Thermal structure of a shallow lake with submersed macrophytes: a case study of Lake Taihu

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Outline

1. Background

2. Methods and Data
   ✓ model description
   ✓ model development
   ✓ Sensitivity analysis

3. Two Lake Models Comparison

4. On-going work
The vertical eddy diffusivity is important for the description of the vertical transfer of substance in various numerical models. Bin Deng et al. parameterized the eddy diffusivity $k_e$. Piao Meihua evaluated the performance of the calibrated CLM4-LISSS across the BFG site, the effect of macrophytes is not considered.

William R. Herb et al. developed and explored a mechanistic model of stratification and vertical diffusion in a shallow lake with rooted plants. This model is based on coupled equations for heat transfer and turbulent kinetic energy. (William R. Herb et al., 2005).
Methods and Data

• E-ε closed lake model description

- solar radiation
- wind speed
- air temperature
- dew point
- cloud cover

One –dimensional equation for production, transport, and dissipation of turbulent kinetic energy

A vertical heat transfer equation

- water temperature
- turbulent kinetic energy
$Q_o$ is the heat transfer rate at the water surface

$$Q_o = Q_s + Q_a - Q_c - Q_e - Q_b$$

- $Q_s$: net solar radiation
- $Q_a$: long-wave atmospheric radiation
- $Q_c$: sensible heat flux
- $Q_e$: latent heat flux
- $Q_b$: back radiation

$$Q_c = 0.47 f(W)(T_s - T_a)$$

$$Q_e = \beta_e f(W)(T_s - T_d)$$

$$f(W) = 20.6 \times (9.2 + 0.46W^2)$$

$$\beta_e = 0.35 + 0.015 \left(\frac{T_d + T_s}{2}\right) + 0.0012 \left(\frac{T_d + T_s}{2}\right)^2$$

$W$: wind speed  $T_s$: surface water temperature  $T_a$: air temperature  $T_d$: dew point temperature
A one-dimensional heat transfer equation which is coupled to the TKE equation:

\[
\frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( K_z \frac{\partial T}{\partial z} \right) + \frac{H}{\rho c_p}
\]

\(\rho\): the density \hspace{1cm} \(c_p\): specific heat of water
\(H\): internal heat generation from solar radiation

\[H(z) = (1 - \alpha_l)(1 - \beta)I_s \exp(-(K_{wc} + K_m \rho)z)\]

\(\alpha_l\): the albedo
\(\beta\): the IR fraction of total radiation
\(K_{wc}\): the light attenuation coefficient for water plus dissolved and suspended substances
\(K_m\): the specific light attenuation coefficient for macrophytes
\(\rho\): the plant mass per unit volume
An equation for production, diffusion, and dissipation of TKE (turbulent kinetic energy).

\[
\frac{\partial E}{\partial t} = \frac{\partial}{\partial z} \left( K_z \frac{\partial E}{\partial z} \right) + K_z \alpha g \frac{\partial T}{\partial z} - \varepsilon
\]

\(E\): turbulent kinetic energy per unit mass  
\(K_z\): vertical turbulent diffusion coefficient  
\(g\): acceleration of gravity  
\(\alpha\): the thermal expansion coefficient  
\(t\): time  
\(z\): depth  
\(\varepsilon\): dissipation

\[
\varepsilon = \hat{a} C_D E^{3/2}
\]

\(\hat{a}\): the plant surface area per unit volume  
\(C_D\): the total drag coefficient  
\(\hat{a} = 0.05 p\)

\(p\) is the plant mass per unit volume

\[
K_z = C_k Z_m \sqrt{E}
\]

\(C_k\): a constant of the order of 0.1  
\(Z_m\): the mixed layer depth
Observation Data

Site: BFG
Time: August, 2013

Data sources:
- micrometeorology system
- China meteorological data sharing service system
- temperature probes
- eddy covariance system
Table 1. Model parameter values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Nominal Value (units)</th>
<th>source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{sed}$</td>
<td>Temperature at sediment/water interface</td>
<td>30.49°C</td>
<td>measured</td>
</tr>
<tr>
<td>$K_{wc}$</td>
<td>light attenuation coefficient for water</td>
<td>2m$^{-1}$</td>
<td>calibrated</td>
</tr>
<tr>
<td>$K_m$</td>
<td>specific light attenuation coefficient for macrophytes</td>
<td>0.02m$^2$gdw$^{-1}$</td>
<td>Westlake [1964]</td>
</tr>
<tr>
<td>$P$</td>
<td>macrophyte biomass density</td>
<td>300gdwm$^{-3}$</td>
<td>calibrated</td>
</tr>
<tr>
<td>$h$</td>
<td>macrophyte stand height</td>
<td>1.2m</td>
<td>calibrated</td>
</tr>
<tr>
<td>$d$</td>
<td>water depth</td>
<td>2 m</td>
<td>measured</td>
</tr>
<tr>
<td>$C_k$</td>
<td>mixing length coefficient</td>
<td>0.1</td>
<td>Herb [2005]</td>
</tr>
<tr>
<td>$C_D$</td>
<td>drag coefficient</td>
<td>1.0</td>
<td>Finnigan [2000]</td>
</tr>
<tr>
<td>$K_h$</td>
<td>hypolimnetic diffusivity</td>
<td>0.03m$^2$d$^{-1}$</td>
<td>Herb [2005]</td>
</tr>
<tr>
<td>$C_w$</td>
<td>wind correction coefficient</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>nz</td>
<td>number of discrete depth increments</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>time increment</td>
<td>30 min</td>
<td></td>
</tr>
</tbody>
</table>
Model development

• Introducing the observed temperature at sediment-water interface ($T_{sed}$) into model.

• Introducing the water temperature profile of initial field.
Figure 1. Temperature comparison for DOY 213-243, 2013
Figure 2. Temperature comparison for DOY 213-243, 2013
Figure 3: Temperature versus time and depth for BFG site for DOY 213-243, 2013. Measured water temperatures and model simulations.

- **Figure a**: Temperature at 0.2m (obs: black, model: red)
  - $R^2$: 0.97
  - RMSE: 0.58

- **Figure b**: Temperature at 0.5m
  - $R^2$: 0.96
  - RMSE: 0.51

- **Figure c**: Temperature at 1.0m (obs: black, model: red)
  - $R^2$: 0.96
  - RMSE: 0.69

- **Figure d**: Temperature at 1.5m
  - $R^2$: 0.90
  - RMSE: 1.16
Sensitivity analysis

- Macrophyte stand height ($MH$)
  $MH$: 0.2m, 1.2m, 1.6m, 2.0m

- Macrophyte biomass density ($P$)
  $P$: 0gDW/m$^3$, 100gDW/m$^3$, 300gDW/m$^3$

- Mixing length coefficient ($C_k$)
  $C_k$: 0.1, 3.0, 5.0
Figure 4. Water temperature versus time for macrophyte stand height $MH=0.2, 1.2, 1.6, 2.0\text{m}$ at different depth for DOY 213-243, 2013.
Figure 5. Water temperature versus time for macrophyte biomass density $P = 0\, \text{gDW/m}^3$, $100\, \text{gDW/m}^3$, $300\, \text{gDW/m}^3$ at different depth for DOY 213-243, 2013.
Figure 6. Water temperature versus time for mixing length coefficient $C_k = 0.1, 3.0, 5.0$ at different depth for DOY 213-243, 2013.
Two Lake Models Comparison

- Water temperature
- Sensible heat flux
- Latent heat flux
- $u^*$
Figure 7. Comparison between the observed and the model-predicted water temperature from DOY 213 to DOY 243, 2013.
Figure 8. Comparison between the observed and the model-predicted sensible heat flux, latent heat flux and friction velocity from DOY 213 to DOY 243, 2013.
On-going work

• Studying the thermal and dynamic characteristics of BFG site in different growing periods.

• Developing the computation modules for radiation and $u_*$.

• Simulating the vertical turbulent diffusivity ($K_z$), making comparative analysis of two model.
Thank you