蒸发过程中同位素分馏的观测和模拟研究

肖薇[1]，谢成玉[1]，胡勇博[1]，Xuhui Lee [2]

1. 南京信息工程大学 应用气象学院
2. Yale University School of Forestry and Environment

2020年11月2~4日，北京

汇报提纲

1. 基本理论
2. 蒸发同位素组分的观测方法
3. 动力学分馏系数及其影响机制

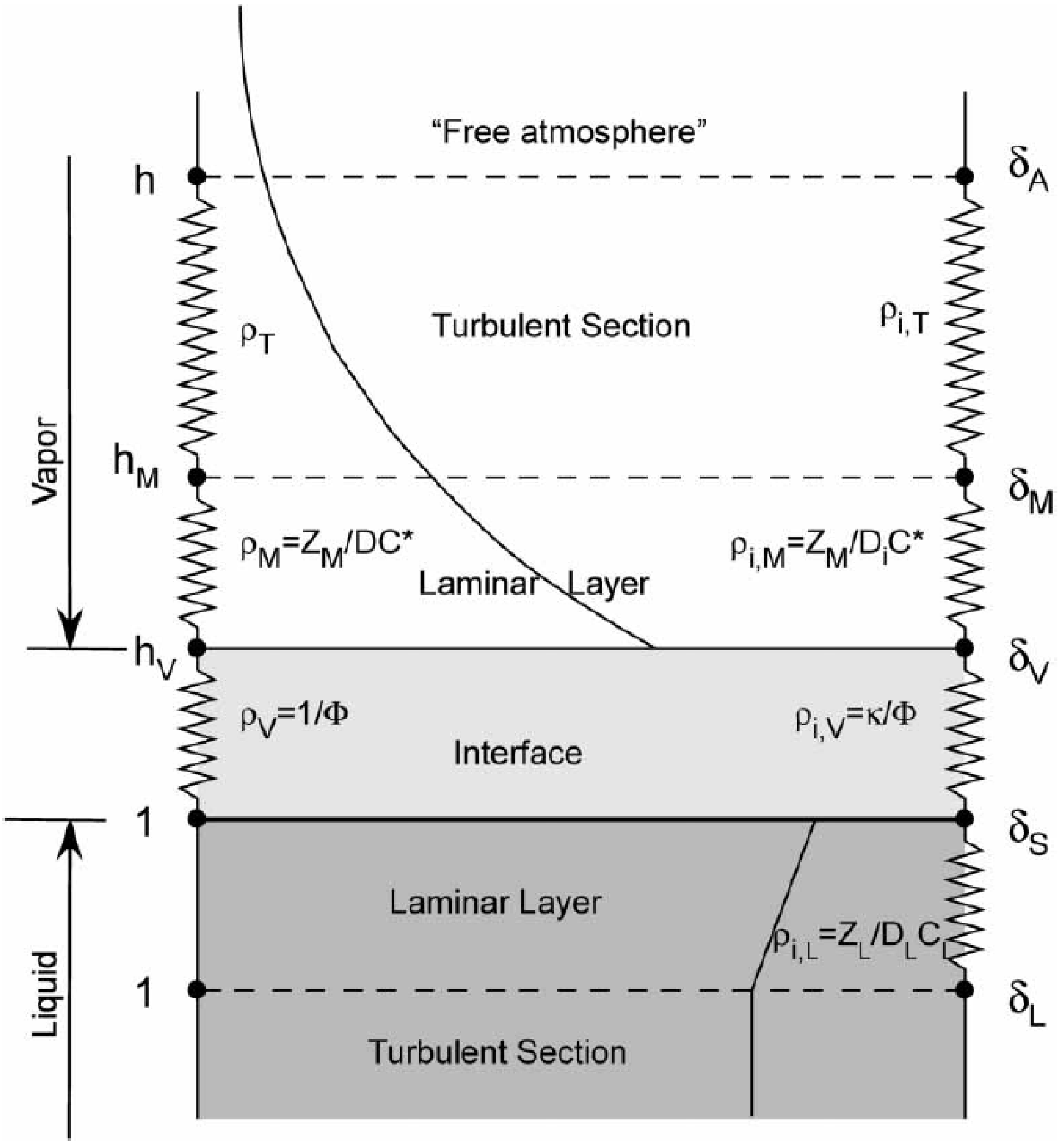
开放水面蒸发同位素分馏的理论框架

湍流扩散

分子扩散

分子扩散

湍流扩散



动力学分馏

平衡分馏

(Craig & Gorden, 1965)

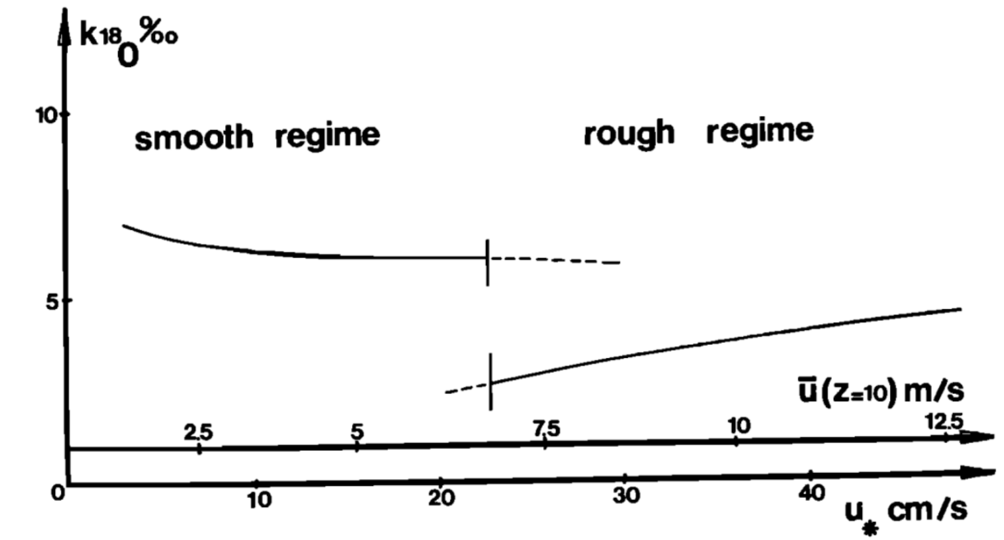
动力学分馏系数存在争议

Lake

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

$$n = 0.5$$

Ocean



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

For $H_2{}^{18}O$ $\varepsilon_k \approx 6.2‰$

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

开放水面蒸发同位素组分的模型

Craig-Gordon model

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

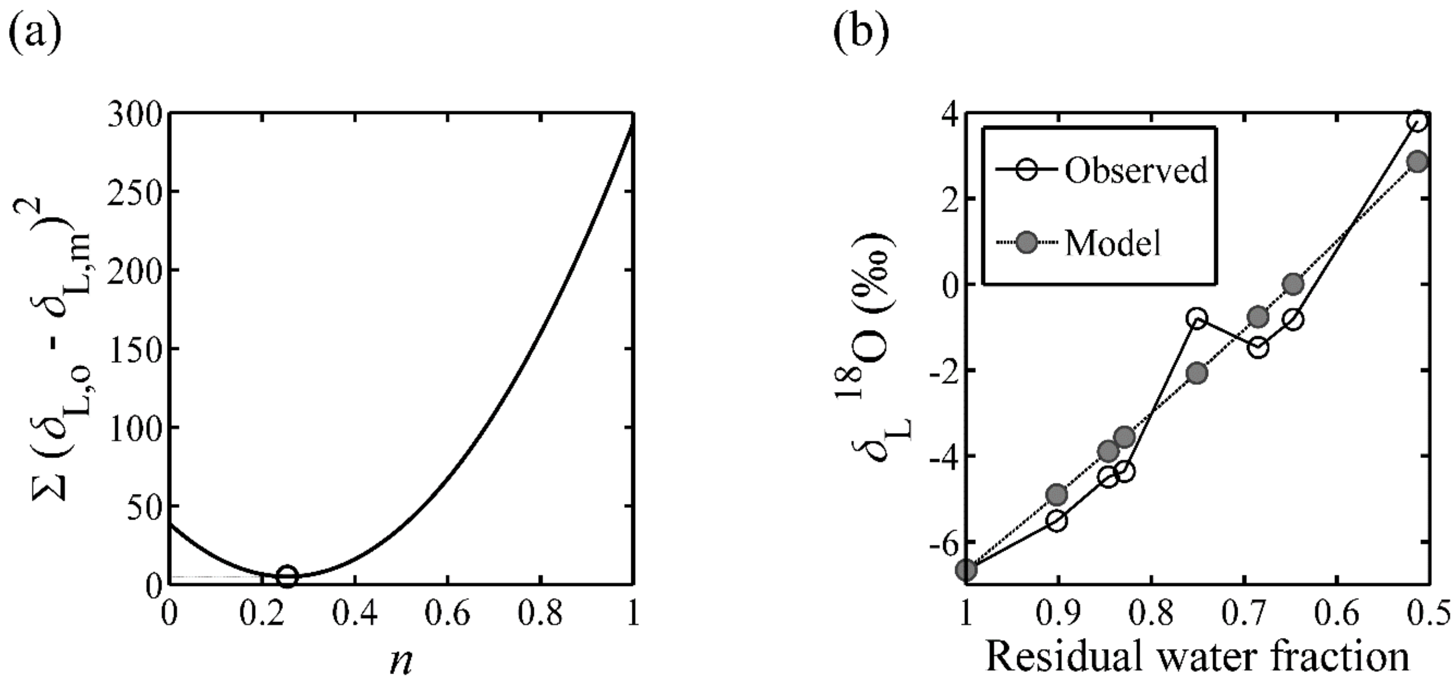
(Craig & Gordon 1965)

开放水面蒸发同位素组分的模型

Unified CG (UCG) model

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

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



(Gonfiantini et al., 2018)

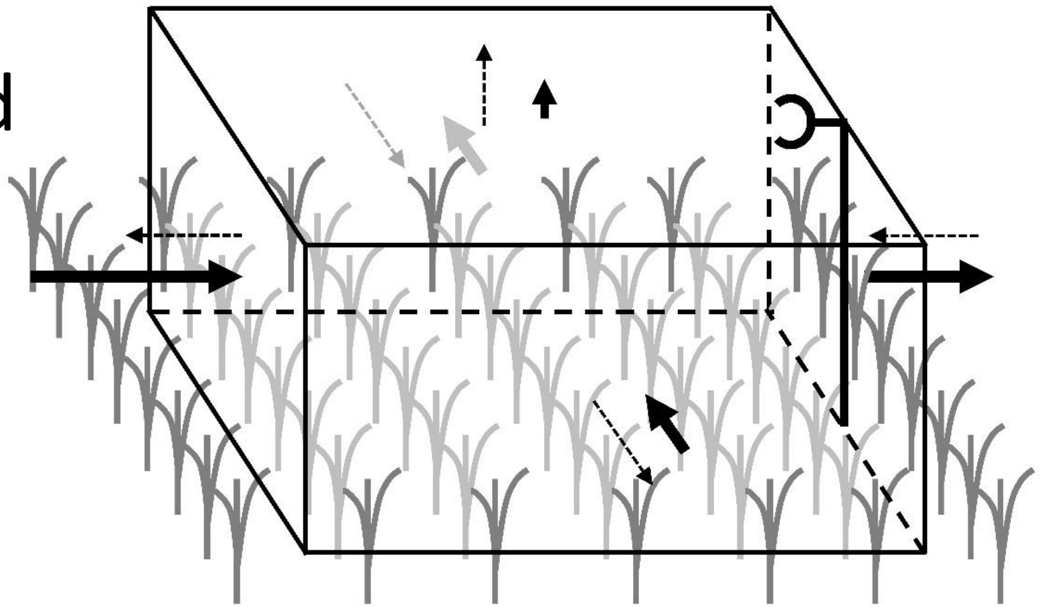
汇报提纲

1. 基本理论
2. 蒸发同位素组分的观测和计算方法
3. 动力学分馏系数及其影响机制

观测方法：通量梯度法

Eddy covariance control volume

- NEE as a residual of the integrated mass conservation equation



$$
\begin{aligned}
\mathrm{NEE} \;=\; & \underbrace{\int_0^z \overline{\rho}_d \frac{\partial \overline{s}_c}{\partial t}\mathrm{d}z'}_{\mathrm{I}} + \underbrace{\overline{\rho}_d \overline{w' s_c'}}_{\mathrm{II}} \\
& + \underbrace{\int_0^z \overline{\rho}_d \overline{u} \frac{\partial \overline{s}_c}{\partial x}\mathrm{d}z'}_{\mathrm{III}} + \underbrace{\int_0^z \overline{\rho}_d \overline{w} \frac{\partial \overline{s}_c}{\partial z}\mathrm{d}z'}_{\mathrm{IV}} + \underbrace{\int_0^z \overline{\rho}_d \frac{\partial \overline{u' s_c'}}{\partial x}\mathrm{d}z'}_{\mathrm{V}}
\end{aligned}
$$

(Lee 2018)

观测方法：通量梯度法

Eddy covariance in advection-free conditions

- Measurement equation

$$\mathrm{NEE} = \int_0^z \overline{\rho}_d \frac{\partial \overline{s}_c}{\partial t} \mathrm{d}z' + \overline{\rho}_d \overline{w' s_c'}$$

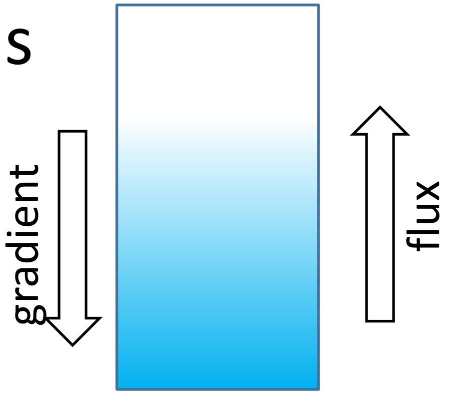
- Implicit assumption: by placing the measurement tower in an extensive, uniform and leveled field, the horizontal and vertical advection effects are negligible

观测方法：通量梯度法

Local first-order closure

- Fick’s law of molecular diffusion: flux due to molecular diffusion is proportional to the concentration gradient and is directed from point of high concentration to points of low concentration

$$F = -\kappa \frac{\partial c}{\partial z}$$



- Closure parameterizations or schemes for turbulent diffusion:

1 $$\overline{u'w'} = -K_m \frac{\partial \overline{u}}{\partial z}$$

2 $$\overline{v'w'} = -K_m \frac{\partial \overline{v}}{\partial z}$$

3 $$\overline{w'\theta'} = -K_h \frac{\partial \overline{\theta}}{\partial z}$$

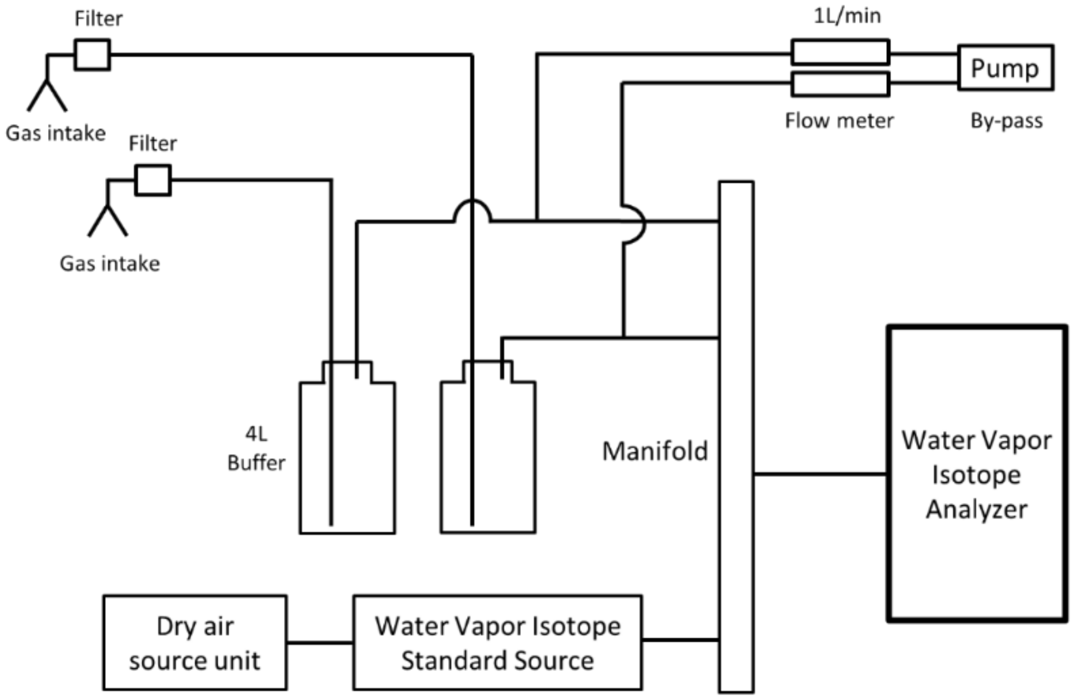
4 $$\overline{w's_v'} = -K_v \frac{\partial \overline{s}_v}{\partial z}$$

5 $$\overline{w's_c'} = -K_c \frac{\partial \overline{s}_c}{\partial z}$$

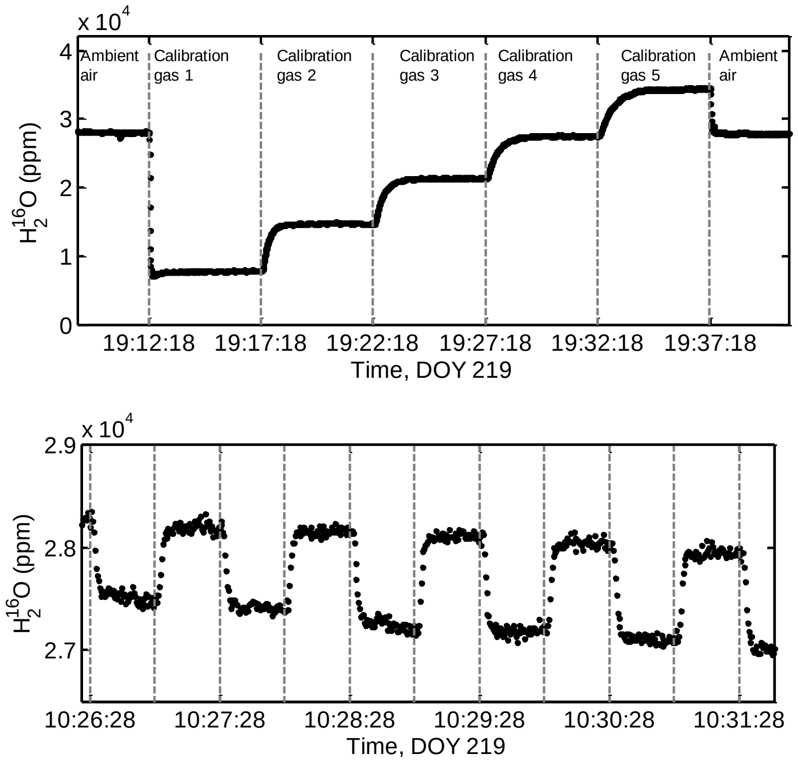
观测方法：通量梯度法

Experiment method: Flux-gradient method

$$F_{ET} = -\frac{K}{M_V}\frac{\Delta C}{\Delta z} \quad \& \quad F'_{ET} = -\frac{K}{M'_V}\frac{\Delta C'}{\Delta z} \Rightarrow R_{ET} = \frac{F'_{ET}}{F_{ET}} = \frac{\Delta C'}{\Delta C} \Rightarrow R_{ET} = \frac{\hat{c}'_{a,2} - \hat{c}'_{a,1}}{\hat{c}_{a,2} - \hat{c}_{a,1}}$$



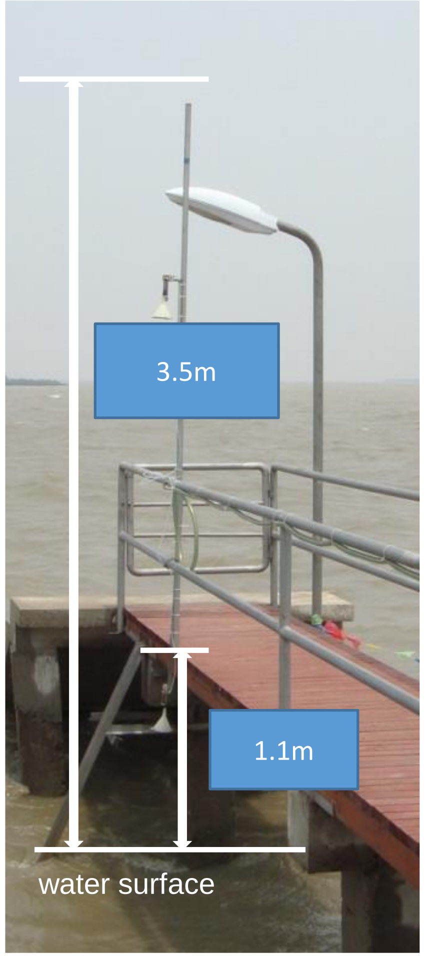
通量梯度观测系统示意图



标气和大气水汽切换示意图

观测方法：通量梯度法

通量梯度法观测大型湖泊太湖蒸发的$H_2^{18}O$和HDO组分



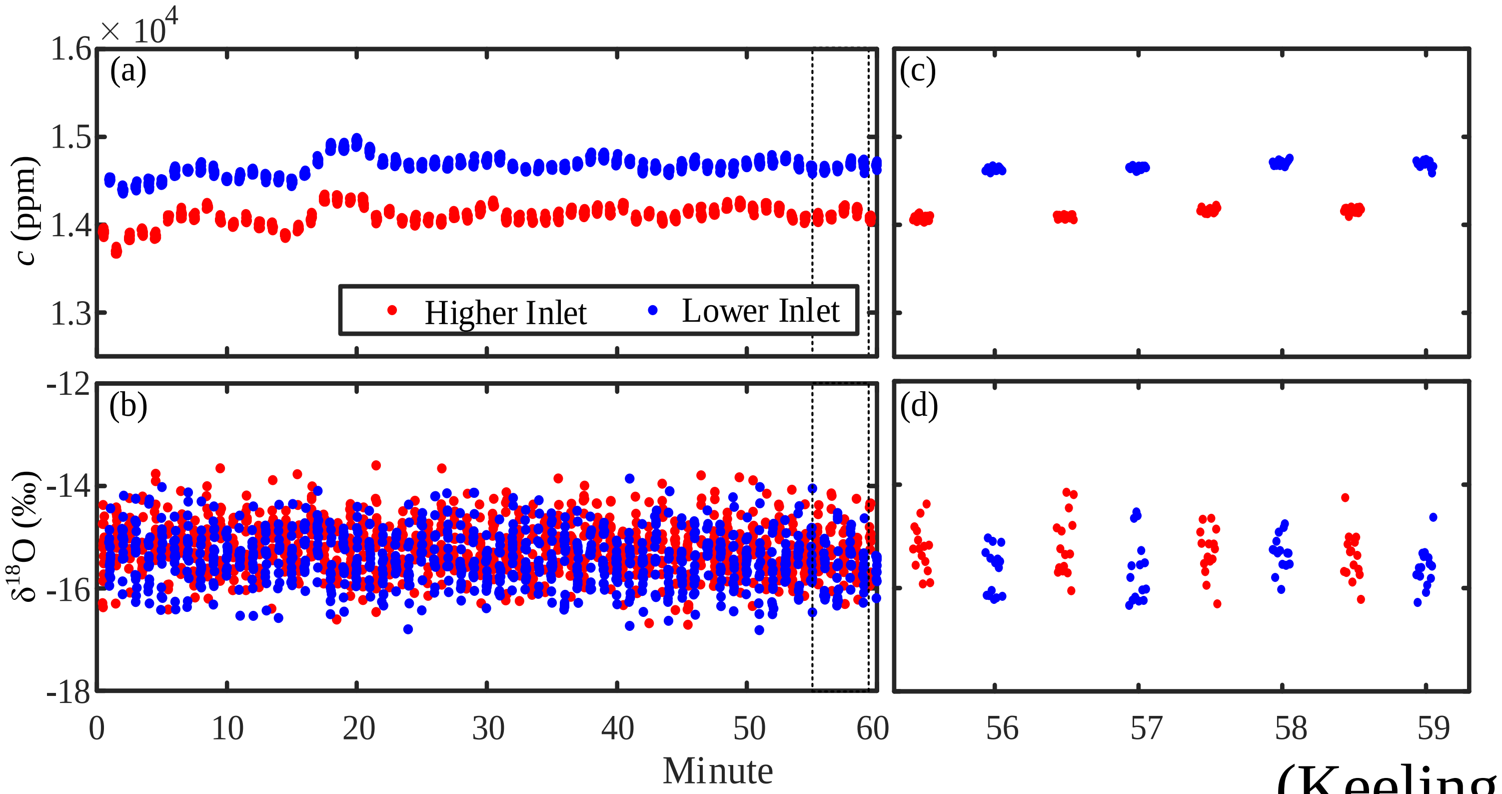
(Xiao et al., 2017, JGRA)

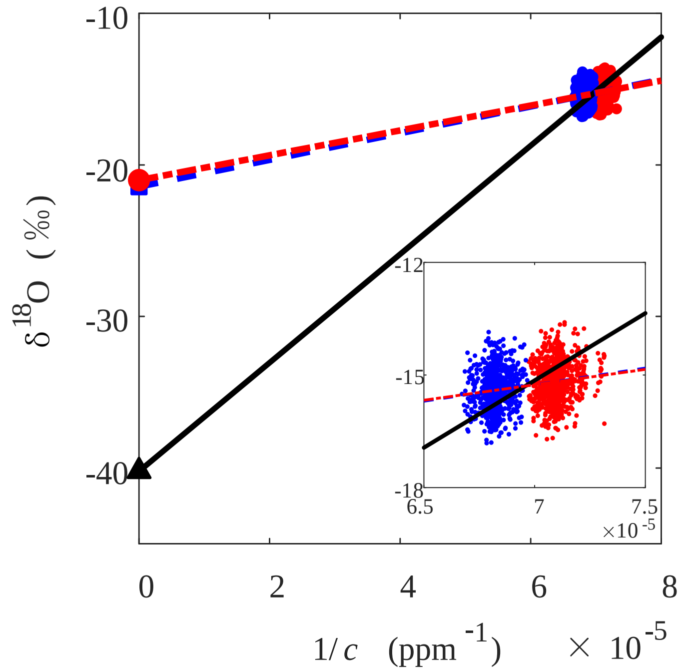
观测方法：Keeling Plot法

$$c_o = c_b + c_s$$

$$c_o\delta_o = c_b\delta_b + c_s\delta_s$$

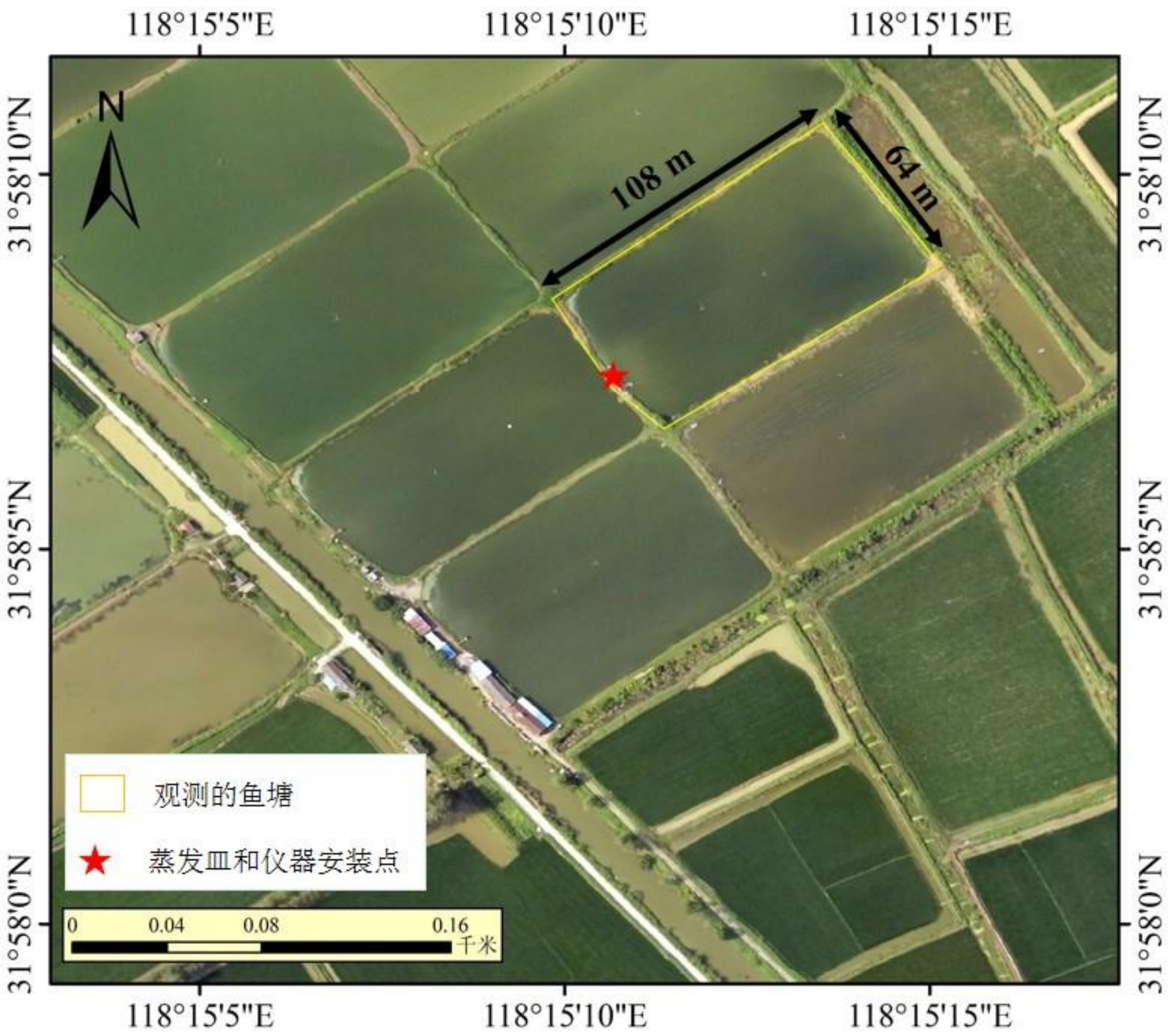
$$\Rightarrow \quad \delta_o = \frac{1}{c_o}(c_b\delta_b - c_b\delta_s) + \delta_s$$





(Keeling et al. 1958; Hu, Xiao et al. In review)

估算方法：稳定同位素质量守恒法



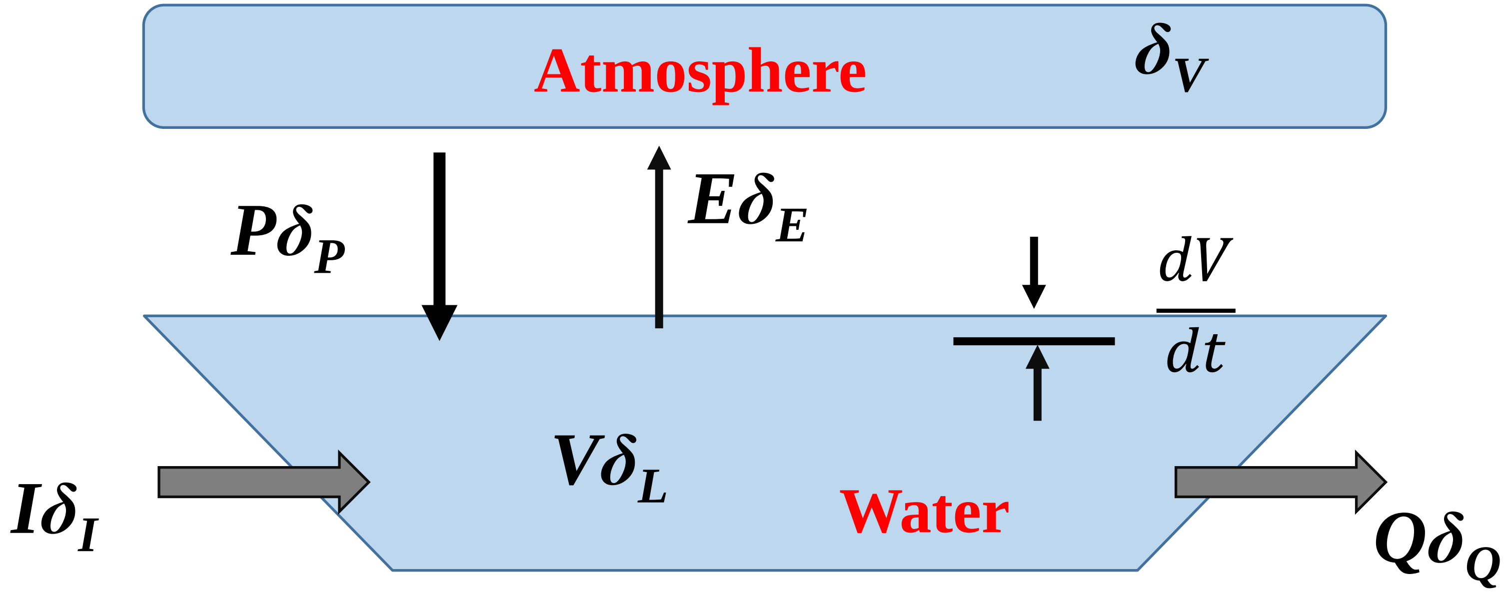
型号ADM7 直径20 cm

型号E601B 直径60 cm

(Xie, Xiao, et al., In review)

估算方法：稳定同位素质量守恒法

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



估算方法：稳定同位素质量守恒法

Water mass balance equation

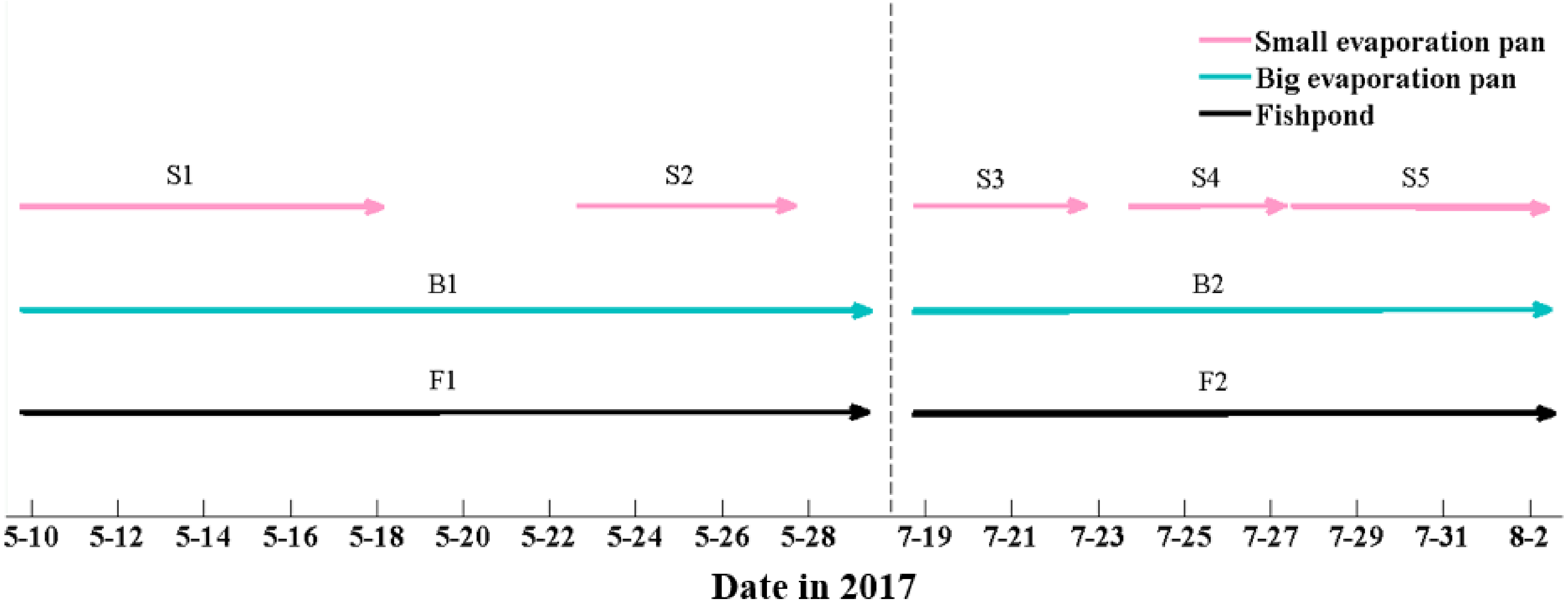
$$\mathrm{M}\delta_L = \mathrm{M}^*\delta_L^* + m\delta_L' + E\delta_E$$

Craig-Gordon model

$$\delta_\mathrm{E} = \frac{\alpha_\mathrm{eq}^{-1}\delta_\mathrm{L} - h\delta_\mathrm{V} - \varepsilon_\mathrm{eq} - (1-h)\varepsilon_\mathrm{k}}{1-h+10^{-3}(1-h)\varepsilon_\mathrm{k}}$$

Unified Craig-Gordon model

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



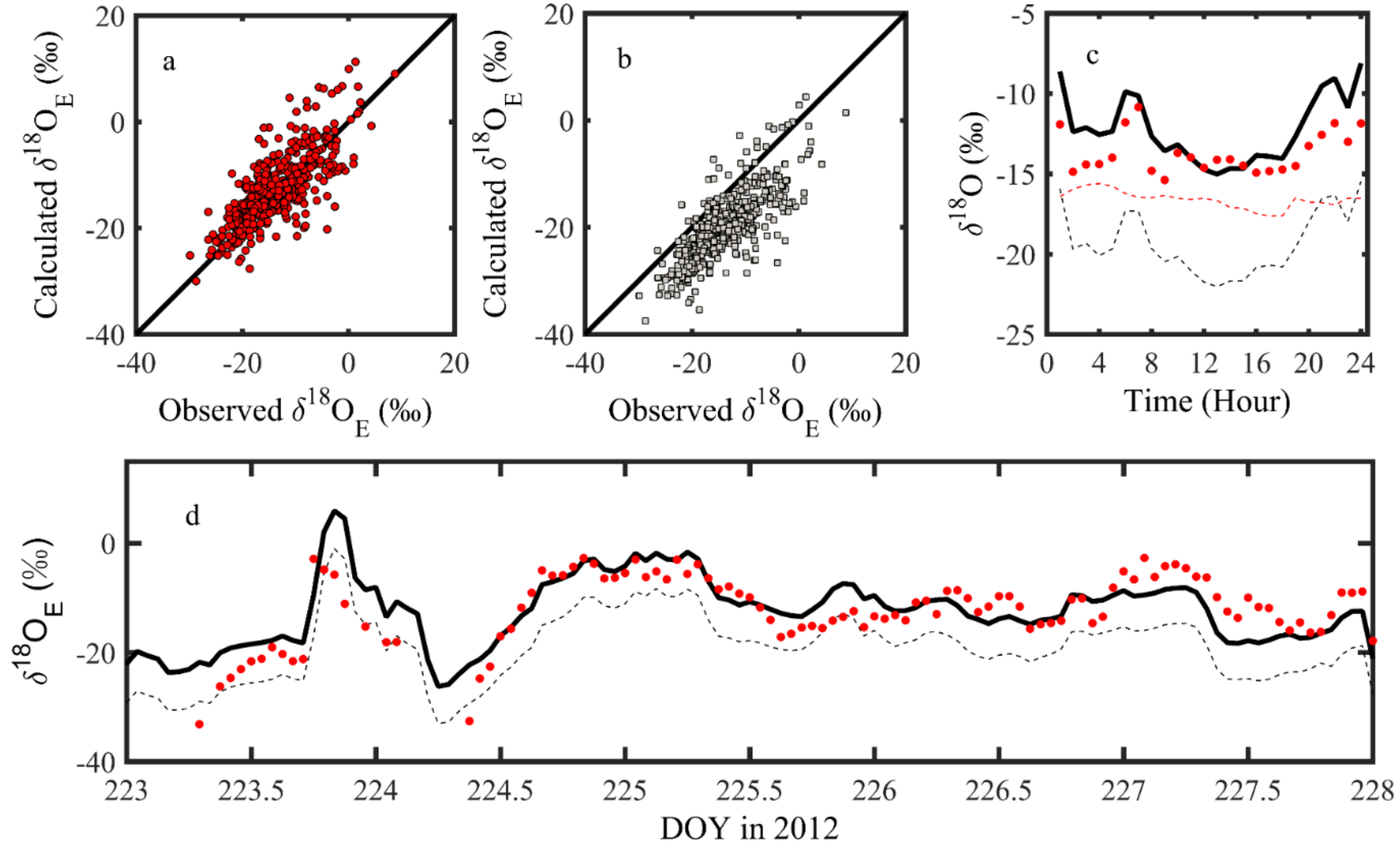
汇报提纲

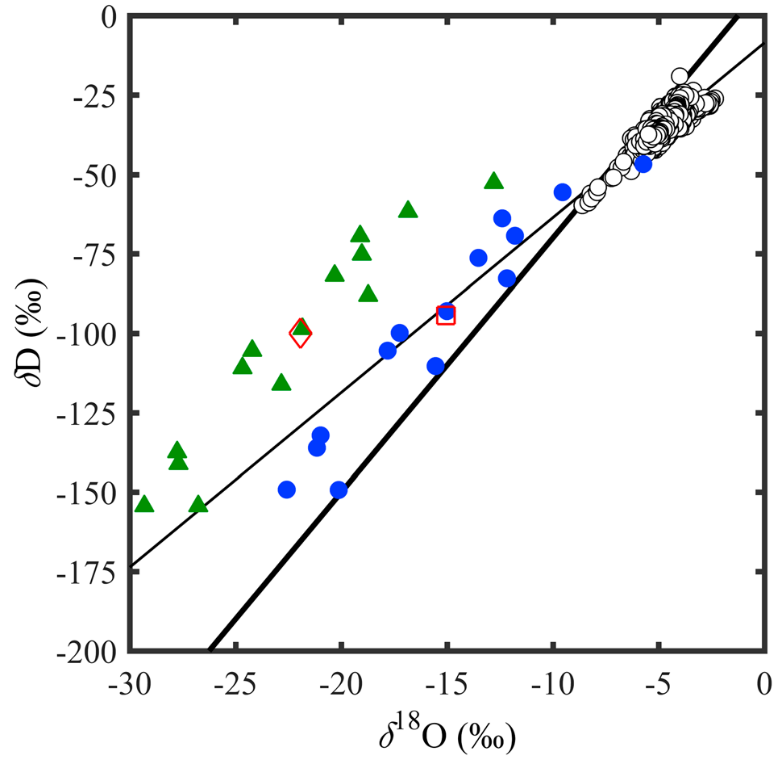
1. 基本理论
2. 蒸发同位素组分的观测方法
3. 动力学分馏系数及其影响机制

大型湖泊的动力学分馏系数

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

Ocean factor **Lake factor**



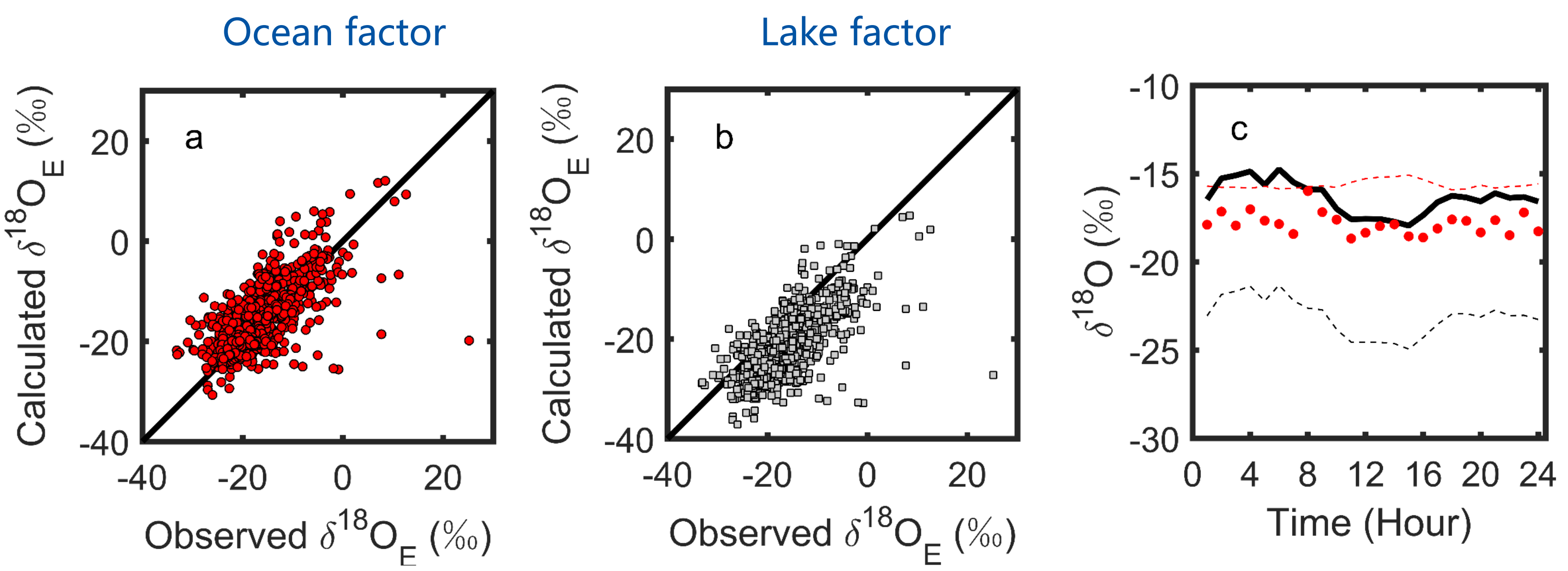


(Xiao et al., JGRA, 2017)

大型湖泊的动力学分馏系数

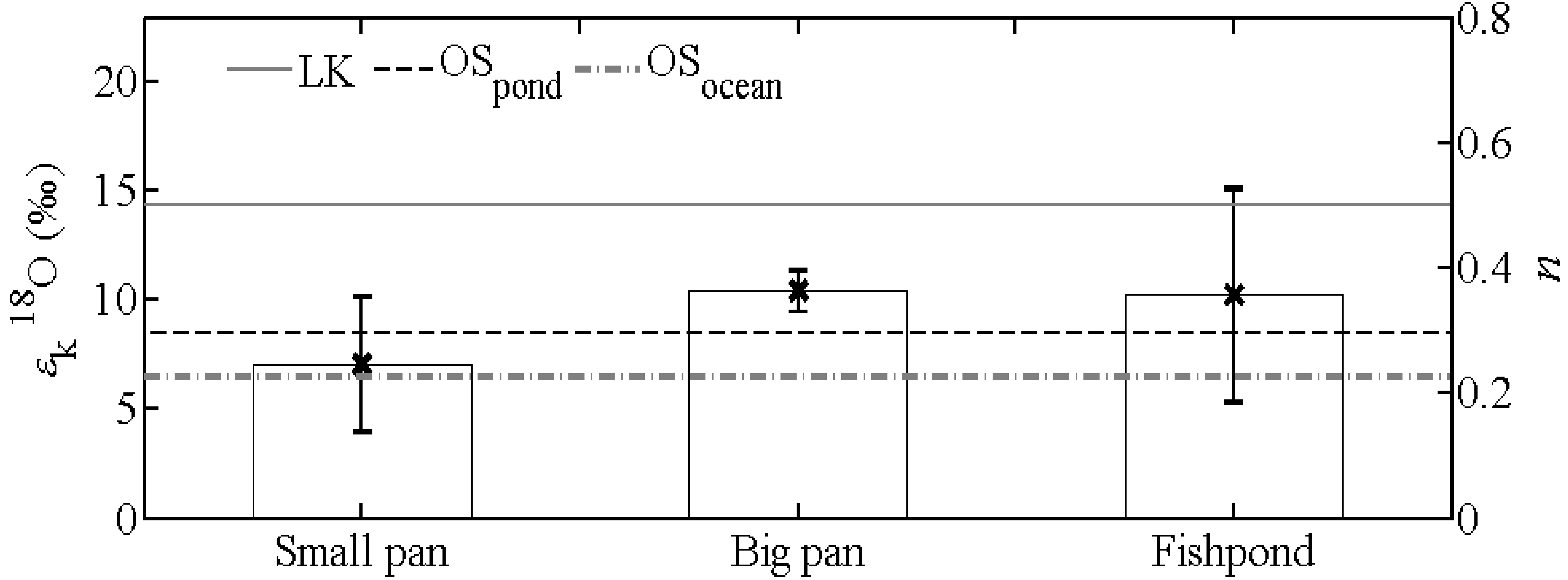
Lake with short fetch

Answer: The effective ε_k was not very sensitive to fetch.



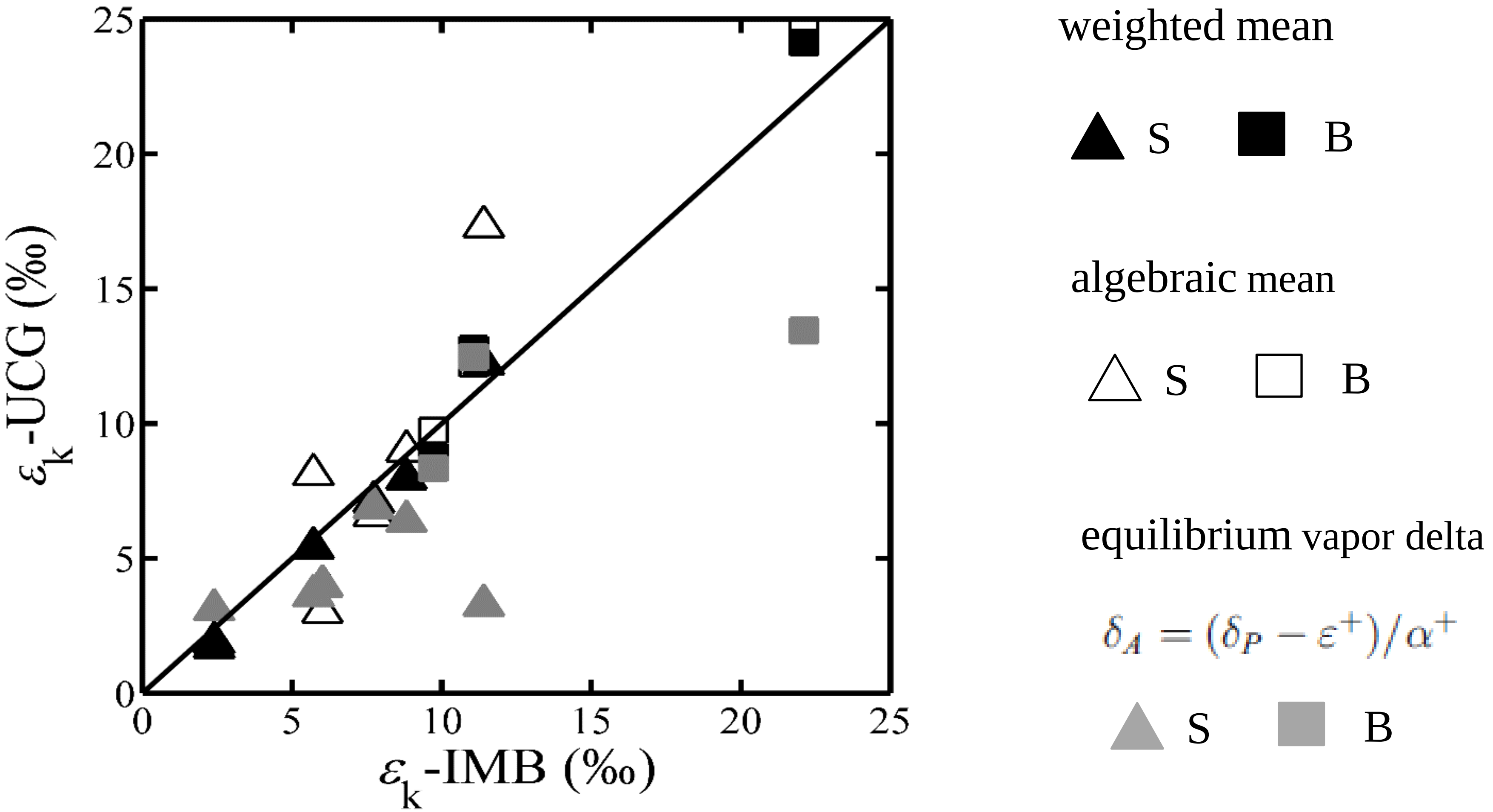
(Xiao et al., JGR, 2017)

水塘和蒸发皿的动力学分馏系数



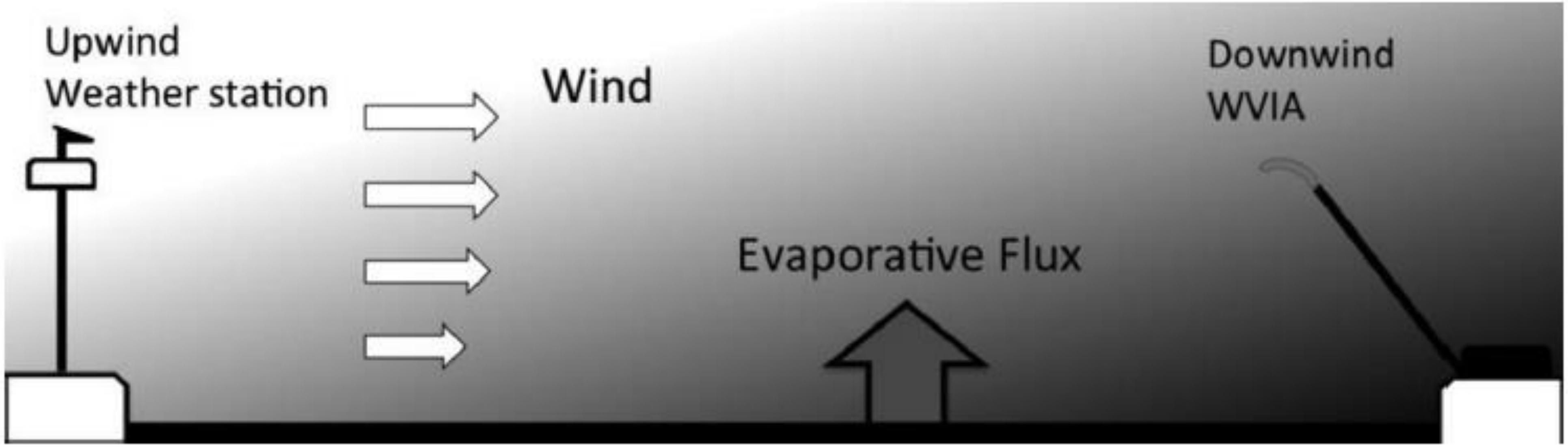
CG vs UCG

基于直接观测大气水汽同位素和蒸发加权平均值输入变量这两点的改进，UCG模型计算的ε_k与同位素质量守恒法计算的结果非常一致



动力学分馏效应的影响因素——水体面积?

➢ **Dependence of kinetic factor on lake location and size**



‘Lake size effect’

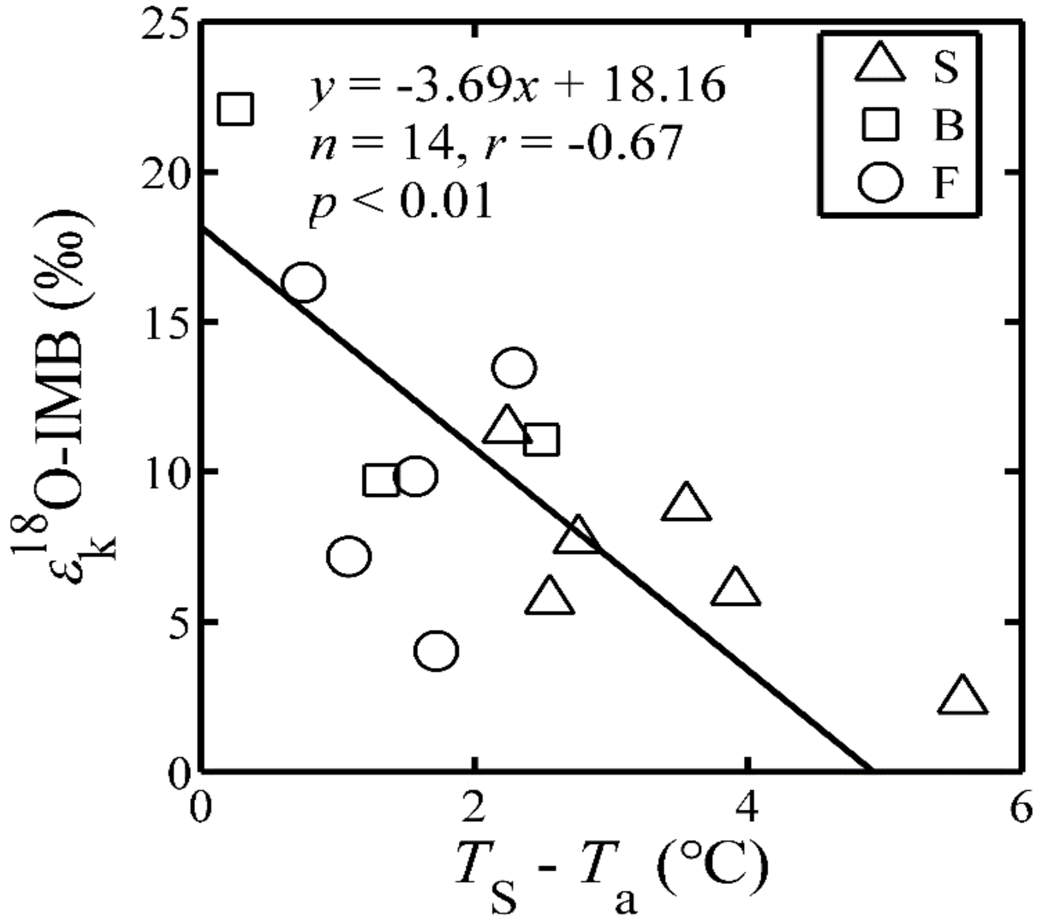
Feng et al., 2016

动力学分馏效应的影响因素——水体面积? No！

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	14.20	UCG	Craig et al. (1963); Gonfiantini et al. (2018)
Evap Pan S	1.13 m^2	11.36	UCG	Skrzypek et al. (2015); Gonfiantini et al. (2018)
Lake Gara	160 m^2	8.52	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		**9.64 ± 2.80**		
		Large water body		
Lake Burdur	250 km^2	11.93	Simplified IMB	Dincer (1968); Zuber (1983)
Lake Ihotry	91 km^2	7.1	θ = 0.5, LK value	Poulin et al. (2019)
Lake Taihu	2400 km^2	8.26	gradient-diffusion	Xiao et al. (2017)
mean ± 1 SD		**9.10 ± 2.52**		

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

动力学分馏效应的影响因素——对流or湍流？ 对流！



- 与相对湿度h_L的相关性不显著
- 与摩擦风速u_*的相关性不显著
- $T_s - T_a$驱动大气表层产生垂直方向上的对流
- 垂直方向的对流相对于机械湍流更能影响动力分馏效应

感谢您的聆听，敬请批评指正！

Thank you for your attention!

Email: wei.xiao@nuist.edu.cn

https://yncenter.sites.yale.edu