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Dynamics of vertical mixing in a shallow lake with submersed macrophytes

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Outline

- Introduction
- Model Formulation
- Model Application
- Discussion and Conclusions

Introduction

- Submersed macrophytes in lakes increase the strength of temperature stratification, reduce local flow velocities, influence the resuspension and distribution of sediment.

- To include macrophytes in lake models, it is necessary to consider the effect of submersed macrophytes on vertical turbulent mixing and the associated transport of solutes and suspended particles.

Model Formulation

- The model formulation is based on an equation for production, diffusion, and dissipation of TKE (turbulent kinetic energy).

$$\frac{\partial E}{\partial t} = \frac{\partial}{\partial z}\left(Kz\frac{\partial E}{\partial z}\right) + Kz\alpha g\frac{\partial T}{\partial z} - \varepsilon$$

I II III IV

Ⅰ the unsteady term Ⅱ turbulent transport

Ⅲ buoyancy production Ⅳ dissipation

E: turbulent kinetic energy per unit mass

Kz: vertical turbulent diffusion coefficient

g: acceleration of gravity

α: the thermal expansion coefficient

t: time z: depth ε: dissipation

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

$\hat{a}$: the plant surface area per unit volume

$$\hat{a} = 0.05p$$

(p is the plant mass per unit volume,$50\ \mathrm{gdw\ m^{-3}} < p < 800\ \mathrm{gdw\ m^{-3}}$)

C_D: the total drag coefficient

$$K_z = C_k z_m \sqrt{E}$$

C_k: a constant of the order of 0.1

Z_m: the mixed layer depth

A one-dimensional heat transfer equation which is coupled to the TKE equation :

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

ρ: the density Cp: specific heat of water

H: internal heat generation from solar radiation

$$H(z) = (1-\alpha_1)(1-\beta)I_s \exp(-(K_{wc} + K_m P)z)$$

α1: the albedo

β: the IR fraction of total radiation

Kwc: the light attenuation coefficient for water plus dissolved and suspended substances

Km: the specific light attenuation coefficient for macrophytes.

Q_0 is the heat transfer rate at the water surface

$$Q_0 = Q_s + Q_a - Q_c - Q_e - Q_b$$

Q_s : net solar radiation

Q_a : net long-wave atmospheric radiation

Q_c : convective heat flux

Q_e : evaporative heat flux

Q_b : back radiation

Model application

This model was applied to Otter Lake, a shallow lake. The total lake area is 1.34 km^2, and the maximum depth is 6.4 m. Measurements were taken in locations at the south end of the lake, where the water depth was 1.8 to 2.2 m, with abundant submersed macrophytes.

- Measurement site 1: relatively open water with a plant stand height of about 0.7 m.
- Measurement site 2: an area in a dense macrophyte bed extending to the water surface.

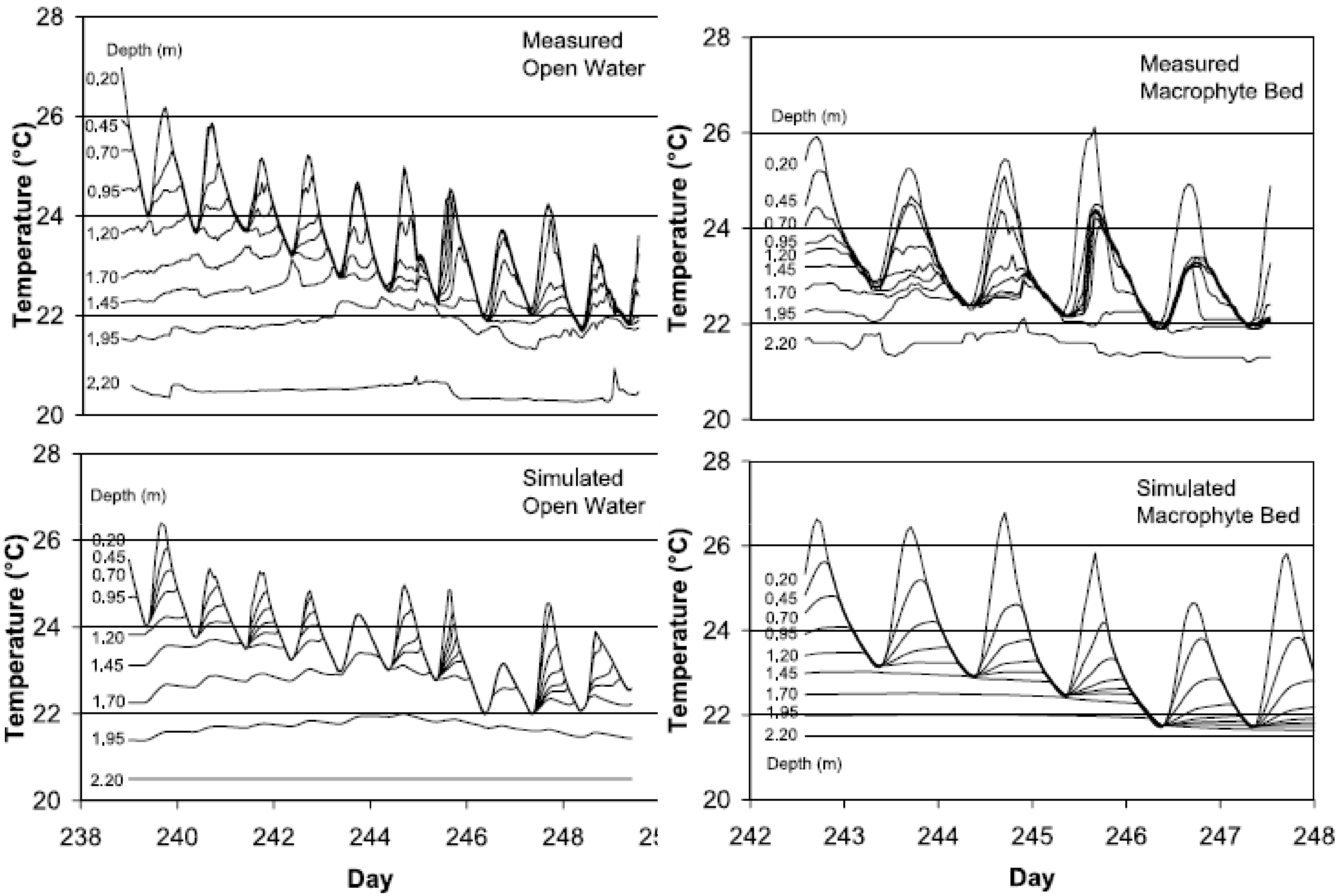

Figure 1. Water temperature versus time and depth at Otter Lake site 1 and site 2. Measured (top) water temperatures and (bottom) model simulations.

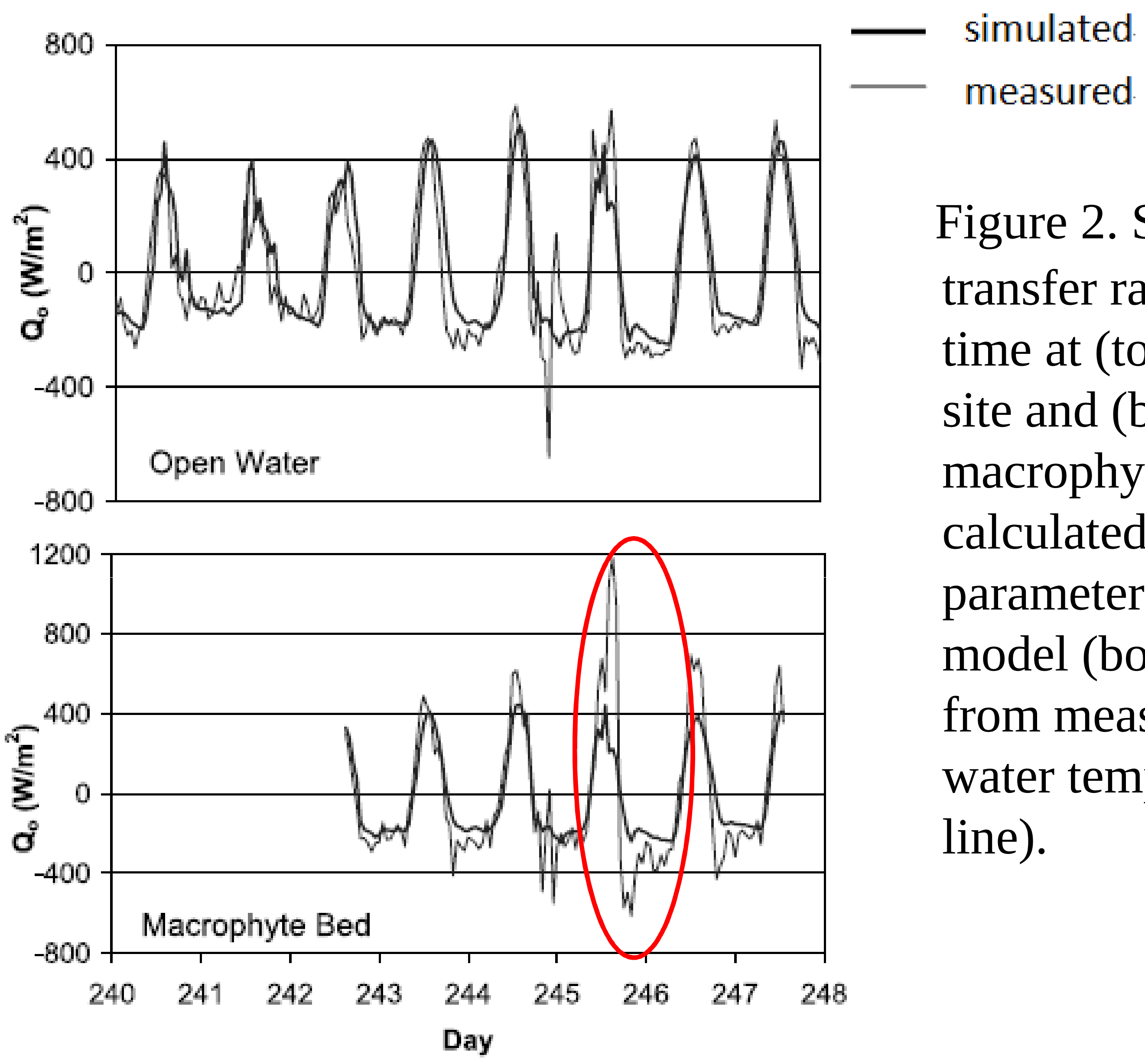

Figure 2. Surface heat transfer rate (Q_0) versus time at (top) open water site and (bottom) macrophyte bed site, calculated from weather parameters in the TKE model (bold line) and from measured change in water temperature (thin line).

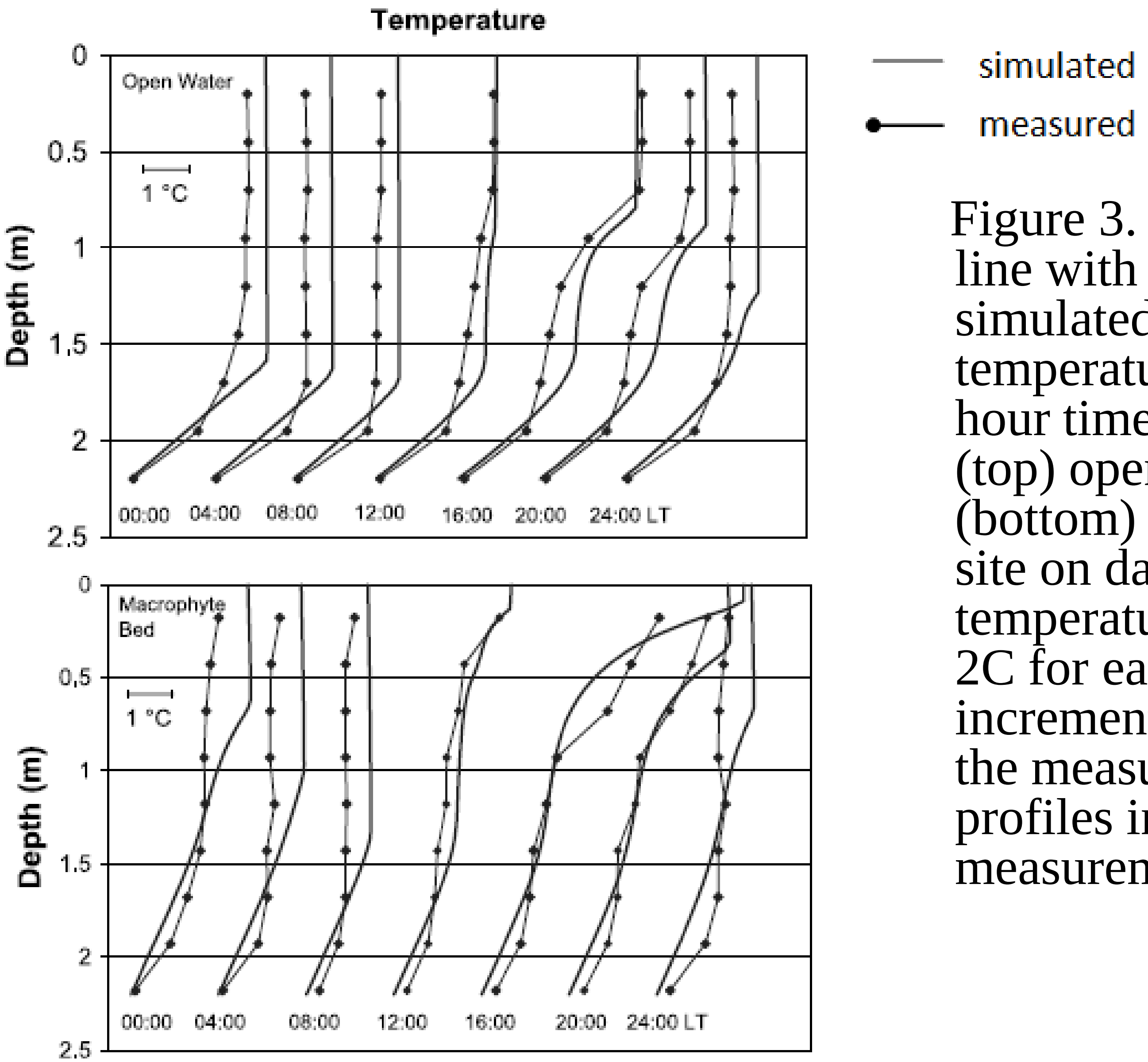

Figure 3. Measured (thin line with diamonds) and simulated (bold line) temperature profiles at 4 hour time increments at (top) open water site and (bottom) macrophyte bed site on day 244. The temperature scale is offset 2C for each 4 hour time increment. Diamonds on the measured temperature profiles indicate the measurement points.

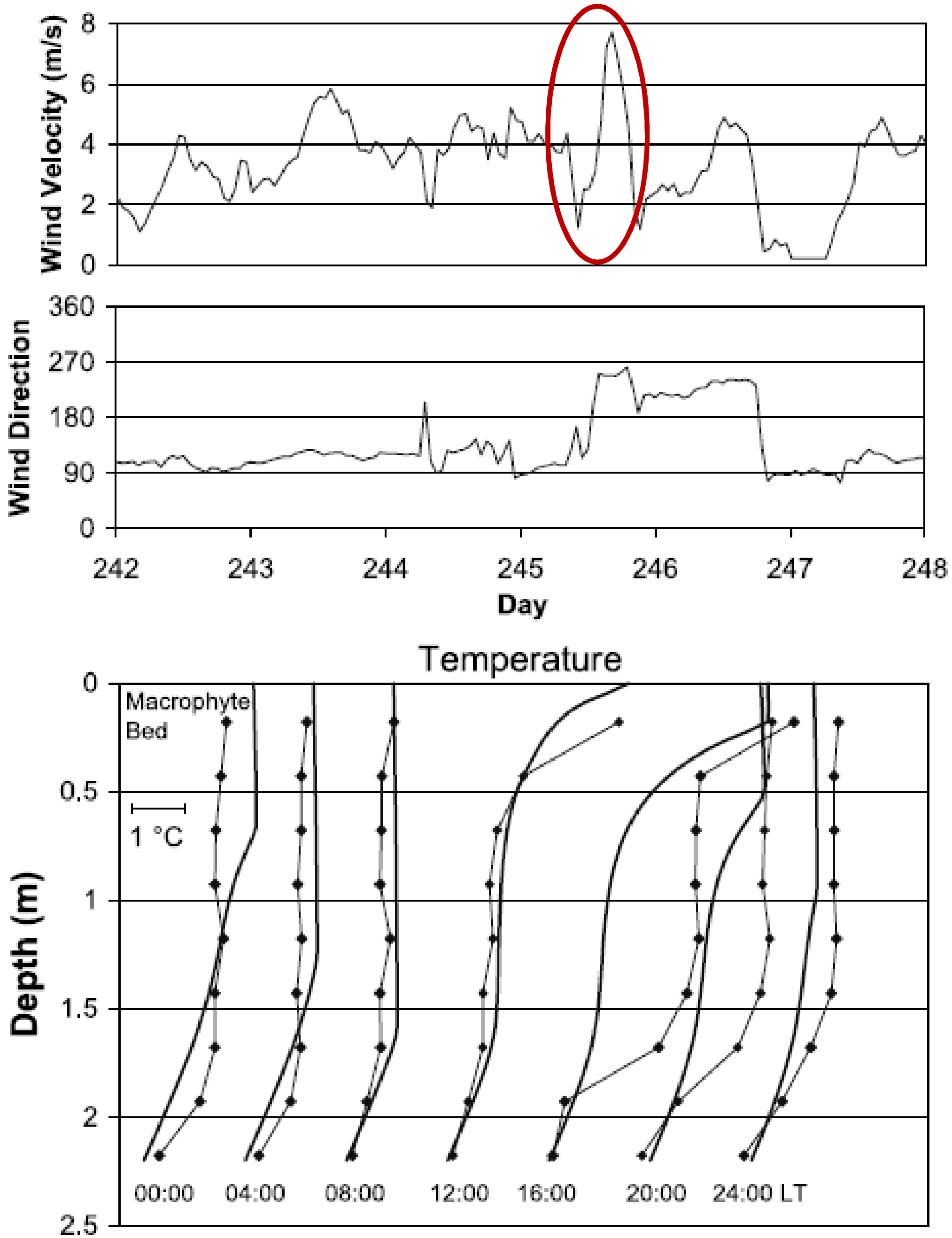

Figure 4. Measured (thin line with diamonds) and simulated (bold line) temperature profiles at 4 hour time increments at macrophyte bed site on day 245. The temperature scale is offset 2C for each 4 hour time increment. The wind velocity and direction history at the measurement site are give in the top two plots.

The order of magnitude of the horizontal heat transfer can be estimated on the basis of the drift velocity and the lateral temperature gradient (dT/dx).

$$Q_h = \rho c_p \bar{u} h \, dT/dx$$

Q_h: horizontal heat

$\bar{u}$: the mean drift velocity

h: macrophyte stand height

The lateral temperature gradient : 0.1℃ m^{-1}

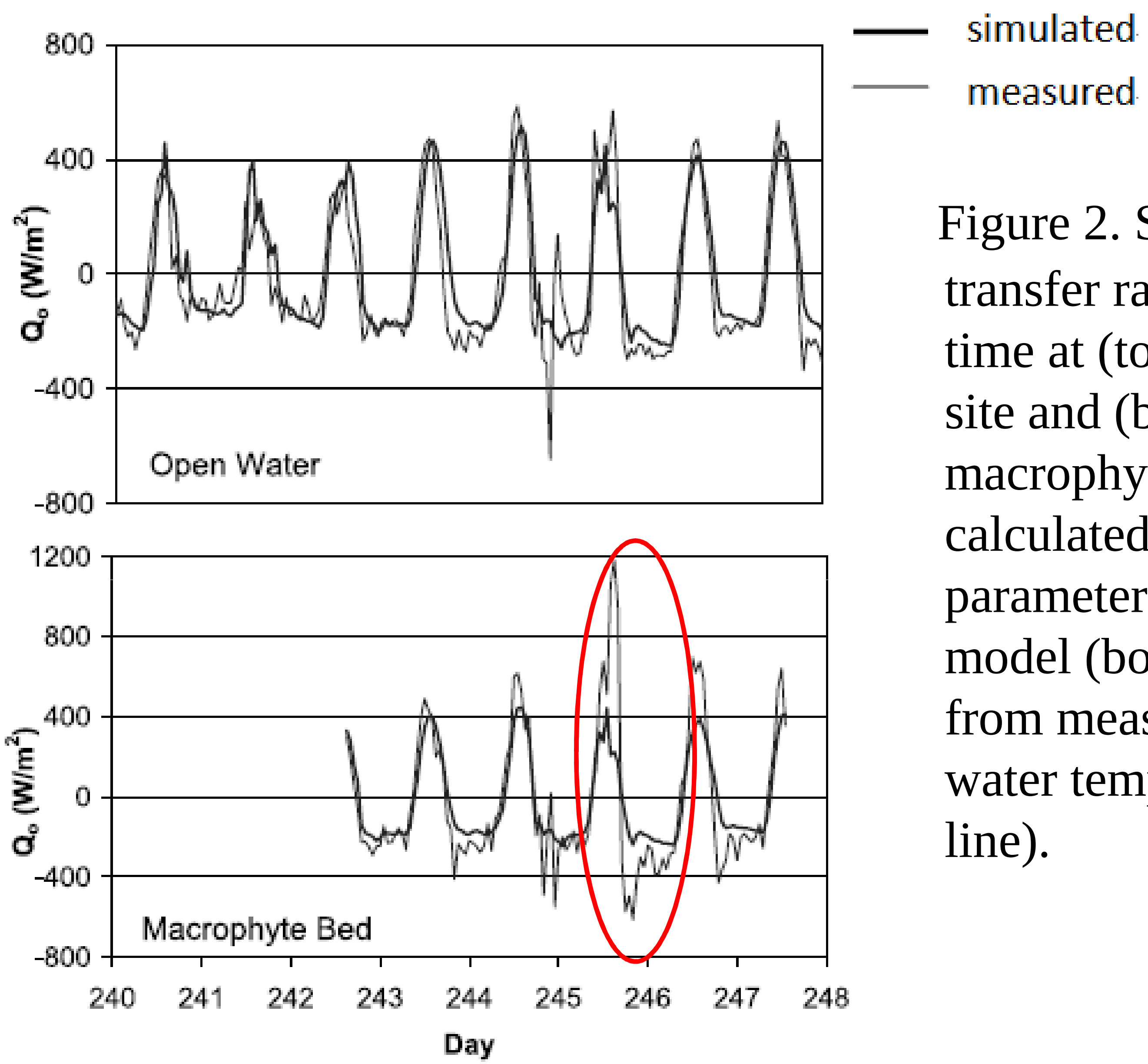

Figure 2. Surface heat transfer rate (Q_0) versus time at (top) open water site and (bottom) macrophyte bed site, calculated from weather parameters in the TKE model (bold line) and from measured change in water temperature (thin line).

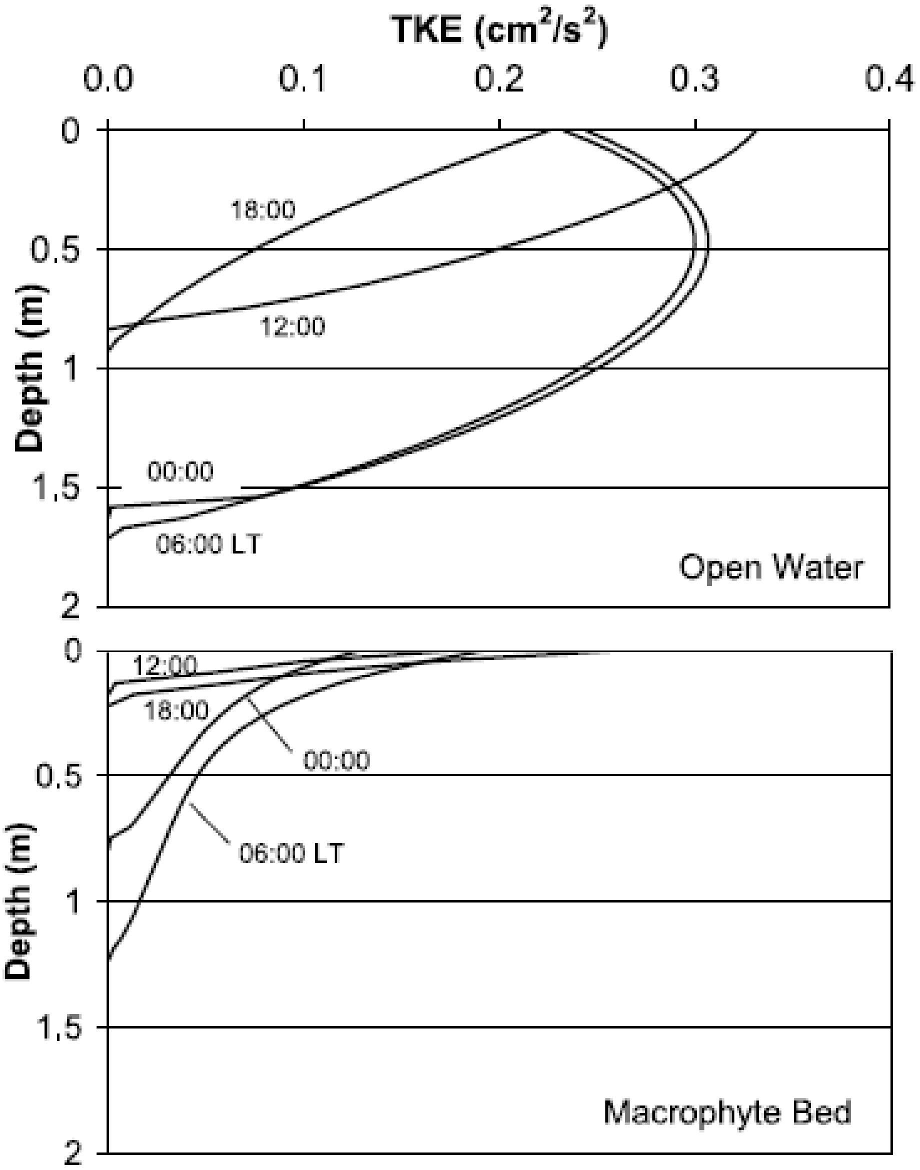

Figure 5. Turbulent kinetic energy (TKE) versus depth profiles at 6 hour time increments for (top) open water site and (bottom) macrophyte bed site on day 244.

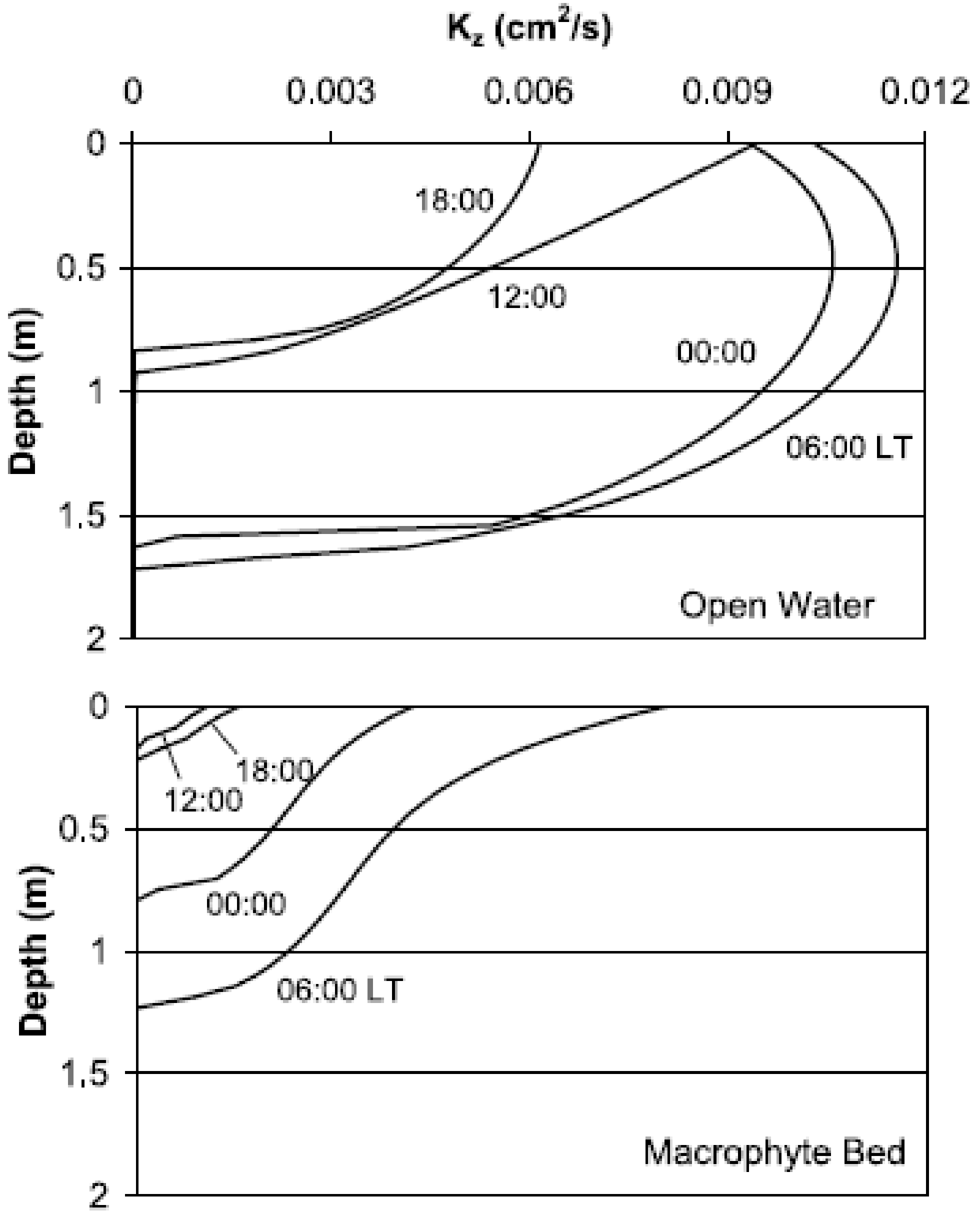

Figure 6. Vertical turbulent diffusivity (Kz) versus depth profiles at 6 hour time increments at (top) open water site and (bottom) macrophyte bed site on day 244.

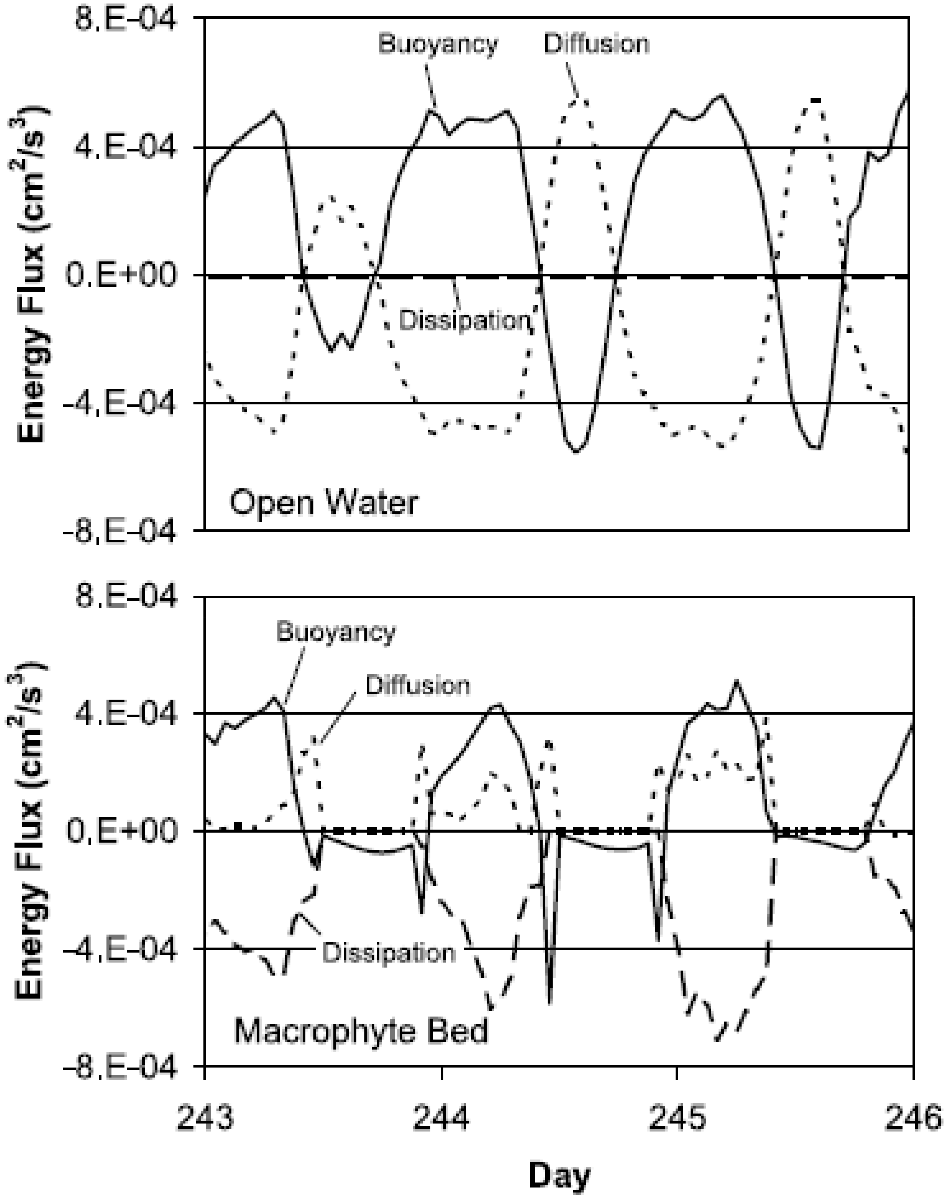

Figure 7. Buoyancy, diffusion, and dissipation terms versus time at z = 0.5 m, for TKE solution, using parameters for (top) open water site and (bottom) macrophyte bed site.

Discussion and Conclusions

- The model is based on a one-dimensional equation for production, transport and dissipation of turbulent kinetic energy, coupled with a vertical heat transfer equation.
- Macrophyte beds enhance daytime stratification and reduce mixed layer depths by increased solar radiation attenuation and reduced wind mixing. The model quantifies these effects.
- Horizontal advective transfer has a significant effect on the vertical distribution of temperature and momentum, limiting the accuracy of one-dimensional transport models.

Thank you