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Isotopic kinetic fractionation of evaporation from small water bodies

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2020/07/03

- **Introduction**
- **Method**
- **Result**
- **Discussion**
- **Conclusion**

1 Introduction

- Small lakes and ponds (area < 1 km^2) comprise over 99 % of the 300 million water bodies in the world and occupy about half of the total water area on land (Downing et al., 2006; Messager et al., 2016; Verpoorter et al., 2014). Accurate quantification of their evaporative water loss to the atmosphere is an important step for global water evaporation.

- For evaporation observation of small water bodies, Priestley-Taylor model, gradient-diffusion technique and eddy covariance are not suitable for advection effect and insufficient fetch (Assouline et al., 2016; Xiao et al. 2018; Zhao et al., 2019).

- Lake evaporation can be determined with isotopic mass balance (IMB) method (Gat et al, 1994; Jasechko et al, 2014; Zuber, 1983). Evaporation δ_E calculated with the Craig-Gordon (CG) model, one of the most critical parameters for the CG model calculation is the kinetic fractionation factor (ε_k) (Horita, 2008; Xiao et al., 2017).

C-G model

$$\delta_E = \frac{\alpha_{eq}^{-1}\delta_L - h\delta_V - \varepsilon_{eq} - (1-h)\varepsilon_k}{1-h+0.001(1-h)\varepsilon_k}$$

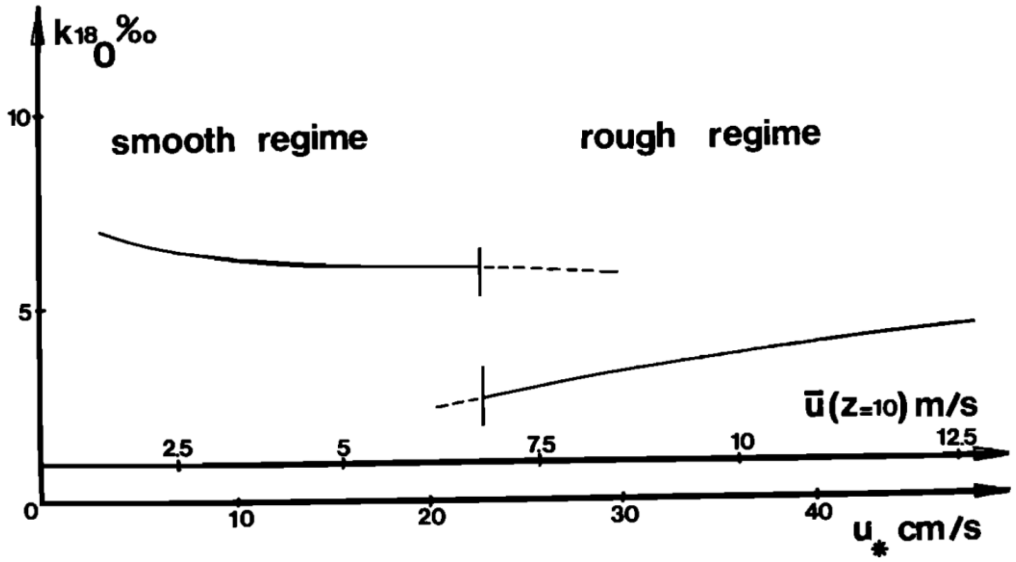
LK

$$\varepsilon_k = n\left(\frac{D}{D_i} - 1\right)10^3 \qquad n = 0.5$$

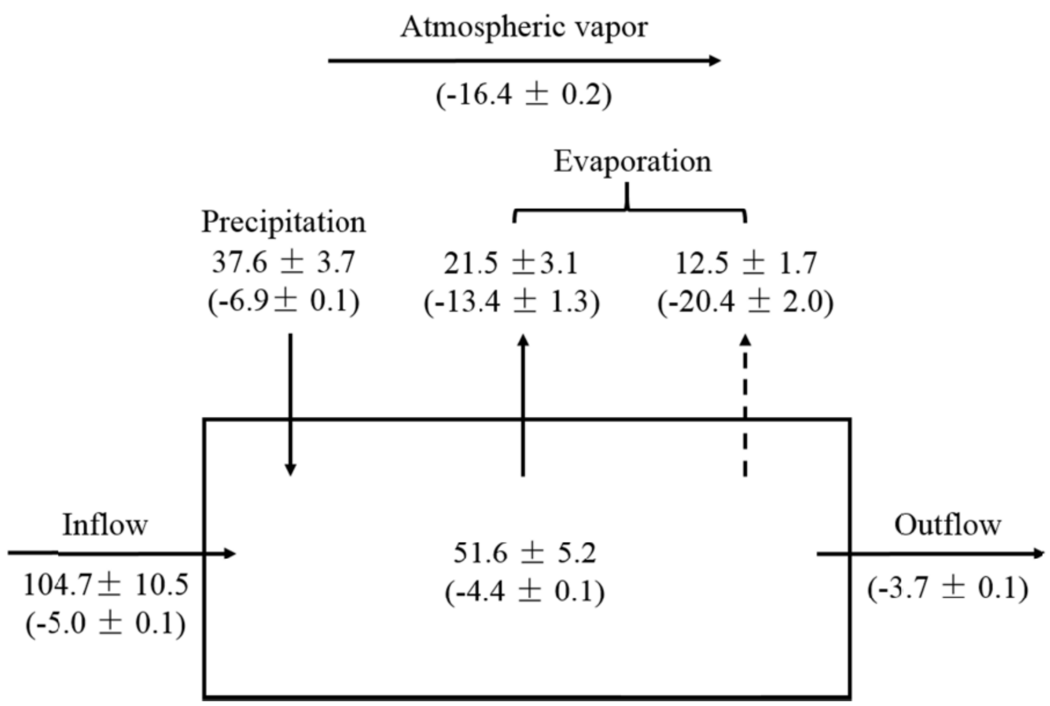
For $H_2{}^{18}O$ $\varepsilon_k = 14.2‰$

For HDO $e_k = 12.5‰$

OS



(Craig and Gordon, 1965; Merlivat and Jouzel, 1979)



E=21.5*10^8 m^3 water y^{-1}, OS ε_k

72%

E=12.5*10^8 m^3 water y^{-1}, LK ε_k

$\boldsymbol{E \sim \delta_E \sim \varepsilon_k \sim n}$

37%↑ 23%↓ 40%↓ 0.2 ↓

(Xiao et al., 2017)

Survey	ε_k	Method	Drawback
Fontes and Gonfiantini, 1967	8.55 ‰	unified CG model	δ_V was not measured
Xiao et al. (2017)	6.2 ‰	gradient-diffusion	large lake
Gonfiantini et al. (2018)	8.5 ‰	unified CG model	δ_V was not measured

Objectives

(1) To measure the ε_k of evaporation of small water bodies for the oxygen isotopes,

(2) To investigate the relationship between ε_k and the slope of the local evaporation line (LEL),

(3) To test the hypothesis that the strength of the kinetic effect decreases with increasing lake size.

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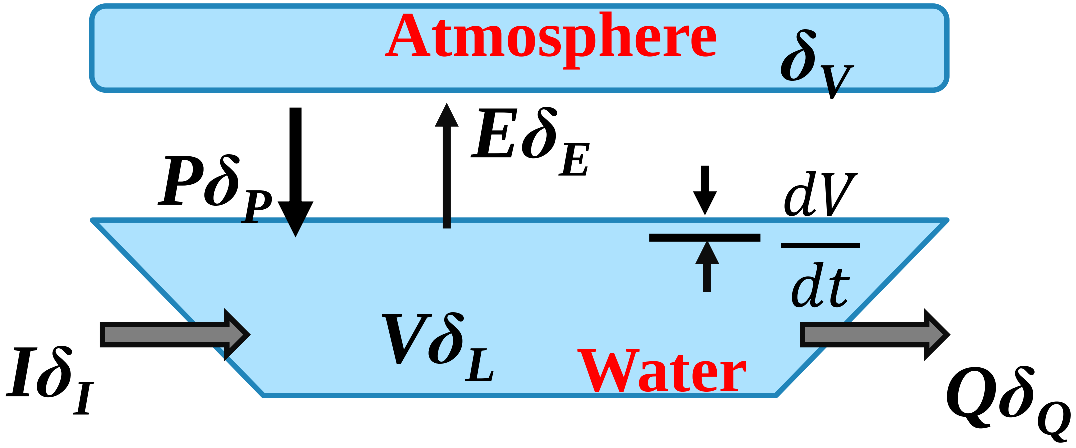
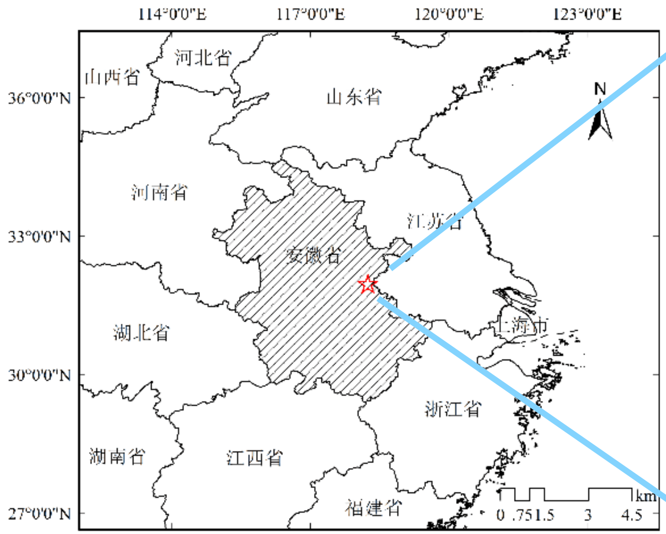
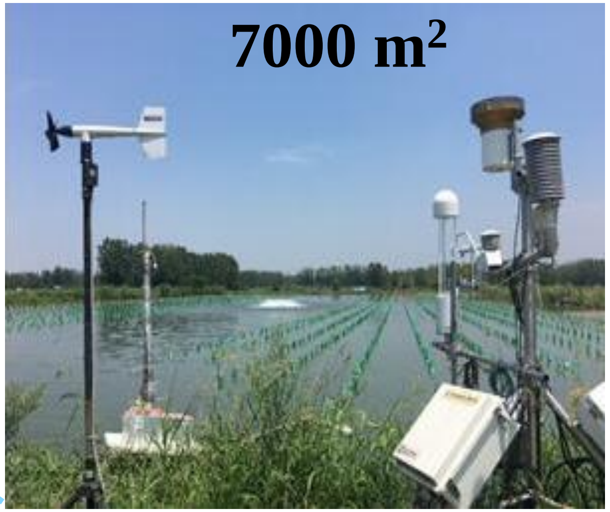
Isotope mass balance (IMB) model

$$I\delta_I + P\delta_P = E\delta_E + Q\delta_Q + \frac{dV\delta_L}{dt}$$



IMB model → IMB δ_E → **C-G model**





Small Pan
ADM 7: diameter 20cm

Big Pan
E601B: diameter 60cm

Table 1. Summary of environmental variables. Here, δ_V, $u*$, h_L and T_S were weighted mean values by $\rho_a u(q_s - q_a)$.

Trial	Period	D $\delta_{L,0}$ ‰	D $\delta_{L,f}$ ‰	D δ_V ‰	^{18}O $\delta_{L,0}$ ‰	^{18}O $\delta_{L,f}$ ‰	^{18}O δ_V ‰	$u*$ m s^{-1}	h_L	T_S °C	E g m^{-2} s^{-1}
Small evaporation pan											
S1	2017/05/09 — 2017/05/17	-46.8	5.3	-83.7	-6.7	3.8	-13.1	0.18	0.40	28.72	0.103
S2	2017/05/24 — 2017/05/27	-45.9	-12.3	-80.8	-5.0	0.2	-12.7	0.17	0.37	31.05	0.121
S3	2017/07/18 — 2017/07/22	-40.0	-20.9	-101.8	-6.6	0.0	-14.3	0.14	0.47	36.65	0.100
S4	2017/07/23 — 2017/07/28	-36.9	-9.8	-78.9	-5.6	0.0	-11.2	0.10	0.46	40.70	0.096
S5	2017/07/28 — 2017/08/02	-37.9	-27.3	-97.9	-6.4	-3.0	-13.7	0.22	0.62	35.51	0.102
S6	2017/10/31 — 2017/11/10	-35.2	-6.6	-122.9	-5.2	-0.1	-20.0	0.22	0.55	18.15	0.033
Big evaporation pan											
B1	2017/05/09 — 2017/05/29	-45.9	-23.1	-83.1	-6.8	-1.9	-12.9	0.19	0.45	27.76	0.064
B2	2017/07/18 — 2017/08/01	-40.1	-28.7	-92.5	-6.6	-3.5	-13.1	0.14	0.55	34.70	0.056
B3	2017/10/31 — 2017/11/13	-46.6	-38.1	-126.9	-7.0	-5.2	-20.6	0.19	0.57	14.65	0.022
Fishpond											
F1	2017/05/09 — 2017/05/29	-15.7	-10.5	-82.8	-1.5	-1.0	-12.9	0.21	0.49	25.77	0.047
F2	2017/07/18 — 2017/08/01	-22.0	-20.5	-97.6	-2.3	-1.9	-13.7	0.19	0.55	34.62	0.075
F3	2018/07/30 — 2018/08/13	-13.8	-16.3	-91.8	-1.0	-0.7	-13.5	0.17	0.58	33.63	0.051
F4	2018/08/29 — 2018/10/06	-24.0	-20.8	-104.9	-1.6	-1.1	-15.5	0.18	0.56	26.68	0.078
F5	2018/10/11 — 2018/11/30	-20.9	-17.1	-103.9	-0.8	-0.2	-16.5	0.20	0.54	16.80	0.027

Note, subscript 0 denotes the initial state of experiment, subscript f denotes the final state of experiment.

Unified CG (UCG) model

$$\delta = \left[\delta_0 + 1 + \frac{A}{B}(\delta_A + 1)\right] f^B - \left[1 + \frac{A}{B}(\delta_A + 1)\right]$$

$$A = -\frac{h}{\alpha_{dif}^{X}(1 - h)} \qquad B = \frac{1}{\alpha_{eq}\alpha_{dif}^{X}(1-h)}\text{-}1$$

$$\frac{A}{B} = -\frac{h\alpha_{eq}}{1 - \alpha_{eq}\alpha_{dif}^{X}(1 - h)}$$

Gonfiantini et al., 2018

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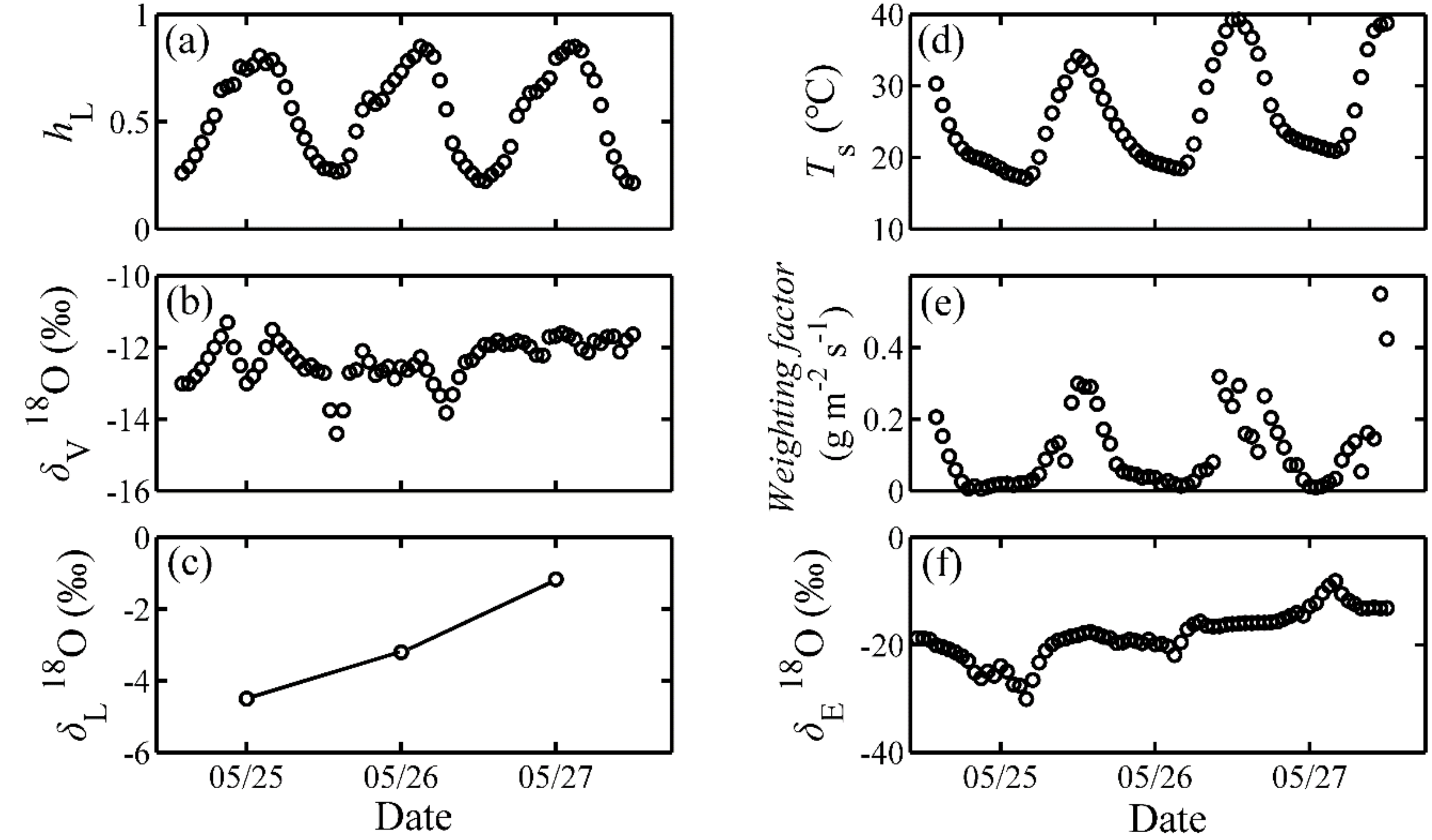


$$E_t' = \rho_a u(q_s - q_a)$$

ε_k of 6.01 ‰ for ^{18}O

Figure 1. Time series of environmental variables during Experiment S2.

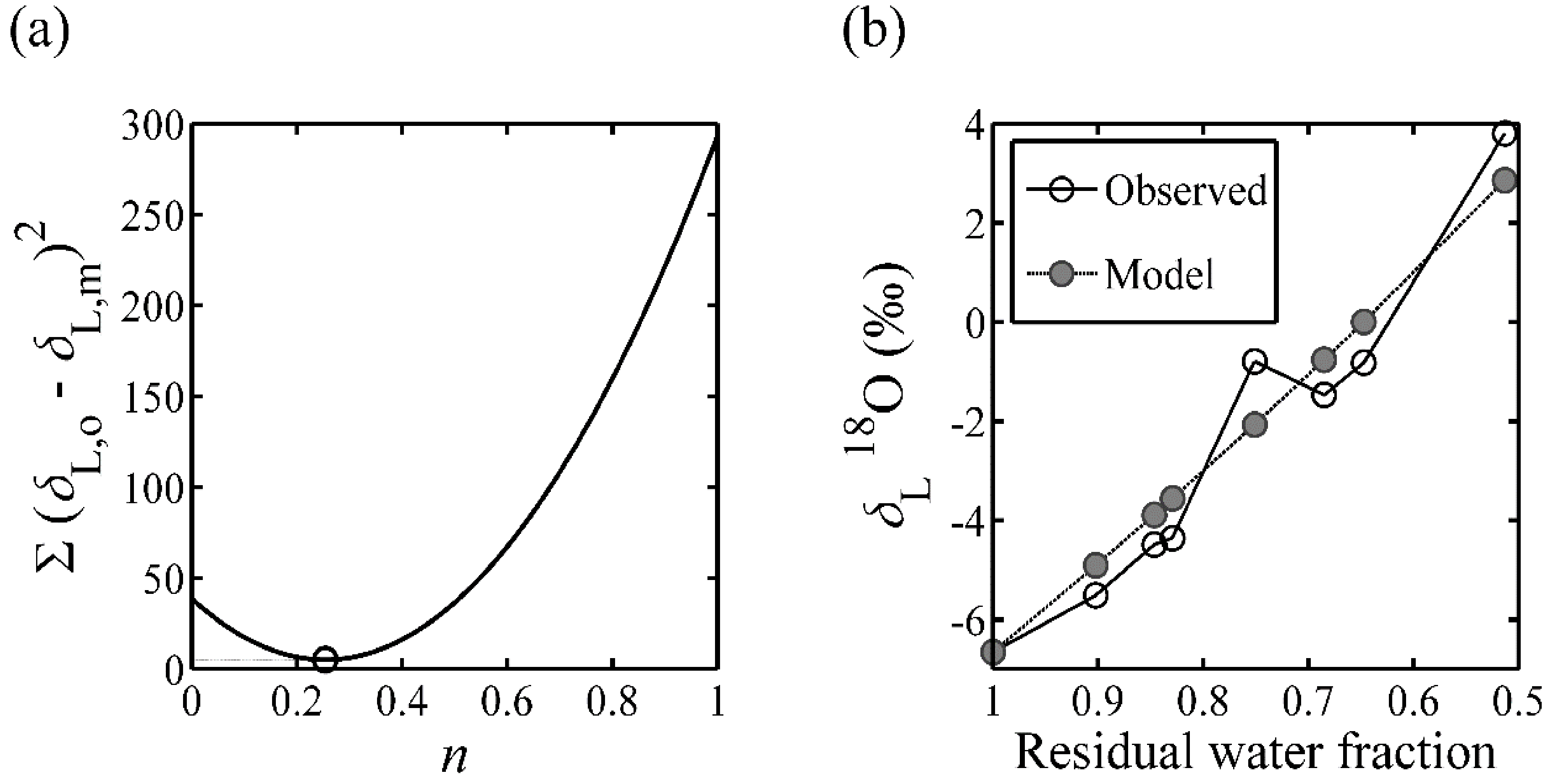


Figure 2. Application of the unified Craig-Gordon model to Experiment S1.

$\Sigma(\delta_{L,o} - \delta_{L,m})^2 = 5.08$ $n_{IMB} = 0.28$ $n_{model} = 0.25$ $\varepsilon_k = 7.23$ ‰

UCG

weighted mean

algebraic mean

equilibrium vapor delta

$$\delta_A = (\delta_P - \varepsilon^+)/\alpha^+$$

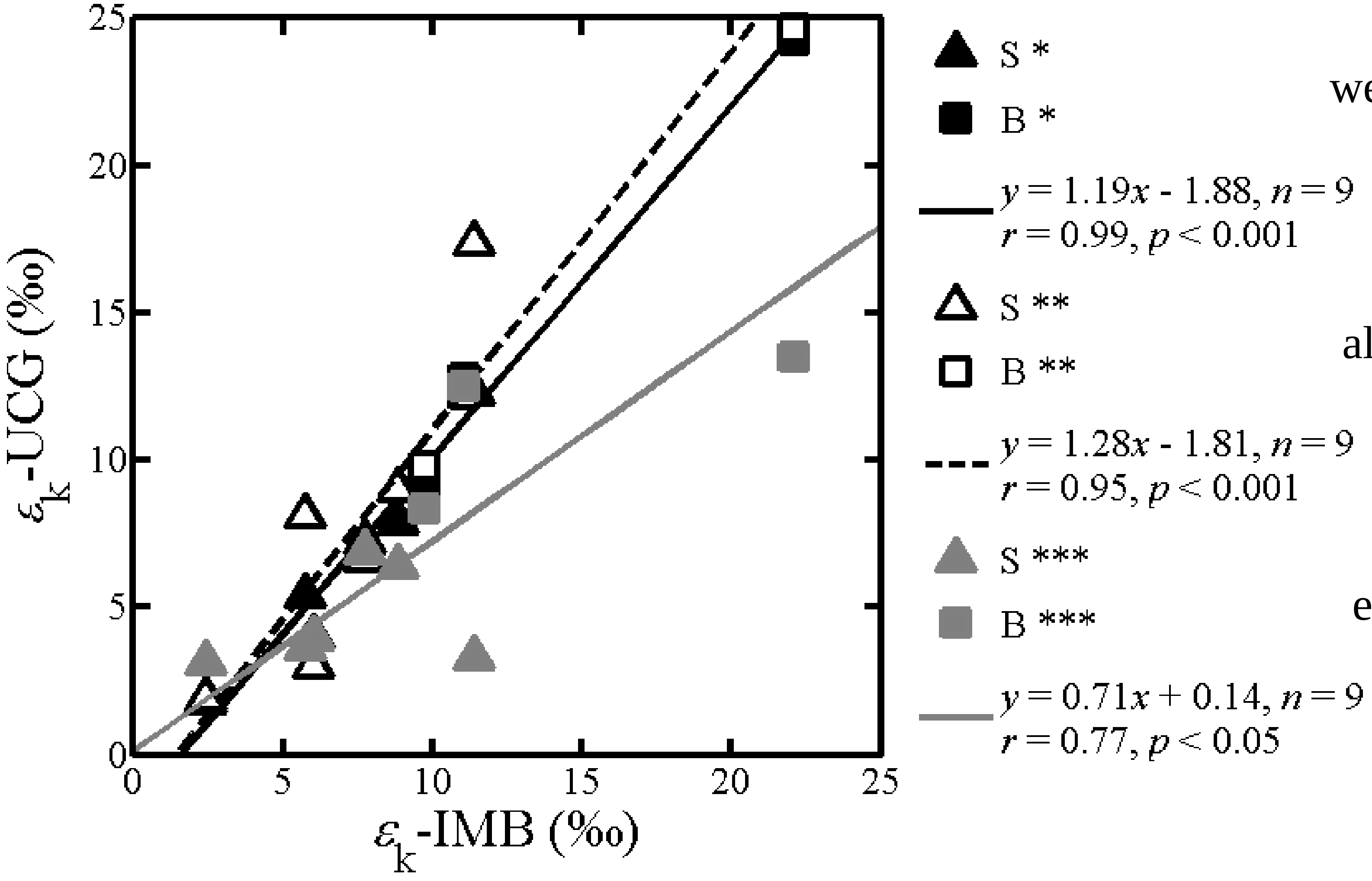


Figure 3. Comparison of the ^{18}O kinetic factor determined with the isotopic mass balance (IMB) and that determined with the unified Craig-Gordon model (UCG) for the pan experiments.

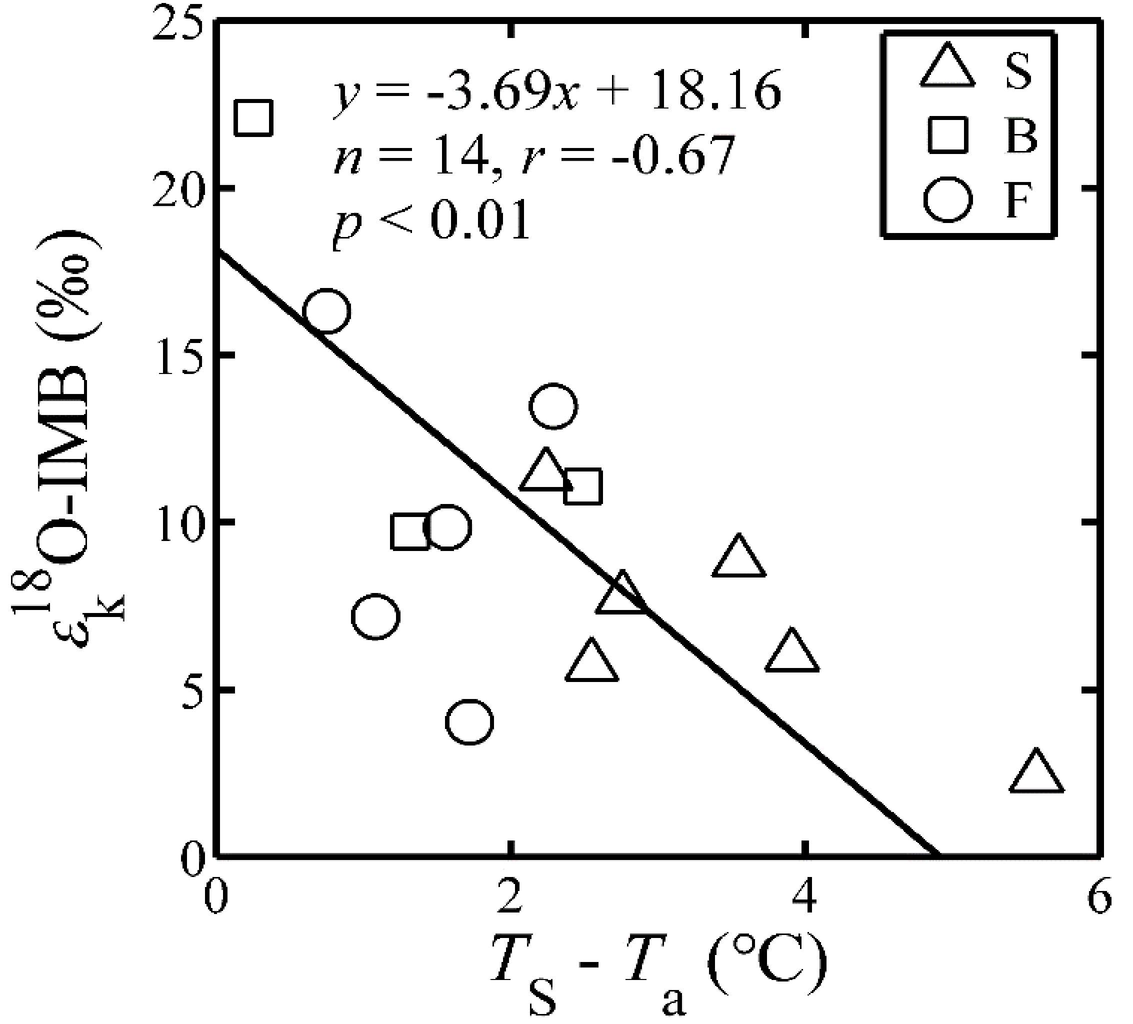
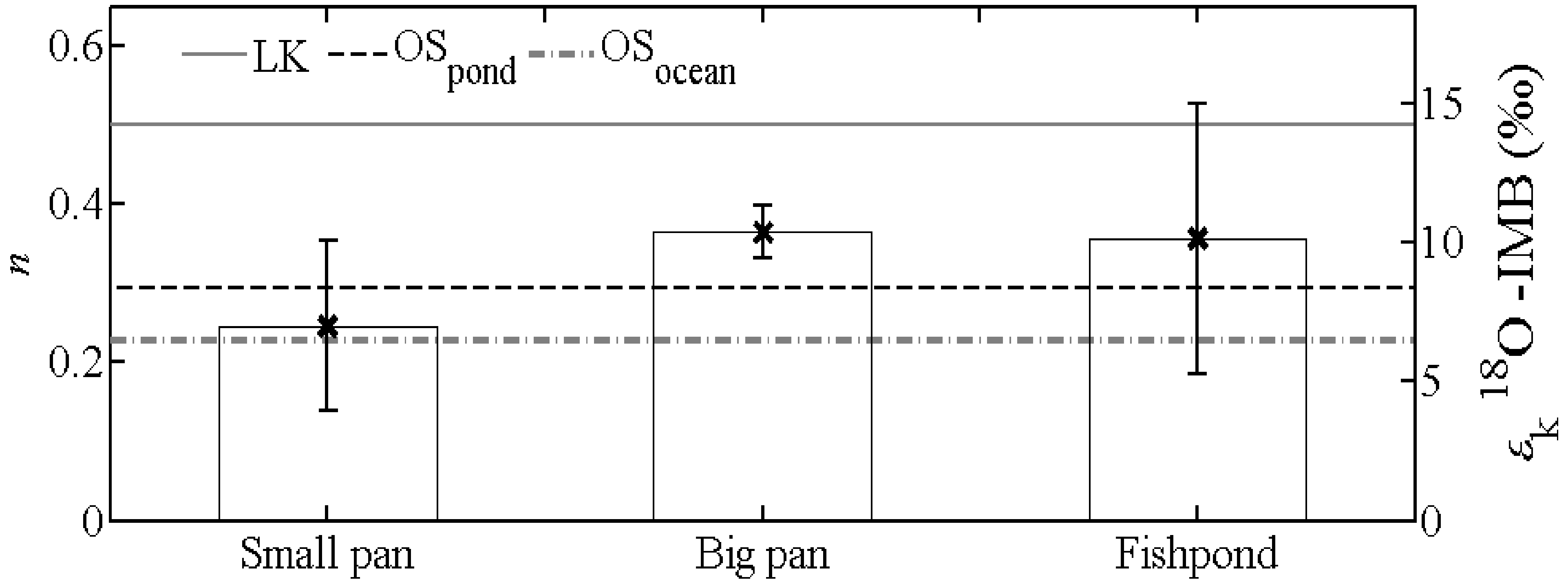


Figure 4. Relationship between water-to-air temperature difference $T_s - T_a$ and ^{18}O kinetic fractionation factor ε_k from isotope mass balance method.



7.0 ± 3.1 ‰ | 10.4 ‰ | 10.2 ± 4.9 ‰

Figure 5. Comparison of measured turbulent parameter *n* and kinetic factor ε_k with standard lake values (LK) and parameterization for ocean evaporation under smooth conditions (OS_{ocean}; Araguas-Araguas et al., 2000; Sturm et al., 2010) and using the observed wind speed of 1.64 m s^{-1} (OS_{pond}).

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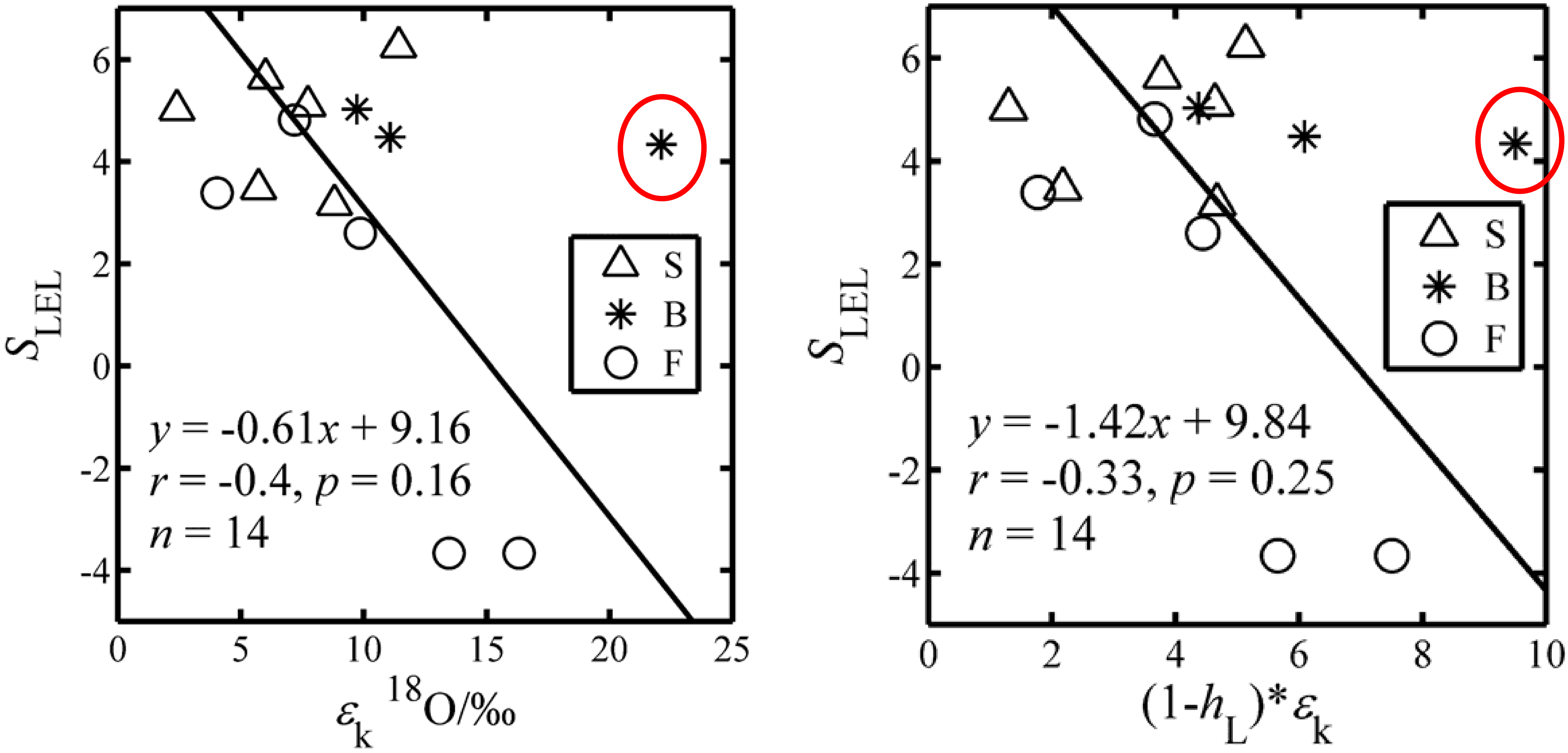
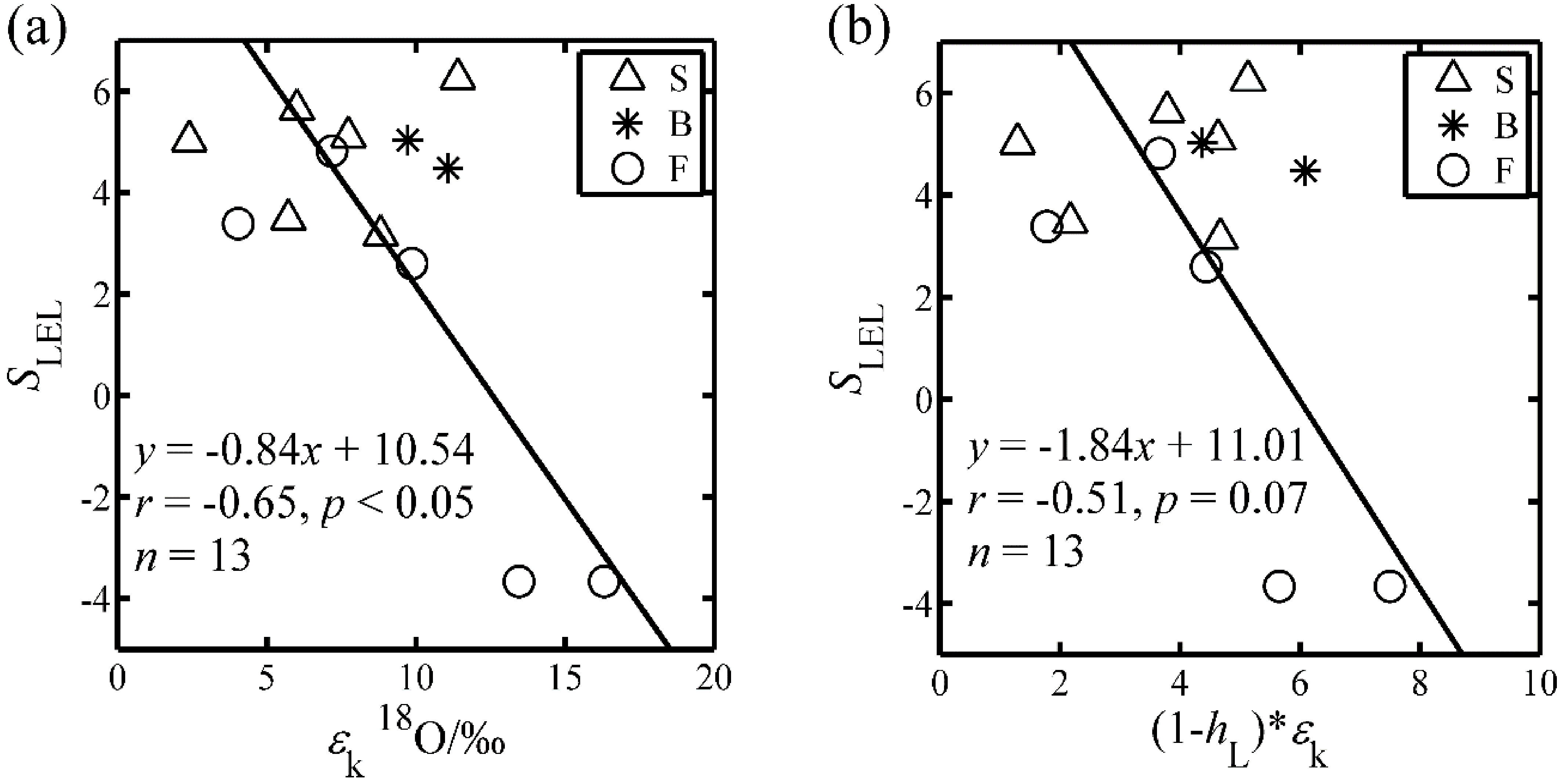
- **Relationship between the LEL slope and kinetic fractionation**





(a)
S
B
F
y = -0.84x + 10.54
r = -0.65, p < 0.05
n = 13
S_LEL
ε_k ^18O/‰
(b)
S
B
F
y = -1.84x + 11.01
r = -0.51, p = 0.07
n = 13
S_LEL
(1-h_L)*ε_k

Model 1

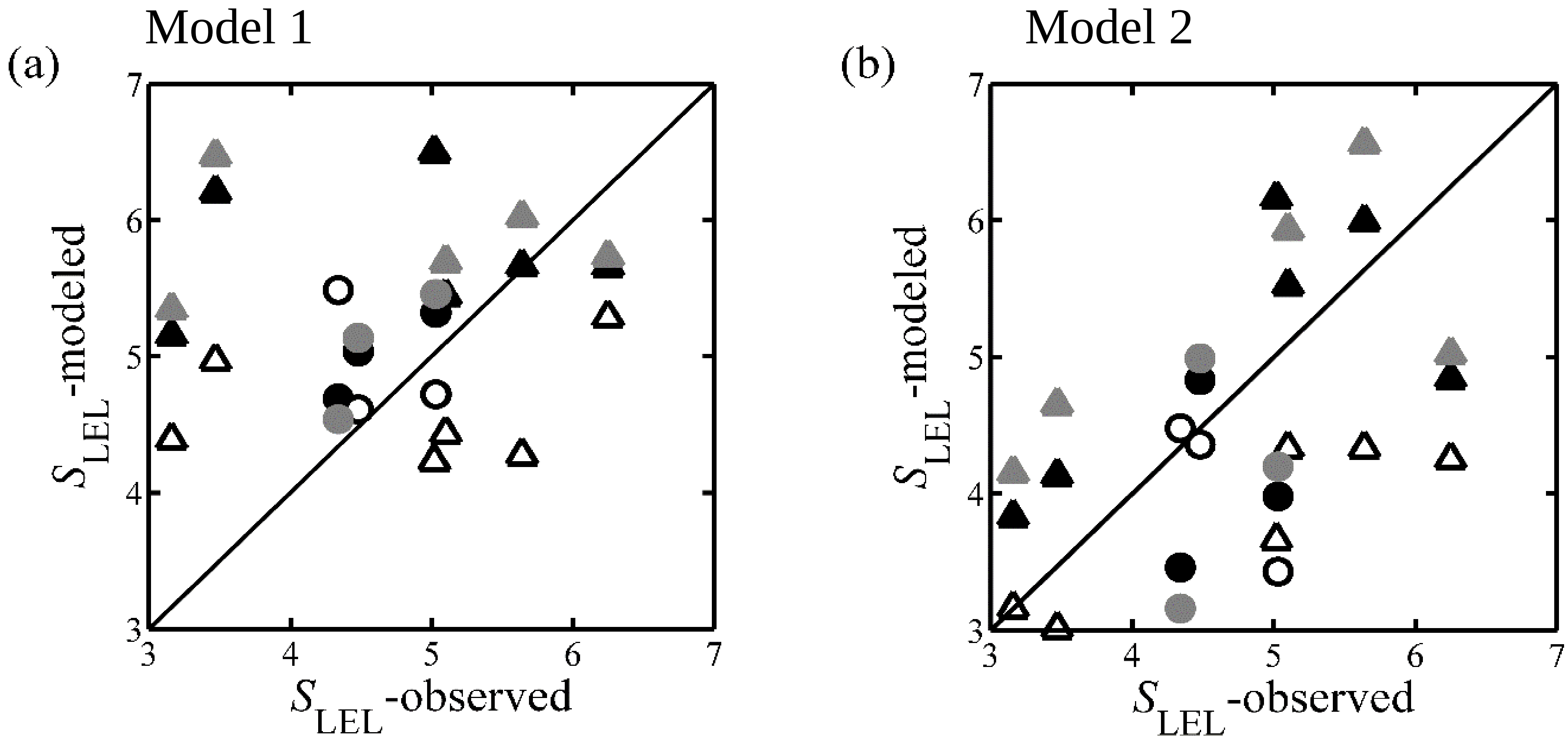
$$S_{\text{LEL}} = \frac{\left[\varepsilon_{eq} + (1-h)\varepsilon_k\right]_2}{\left[\varepsilon_{eq} + (1-h)\varepsilon_k\right]_{18}}$$

Brooks et al., 2014; Gat , 2010

Model 2

$$S_{\text{LEL}} = \frac{\left[\frac{h(\delta_V - \delta_{L,0}) + (1 + 10^{-3}\delta_{L,0})\left[(1-h)\varepsilon_k + \alpha_{eq}^{-1}\varepsilon_{eq}\right]}{10^3 h - (1-h)\varepsilon_k + \alpha_{eq}^{-1}\varepsilon_{eq}}\right]_2}{\left[\frac{h(\delta_V - \delta_{L,0}) + (1 + 10^{-3}\delta_{L,0})\left[(1-h)\varepsilon_k + \alpha_{eq}^{-1}\varepsilon_{eq}\right]}{10^3 h - (1-h)\varepsilon_k + \alpha_{eq}^{-1}\varepsilon_{eq}}\right]_{18}}$$

Gibson et al., 2008

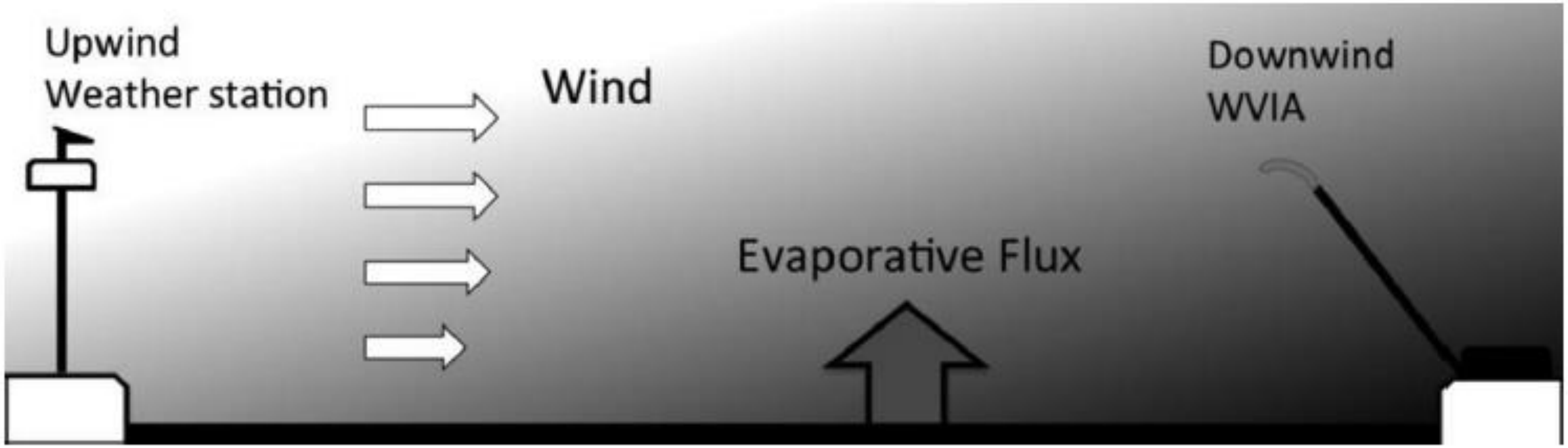


mean bias = 0.59, RMSE = 1.25

mean bias = -0.15, RMSE = 1.04

		S_{LEL} in model 1	S_{LEL} in model 2
Set 1 solid symbols	ε_k (^{18}O - IMB, D - IMB)	5.52 ± 0.56	4.75 ± 0.98
Set 2 open symbols	ε_k (^{18}O - LK, D - LK)	4.71 ± 0.45	3.89 ± 0.58
Set 3 grey symbols	ε_k (^{18}O - IMB, D - LK)	5.72 ± 0.75	5.09 ± 1.26

➢ Dependence of kinetic factor on lake location and size



'Lake size effect'

Feng et al., 2016

Table 3. Summary of ε_k (^{18}O) values in natural experiments.

Type	Area	ε_k (‰)	Method	Data source
		Small water body		
Small Pan	0.13 m^2	7.01	IMB	This study
Big Pan	1.20 m^2	10.39	IMB	This study (excluding B3)
Fishpond	6900 m^2	10.17	IMB	This study
Evap Pan G	0.36 m^2	14.25	UCG	Craig et al. (1963); Gonfiantini et al. (2018)
Evap Pan S	1.13 m^2	11.4	UCG	Skrzypek et al. (2015); Gonfiantini et al. (2018)
Lake Gara	160 m^2	8.55	UCG	Fontes and Gonfiantini (1967); Gonfiantini et al. (2018)
Lake Waid	0.22 km^2	5.86	Simplified IMB	Zimmermann (1979); Zuber (1983)
mean ± 1 SD		9.66 ± 2.82		
		Large water body		
Lake Burdur	250 km^2	11.93	Simplified IMB	Dincer (1968); Zuber (1983)
Lake Ihotry	91 km^2	7.1	$\theta = 0.5$, LK value	Poulin et al. (2019)
Lake Taihu	2400 km^2	8.19	gradient-diffusion	Xiao et al. (2017)
mean ± 1 SD		9.07 ± 2.53		

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- Our experimental study seems to be the first to accurately quantify kinetic fractionation factor for small water bodies.

- According to the result of IMB method, the mean kinetic factor measured in this study was 7.0 ± 3.1 ‰ with the small evaporation pan, 10.4 ‰ with the big evaporation pan, and 10.2 ± 4.9 ‰ with the fishpond between OS value and LK value.

- The kinetic factor shows a strong negative correlation with the water-to-air temperature difference $T_s - T_a$, suggesting that convective turbulence played a much more dominant role in controlling the kinetic effect.

- Kinetic effect plays an important role in determining the LEL slope, other factors, such as the isotopic compositions of water vapor and local water input, can also influence the slope value.

- There is no significant relationship between ε_k and lake size.




Thank you for listening !