Energy partitioning of inland water bodies

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Outlines

1. Introduction
2. Objective
3. Theoretical consideration
4. Methods
5. Results
6. Next step
1. Introduction

- Bowen ratio is critical in determining hydrologic cycle (*Yin et al., 2012*), boundary layer dynamics (*Schär et al., 1999*), weather and climate (*Wilson et al., 2002*).

- Bowen ratio yields an estimate of turbulent fluxes when the variable energy is known (*Andreas et al., 2013*).

- Constituting 4% of world land area, inland water bodies can influence regional climate (*Subin et al., 2012*).

- Energy partitioning process at water surface differs from those at terrestrial surface (*Henderson-Sellers, 1986*).
Introduction-continued

- Relationship between air temperature and Bowen ratio from observations (Cho et al., 2012; Wilson et al., 2002) and theoretical models (Priestley and Taylor, 1972; Bateni and Entekhabi, 2012).

\[
\beta = \frac{1}{\alpha \Delta} + \frac{1}{\alpha} - 1 \quad \frac{1}{\beta} = \delta \frac{\Delta}{\gamma}
\]

- Inland waters showed rapid surface warming since 1985 (average 0.045 \( \pm \) 0.011°C yr\(^{-1}\), maximum 0.10 \( \pm \) 0.01°C yr\(^{-1}\)) (Schneider and Hook, 2010).

- Inland waters morphology influence heat content (Ambrosetti and Barbanti, 2002), thermal structure (Mazumder and Taylor, 1994), surface temperature (Becker and Daw, 2005), radiation transmission, eddy mixing (Subin et al., 2012) and transfer coefficients (Panin et al., 2006).
2. Objective

- **Spatially**, what variable (air temperature or depth, size) controls the energy partitioning of inland water bodies?

- Does Bowen ratio have *seasonal* variation? If so, what is the dominantly contributing factor?

- **Interannually**, does the sensitivity of Bowen ratio to air temperature projected by GCMs agree with the historical trend? If not, what is the main reason for this discrepancy?
3. Theoretical consideration

The Priestley-Taylor (PT) model

\[ \beta = \frac{H}{\lambda E} \]

\[ R_n - G = H + \lambda E \]

\[ H = \rho_a c_p C_H u (T_s - T_a) \]

\[ \lambda E = \rho_a \lambda C_E u (q_s - q_a) \]

\[ \lambda E = \alpha \frac{\Delta}{\Delta + \gamma} (R_n - G) \]

\[ \beta_e = \frac{\gamma}{\Delta} \]

\[ \beta = \frac{1}{\alpha \Delta} + \frac{1}{\alpha} - 1 \]

(Brutsaert, 1982; Garratt, 1992; Priestley and Taylor, 1972)
Variation of saturated vapor pressure with air temperature

\[(T_s-T_a)_1=(T_s-T_a)_2\]

\[(e^*_s-e^*_a)_1<(e^*_s-e^*_a)_2\]

(after Monteith, 1981)
Temperature dependence of (a) Bowen ratio and (b) Bowen ratio sensitivity to air temperature.
# 4. Methods

<table>
<thead>
<tr>
<th>Type</th>
<th>Spatial resolution</th>
<th>Source</th>
<th>Temporal resolution</th>
<th>Spatial resolution</th>
<th>Variables</th>
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<tr>
<td>Spatial</td>
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<td>Literature</td>
<td>Annual, open water</td>
<td>1/2°lat×2/3°lon</td>
<td>$T_a$, $H$, $\lambda E$</td>
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<tr>
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<td>Literature</td>
<td>Monthly, open water</td>
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<td>Lake Taihu</td>
<td></td>
<td>MERRA, SLM</td>
<td>1979-2012</td>
<td>1/2°lat×2/3°lon</td>
<td>$T_a$, $q_a$, $U$, $P_a$, $K \downarrow$, $L \downarrow$</td>
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<tr>
<td>Historical</td>
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<td>Ross Barnett Reservoir</td>
<td>MERRA, SLM</td>
<td>1979-2012</td>
<td>1/2°lat×2/3°lon</td>
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<tr>
<td>Interannal</td>
<td></td>
<td>OAFlux</td>
<td>1979-2012</td>
<td>1°lat×1°lon</td>
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<tr>
<td>the Great Lakes</td>
<td></td>
<td>ERA-Interim</td>
<td>1979-2012</td>
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<td>$T_a$, $H$, $\lambda E$</td>
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<td>NARR</td>
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<td>Future</td>
<td>Lake Taihu</td>
<td>CESM1-CAM5, SLM</td>
<td>2006-2100, 3RCPs</td>
<td>0.94°lat×1.25°lon</td>
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<td>2006-2100, 3RCPs</td>
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<td>the Great Lakes</td>
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<td>$T_a$, $H$, $\lambda E$</td>
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</table>
Simple lake model (SLM)

\[(1 - \alpha)K_\downarrow + \varepsilon L_\downarrow - \varepsilon \sigma T_s^4 = H + \lambda E\]

\[H = \rho_a c_p C_H u(T_s - T_a)\]

\[\lambda E = \rho_a \lambda C_E u(q_s - q_a)\]

Meteorological drives

\[\beta\] slightly sensitive to wind speed
\[\beta\] not sensitive to radiation
\[\beta\] decrease with air temperature

Linearization of \(T_s\) and \(q_s\)

Solution of \(T_s\)

(Developed by Lee, 2012)
Calibration of MERRA inputs and accuracy assessment of SLM simulations

<table>
<thead>
<tr>
<th>Waters</th>
<th>Data</th>
<th>$T_a$</th>
<th>$q_a$</th>
<th>$P_a$</th>
<th>$u$</th>
<th>$K_\downarrow$</th>
<th>$L_\downarrow$</th>
<th>$T_s$</th>
<th>$q_s$</th>
<th>$H$</th>
<th>$\lambda E$</th>
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<td>0.011</td>
<td>101.1</td>
<td>1.1</td>
<td>181.4</td>
<td>341.0</td>
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<td>16.2</td>
<td>0.009</td>
<td>101.5</td>
<td>2.7</td>
<td>143.8</td>
<td>356.9</td>
<td>17.2</td>
<td>0.014</td>
<td>9.7</td>
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<td>16.2</td>
<td>0.009</td>
<td>101.5</td>
<td>2.7</td>
<td>143.8</td>
<td>356.9</td>
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<td></td>
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<td>Simulated</td>
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<td>18.1</td>
<td>0.013</td>
<td></td>
<td></td>
<td>9.6</td>
<td>76.4</td>
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<td>Taihu 2011</td>
<td>MERRA</td>
<td>17.9</td>
<td>0.011</td>
<td>100.6</td>
<td>0.4</td>
<td>196.7</td>
<td>349.7</td>
<td>35.7</td>
<td>0.036</td>
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<td>17.7</td>
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<td>100.0</td>
<td>3.9</td>
<td>177.5</td>
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<td>Simulated</td>
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<td>21.0</td>
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<td>17.8</td>
<td>84.8</td>
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</table>
Accuracy assessment of flux products at the Great Lakes

(Blanken et al, 2011)
5. Results

- Spatial variation
- Seasonal variation
- Interannual variation
Spatial: Literature survey
(34 inland waters, open water period)
**Spatial: Turbulent fluxes vs. air temperature**

![Graphs showing the relationship between turbulent fluxes and air temperature.](image)

**Graph a:**
- Equation: $y = -1.26(\pm 0.39)x + 33.67$
- Data points: $N=34$, $R=-0.50$, $P<0.01$

**Graph b:**
- Equation: $y = 5.88(\pm 1.54)x - 2.96$
- Data points: $N=34$, $R=0.69$, $P<0.01$
Partial correlation coefficients between Bowen ratio and surface area and mean depth was 0.22 ($p = 0.23$) and -0.02 ($p = 0.92$), respectively.
Seasonal: Bowen ratio vs. (left) air temperature and (right) heat storage

Lake Taihu (1.9 m)

Ross Barnett Reservoir (5 m)
Seasonal-continued

Yamdrok Yumco (23.6 m)

Lake Ikeda (125 m)
Seasonal-continued

Lake Superior (148 m)
Historical: Bowen ratio vs. air temperature
Future: Bowen ratio vs. air temperature

(a) Lake Taihu, (b) Ross Barnett Reservoir, (c) the Great Lakes.
## Interannual summary

<table>
<thead>
<tr>
<th>Type</th>
<th>Waters</th>
<th>Data Source</th>
<th>Sensitivity °C⁻¹</th>
<th>R</th>
<th>p</th>
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</thead>
<tbody>
<tr>
<td>Historical</td>
<td>Lake Taihu</td>
<td>SLM MERRA</td>
<td>-0.05±0.013</td>
<td>-0.67</td>
<td>&lt;0.01</td>
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<tr>
<td>1979-2012</td>
<td>Ross Barnett Reservoir</td>
<td>SLM MERRA</td>
<td>-0.058±0.011</td>
<td>-0.86</td>
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<td>the Great Lakes</td>
<td>OAFlux</td>
<td>-0.149±0.039</td>
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<td>&lt;0.01</td>
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<td></td>
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<td>ERA-Interim</td>
<td>-0.121±0.025</td>
<td>-0.82</td>
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<tr>
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<td>NARR</td>
<td>-0.087±0.030</td>
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<td>=0.11</td>
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<td>Future</td>
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<td>-0.02±0.004</td>
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<tr>
<td>2013-2100</td>
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<td>SLM CESM1-CAM5 RCP4.5</td>
<td>-0.018±0.002</td>
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<td>&lt;0.01</td>
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<tr>
<td></td>
<td></td>
<td>SLM CESM1-CAM5 RCP8.5</td>
<td>-0.017±0.001</td>
<td>-0.94</td>
<td>&lt;0.01</td>
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<td>Ross Barnett Reservoir</td>
<td>SLM CESM1-CAM5 RCP2.6</td>
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<td>-0.55</td>
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<td>SLM CESM1-CAM5 RCP4.5</td>
<td>-0.027±0.003</td>
<td>-0.82</td>
<td>&lt;0.01</td>
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<td>SLM CESM1-CAM5 RCP8.5</td>
<td>-0.024±0.002</td>
<td>-0.89</td>
<td>&lt;0.01</td>
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<td>the Great Lakes</td>
<td>CanESM2 RCP2.6</td>
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<td>-0.69</td>
<td>&lt;0.01</td>
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<td>CanESM2 RCP4.5</td>
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<td>-0.63</td>
<td>&lt;0.01</td>
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<td></td>
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<td>CanESM2 RCP8.5</td>
<td>-0.037±0.006</td>
<td>-0.70</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>
Energy partitioning in response to global warming

\[
\frac{-\Delta \beta}{\beta \Delta T_s} = \frac{dq^*}{q^* dT} + \left[ \frac{RH \cdot \beta \lambda q^* (T_a)}{c_p} \frac{dq^*}{q^* dT} \right] \frac{\Delta (T_s - T_a)}{(T_s - T_a) \Delta T_s} - \frac{1}{1 - \text{RH}} \frac{\Delta \text{RH}}{\Delta T_s}
\]

7.5% K\(^{-1}\) 6-6.5% K\(^{-1}\) 2.4-2.7% K\(^{-1}\) 0.1-0.3% K\(^{-1}\)

(Lu and Cai, 2009)
Conclusion

- **Spatial** variation in annual Bowen ratio was excellently predicted by the PT model. No statistical relationship was found between annual Bowen ratio and the size, depth of inland water bodies.

- Depth influences energy partitioning of inland waters through changes in heat storage at monthly scale for deep waters.

- All the 21\textsuperscript{st} century predictions have underestimated the decreasing trend of Bowen ratio to global warming. The PT model showed unsatisfactory prediction of interannual variations of Bowen ratio, especially for historical series.
Next step

- Simulating energy partitioning process of inland water bodies by coupled GCMs and Lake model.
- Manuscript refinement.
Thank you!

Suggestions and questions are welcome.