Isotopic kinetic fractionation of evaporation from small water bodies

Chengyu Xie

2020/07/03
Introduction

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Result

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Conclusion
1 Introduction

- Small lakes and ponds (area < 1 km²) 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 $\delta_E$ calculated with the Craig-Gordon (CG) model, one of the most critical parameters for the CG model calculation is the kinetic fractionation factor ($\varepsilon_k$) (Horita, 2008; Xiao et al., 2017).
C-G model

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

LK

\[\varepsilon_k = n \left( \frac{D}{D_i} - 1 \right) 10^3 \quad n = 0.5\]

For \(H_2^{18}O\) \(\varepsilon_k = 14.2\%\)

For HDO \(\varepsilon_k = 12.5\%\)

(OS)

(Craig and Gordon, 1965; Merlivat and Jouzel, 1979)
\[ E = 21.5 \times 10^8 \text{ m}^3 \text{ water y}^{-1}, \text{OS } \varepsilon_k \] 72%

\[ E = 12.5 \times 10^8 \text{ m}^3 \text{ water y}^{-1}, \text{LK } \varepsilon_k \]

\[ E \sim \delta_E \sim \varepsilon_k \sim n \]

37%↑ 23%↓ 40%↓ 0.2↓

(Xiao et al., 2017)

<table>
<thead>
<tr>
<th>Survey</th>
<th>( \varepsilon_k )</th>
<th>Method</th>
<th>Drawback</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fontes and Gonfiantini, 1967</td>
<td>8.55 %0</td>
<td>unified CG model</td>
<td>( \delta_V ) was not measured</td>
</tr>
<tr>
<td>Xiao et al. (2017)</td>
<td>6.2 %0</td>
<td>gradient-diffusion</td>
<td>large lake</td>
</tr>
<tr>
<td>Gonfiantini et al. (2018)</td>
<td>8.5 %0</td>
<td>unified CG model</td>
<td>( \delta_V ) was not measured</td>
</tr>
</tbody>
</table>
Objectives

(1) To measure the $\varepsilon_k$ of evaporation of small water bodies for the oxygen isotopes,

(2) To investigate the relationship between $\varepsilon_k$ 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** → **C-G model**

**Atmosphere**

\[ \delta_V \]

\[ P \delta_P \]

\[ E \delta_E \]

\[ \frac{dV \delta_L}{dt} \]

\[ V \delta_L \]

\[ Q \delta_Q \]

**Small Pan**

ADM 7: diameter 20cm

**Big Pan**

E601B: diameter 60cm

7000 m²
### Table 1. Summary of environmental variables. Here, $\delta_V$, $u^*$, $h_L$ and $T_S$ were weighted mean values by $\rho_a u (q_s - q_a)$.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Period</th>
<th>D</th>
<th>$18$O</th>
<th>$u^*$</th>
<th>$h_L$</th>
<th>$T_S$</th>
<th>$E$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\delta_{L,0}$</td>
<td>$\delta_{L,f}$</td>
<td>$\delta_V$</td>
<td>$\delta_{L,0}$</td>
<td>$\delta_{L,f}$</td>
<td>$\delta_V$</td>
</tr>
<tr>
<td>S1</td>
<td>2017/05/09 — 2017/05/17</td>
<td>-46.8</td>
<td>5.3</td>
<td>-83.7</td>
<td>-6.7</td>
<td>3.8</td>
<td>-13.1</td>
</tr>
<tr>
<td>S2</td>
<td>2017/05/24 — 2017/05/27</td>
<td>-45.9</td>
<td>-12.3</td>
<td>-80.8</td>
<td>-5.0</td>
<td>0.2</td>
<td>-12.7</td>
</tr>
<tr>
<td>S3</td>
<td>2017/07/18 — 2017/07/22</td>
<td>-40.0</td>
<td>-20.9</td>
<td>-101.8</td>
<td>-6.6</td>
<td>0.0</td>
<td>-14.3</td>
</tr>
<tr>
<td>S4</td>
<td>2017/07/23 — 2017/07/28</td>
<td>-36.9</td>
<td>-9.8</td>
<td>-78.9</td>
<td>-5.6</td>
<td>0.0</td>
<td>-11.2</td>
</tr>
<tr>
<td>S5</td>
<td>2017/07/28 — 2017/08/02</td>
<td>-37.9</td>
<td>-27.3</td>
<td>-97.9</td>
<td>-6.4</td>
<td>-3.0</td>
<td>-13.7</td>
</tr>
<tr>
<td>S6</td>
<td>2017/10/31 — 2017/11/10</td>
<td>-35.2</td>
<td>-6.6</td>
<td>-122.9</td>
<td>-5.2</td>
<td>-0.1</td>
<td>-20.0</td>
</tr>
<tr>
<td>B1</td>
<td>2017/05/09 — 2017/05/29</td>
<td>-45.9</td>
<td>-23.1</td>
<td>-83.1</td>
<td>-6.8</td>
<td>-1.9</td>
<td>-12.9</td>
</tr>
<tr>
<td>B2</td>
<td>2017/07/18 — 2017/08/01</td>
<td>-40.1</td>
<td>-28.7</td>
<td>-92.5</td>
<td>-6.6</td>
<td>-3.5</td>
<td>-13.1</td>
</tr>
<tr>
<td>B3</td>
<td>2017/10/31 — 2017/11/13</td>
<td>-46.6</td>
<td>-38.1</td>
<td>-126.9</td>
<td>-7.0</td>
<td>-5.2</td>
<td>-20.6</td>
</tr>
<tr>
<td>F1</td>
<td>2017/05/09 — 2017/05/29</td>
<td>-15.7</td>
<td>-10.5</td>
<td>-82.8</td>
<td>-1.5</td>
<td>-1.0</td>
<td>-12.9</td>
</tr>
<tr>
<td>F2</td>
<td>2017/07/18 — 2017/08/01</td>
<td>-22.0</td>
<td>-20.5</td>
<td>-97.6</td>
<td>-2.3</td>
<td>-1.9</td>
<td>-13.7</td>
</tr>
<tr>
<td>F3</td>
<td>2018/07/30 — 2018/08/13</td>
<td>-13.8</td>
<td>-16.3</td>
<td>-91.8</td>
<td>-1.0</td>
<td>-0.7</td>
<td>-13.5</td>
</tr>
<tr>
<td>F4</td>
<td>2018/08/29 — 2018/10/06</td>
<td>-24.0</td>
<td>-20.8</td>
<td>-104.9</td>
<td>-1.6</td>
<td>-1.1</td>
<td>-15.5</td>
</tr>
<tr>
<td>F5</td>
<td>2018/10/11 — 2018/11/30</td>
<td>-20.9</td>
<td>-17.1</td>
<td>-103.9</td>
<td>-0.8</td>
<td>-0.2</td>
<td>-16.5</td>
</tr>
</tbody>
</table>

Note, subscript 0 denotes the initial state of experiment, subscript f denotes the final state of experiment.
Unified CG (UCG) model

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

\[ A = -\frac{h}{\alpha_{dif}^x (1 - h)} \quad B = \frac{1}{\alpha_{eq} \alpha_{dif}^x (1 - h)} - 1 \]

\[ \frac{A}{B} = -\frac{h \alpha_{eq}}{1 - \alpha_{eq} \alpha_{dif}^x (1 - h)} \]

Gonfiantini et al., 2018
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Figure 1. Time series of environmental variables during Experiment S2.

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

$\epsilon_k$ of 6.01 %o for $^{18}$O
Figure 2. Application of the unified Craig-Gordon model to Experiment S1.

\[ \sum (\delta_{L,o} - \delta_{L,m})^2 = 5.08 \quad n_{\text{IMB}} = 0.28 \quad n_{\text{model}} = 0.25 \quad \varepsilon_k = 7.23 \% \]
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 $\varepsilon_k$ from isotope mass balance method.
Figure 5. Comparison of measured turbulent parameter $n$ and kinetic factor $\varepsilon_k$ with standard lake values (LK) and parameterization for ocean evaporation under smooth conditions ($OS_{\text{ocean}}$; Araguas-Araguas et al., 2000; Sturm et al., 2010) and using the observed wind speed of 1.64 m s$^{-1}$ ($OS_{\text{pond}}$).
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➢ Relationship between the LEL slope and kinetic fractionation

![Graph](image)

- For the first graph:
  - Equation: $y = -0.61x + 9.16$
  - Correlation coefficient: $r = -0.4$, $p = 0.16$
  - Number of data points: $n = 14$

- For the second graph:
  - Equation: $y = -1.42x + 9.84$
  - Correlation coefficient: $r = -0.33$, $p = 0.25$
  - Number of data points: $n = 14$
(a) \[ y = -0.84x + 10.54 \]
\[ r = -0.65, \quad p < 0.05 \]
\[ n = 13 \]

(b) \[ y = -1.84x + 11.01 \]
\[ r = -0.51, \quad p = 0.07 \]
\[ n = 13 \]
Model 1

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

Brooks et al., 2014; Gat, 2010

Model 2

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

\[ \frac{[h(\delta_V - \delta_{L,0}) + (1 + 10^{-3}\delta_{L,0})\left[(1-h)\varepsilon_k + \alpha_{eq}^{-1}\varepsilon_{eq}\right]]}{10^3 h - (1-h)\varepsilon_k + \alpha_{eq}^{-1}\varepsilon_{eq}} \] \]

Gibson et al., 2008
Model 1

mean bias = 0.59, RMSE = 1.25

Set 1 solid symbols $\varepsilon_k (^{18}\text{O - IMB, D - IMB})$
5.52 ± 0.56

Set 2 open symbols $\varepsilon_k (^{18}\text{O - LK, D - LK})$
4.71 ± 0.45

Set 3 grey symbols $\varepsilon_k (^{18}\text{O - IMB, D - LK})$
5.72 ± 0.75

Model 2

mean bias = -0.15, RMSE = 1.04

Set 1 solid symbols $\varepsilon_k (^{18}\text{O - IMB, D - IMB})$
4.75 ± 0.98

Set 2 open symbols $\varepsilon_k (^{18}\text{O - LK, D - LK})$
3.89 ± 0.58

Set 3 grey symbols $\varepsilon_k (^{18}\text{O - IMB, D - LK})$
5.09 ± 1.26
Dependence of kinetic factor on lake location and size

‘Lake size effect’

Feng et al., 2016
Table 3. Summary of $\varepsilon_k (^{18}\text{O})$ values in natural experiments.

<table>
<thead>
<tr>
<th>Type</th>
<th>Area</th>
<th>$\varepsilon_k$ (%)</th>
<th>Method</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Small water body</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small Pan</td>
<td>0.13 m²</td>
<td>7.01</td>
<td>IMB</td>
<td>This study</td>
</tr>
<tr>
<td>Big Pan</td>
<td>1.20 m²</td>
<td>10.39</td>
<td>IMB</td>
<td>This study (excluding B3)</td>
</tr>
<tr>
<td>Fishpond</td>
<td>6900 m²</td>
<td>10.17</td>
<td>IMB</td>
<td>This study</td>
</tr>
<tr>
<td>Evap Pan G</td>
<td>0.36 m²</td>
<td>14.25</td>
<td>UCG</td>
<td>Craig et al. (1963); Gonfiantini et al. (2018)</td>
</tr>
<tr>
<td>Evap Pan S</td>
<td>1.13 m²</td>
<td>11.4</td>
<td>UCG</td>
<td>Skrzypek et al. (2015); Gonfiantini et al. (2018)</td>
</tr>
<tr>
<td>Lake Gara</td>
<td>160 m²</td>
<td>8.55</td>
<td>UCG</td>
<td>Fontes and Gonfiantini (1967); Gonfiantini et al. (2018)</td>
</tr>
<tr>
<td>Lake Waid</td>
<td>0.22 km²</td>
<td>5.86</td>
<td>Simplified IMB</td>
<td>Zimmermann (1979); Zuber (1983)</td>
</tr>
<tr>
<td>mean ± 1 SD</td>
<td></td>
<td>9.66 ± 2.82</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Large water body</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lake Burdur</td>
<td>250 km²</td>
<td>11.93</td>
<td>Simplified IMB</td>
<td>Dincer (1968); Zuber (1983)</td>
</tr>
<tr>
<td>Lake Ihotry</td>
<td>91 km²</td>
<td>7.1</td>
<td>$\theta = 0.5$, LK value</td>
<td>Poulin et al. (2019)</td>
</tr>
<tr>
<td>Lake Taihu</td>
<td>2400 km²</td>
<td>8.19</td>
<td>gradient-diffusion</td>
<td>Xiao et al. (2017)</td>
</tr>
<tr>
<td>mean ± 1 SD</td>
<td></td>
<td>9.07 ± 2.53</td>
<td></td>
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</tr>
</tbody>
</table>
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 $7.0 \pm 3.1 \%$ with the small evaporation pan, $10.4 \%$ with the big evaporation pan, and $10.2 \pm 4.9 \%$ 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 $\varepsilon_k$ and lake size.
Thank you for listening!