An Energy Partitioning Perspective on Lake Evaporation Variations to Climate Change

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Outline

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- Scientific questions and hypothesis
- Model and data
- Preliminary results
  - Validation of evaporation simulation
  - Interannual variations
  - Energy partitioning vs. air temperature
  - Freshwater flux
  - Evaporation comparison between lake and surrounding land
- Next steps
Motivation

- **Hypothesis I** – the lake evaporation rate will increase as air temperature rises, at a rate of 7% K\(^{-1}\) predicted by the Clausius-Clapeyron equation (*Held and Soden*, 2006; *Huntington*, 2006; *Wentz et al.*, 2007; *Alessandri et al.*, 2012, *Roderick et al.*, 2014). **Hypothesis II** – lake evaporation variabilities are controlled by the variabilities in the surface solar radiation (*Ohmura and Wild*, 2002; *Liu and Zeng*, 2004; *Fu et al.*, 2009).

- Changes in global water evaporation can be decomposed into two parts: one associated with the net change in radiative flux and the other due to the variability of energy partitioning (*Held and Soden*, 2006).
Surface energy balance and the Priestley-Taylor (PT) model

\[
\beta = \frac{H}{\lambda E} \quad EF = \frac{\lambda E}{R_n - G}
\]

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

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

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

\[
EF = \frac{1}{1 + \beta}
\]

(Priestley and Taylor, 1972; Monteith, 1981; Brutsaert, 1982; Garratt, 1992)
Relationship between $\beta$ (EF) and $T_a$ by PT model
What is the main driver of the interannual variations in lake evaporation? Air temperature or solar radiation?

How are about the mechanisms underlying lake evaporation variability caused by energy partitioning?

The lake evaporation interannual variability are primarily explained by air temperature through its effect on energy partitioning (Bowen ratio or evaporative fraction), not by surface solar radiation.
Configuration of the CLM subgrid hierarchy

(Oleson et al., 2013)
Surface flux solution in CLM4.5-LISSSS (Lake, Ice, Snow, and Sediment Simulator)

\[ \beta \tilde{S}_g - \tilde{L}_g - H_g - \lambda E_g - G = 0 \]

\[ H_g = -\rho_{atm} C_p \left( \frac{\theta_{atm} - T_g}{r_{ah}} \right) \]

\[ E_g = -\rho_{atm} \left( q_{atm} - q_{sat}^T \right) \]

(Oleson et al., 2013)
Global Lake Database version 2 used in CLM4.5-LISSSS

<table>
<thead>
<tr>
<th>Lake type</th>
<th>Number</th>
<th>With depth</th>
<th>Fraction</th>
<th>&lt;5 m</th>
<th>&lt;5 m fraction</th>
<th>&lt;10 m</th>
<th>&lt;10 m fraction</th>
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<tbody>
<tr>
<td>Freshwater</td>
<td>13155</td>
<td>8378</td>
<td>63.69</td>
<td>2247</td>
<td>26.82</td>
<td>6180</td>
<td>73.76</td>
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<tr>
<td>Saline</td>
<td>221</td>
<td>144</td>
<td>65.16</td>
<td>100</td>
<td>69.44</td>
<td>118</td>
<td>81.94</td>
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<tr>
<td>All</td>
<td>13376</td>
<td>8522</td>
<td>63.71</td>
<td>2347</td>
<td>27.54</td>
<td>6298</td>
<td>73.90</td>
</tr>
</tbody>
</table>

Global lake coverage: 2.3 million km².

(Lehner and Doll, 2004; Kourzeneva et al., 2009, 2010, 2012)
CLM4.5-LISSSS simulations

- Historical simulation: 1991-2010, monthly, 10-yr spin-up, 0.9° (latitude) x 1.25° (longitude), by Zack Subin, be validated;

- Future simulation: 2005-2100, monthly (primary files), daily (secondary files), 100-yr spin-up, RCP8.5, 0.9° (latitude) x 1.25° (longitude), by Lei Zhao, research;

- Latent heat: ground + canopy + transpiration
  Sensible heat: ground + canopy
Why open water evaporation?

Global open lake evaporation: $2.16 \times 10^{15} \text{ kg yr}^{-1}$

Year round lake evaporation: $2.18 \times 10^{15} \text{ kg yr}^{-1}$
Validation of monthly evaporation simulations at Lake Taihu

$R^2$-CLM_global-CLM_Taihu: 0.90
$R^2$-CLM_global-Pan: 0.83
RMSE-CLM_global-CLM_Taihu: 23.10 mm month$^{-1}$
RMSE-CLM_global-Pan: 31.93 mm month$^{-1}$
Validation of annual evaporation simulations at 27 lakes

$y = 0.94x$, $N=27$, $R=0.82$, $p<0.01$  
$I = 0.90$, RMSE = 21.27 W m$^{-2}$
Interannual variations in global lake mean air temperature and solar radiation

(a) $0.28 \, ^\circ \text{C} \, \text{10yr}^{-1} ***$

(b) $-0.8 \, \text{W m}^{-2} \, \text{10yr}^{-1} ***$
Interannual variations in global lake mean wind speed and precipitation

(c) -0.00027 m s$^{-1}$ 10yr$^{-1}$

(d) 10.8 mm 10yr$^{-1}$ ***
Interannual variations in global lake mean latent heat, $\beta$ and EF

\[ \lambda E \text{ (W m}^{-2}) \]

\[ \beta \]

\[ 0.85 \text{ W m}^{-2} 10\text{yr}^{-1} *** \]

\[ -0.007 \text{ 10yr}^{-1} *** \]

\[ 0.005 \text{ 10yr}^{-1} *** \]
\( \beta \) (EF) varying with air temperature every lake-year
$\beta$ (EF) varying with air temperature every lake 2005-2100 mean
$\beta$ (EF) varying with air temperature 2005-2100 global lake mean
\( \beta \) difference

2091-2100 mean minus 2006-2015 mean
EF difference
2091-2100 mean minus 2006-2015 mean
Zonal mean of $\beta$ (EF)
Freshwater flux (Evaporation minus Precipitation) difference
2091-2100 mean minus 2006-2015 mean
Zonal mean of FWF
Evaporation comparison between lake and surrounding land
Partitioning of latent heat flux over land
Next steps

- Intensive validation of CLM4.5-LISSS simulations against in-situ observations.

Geophysical Research Letters

Rapid and highly variable warming of lake surface waters around the globe

- Application of the PT model according to the heat flux regimes with corrected PT coefficient.

On the variability of the Priestley-Taylor coefficient over water bodies

On the Application of the Priestley–Taylor Relation on Sub-daily Time Scales