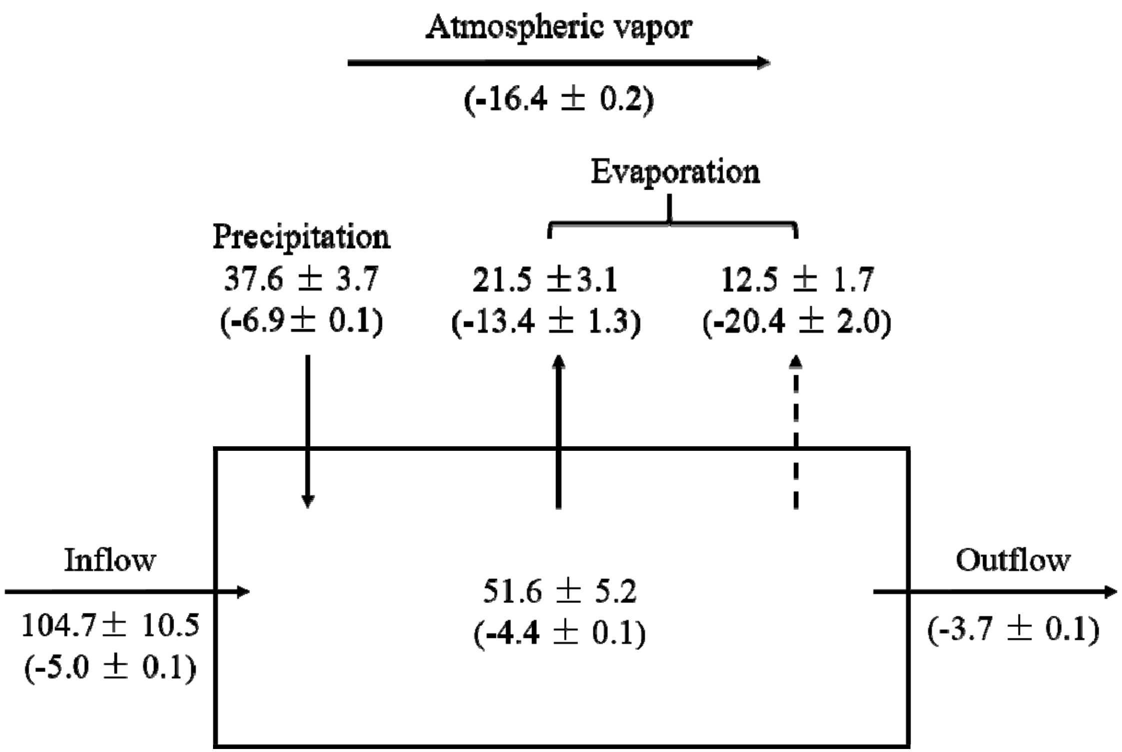


- Eastern Mediterranean Sea (Pfahl & Wernli 2008)
- Mediterranean Sea (Gat et al. 2003)
- The Southern Ocean (Uemura et al. 2008)
- Observation over Lake Taihu
- North Atlantic (Steen-Larsen et al. 2014)
- The south coast of Iceland (Steen-Larsen et al. 2015)
- Eastern North Atlantic Ocean (*Benetti et al.*, 2014)



- Observation over Lake Taihu
- Theoretical line with the OS kinetic factors
- Theoretical line with the LK factors
- Simulation over Lake Taihu with the OS factors
- Simulation over Lake Taihu with the LK factors

Evidence for a weak kinetic effect



Annual evaporation

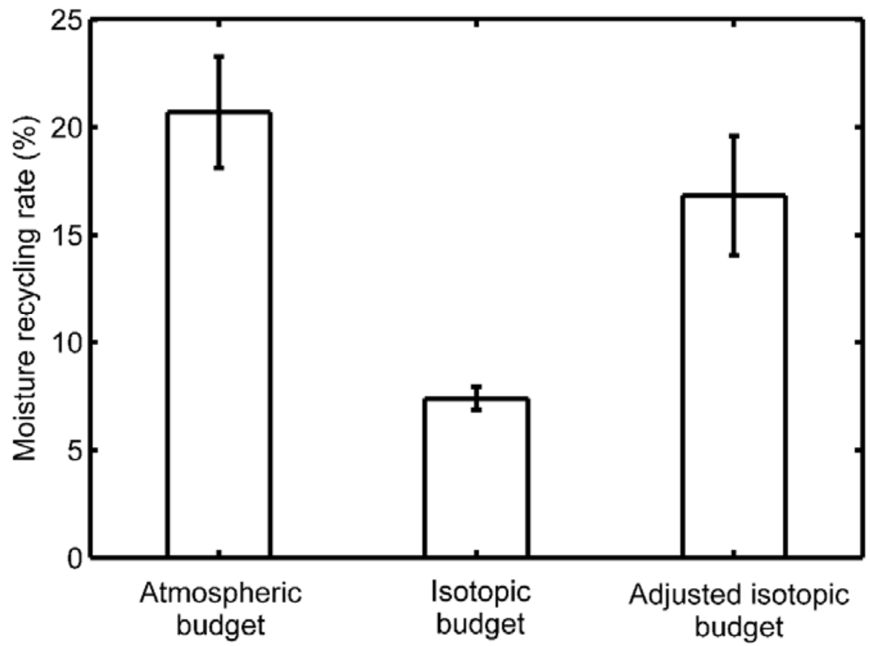
The OS e_k: **897** mm y^{-1}
The LK e_k: **520** mm y^{-1}
EC system: **863** mm y^{-1}

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)

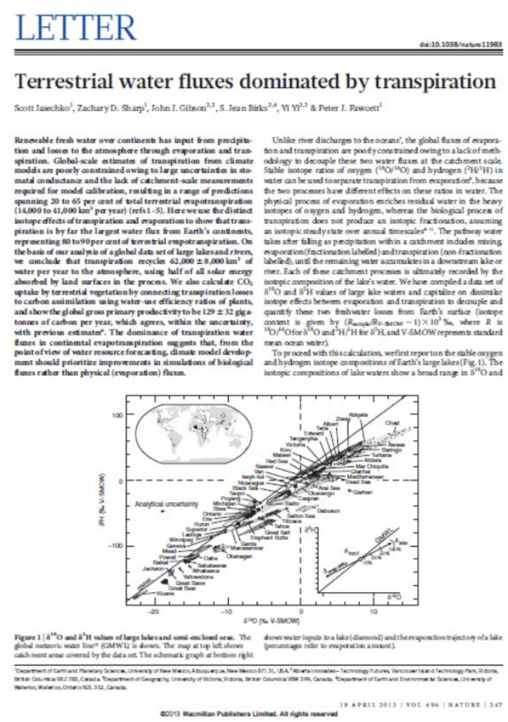
Sensitivity on kinetic factor – E/ET

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

doi:10.1038/nature11983

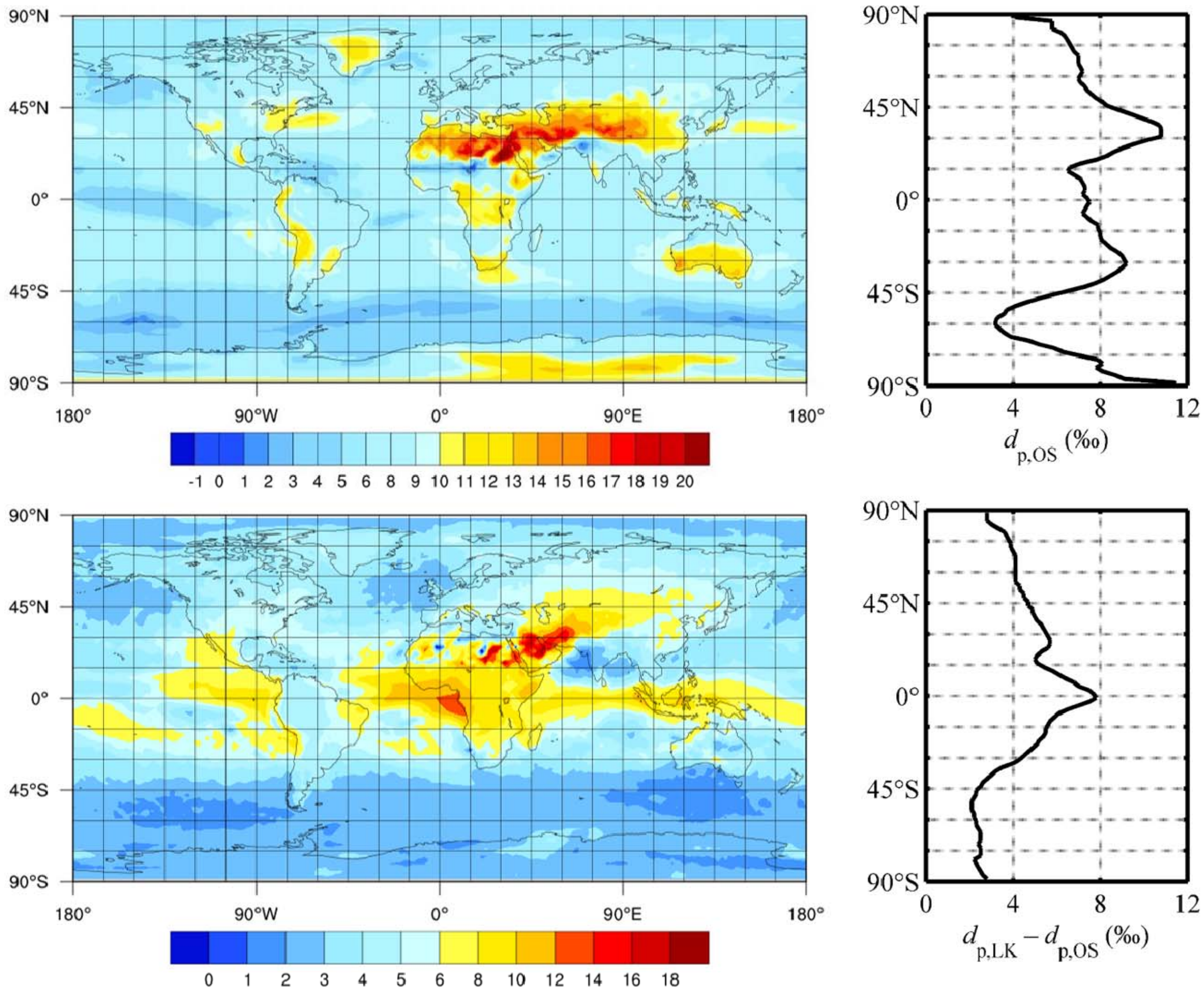
Terrestrial water fluxes dominated by transpiration

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]

(Jasechko et al. 2013)

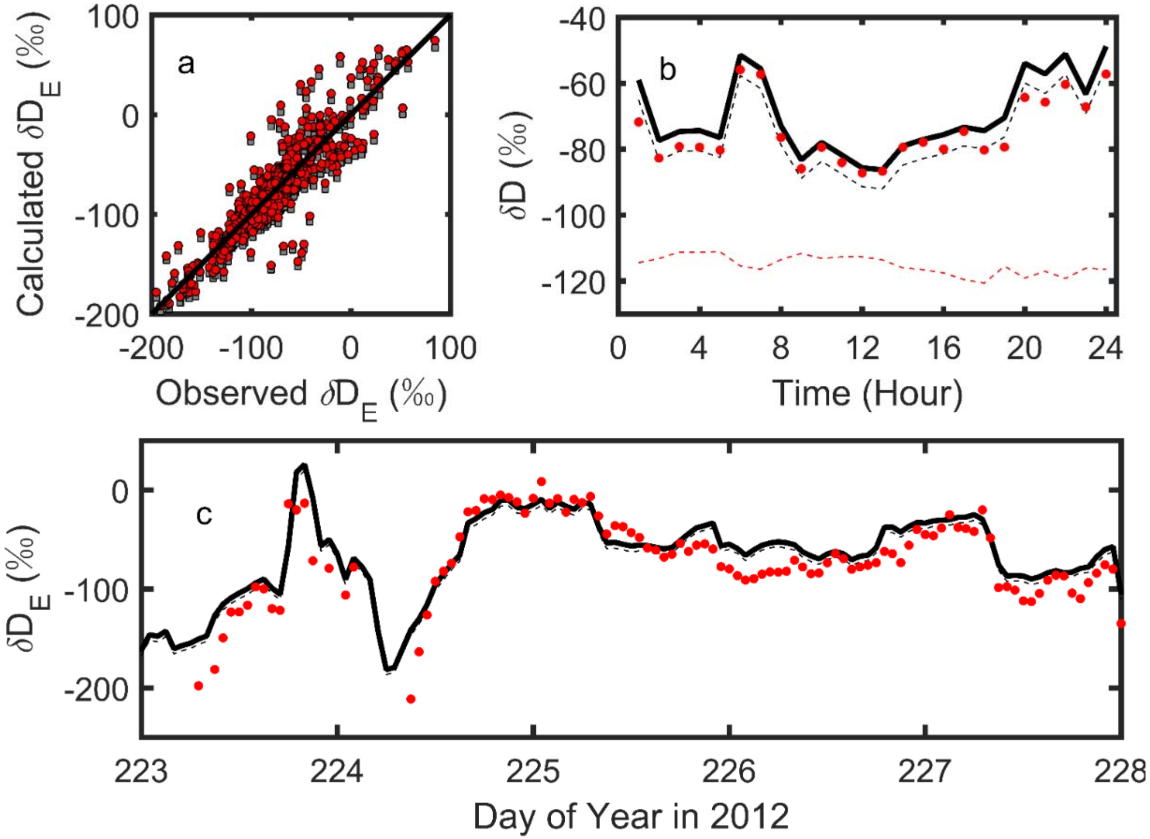
Sensitivity analysis on the kinetic factor –precipitation deuterium excess

ECHAM5-wiso



HDO as a tracer

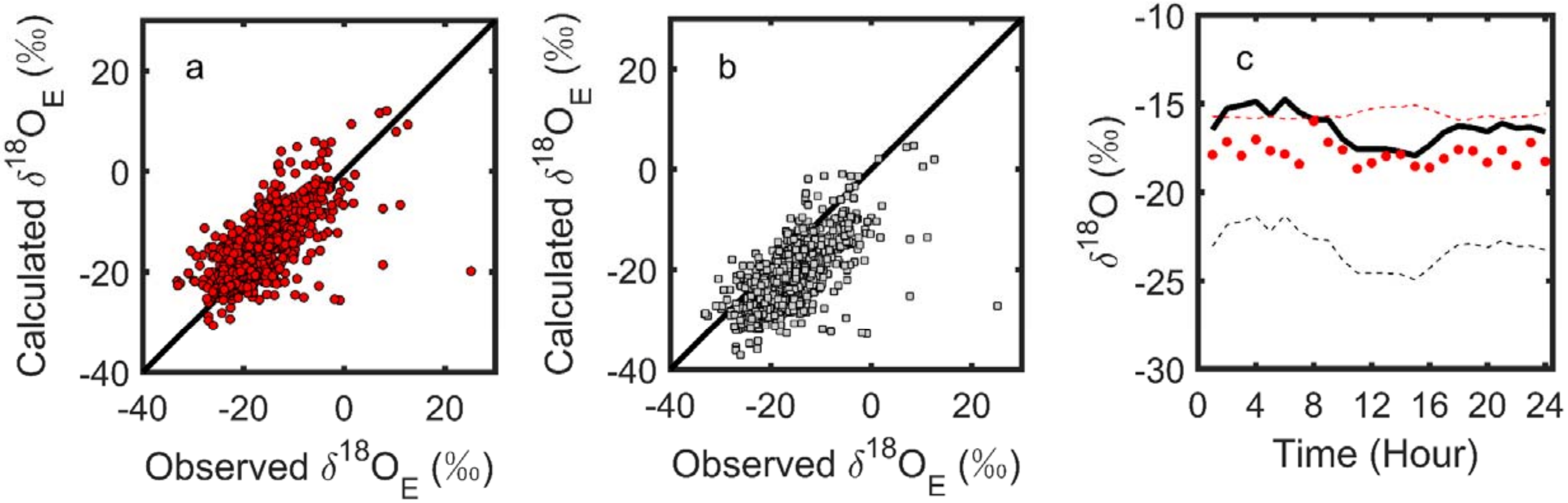
HDO isotopic composition of evaporation at Lake Taihu in open fetch conditions.



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°).

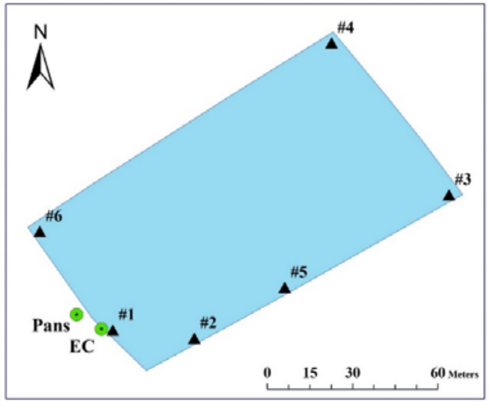


The effective ε_k was not very sensitive to fetch.

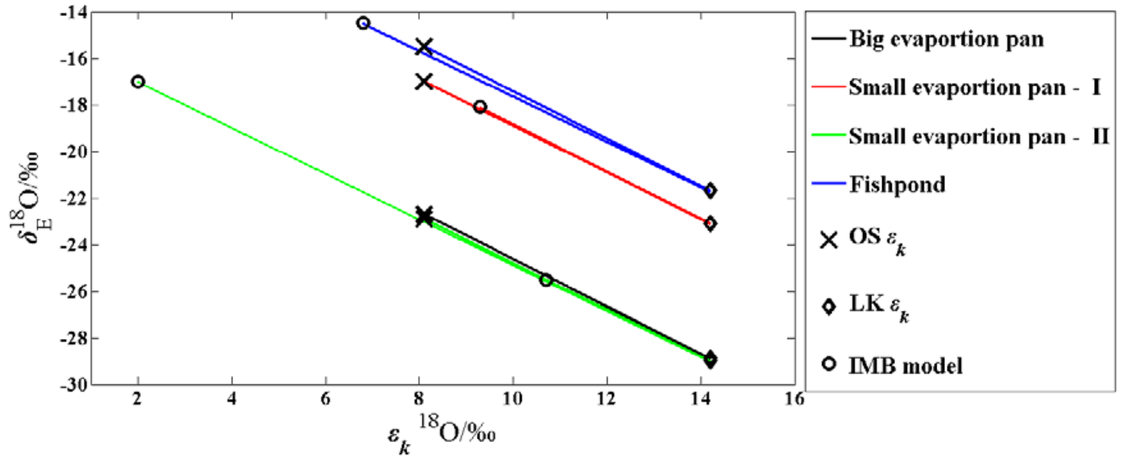
An open question is whether the results reported here for a large lake can be extended to small lakes.

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

时　　间：2017年10月16–19日(October 16-19, 2017)

地　　点：南 京 (Nanjing)

主办单位：中国生态学学会稳定同位素生态专业委员会

承办单位：南京信息工程大学 (Nanjing University of Information Science & Technology)