Coupling a Regional Climate Model to a Lake Tile Model for Prediction of Dissolved Oxygen Profiles in Lakes

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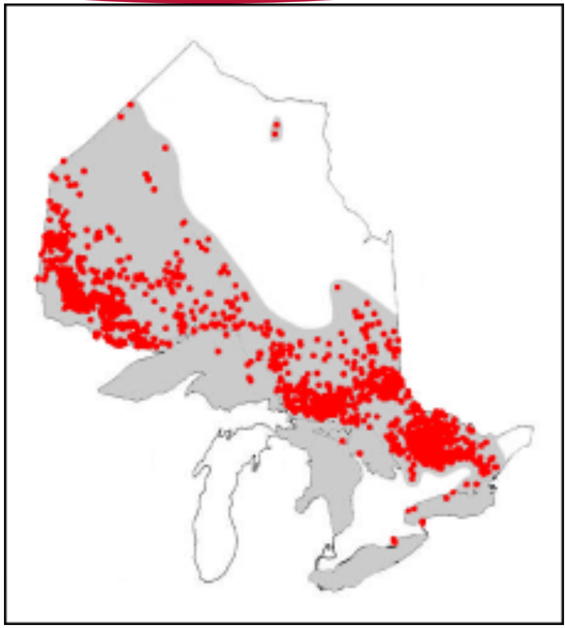
Outline

- Part I: Introduction
- Part II: Bottom boundary layer mixing sub-models
- Part III: Photosynthesis and water column respiration
- Part IV: Summary and Conclusions

Introduction

Lake Trout

- length: 30-80 cm, weight: 1-5 kg
  Ontario record: 28.6 kg
- Valuable ecologically and economically
- Great importance to Ontario's recreational fisheries: over $2.5 billion to the provincial economy (OMNR 2014)



Lake Ontario, Lake Huron, Lake Superior and across the deep, cold lakes of the Canadian Shield (www.ontario.ca)

Introduction

- Narrow tolerances for temperature (T) and dissolved oxygen (DO)

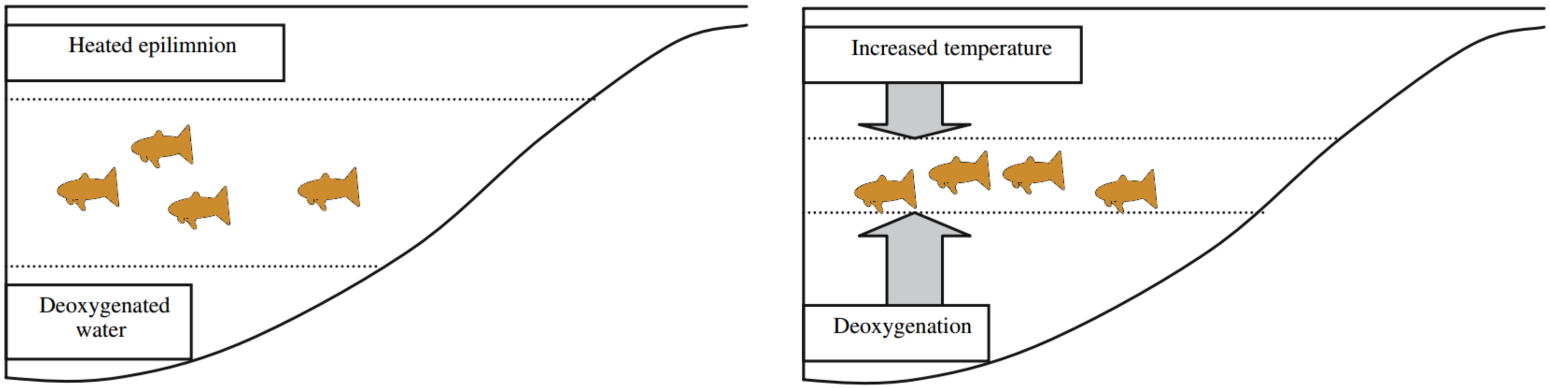
  Temperature: 6-15°C

  DO: 9-12 mg/L

- Vulnerable to many stresses including climate warming:

  Increased T ⇨ Thicker Epilimnion

  Increased fish metabolism ⇨ Decreased concentrations of DO



Effect of climate change on restriction of habitat availability for Lake Trout (Ficke et al., 2007)

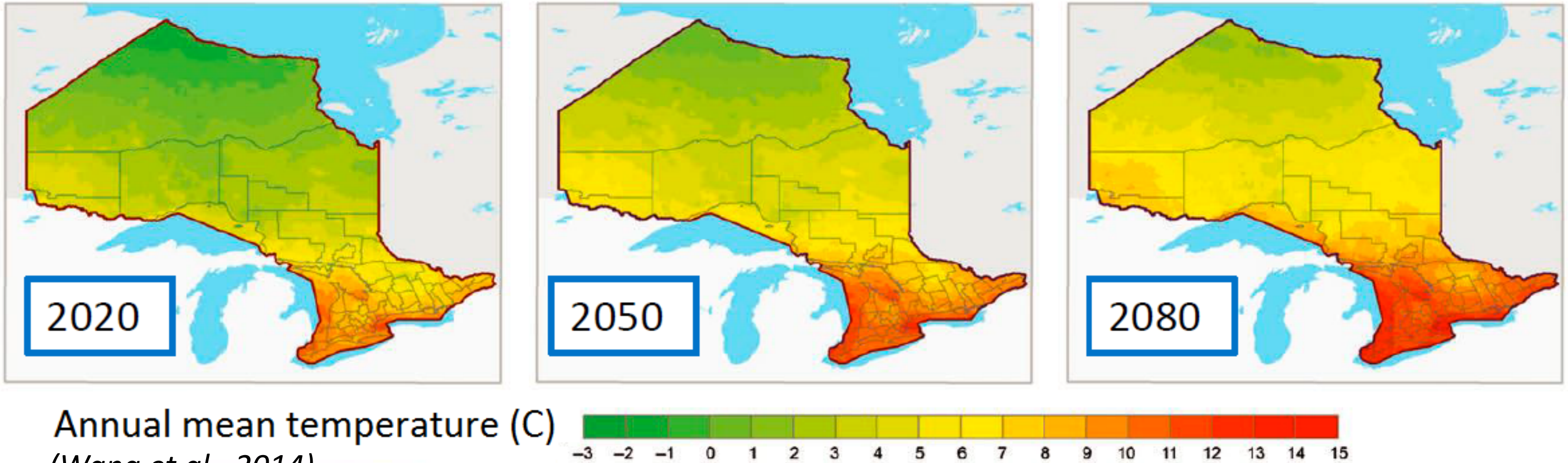
Introduction

- Significant weather changes in central Canada by 2100 (GCM):

  Winter: increase by 3-5°C

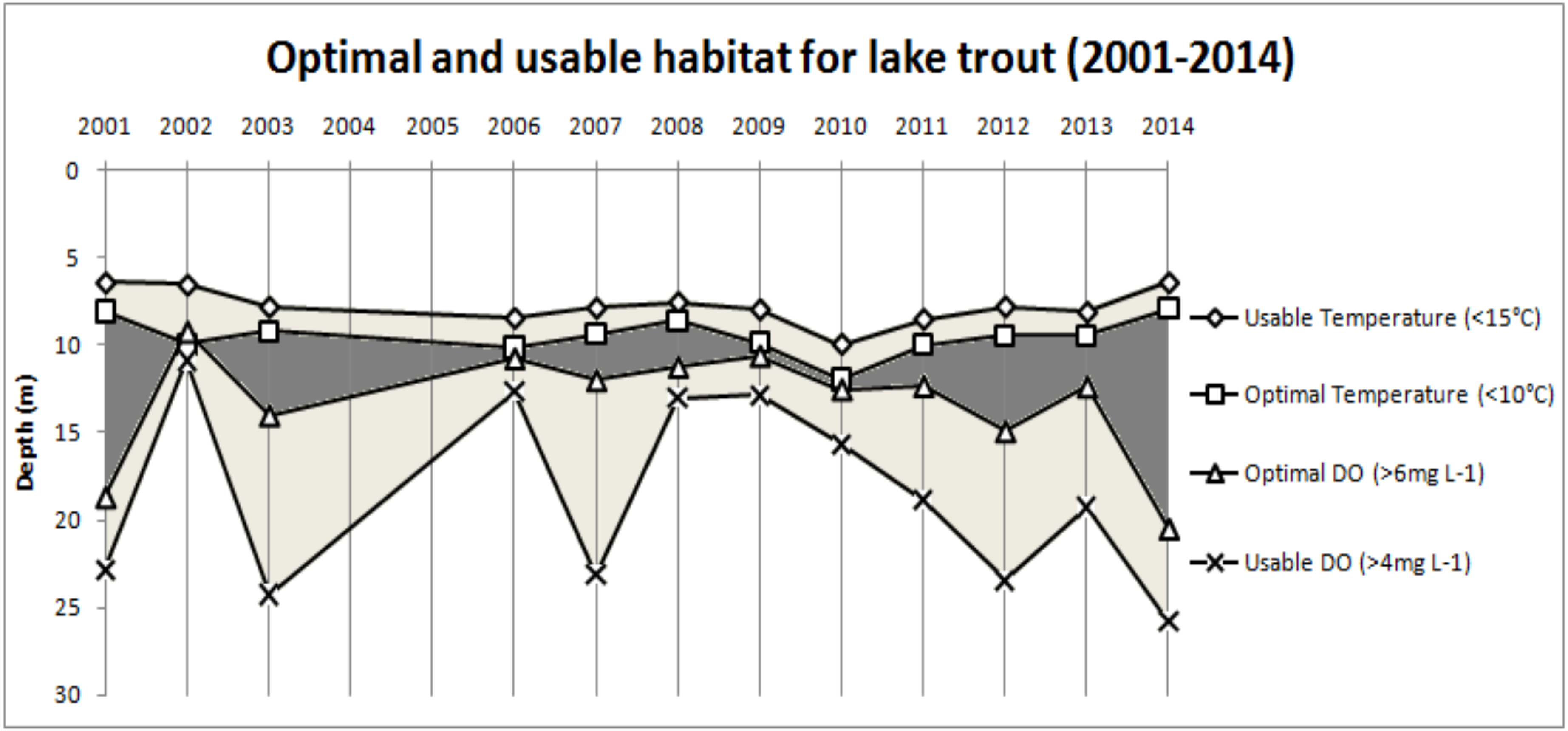
  Summer: increase by 3-4°C (low greenhouse gas emission scenarios)

  Climate changes → lower water levels → less hypolimnion volumes → severe hypoxia



(Wang et al., 2014)

Lake Trout habitat in Eagle Lake



Project Overview

- A 3-part study to:

  Analyze sediment cores to understand the past

  Develop empirical formulae to model the present

  Apply computational models to forecast the future

Theme 1: Understanding the past

Theme 2: Modeling the present

Theme 3: Forecasting the future

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Develop and calibrate models on a common set of study lakes

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Apply models to lakes of significant interest to supporting organizations

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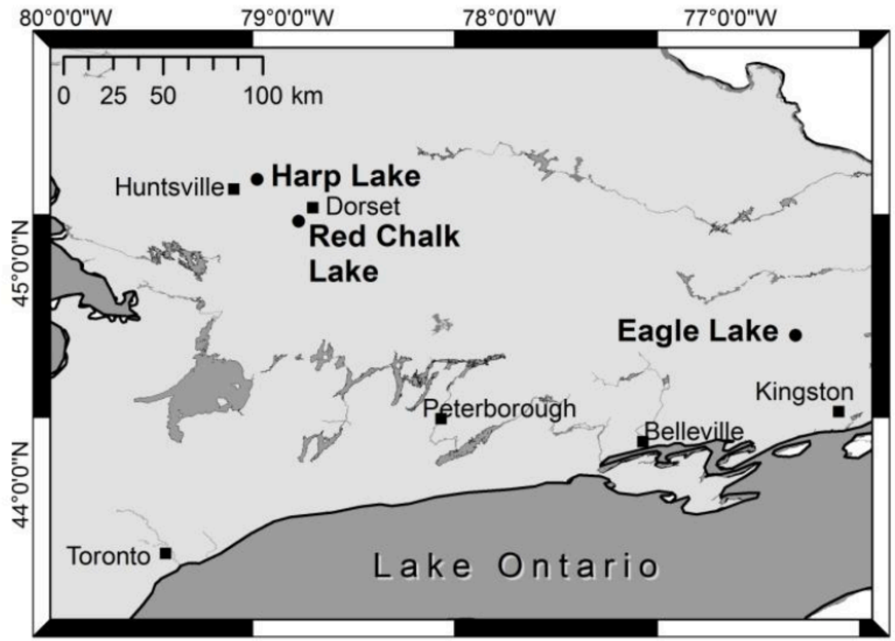
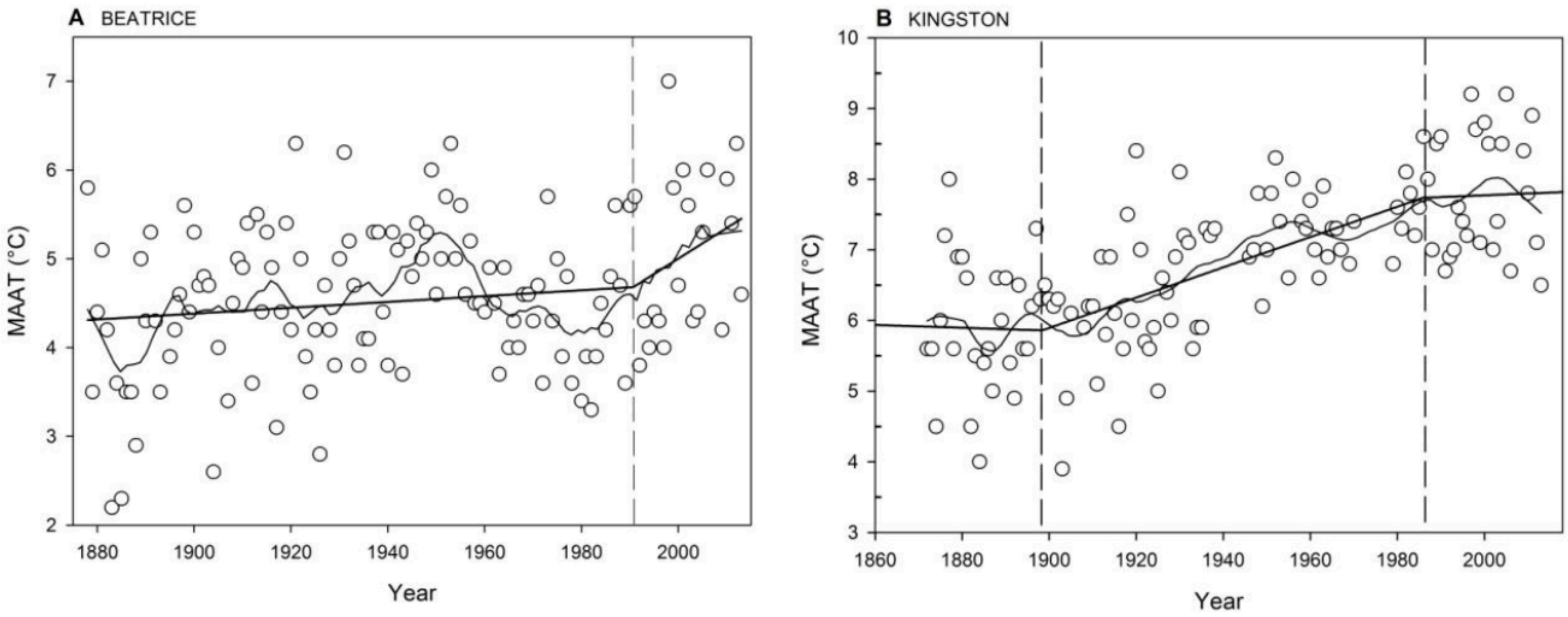
New toolset for lake and resource managers

Harp Lake and Eagle Lake



Variable	Harp Lake	Eagle Lake
Z_{max} (m)	37.5	31.1
TP (µg/L)	5.74	9.00
DOC (mg/L)	4.41	4.05
pH	6.42	7.9
Surface Area (km^2)	0.71	6.65
Length of shoreline (km)	4.74	41.4
Number of cottages	~100	>300

Historical warming near Harp and Eagle Lakes



A) Mean annual air temperature (MAAT) from a climate station located in Beatrice ~35 km from Harp (B) MAAT from Kingston located ~50 km south of Eagle Lake.

Methods

- 1D bulk mixed-layer thermodynamic Canadian Small Lake Model (CSLM) embedded in Canadian Regional Climate Model (CRCM)
- Lakes represented as 1 m^2 watercolumn tiles (Mosaic approach)
- Hundreds of small lakes represented with a few idealized lake tiles
- Surface mixed layer model for surface layer with no mixing below SML (MacKay 2012)

- Added a simple DO sub-model (Hamilton and Schladow 1997)
- DO flux at surface and SOD applied to the first cell

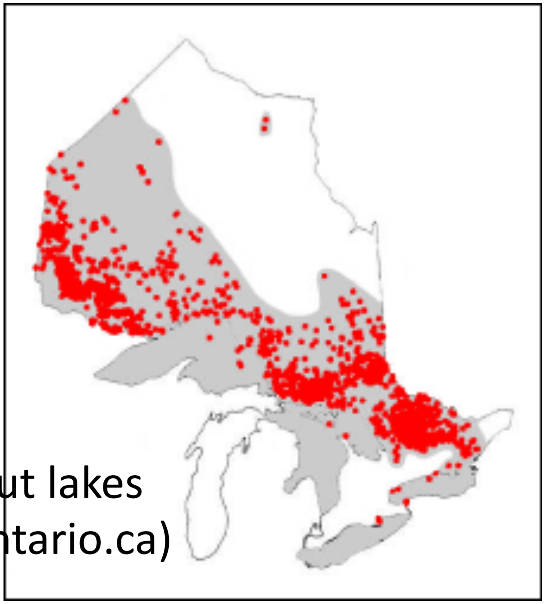
$$SOD = \mu_b \, DO \; / \; (DO + K_m)\alpha_{sed}^{T-20}$$

μ_b =0.46 $gm^{-2}d^{-1}$ (maximum biochemical sediment oxygen uptake)

K_m=1.5 mgL^{-1} (half saturation constant)

α_{sed}=1.08 (sediment temperature multiplier)

T = water temperature



Lake Trout lakes (www.ontario.ca)

Harp Lake: model set-up

- **Calibration and validation:**

  30 years of bi-weekly observations

  July 5th, 1978 to December 31th, 2007

  Maximum depth: 34 m

  Square root of the surface are: 843 m

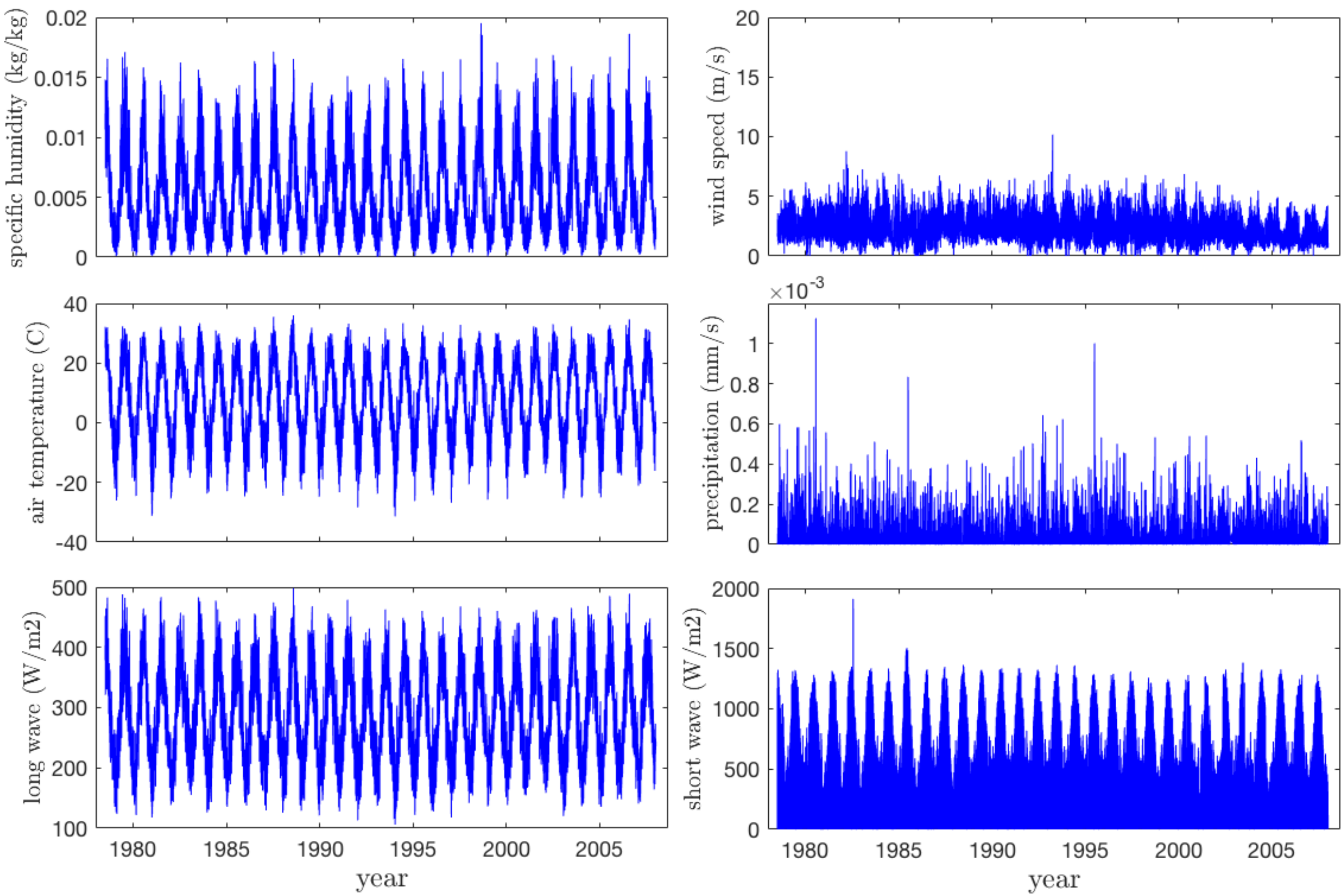
  Extinction coefficient: 0.5 1/m

  Grid spacing: 0.5 m

  Time steps: 10 min

  HOD= 0.03 $gm^{-3}d^{-1}$

Harp Lake: Meteorology



Eagle Lake: model set-up

- **Calibration and validation:**

5 years of high-frequency (10 s to 10 min) observations

June 22nd, 2011 to July 29th, 2015

Maximum depth: 30 m

Square root of the surface are: 250 m

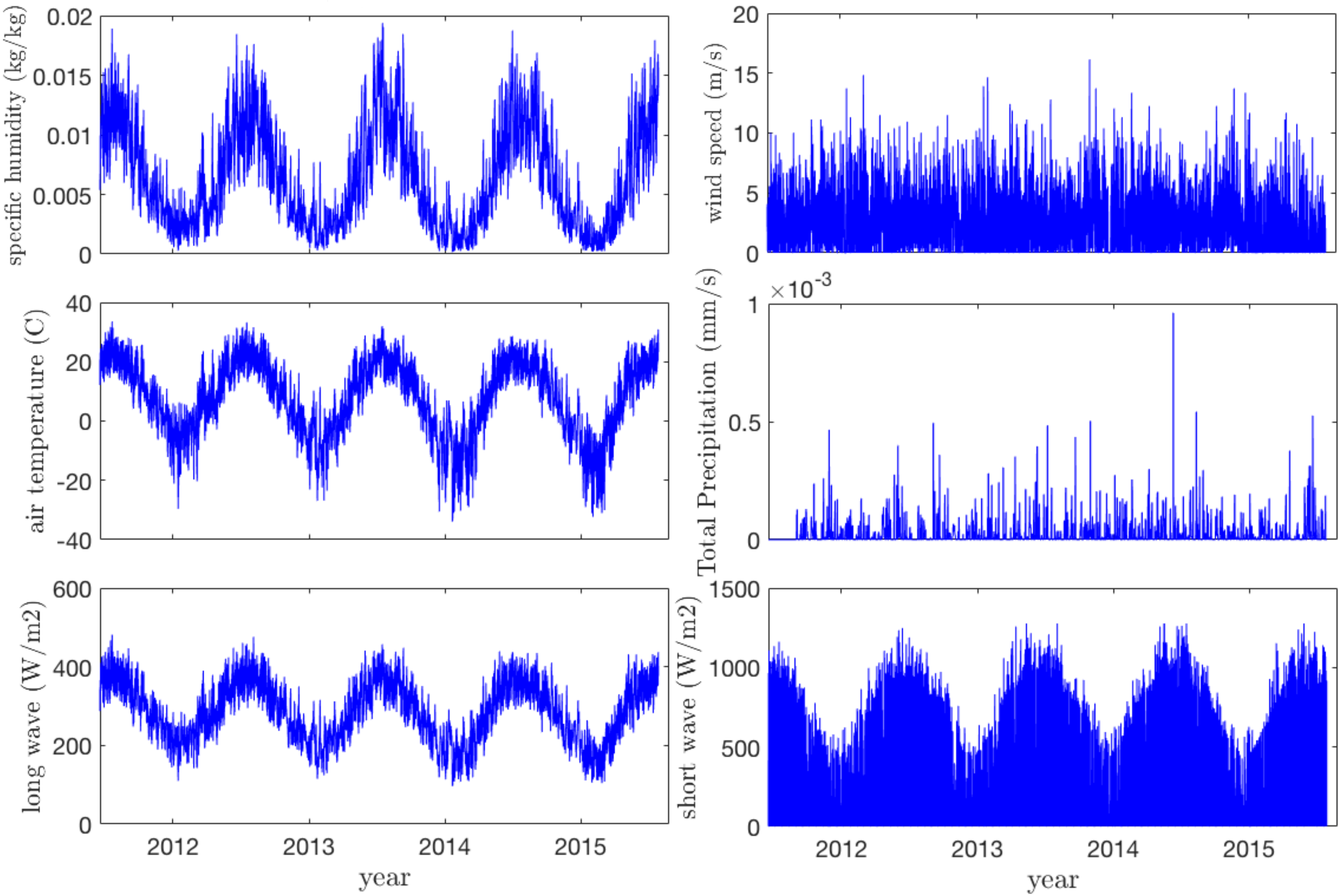
Extinction coefficient: 0.3 1/m

Grid spacing: 0.5 m

Time steps: 10 min

HOD= 0.08 $gm^{-3}d^{-1}$

Eagle Lake: Meteorology



Part II: Bottom boundary layer mixing sub-models

Methods

Bottom boundary layer mixing sub-models

a)

- h_{BML} following a mixed layer approach (Imberger, 1985; Spigel et al., 1986)
- Fully turbulent BML with uniform DO resulting from shear-induced mixing

$$d(uh_{BML})/dt = {u_B^*}^2$$

u: mixed−layer velocity

u_B^*: bottom friction velocity ($u_B^* = 0.2u_S^*$)

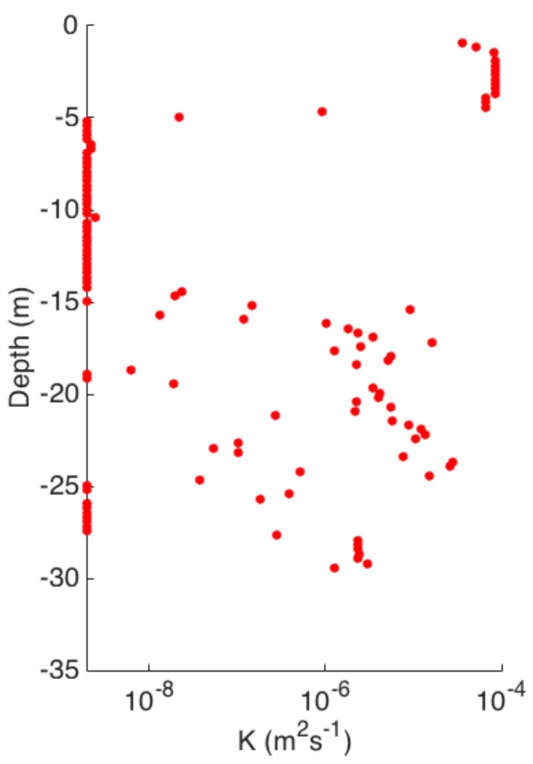
b)

- DO flux computed from Fick's Law

$$J = -K \, dDO \, / \, dz$$

$K = 10^{-7}$ m^2s^{-1}

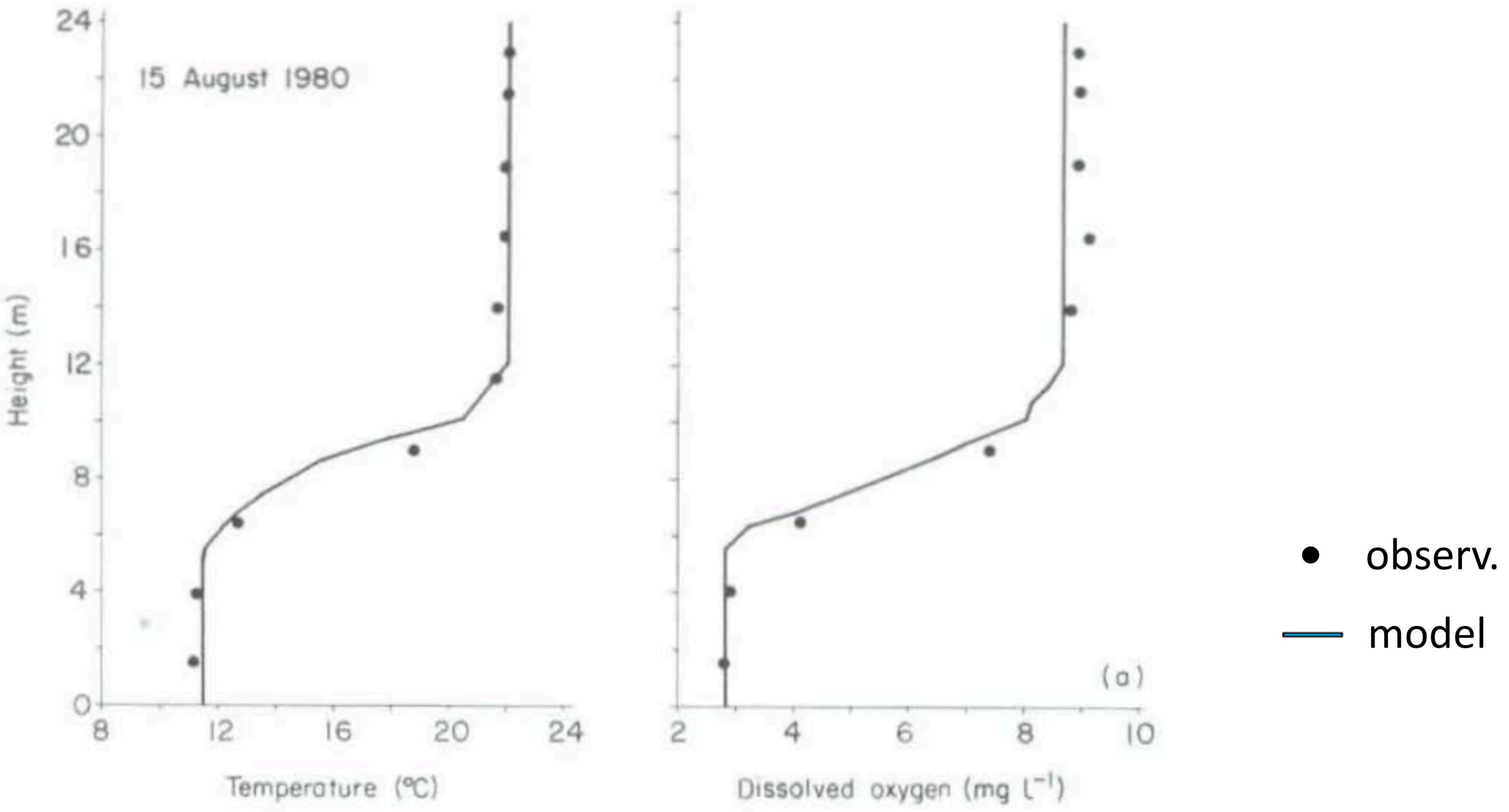
K: average diffusivity from microstructure profiler



Introduction

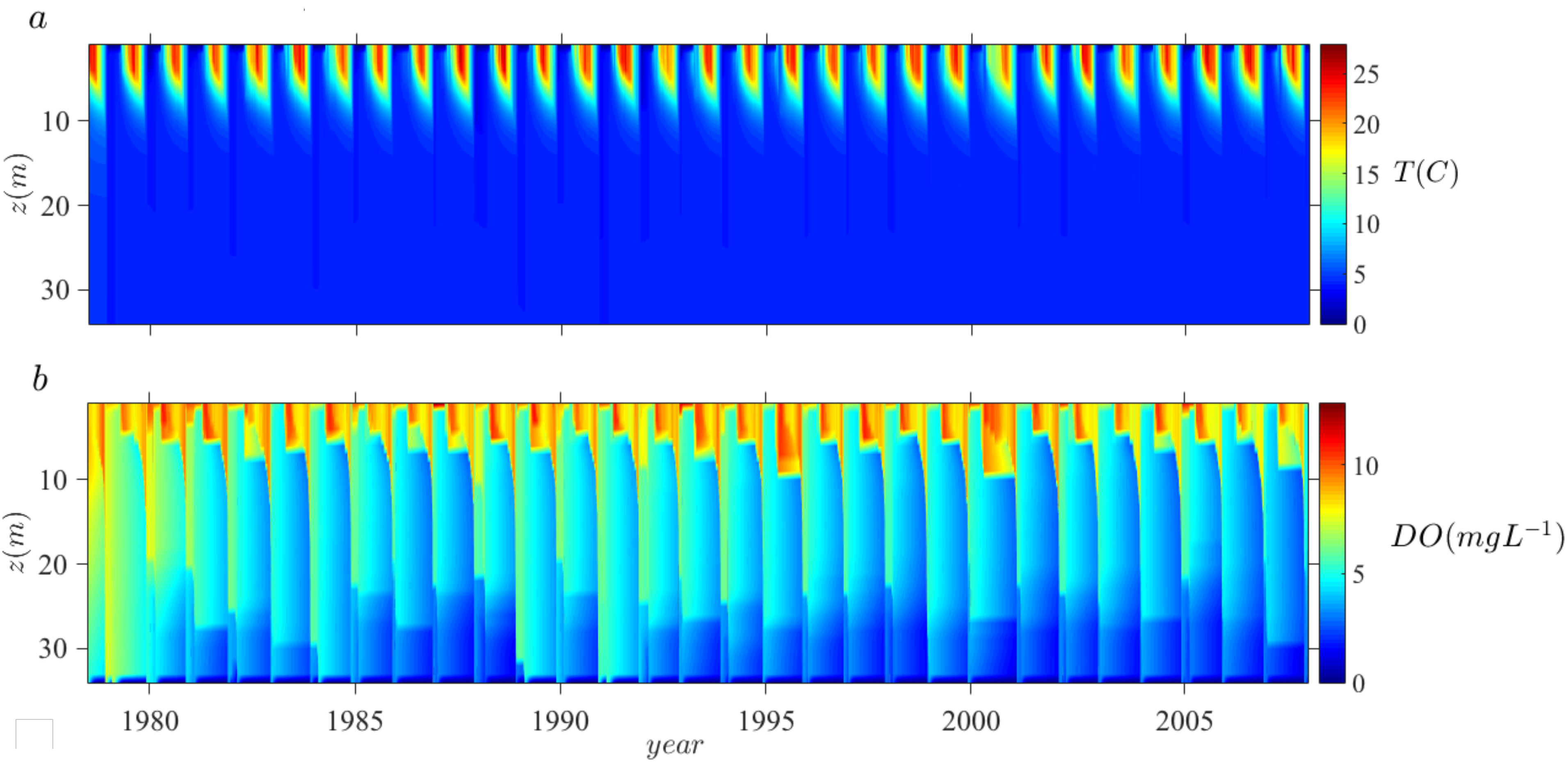
Mixed-layer models in large lakes

Lake Erie

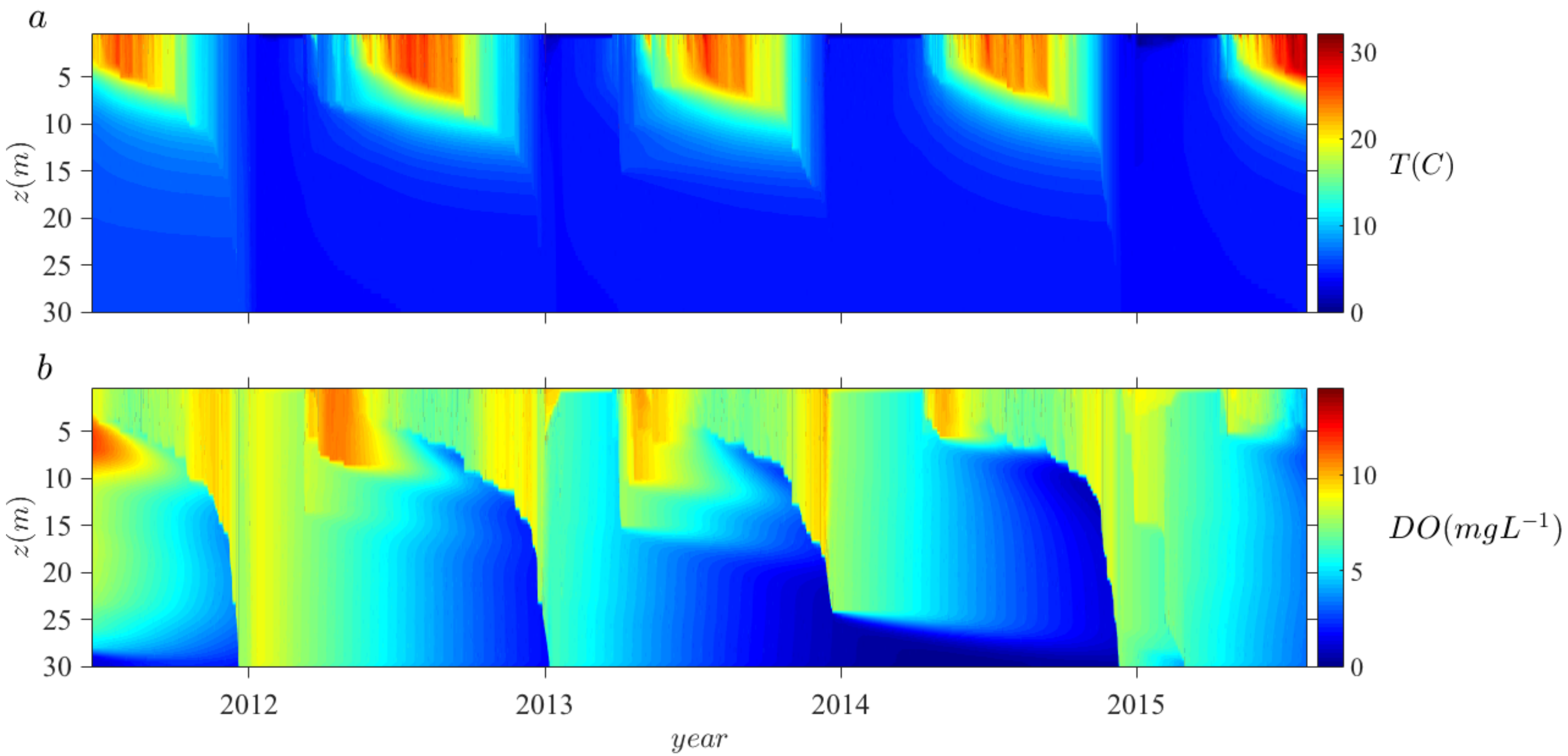


Patterson et al (1985, FRESH. BIO.)

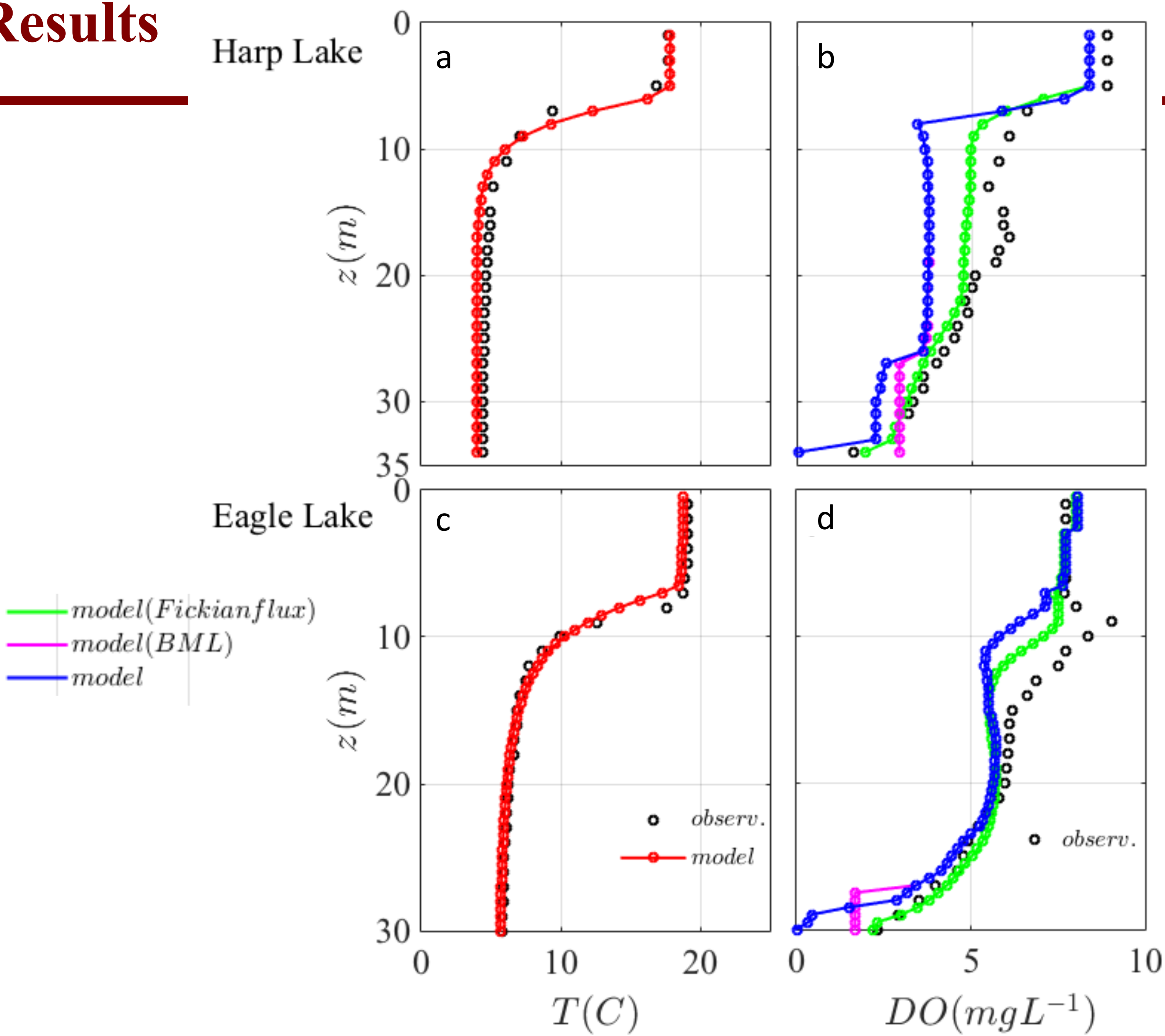
Harp Lake: Results



Eagle Lake: Results



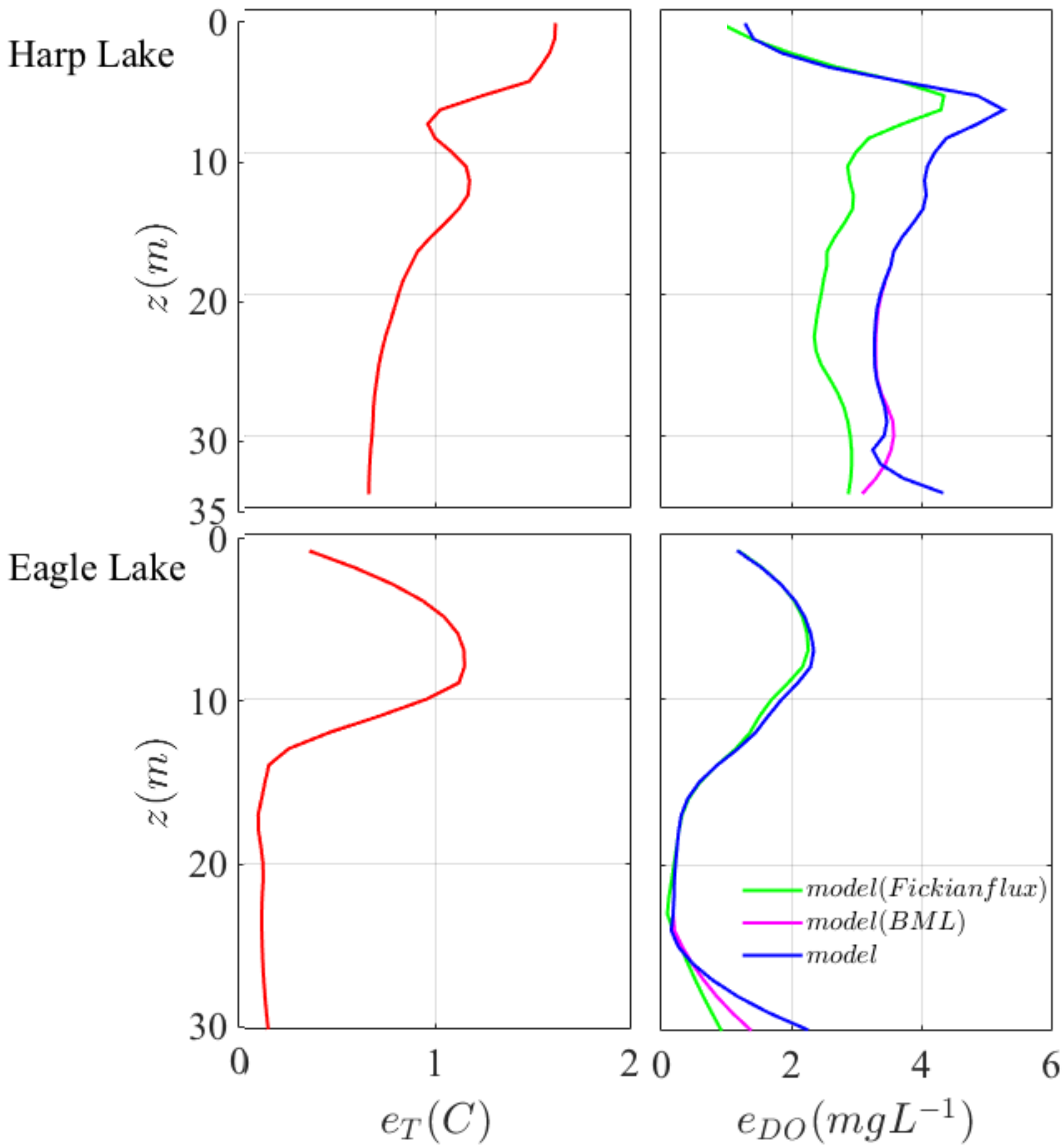
Results



a & b:
Sep. 15th, 1999

c & d:
Sep. 22nd, 2011

Results RMSE



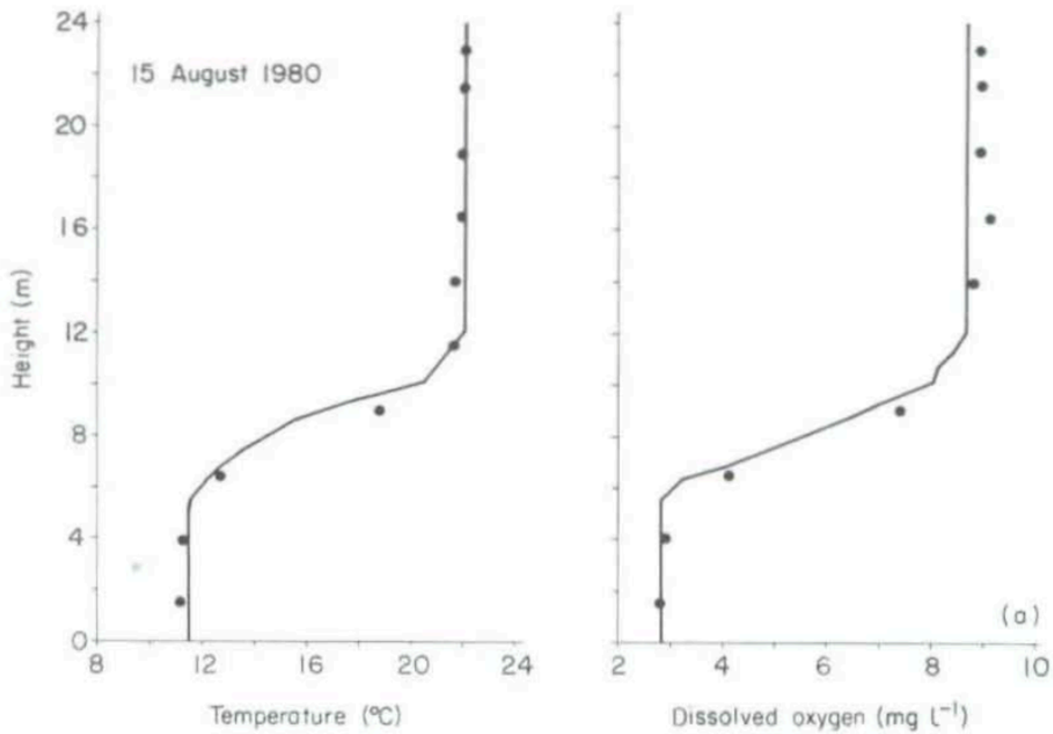
- Less error in DO prediction in BBL using the Fickian flux sub-model
- Smooth decrease in DO profiles using Fickian flux approach
- Fickian flux approach even improves DO predictions above the BBL
- Mixed layer approach is successful in the surface

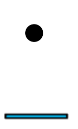
Re dependence of mixed layer models

$$Re_{SML} = h_{SML} u^*_S / \nu \qquad Re_{BML} = h_{BML} u^*_B / \nu$$

- In Lake Erie: u^*_B=0.2 cm/s and $h_{BML} \approx$ 7m; Re_{BML} > 10,000 and BML approach is successful

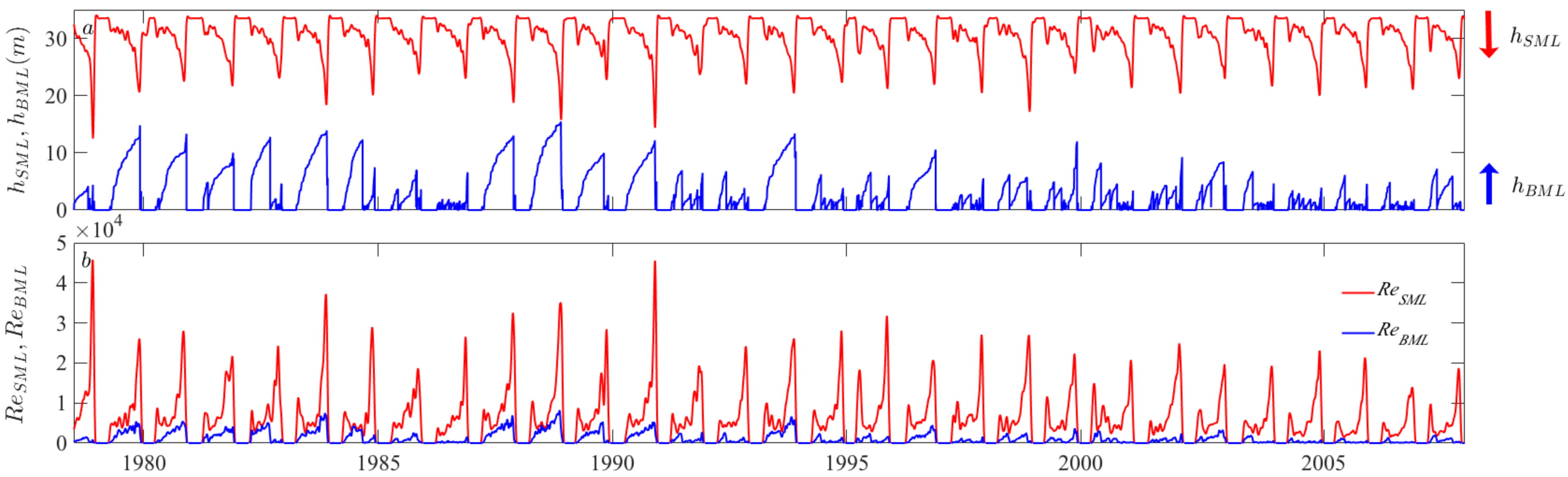
Lake Erie





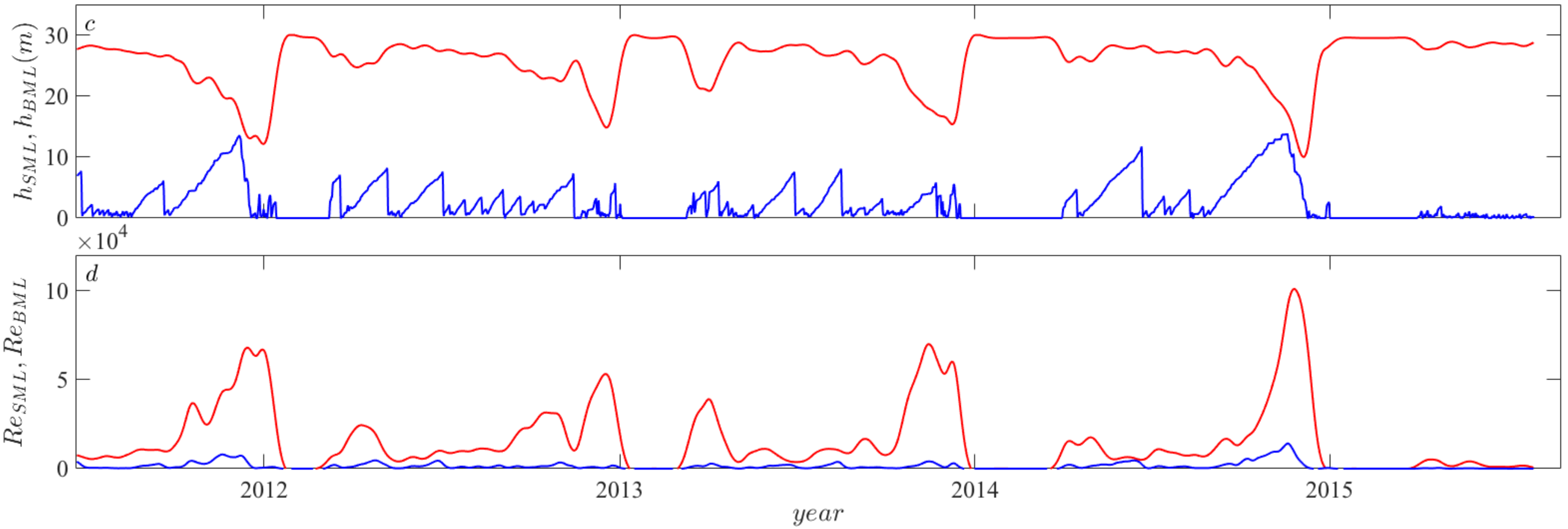
Ivey and Patterson (1984, L&O)

Results: Harp Lake *Re* and mixed layer height



- $h_{SML} > h_{BML}$; h_{BML} <10 m
- $Re_{BML} < Re_{SML}$; Re_{BML} barely exceeds 10,000 ➡ BML approach is not accurate
- $Re_{SML} \geq$ 10,000; higher turbulence at the surface ➡ SML approach is successful

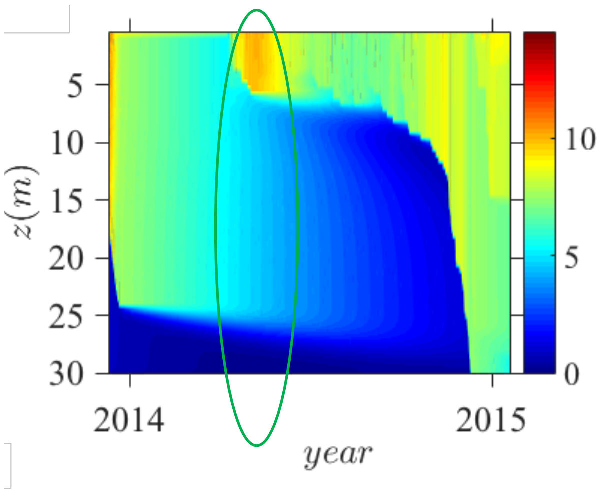
Results: Eagle Lake *Re* and mixed layer height

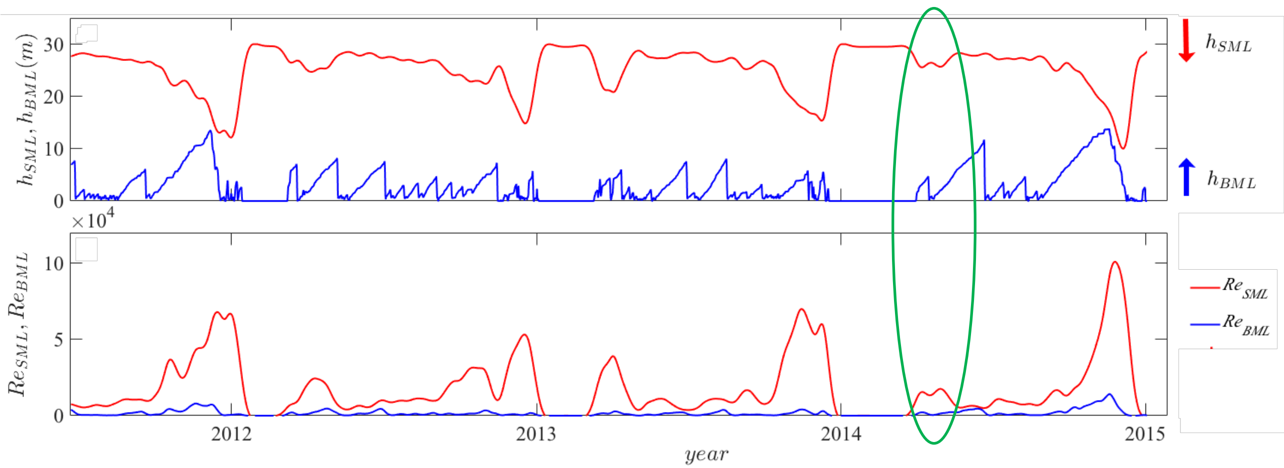


- $h_{SML} > h_{BML}$; $h_{BML} < 10$ m
- $Re_{BML} < Re_{SML}$; Re_{BML} barely exceeds 10,000 → BML approach is not accurate
- $Re_{SML} \geq$ 10,000; higher turbulence at the surface → SML approach is successful

Results: Mixing in turnover events

Understanding deep-water hypoxia through *Re_{SML}*





- *Re_{SML}* can be applied to understand lake turnover and re-oxygenation of the hypolimnion in spring and fall.
- Poor re-oxygenation of hypolimnion in spring 2014 turnover
- *Re_{SML}*≈13,000 (h_{SML} ≈ 3m) is low compared to *Re_{SML}* in other years

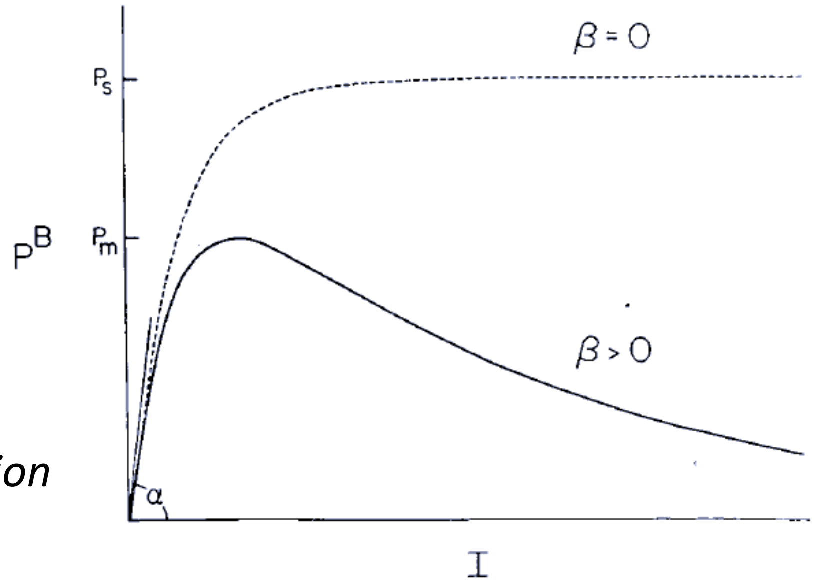
- Part III: Photosynthesis and water column respiration

Methods

Photosynthesis production

Parameterization of the specific production as a function of the light intensity (Platt et al., 1980)

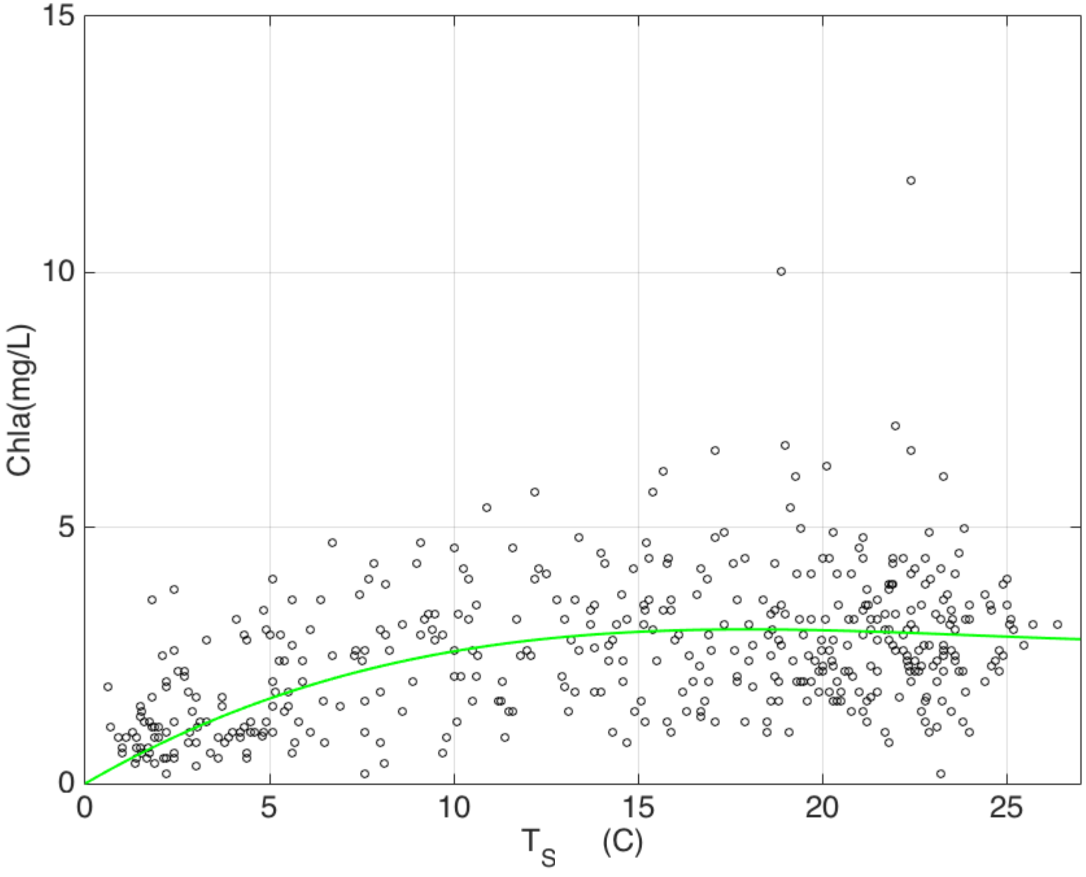
$P^B = P_S^B\{1 - exp(-\alpha I/P_S^B)\}exp(-\beta I/P_S^B)$
P_S^B: Maximum potential specific productivity (41.5 mg O_2/mg Chla/h)
I: light intensity (W/m^2)
α: 0.2 mg O_2 m^2 /mg Chla/hr/W
β: 0.45 mg O_2 m^2 /mg Chla/hr/W



General form of the function (Platt et al., 1980)

Respiration

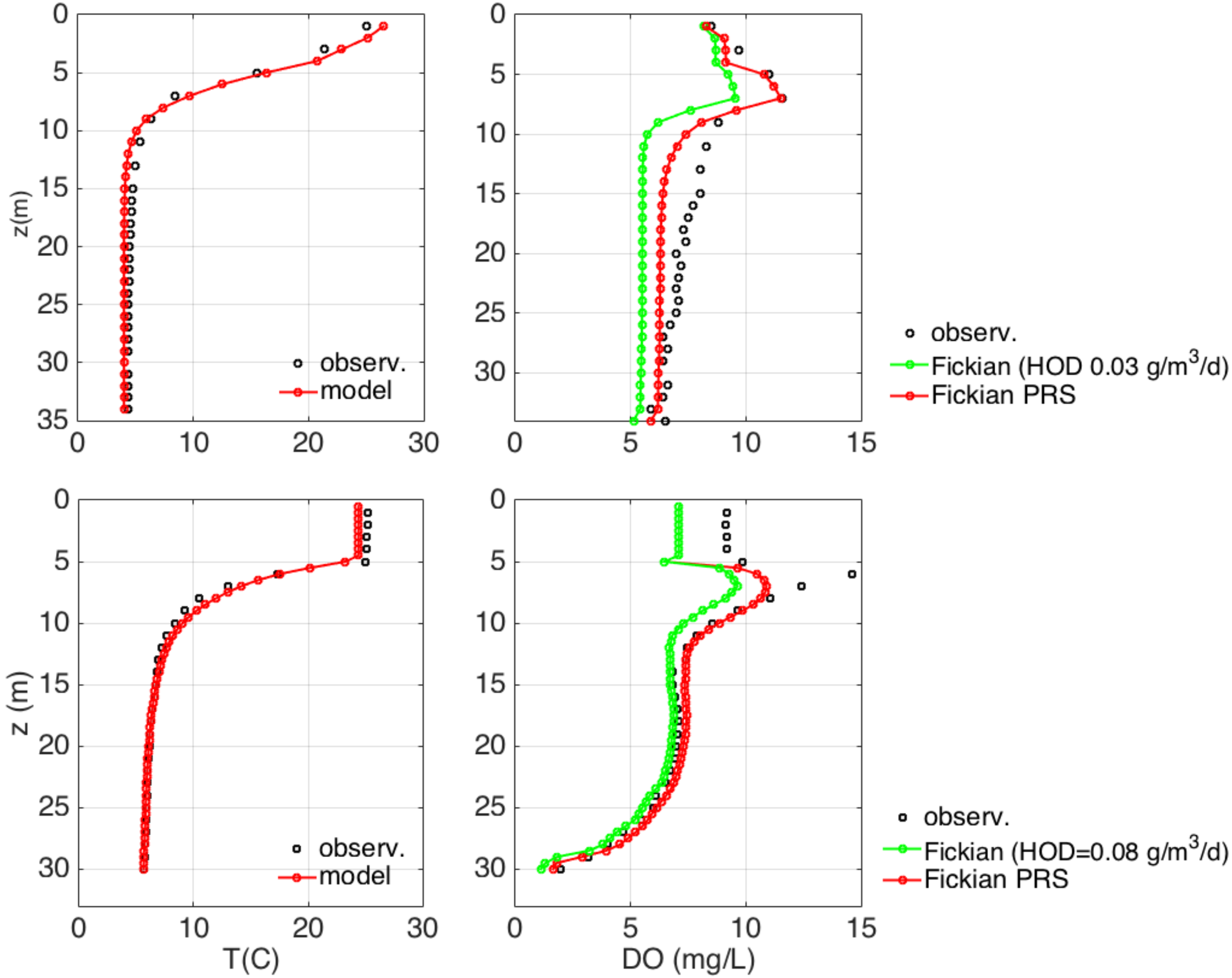
Respiration in upper mixed layer=1.8 photo-assimilation
Respiration in bottom mixed layer=0.2 photo-assimilation



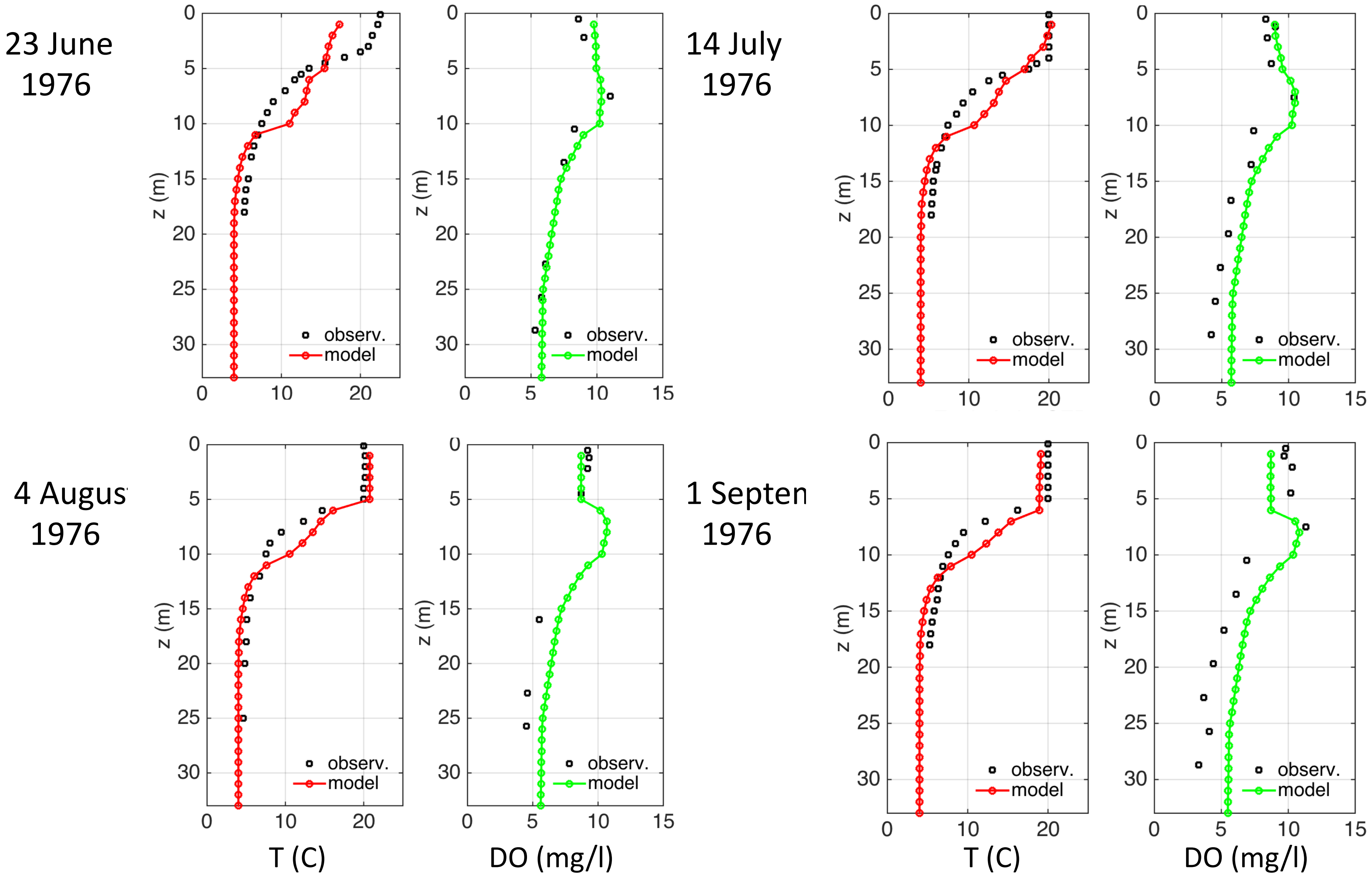
Results

Harp Lake
11 July 1988

Eagle Lake
8 August 2011



Results: Harp Lake GCM



Summary and Conclusions

- In small lakes: $Re_{BML} < Re_{SML}$; $Re_{SML} > 10{,}000$ (Re_{BML} barely exceeds 10,000)
- For Reynolds numbers < 10,000 the flow remains transitional and a Fickian diffusion model is appropriate
- For Reynolds numbers > 10,000, we expect a fully turbulent boundary layer and a mixed layer model should be used
- The best DO predictions are from the simple Fickian flux sub-model at the BBL, but a mixed layer approach in the surface
- Parameterization of the specific production as a function of the light intensity and respiration as a factor of photo-assimilation improves the results

Thank you!