



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

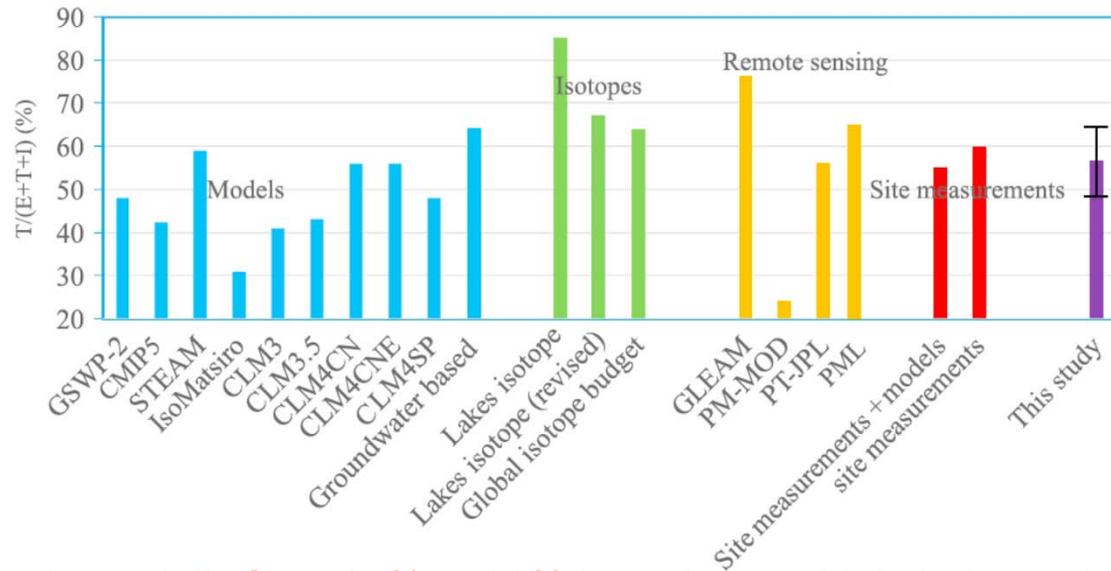
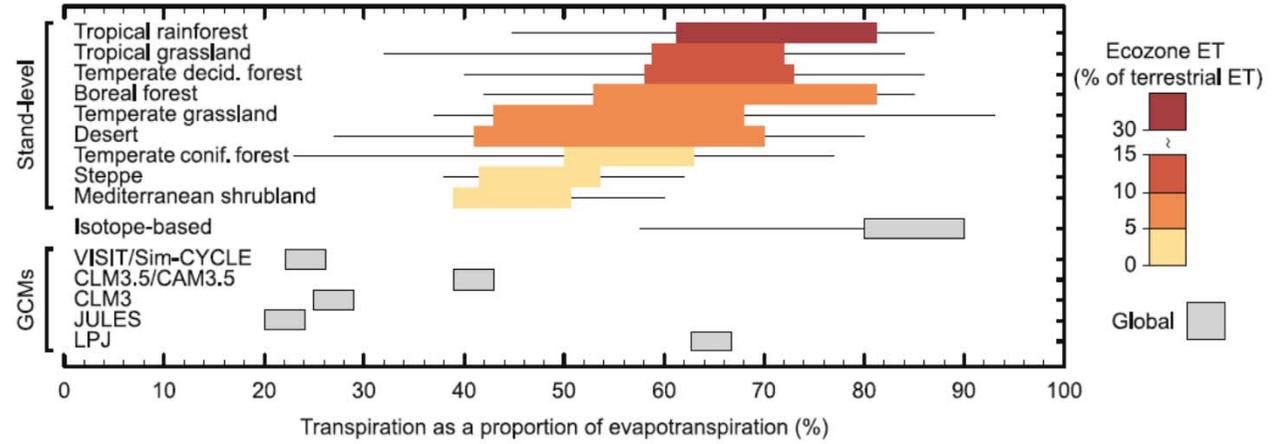
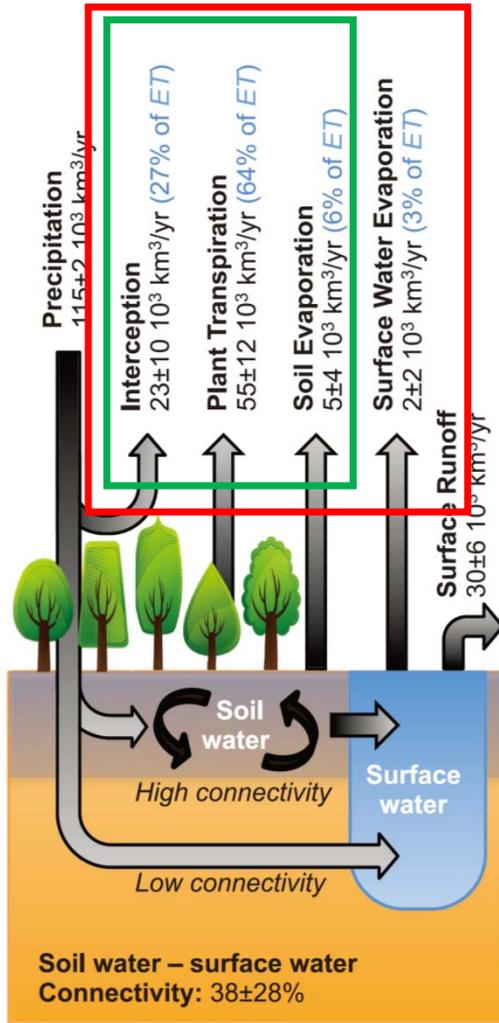
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# Transpiration as a proportion of evapotranspiration



Globally,  $\pi ET$  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  $^{18}\text{O}/^{16}\text{O}$  or D/H ratio of open-water evaporation ( $\delta_E$ ) can be calculated from environmental conditions.

Isotopic mass balance model

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

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

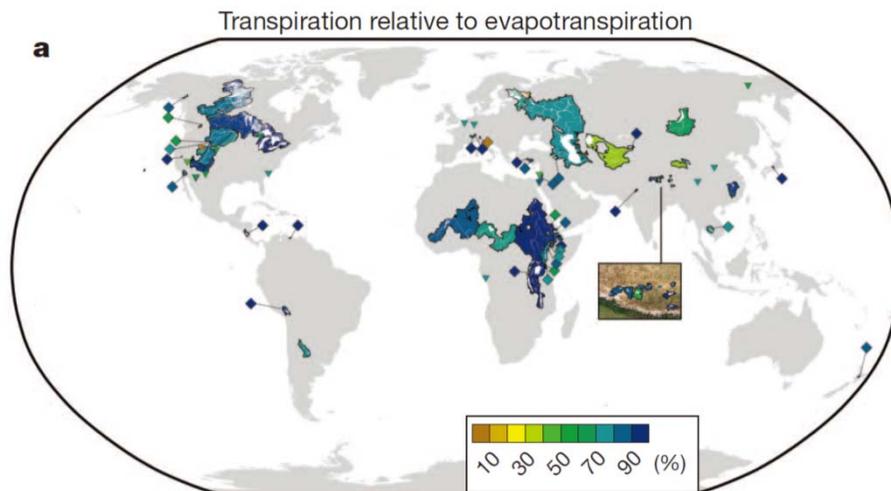
$$T = \frac{I(\delta_I - \delta_E) - Q(\delta_Q - \delta_E) - xP(\delta_P - \delta_E)}{\delta_T - \delta_E}$$

The Craig-Gordon model

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

Kinetic fractionation factor

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

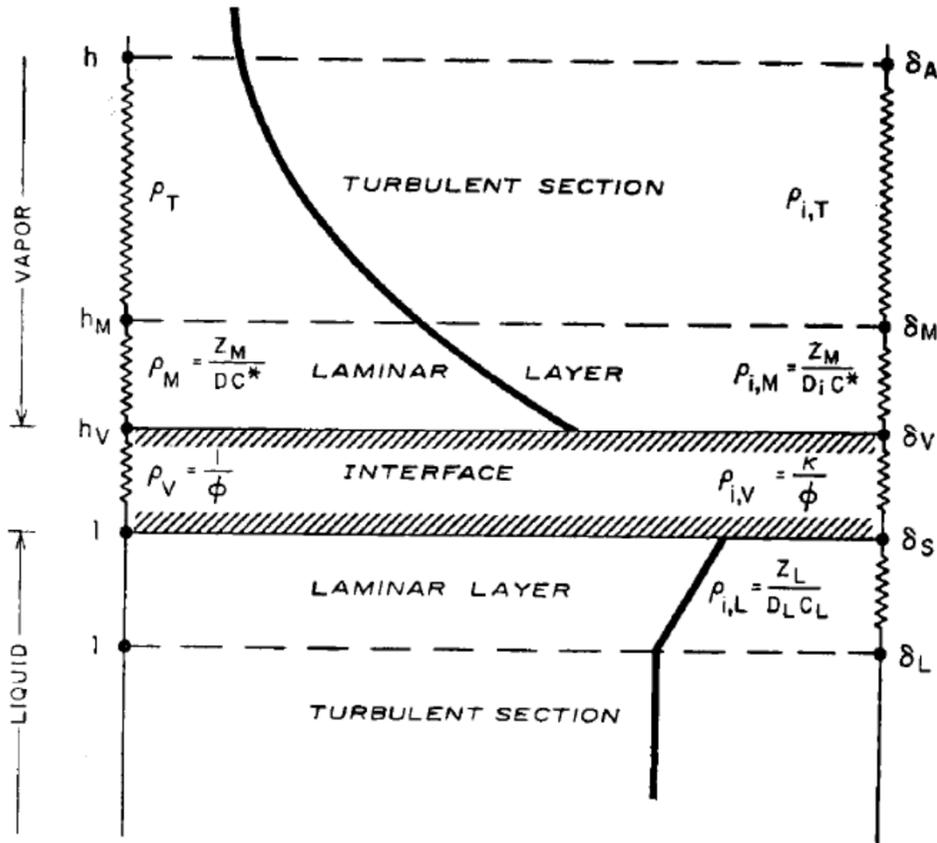


(Craig & Gordon 1965; Jasechko et al. 2013)

# Kinetic fractionation factor

The kinetic effect, an important part of the overall evaporative fractionation against  $\text{H}_2^{18}\text{O}$  and HDO, has been a subject of debate for more than half a century.

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

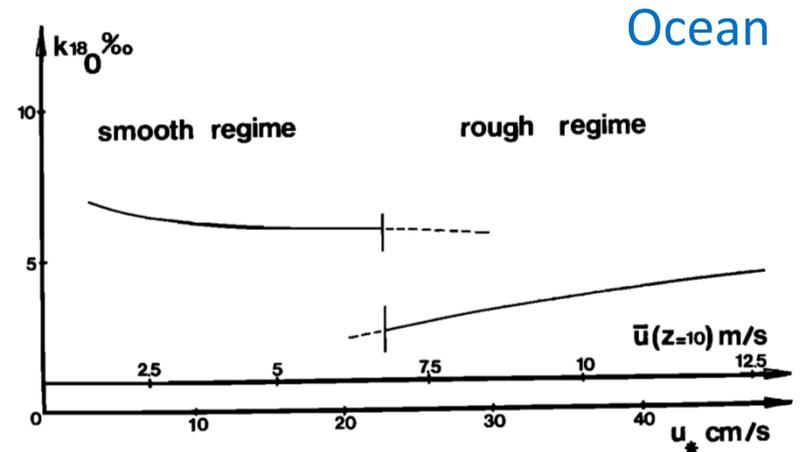


Lake

For  $\text{H}_2^{18}\text{O}$   $\varepsilon_k = 14.2\text{‰}$

$n = 0.5$

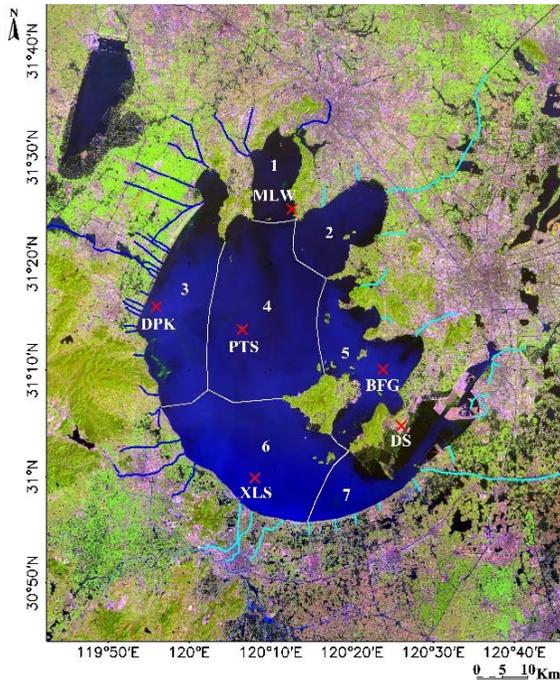
For HDO  $\varepsilon_k = 12.5\text{‰}$



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

# Objectives

- We report the results of an experimental determination of  $\delta^{18}\text{O}_E$  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<sup>2</sup>)



Fish pond  
(area 6912 m<sup>2</sup>)



Big evaporation  
pan (0.28 m<sup>2</sup>)



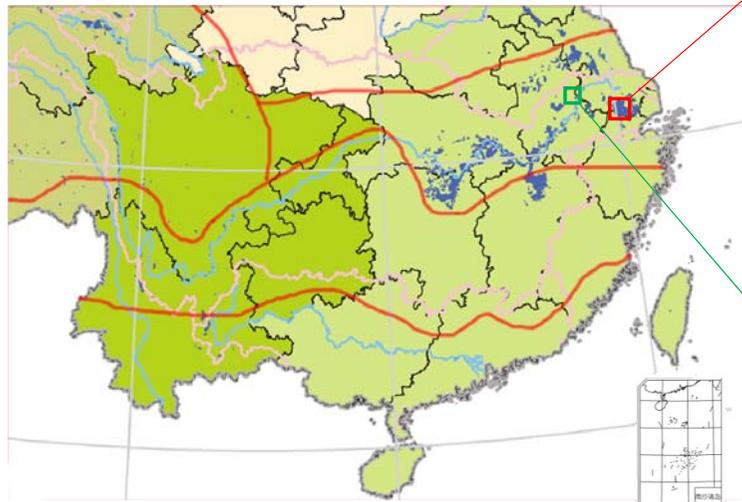
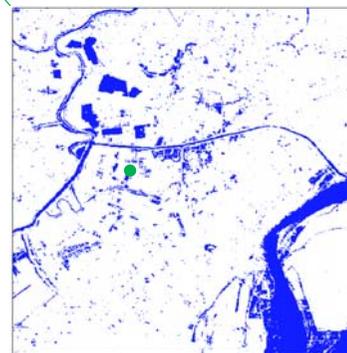
Small evaporation  
pan (0.03 m<sup>2</sup>)

# Experimental sites

Lake Taihu



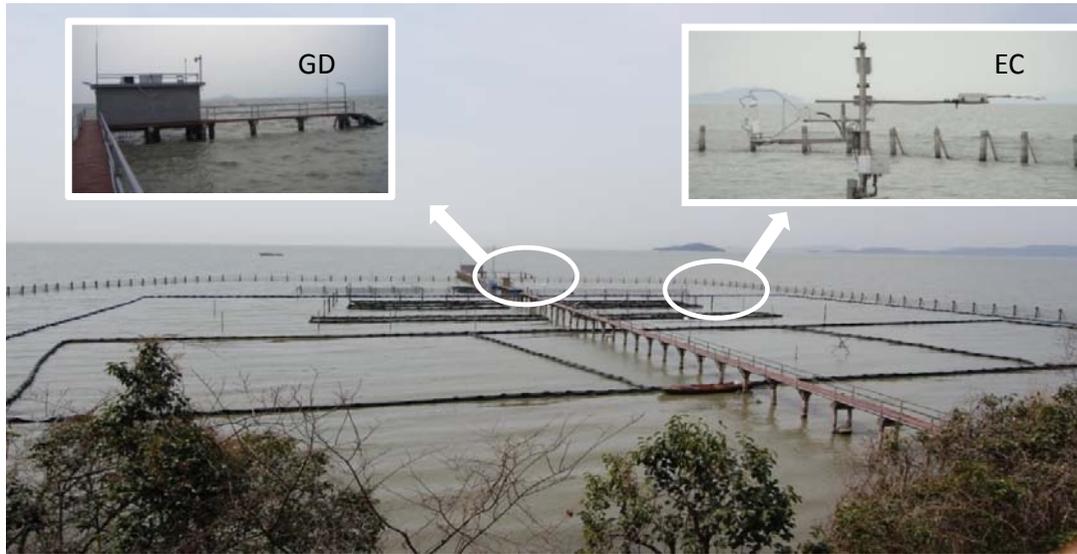
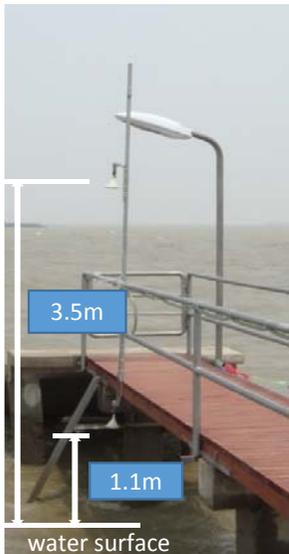
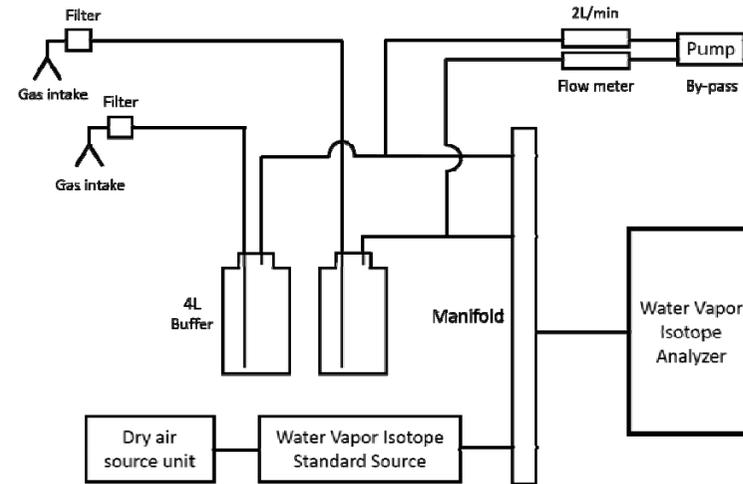
Fish ponds



# In-situ measurement of isotopes over Lake Taihu

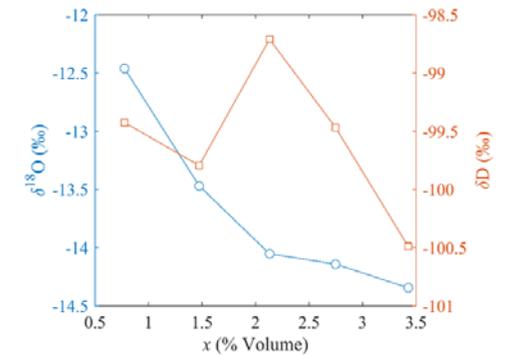
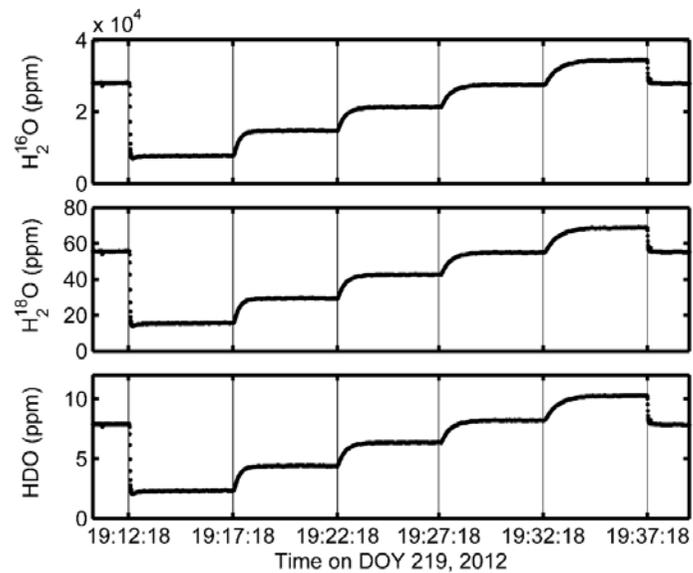
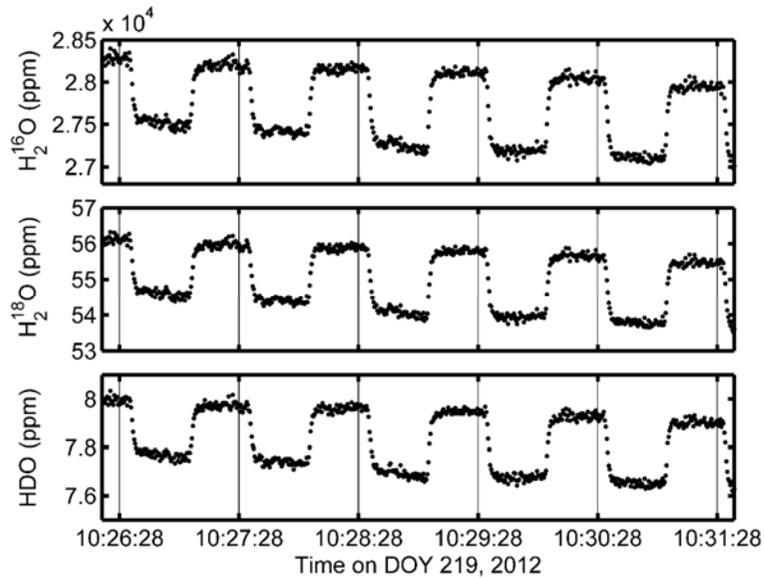
## The gradient-diffusion method

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



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

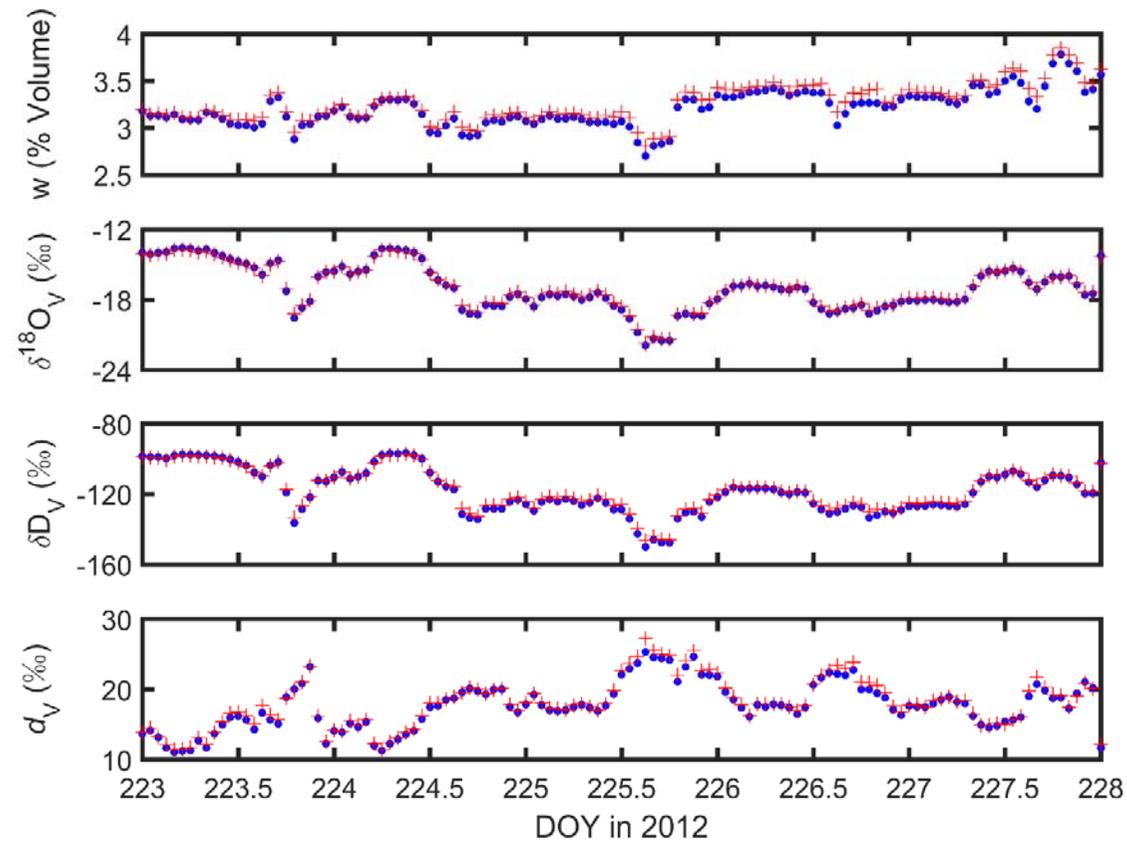
# Step changes in the $\text{H}_2\text{O}$ , $\text{H}_2^{18}\text{O}$ and HDO mixing ratios in response to valve switching and during a calibration cycle



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.

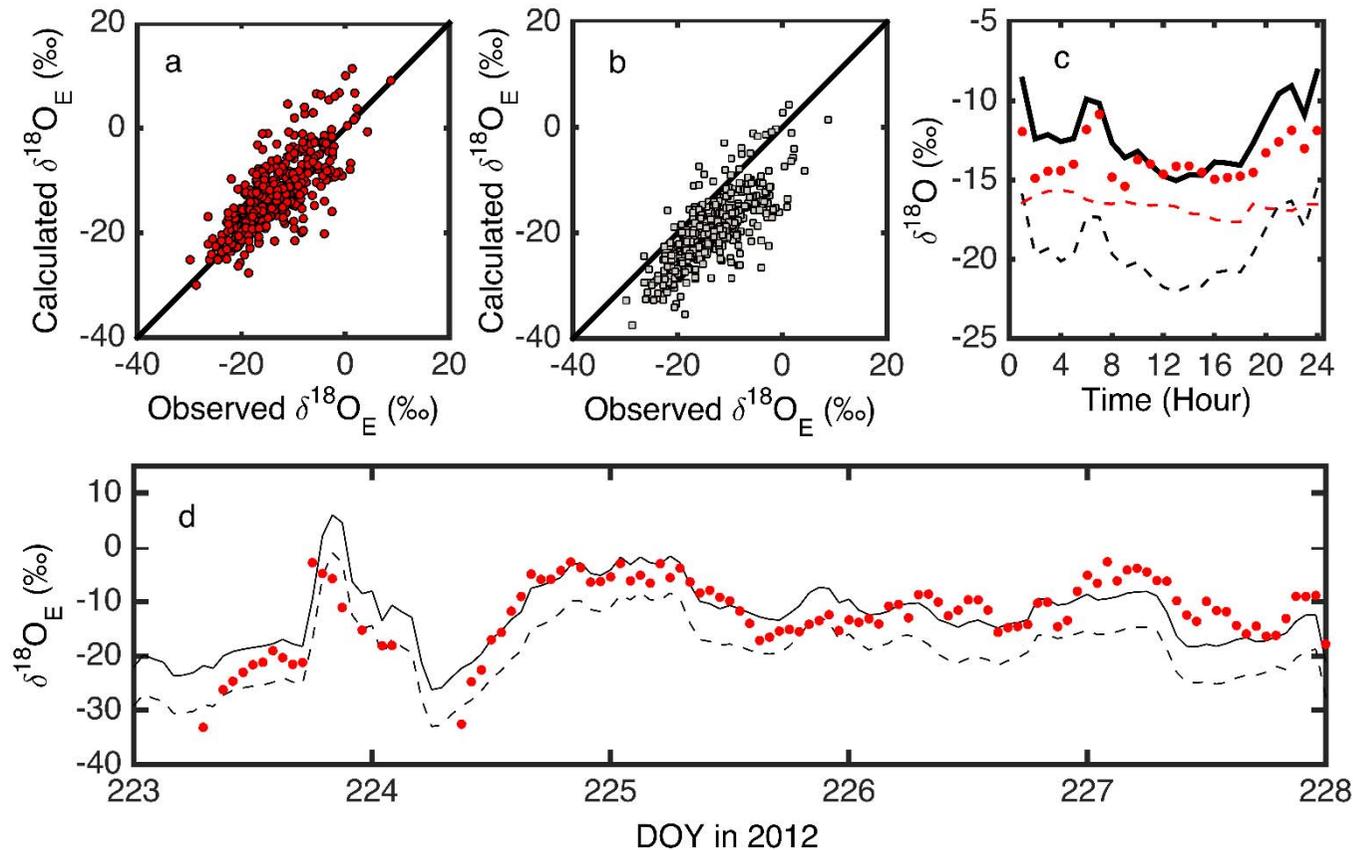
# Time series of the water vapor mixing ratio, $\delta D_V$ , $\delta^{18}O_V$ and $d_V$



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

## Evidence for a weak kinetic effect

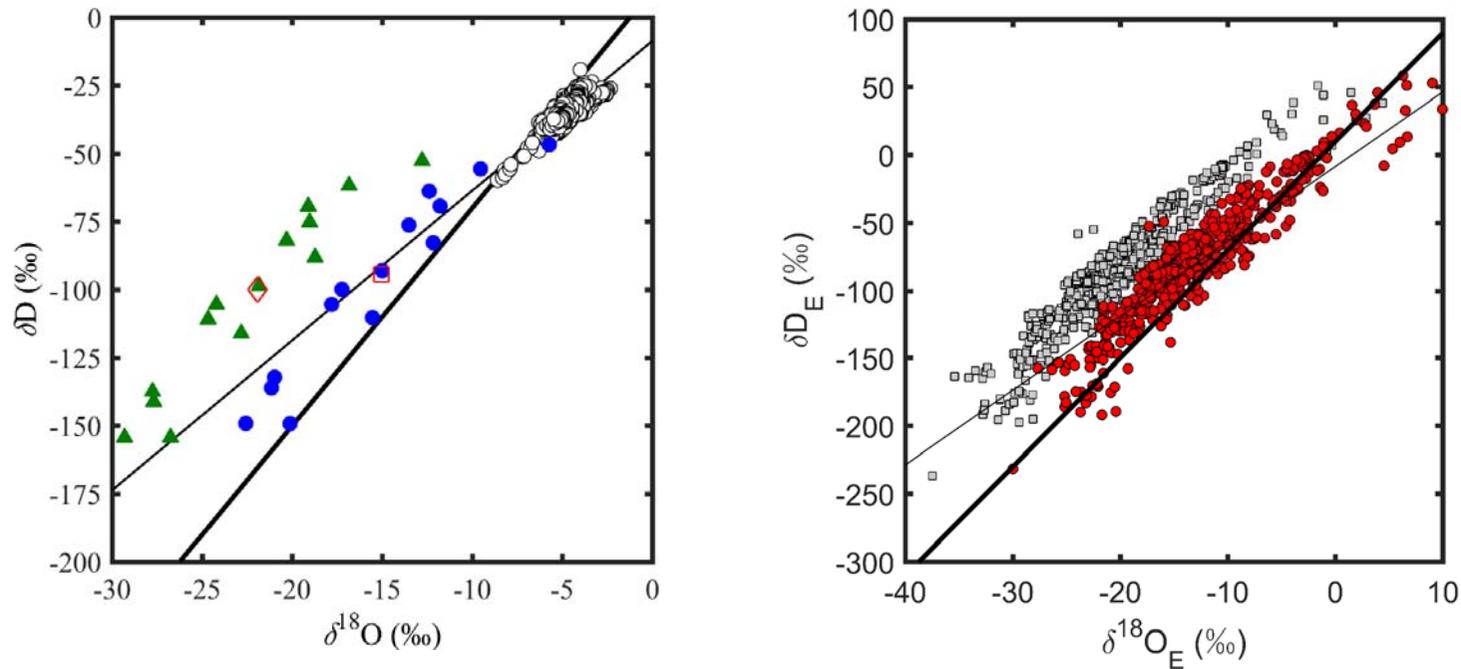
$\text{H}_2^{18}\text{O}$  isotopic composition of evaporation at Lake Taihu under open fetch conditions.



Our results show a much weaker kinetic effect than suggested by the kinetic factor  $\varepsilon_k$  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.

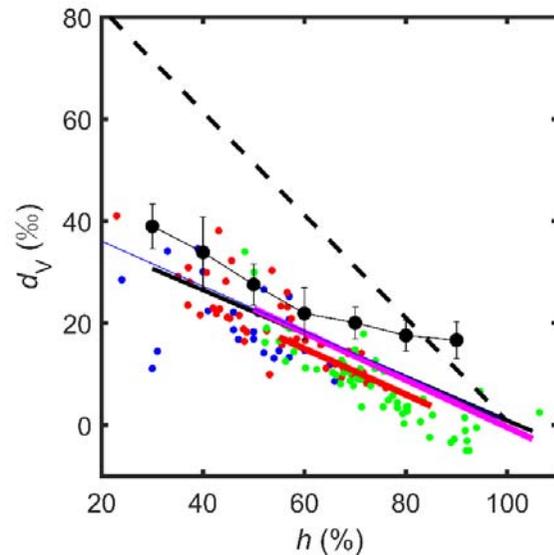


Evidence for a weak kinetic effect is also seen in the  $\text{HDO} - \text{H}_2^{18}\text{O}$  relationship.

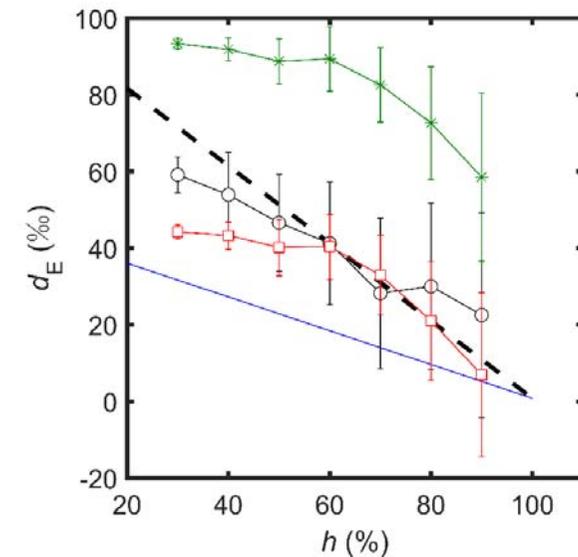
# Evidence for a weak kinetic effect

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

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

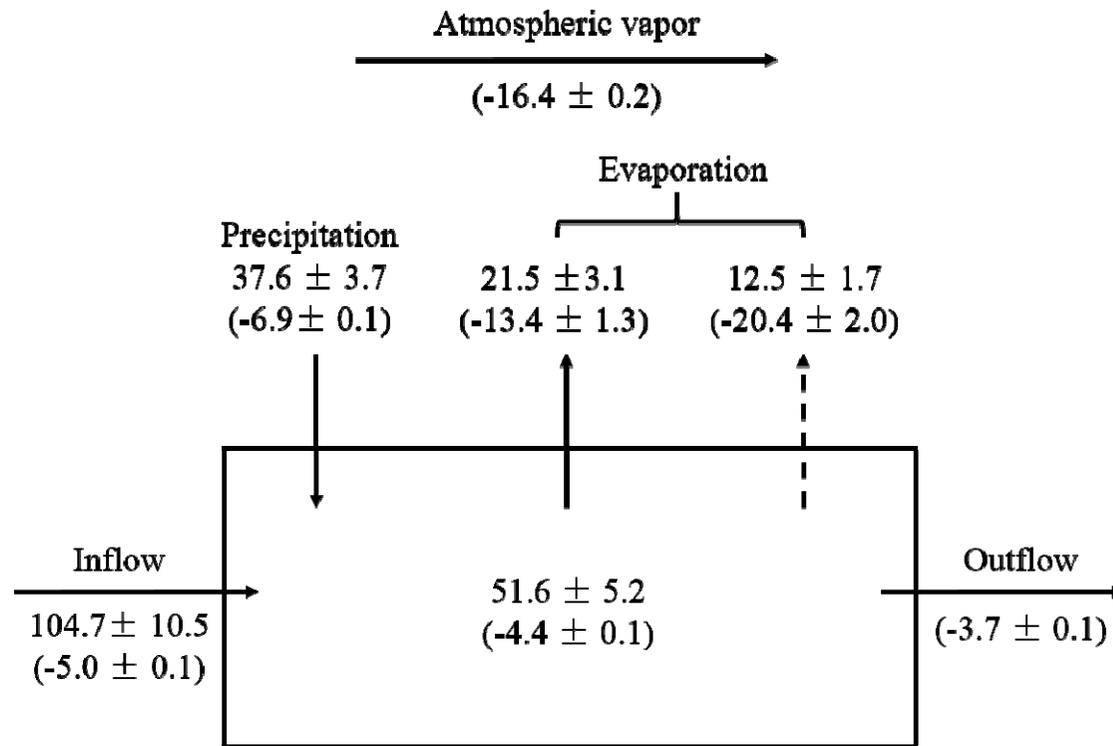


- Eastern Mediterranean Sea (Pfahl & Wernli 2008)
- Mediterranean Sea (Gat et al. 2003)
- The Southern Ocean (Uemura et al. 2008)
- Observation over Lake Taihu
- North Atlantic (Steen-Larsen et al. 2014)
- The south coast of Iceland (Steen-Larsen et al. 2015)
- Eastern North Atlantic Ocean (Benetti et 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  $y^{-1}$

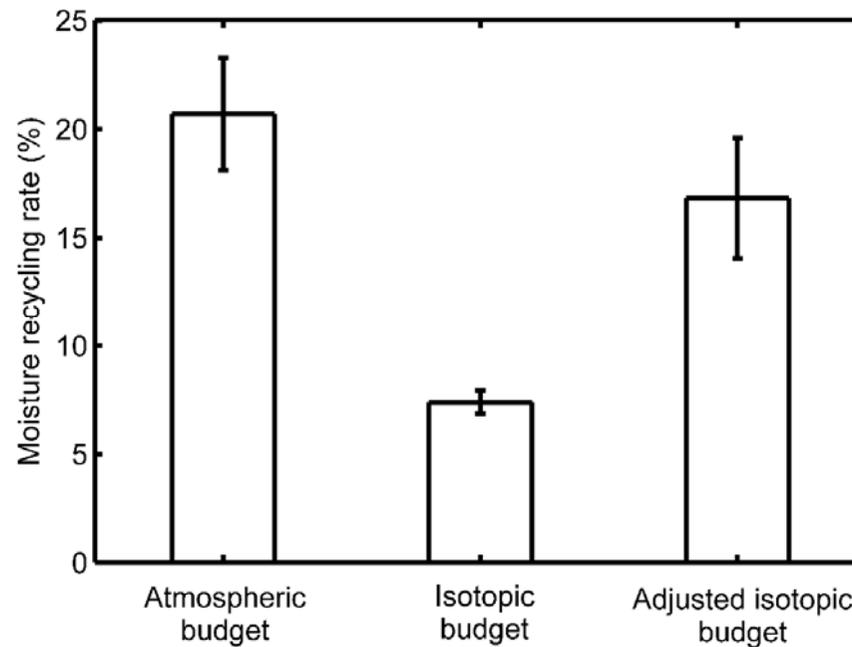
EC system: **863** mm  $y^{-1}$

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



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

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

# Sensitivity on kinetic factor – E/ET

An inaccurate  $\epsilon_k$  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  $\epsilon_k$ : **10-20%**.

The OS  $\epsilon_k$ : **~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

### Terrestrial water fluxes dominated by transpiration

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Renewable fresh water over continents has input from precipitation and loss 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 60 per cent of total terrestrial evapotranspiration (14,000 to 41,000 km<sup>3</sup> per year) (ref. 1–5). Here we use the distinct isotopic 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<sup>3</sup> of water per year to the atmosphere, using half of all solar energy absorbed by land surfaces in the process. We also calculate CO<sub>2</sub> 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 ± 31 gigatonnes of carbon per year, which agrees, within the uncertainty, with previous estimates<sup>6</sup>. The dominance of transpiration water fluxes in continental evapotranspiration suggests that, from the point of view of water resource for farming, climate model development should prioritize improvements in simulations of biological fluxes rather than physical (evaporation) fluxes.

Unlike river discharge to the oceans, 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 (<sup>18</sup>O/<sup>16</sup>O) and hydrogen (<sup>2</sup>H/<sup>1</sup>H) in water can be used to separate transpiration from evaporation, 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<sup>7,8</sup>. 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 <sup>18</sup>O and <sup>2</sup>H values of large lake waters and compared to similar isotope effects between evaporation and transpiration to decouple and quantify these two freshwater losses from Earth's surface (isotope content) is given by  $(R_{\text{lake}}/R_{\text{atmos}} - 1) \times 10^3$ ‰, where  $R$  is <sup>18</sup>O/<sup>16</sup>O or <sup>2</sup>H/<sup>1</sup>H for <sup>18</sup>O and <sup>2</sup>H. 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 <sup>18</sup>O and

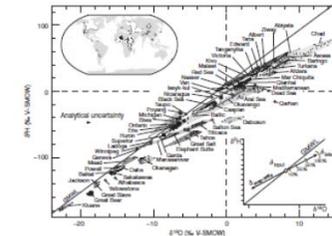


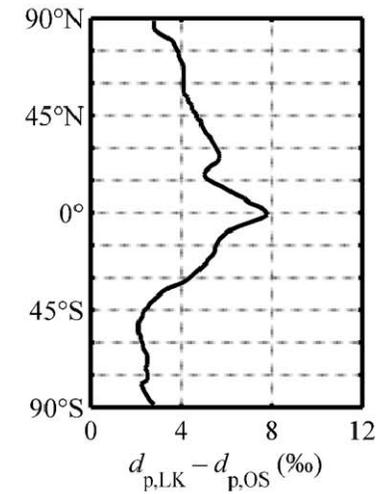
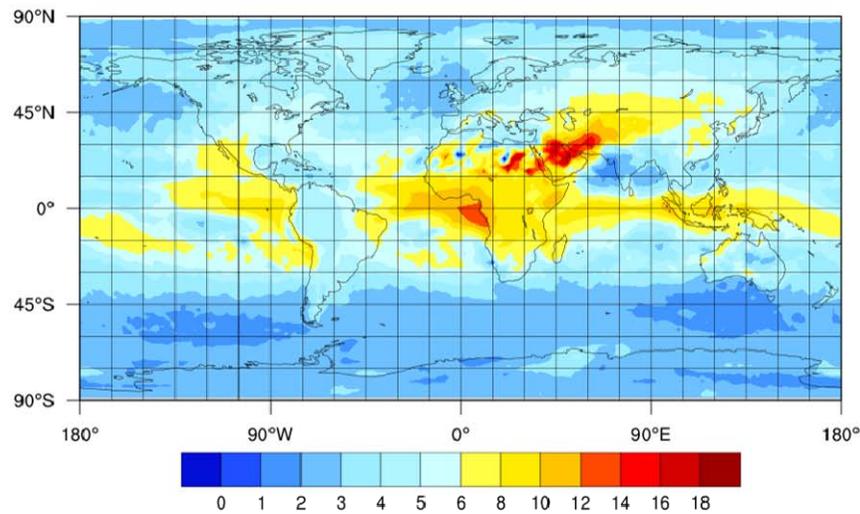
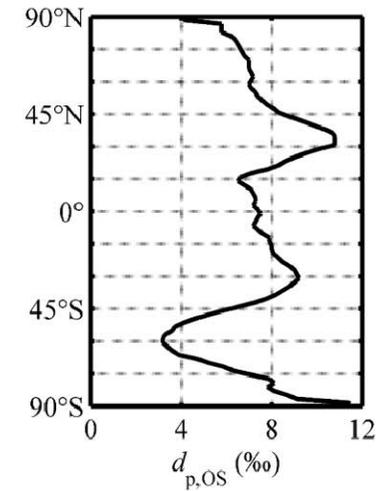
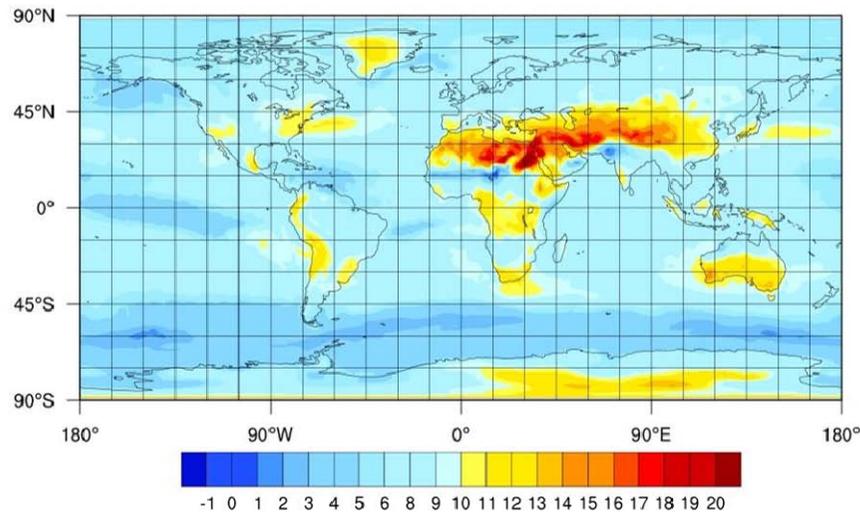
Figure 1 | <sup>18</sup>O and <sup>2</sup>H values of large lakes and river outflow. The global isotopic water flux<sup>9</sup> (GMW) is shown. The map at top left shows catchment areas covered by the data set. The schematic graph at bottom right shows the isotopic composition of lake waters and the evaporation and transpiration isotopic composition (percentages refer to evaporation amount).

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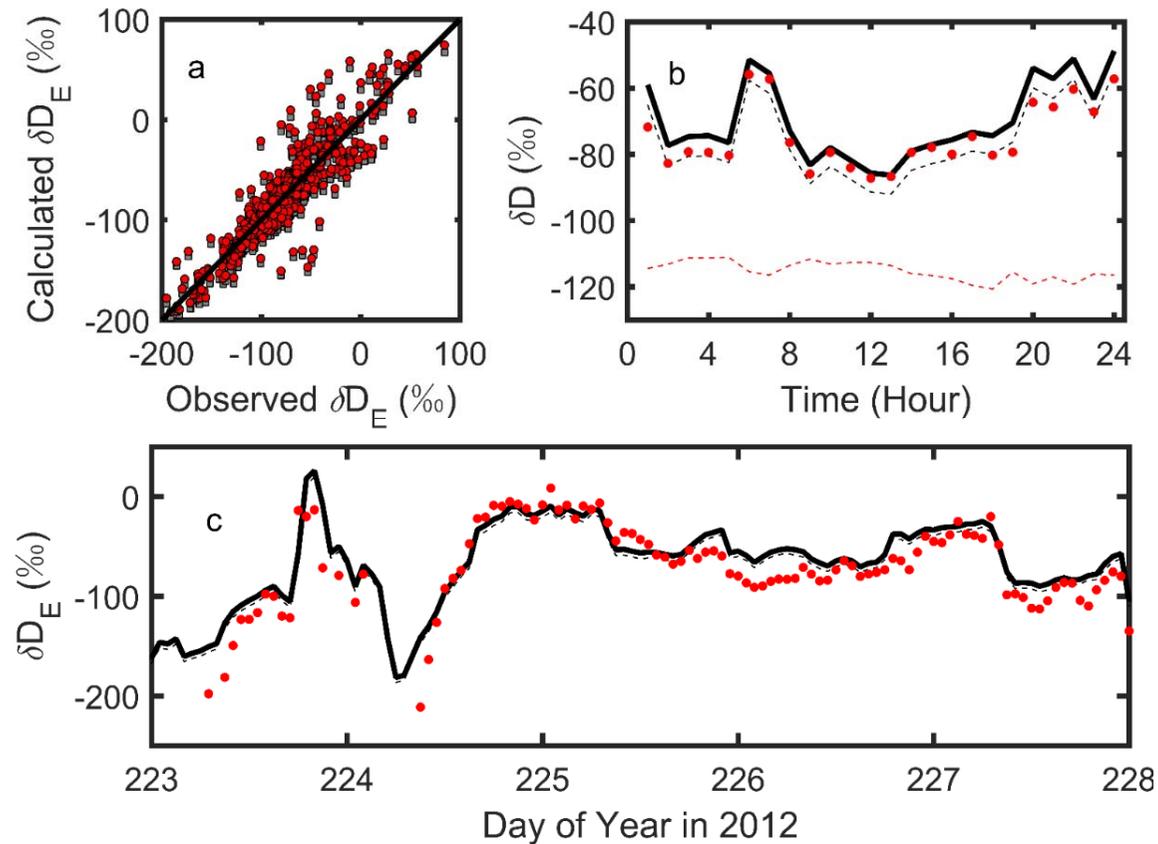
# Sensitivity analysis on the kinetic factor –precipitation deuterium excess

## ECHAM5-wiso



# HDO as a tracer

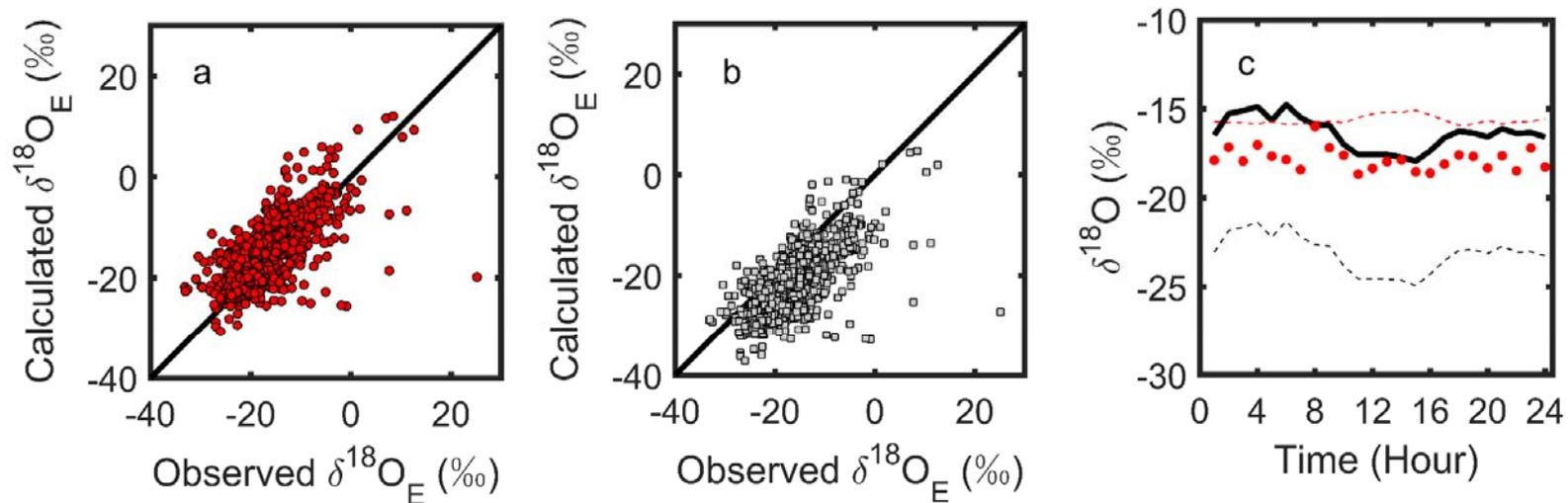
HDO isotopic composition of evaporation at Lake Taihu in open fetch conditions.



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

$\text{H}_2^{18}\text{O}$  isotopic composition of Lake Taihu evaporation in short fetch conditions (wind directions  $315 - 135^\circ$ ).

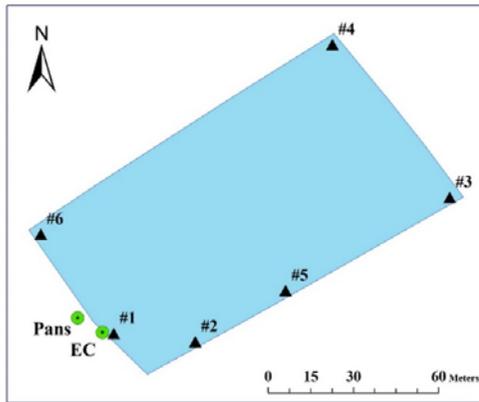


The effective  $\varepsilon_k$  was not very sensitive to fetch.

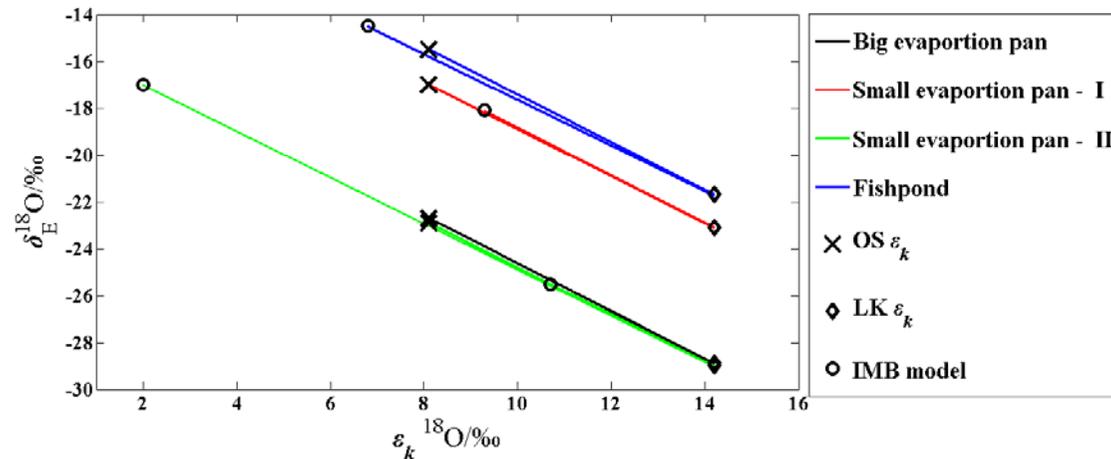
An open question is whether the results reported here for a large lake can be extended to small lakes.

# Experiments on fish pond and evaporation pans

## Fish pond



## Evaporation pans



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

# Summary

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- The success of the OS  $\epsilon_k$  at Lake Taihu implies that atmospheric turbulence plays similar roles in gaseous diffusion in the lake and the marine environment.
- A higher  $\epsilon_k$  would lead to a greater amount of  $\text{H}_2^{18}\text{O}$  accumulated in lakes.
- The isotopic mass balance calculations using the weak  $\epsilon_k$  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  $\epsilon_k$  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)

