Modeling oxygen depletion within stratified bottom boundary layers of lakes

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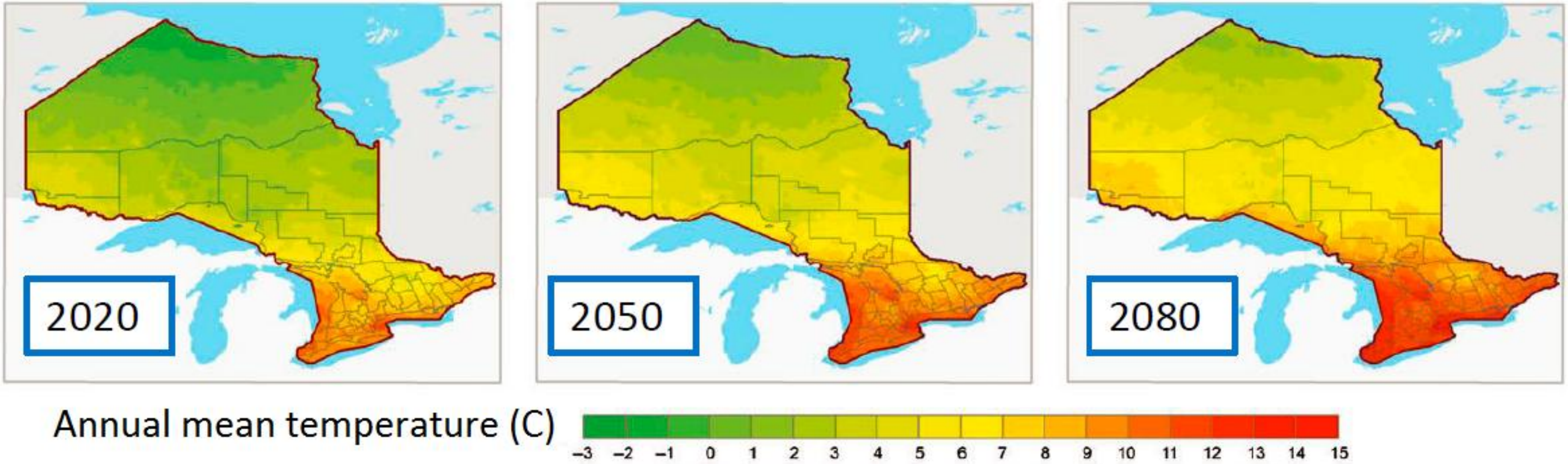
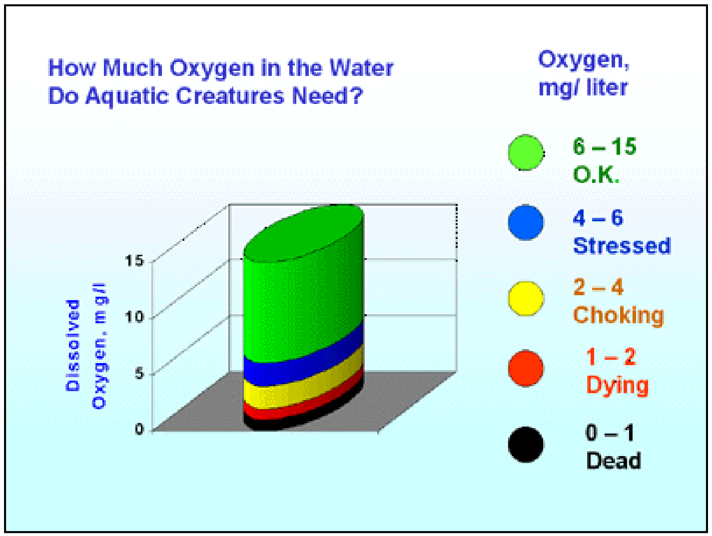
Introduction

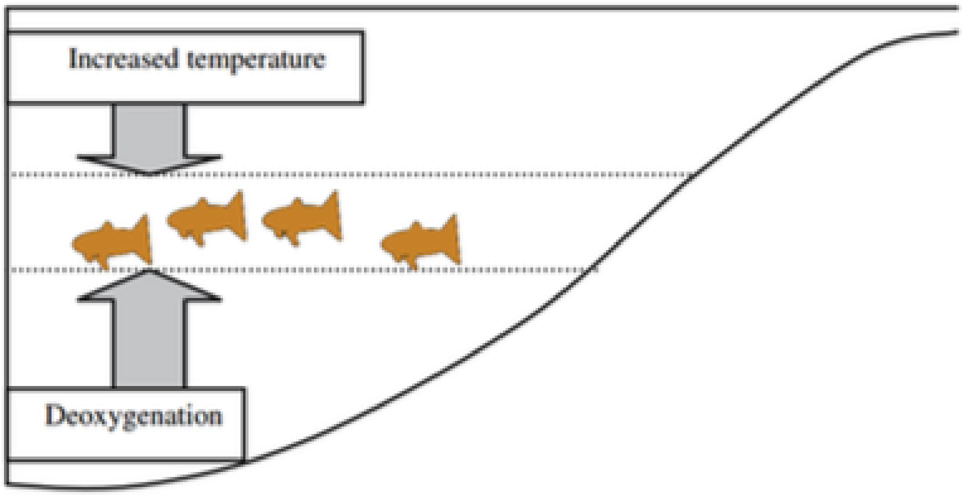
- Prediction of T and DO in Canadian Lake Trout lakes
- Application over future climate-change relevant timescales
- Lake Trout: Narrow physiological tolerances for
  T (<10 °C) and DO (>6 mg/L)
- Vulnerable to many stresses including climate warming



(Wang et al., 2014)

Lake Trout habitat

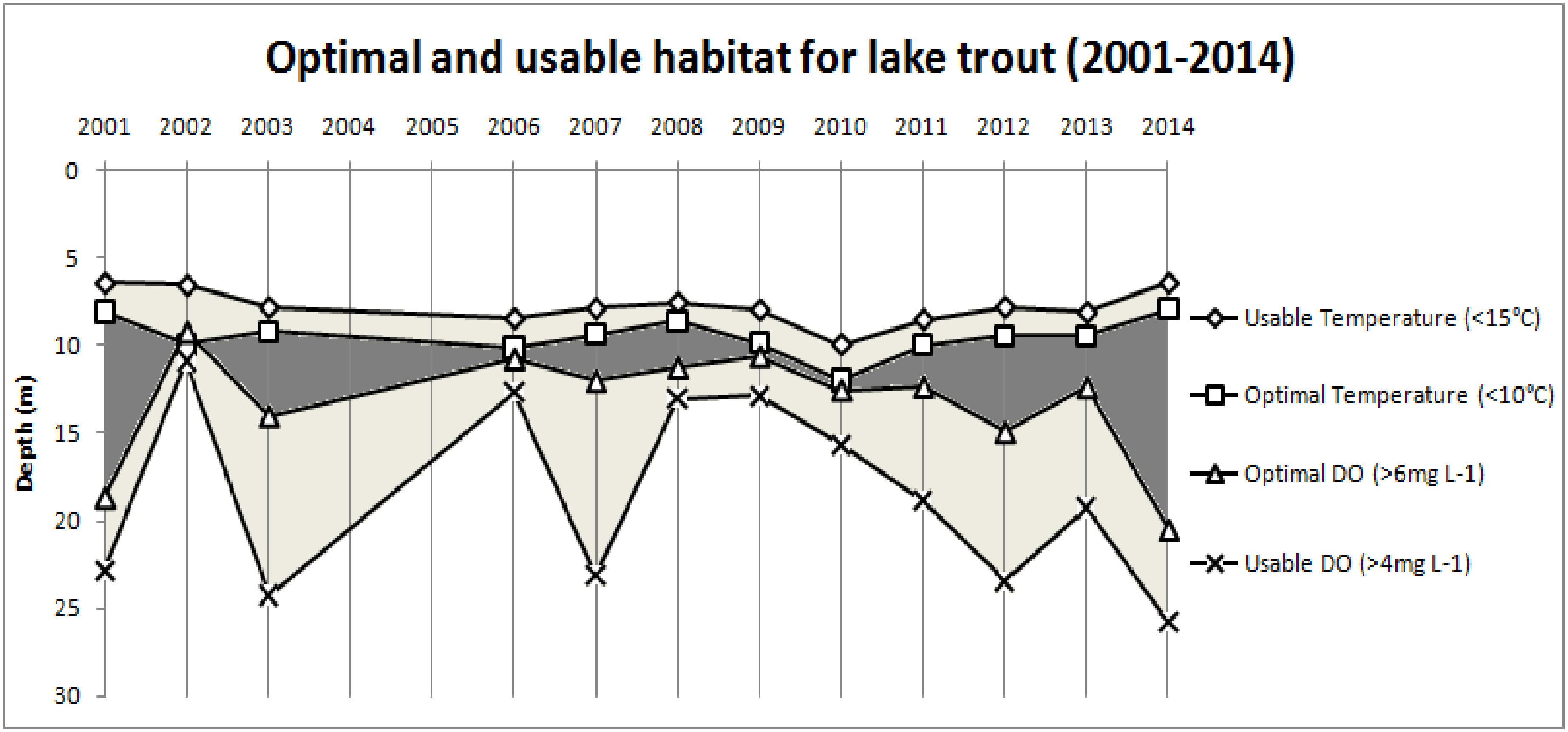




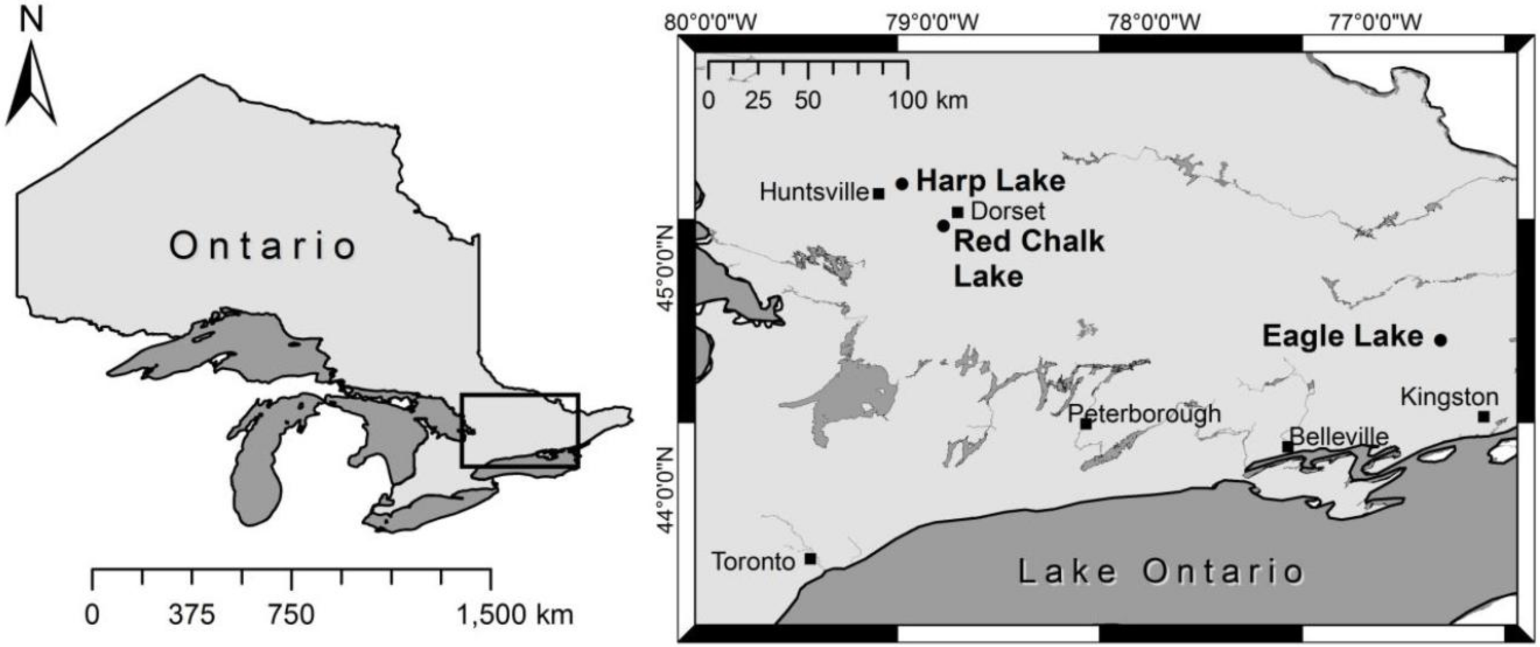
Ficke et al. (2007)

Climate warming increases epilimnion temperature and decreases hypolimnion oxygen, compressing useable lake trout habitat

Lake Trout habitat in Eagle Lake

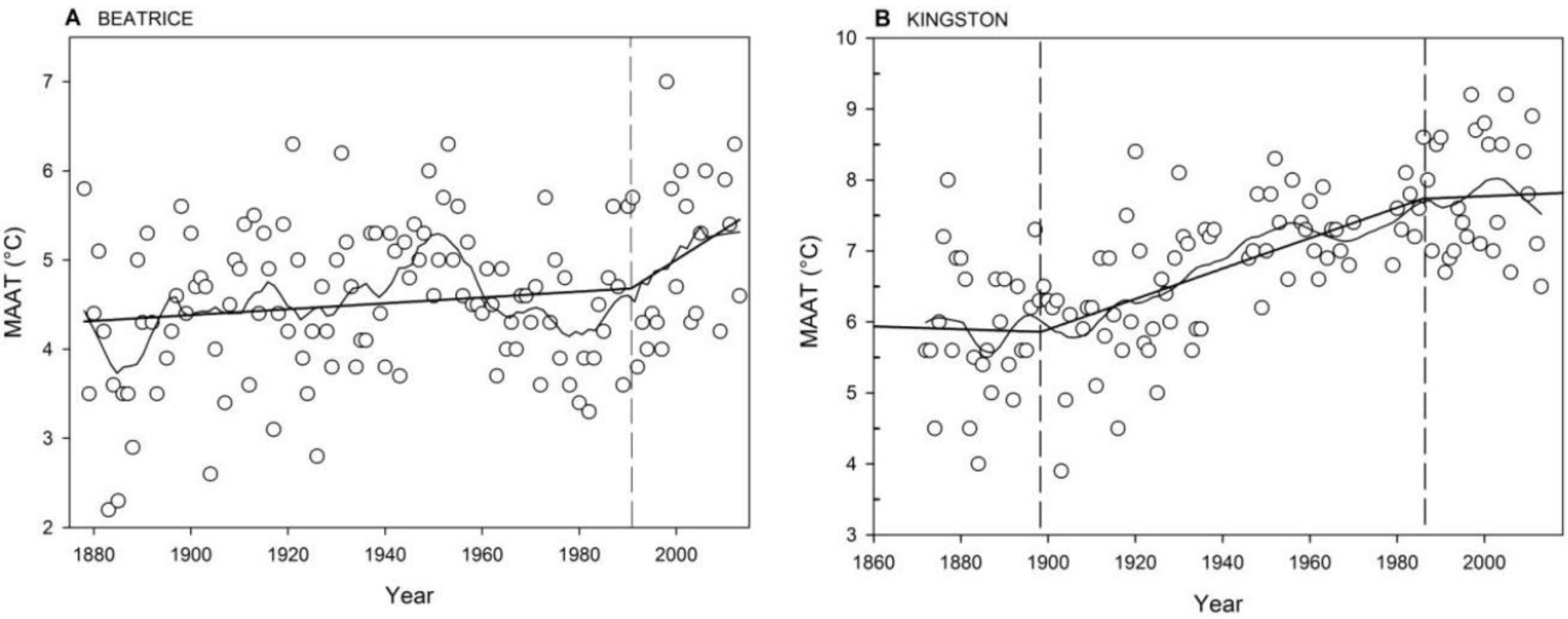


Harp Lake and Eagle Lake



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



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)

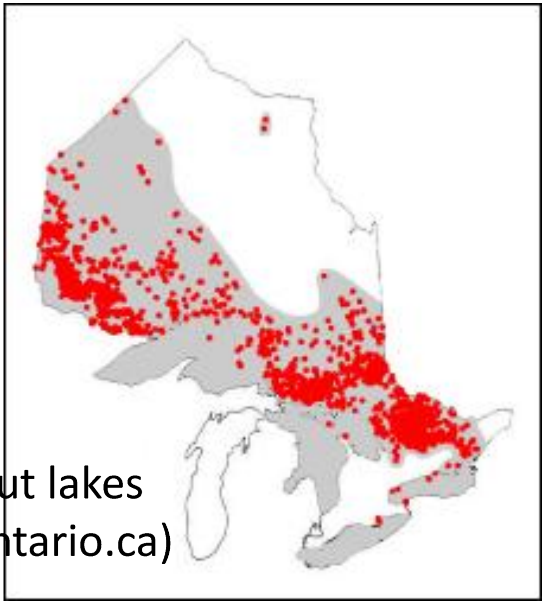
- Added a simple DO sub-model (Hamilton and Schladow 1997)
- DO flux at surface and SOD applied to the first cell

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

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)

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 ($u_B^* = 0.2u_S^*$)

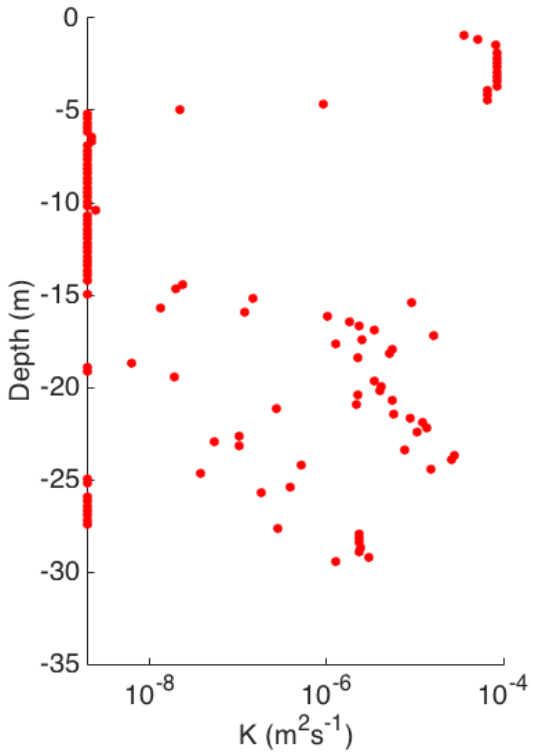
b)

- DO flux computed from Fick's Law

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

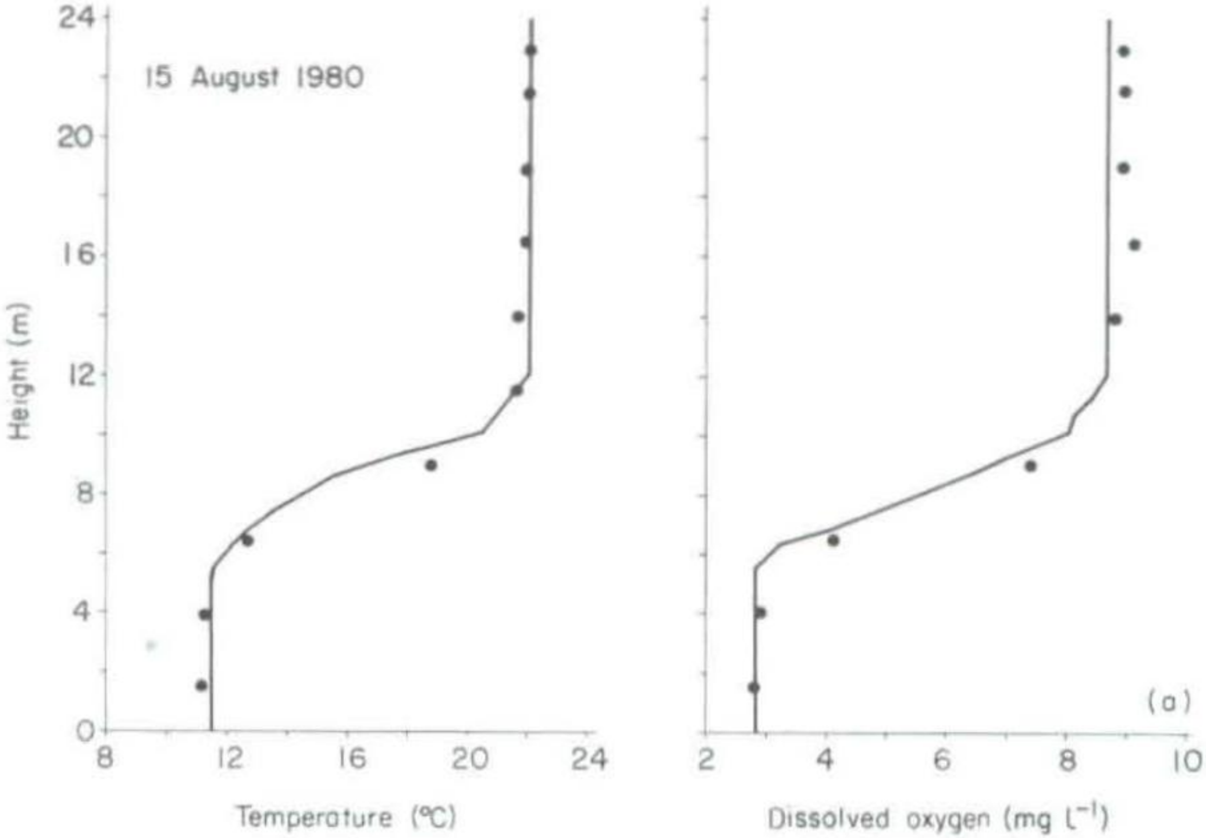
K =10^{-7} m^2s^{-1}

K: average diffusivity from microstructure profiler



Mixed-layer models in large lakes

Lake Erie



• observ.

— model

Ivey and Patterson (1984, L&O)

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

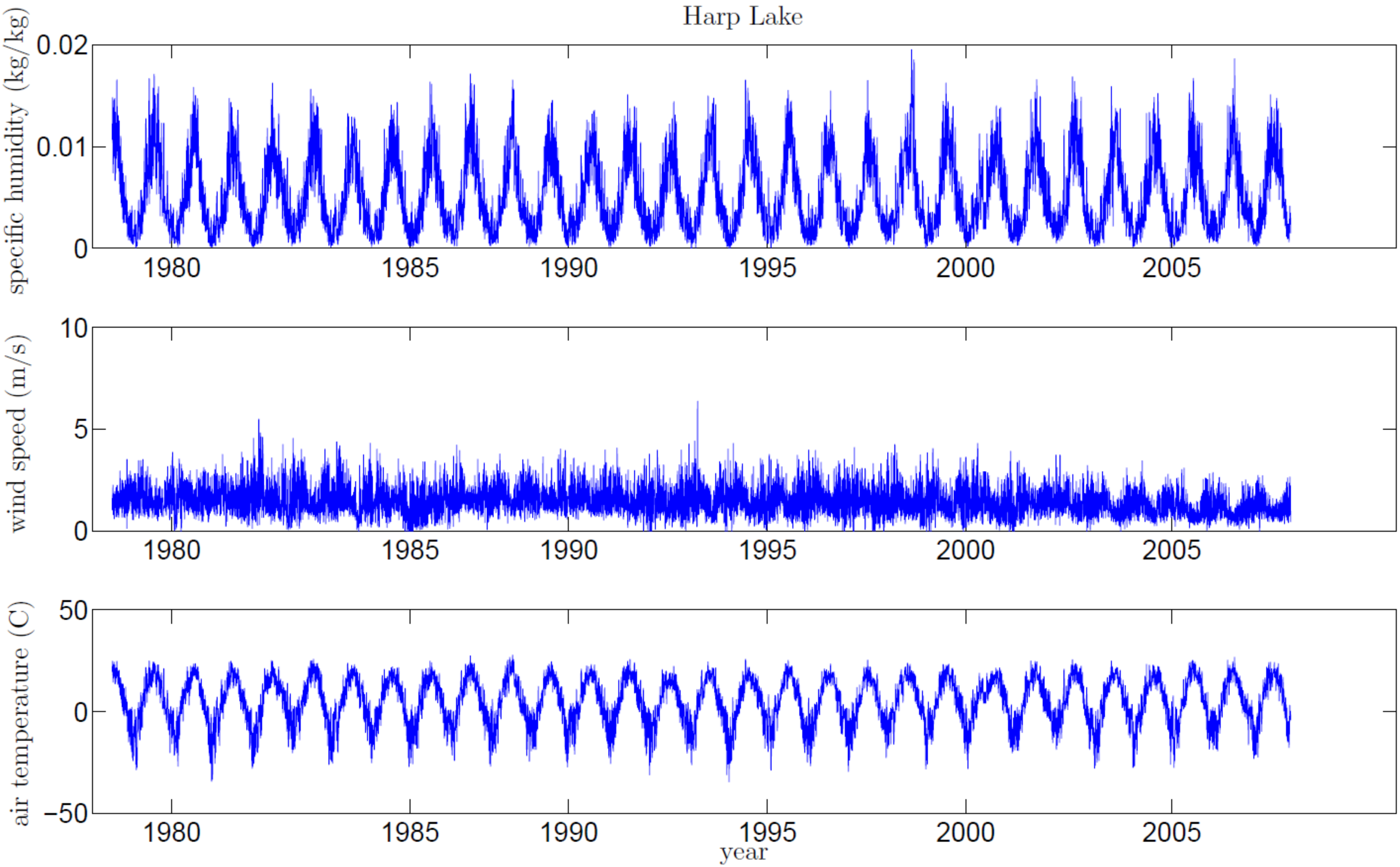
Extinction coefficient: 0.5 1/m

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

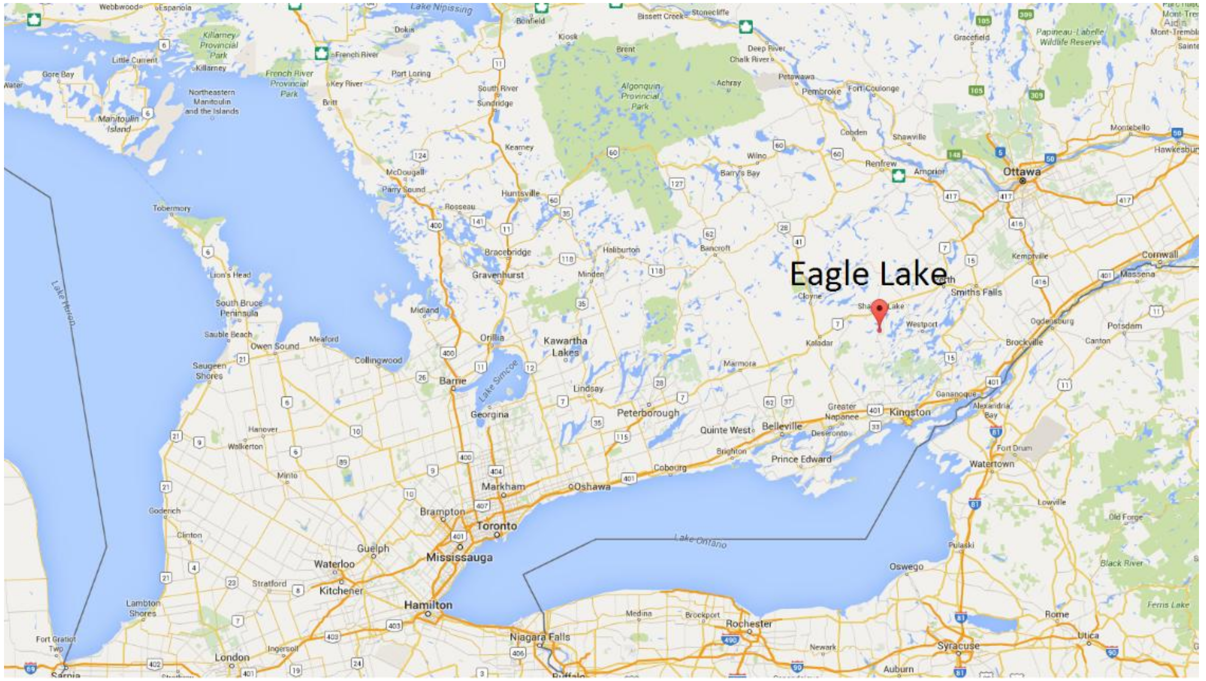
Square root of the surface are: 250 m

Extinction coefficient: 0.3 1/m

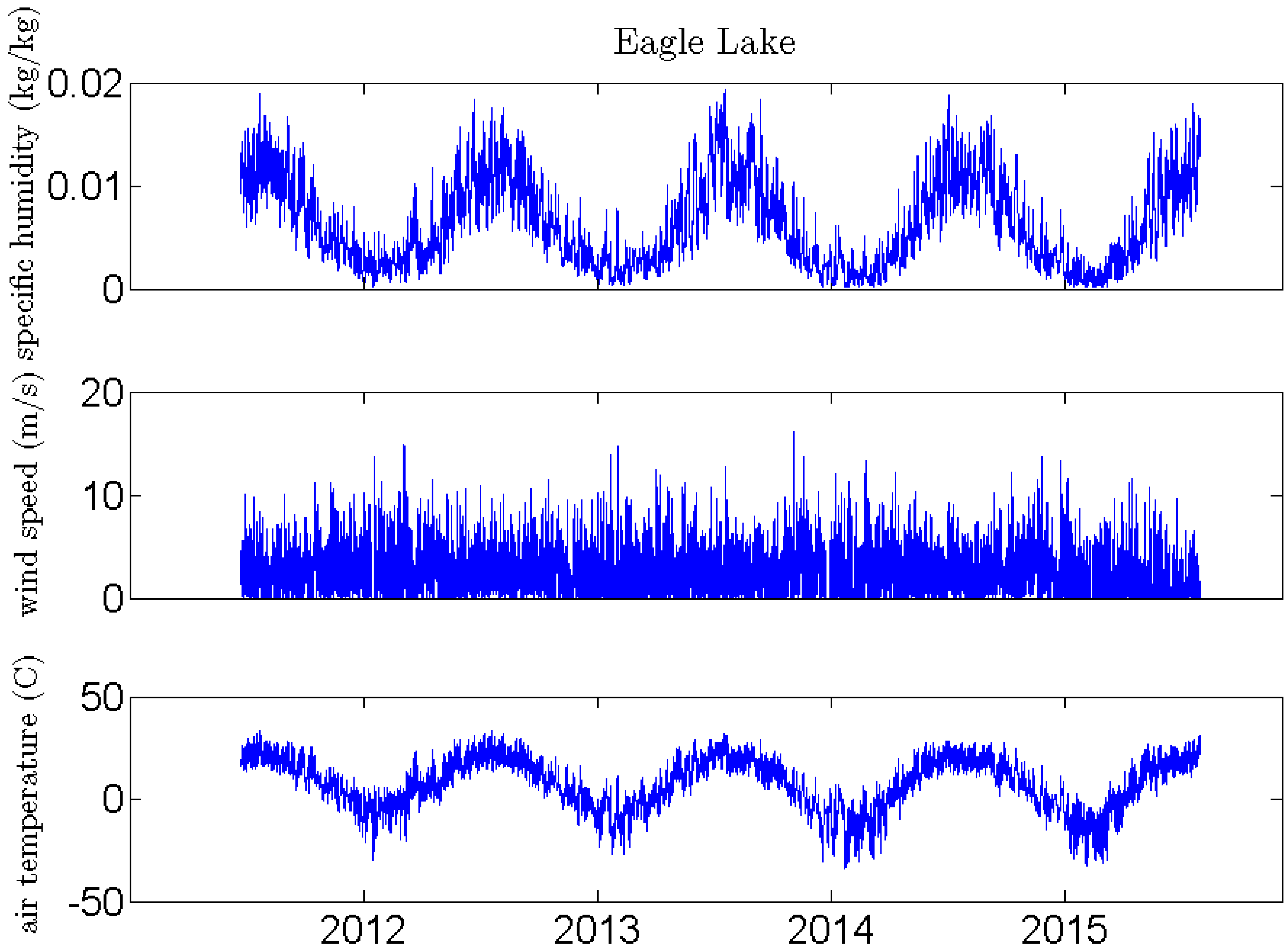
Grid spacing: 0.5 m

Time steps: 10 min

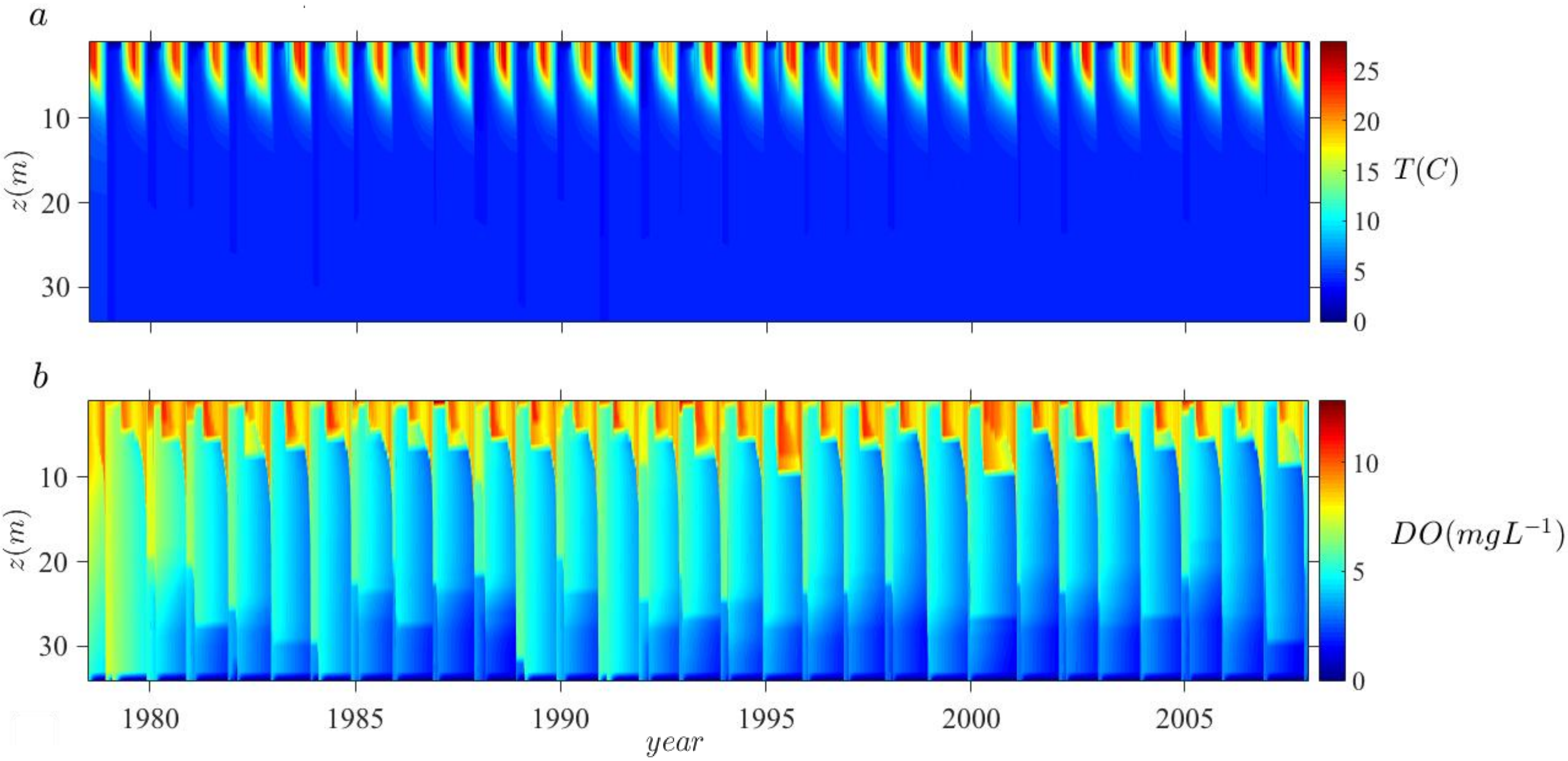
HOD= 0.08 $gm^{-3}d^{-1}$



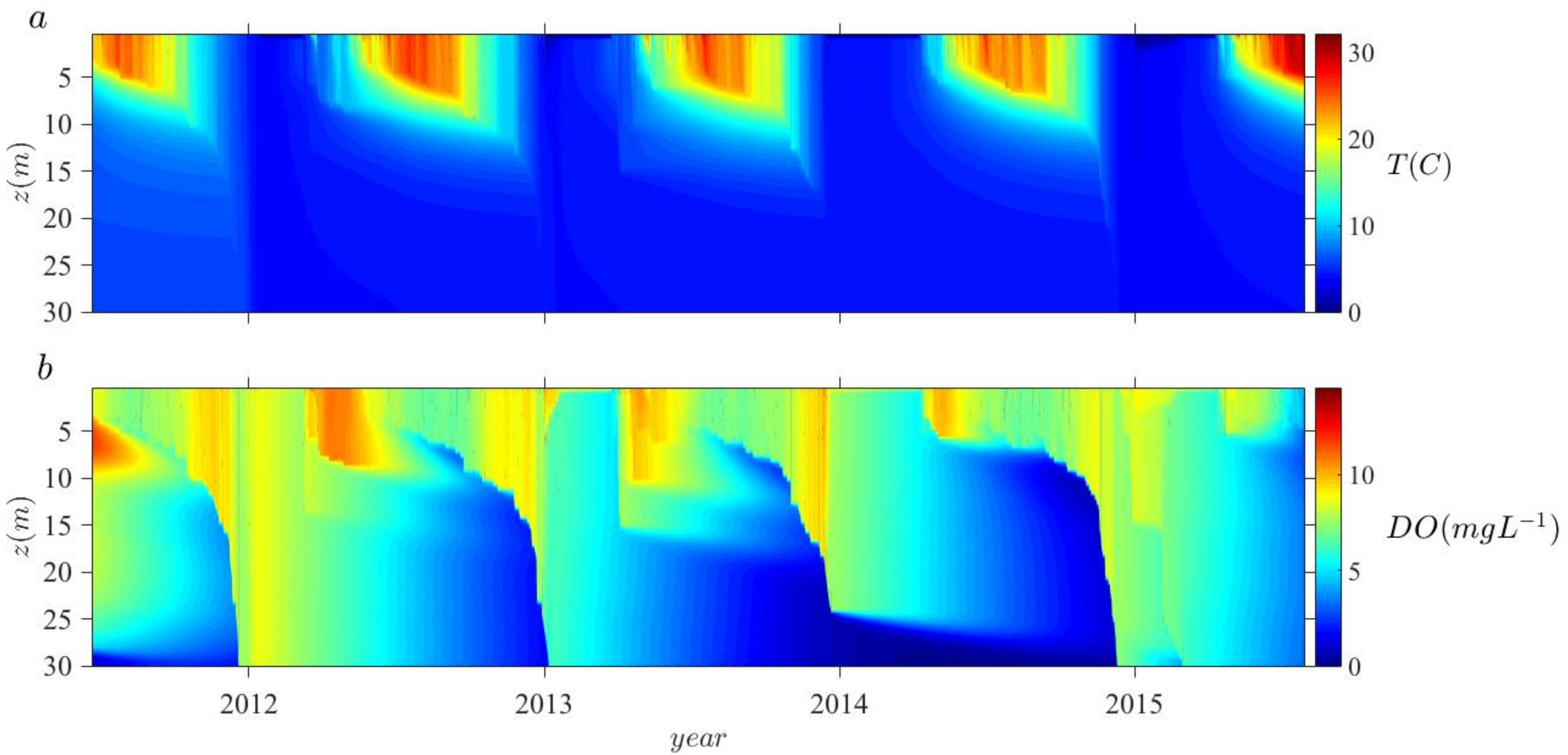
Eagle Lake: Meteorology



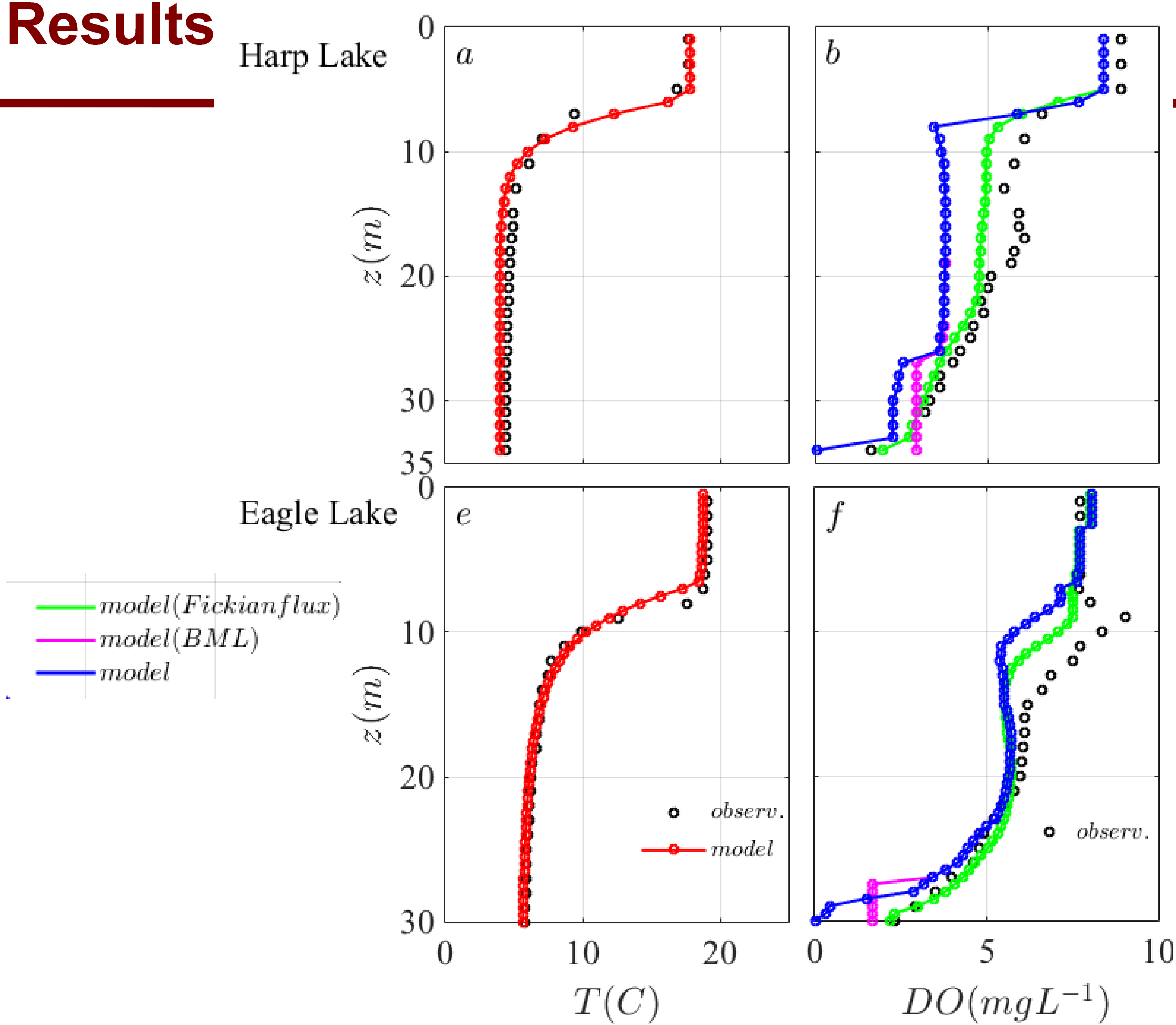
Harp Lake: Results



Eagle Lake: Results



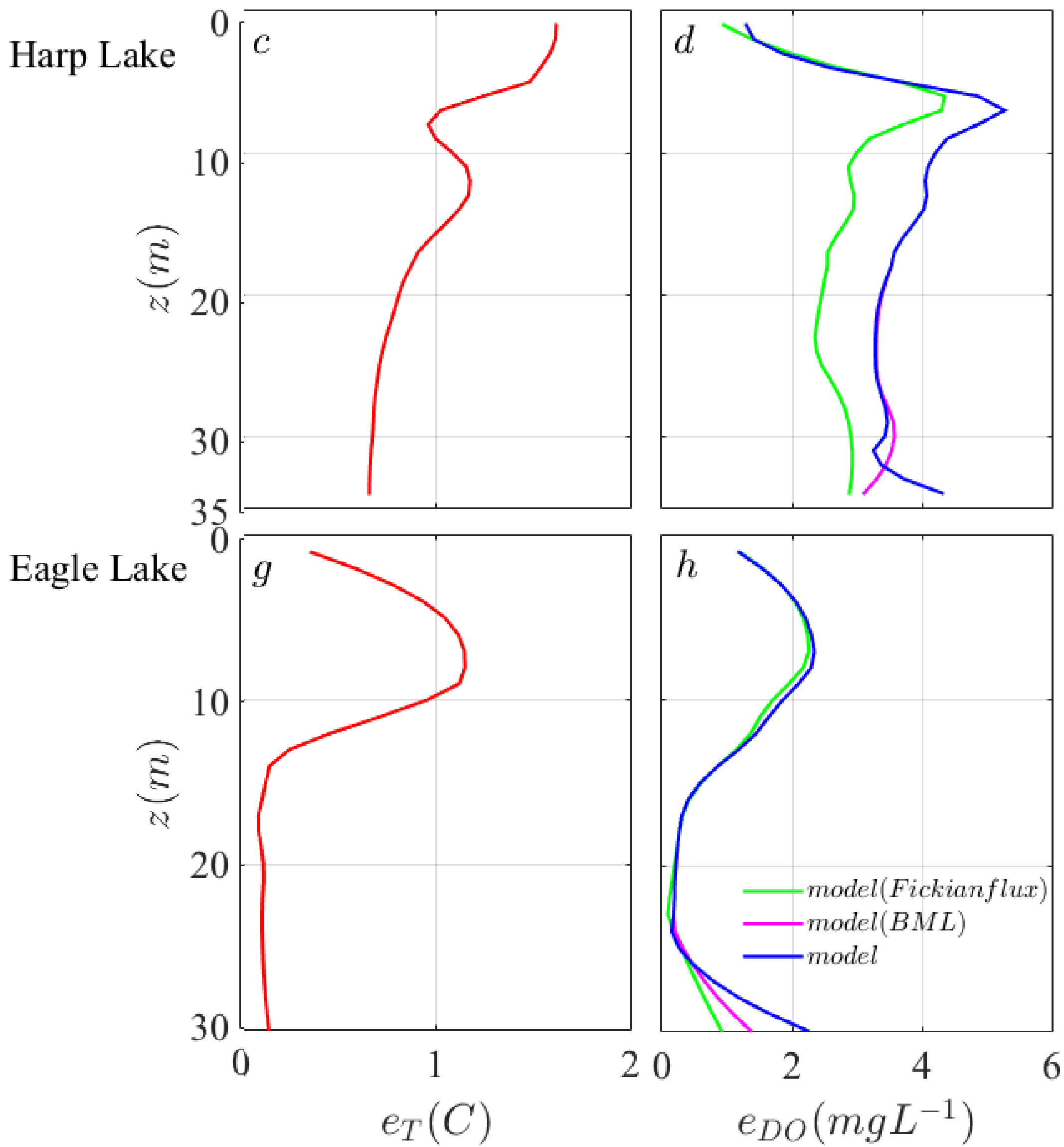
Results



a & b:
Sep. 15th, 1999

e & f:
Sep. 22nd, 2011

Results RMSE



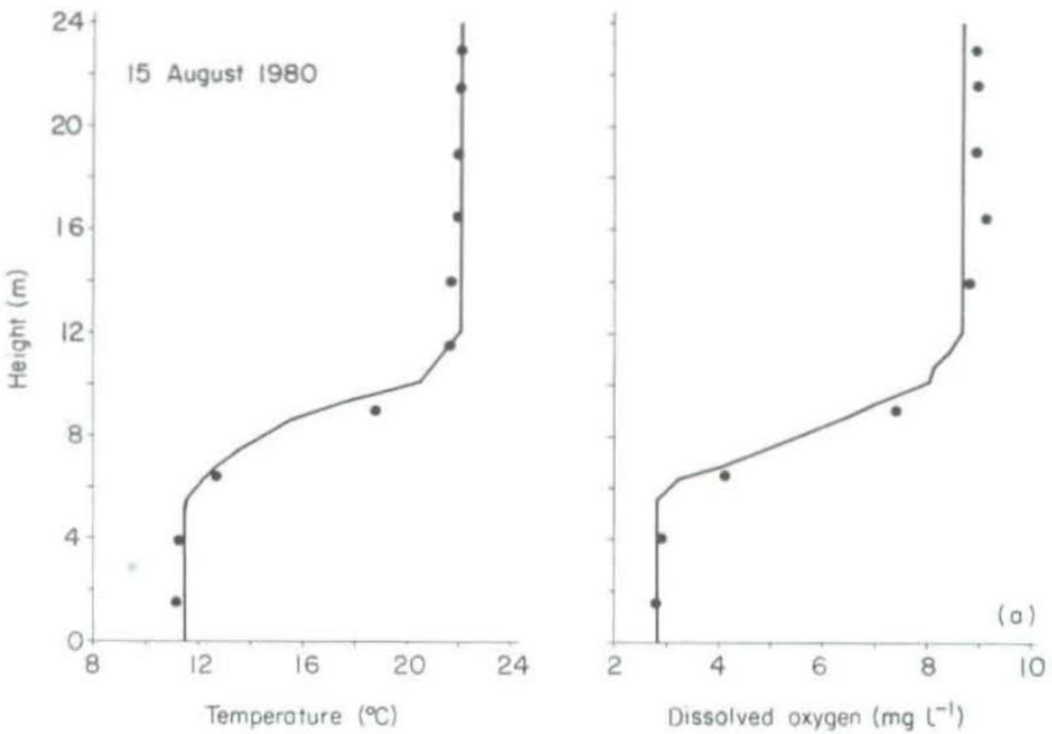
- Less error in DO prediction in BBL using the Fickian flux sub-model
- Smooth decrease in DO profiles using Fickian flux approach
- Fickian flux approach even improves DO predictions above the BBL
- Mixed layer approach is successful in the surface

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



• observ.

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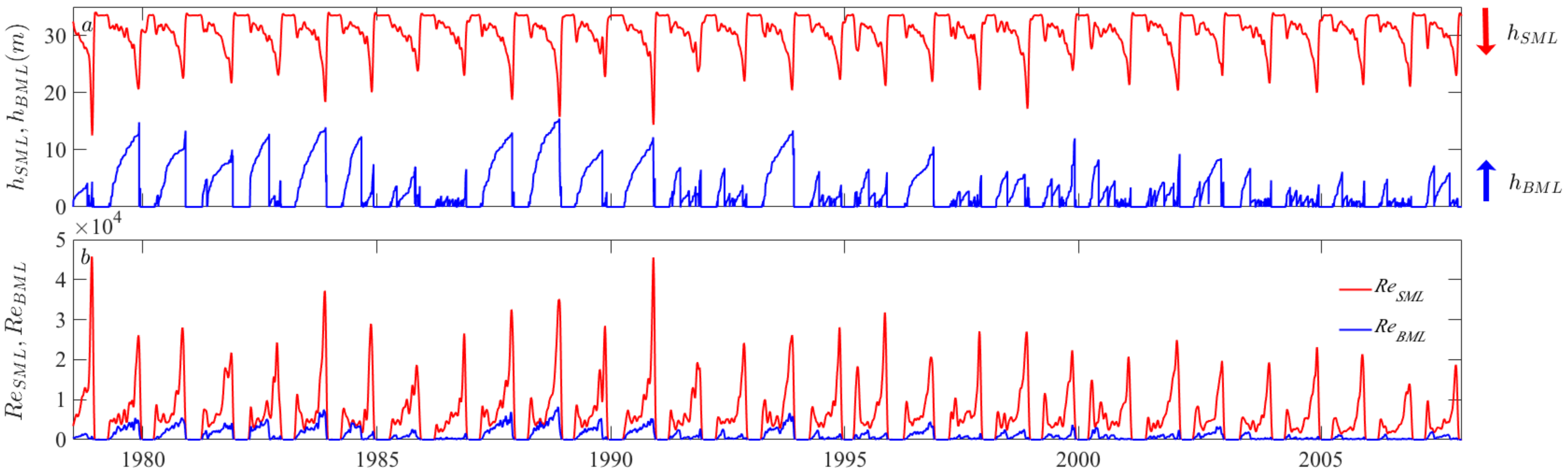
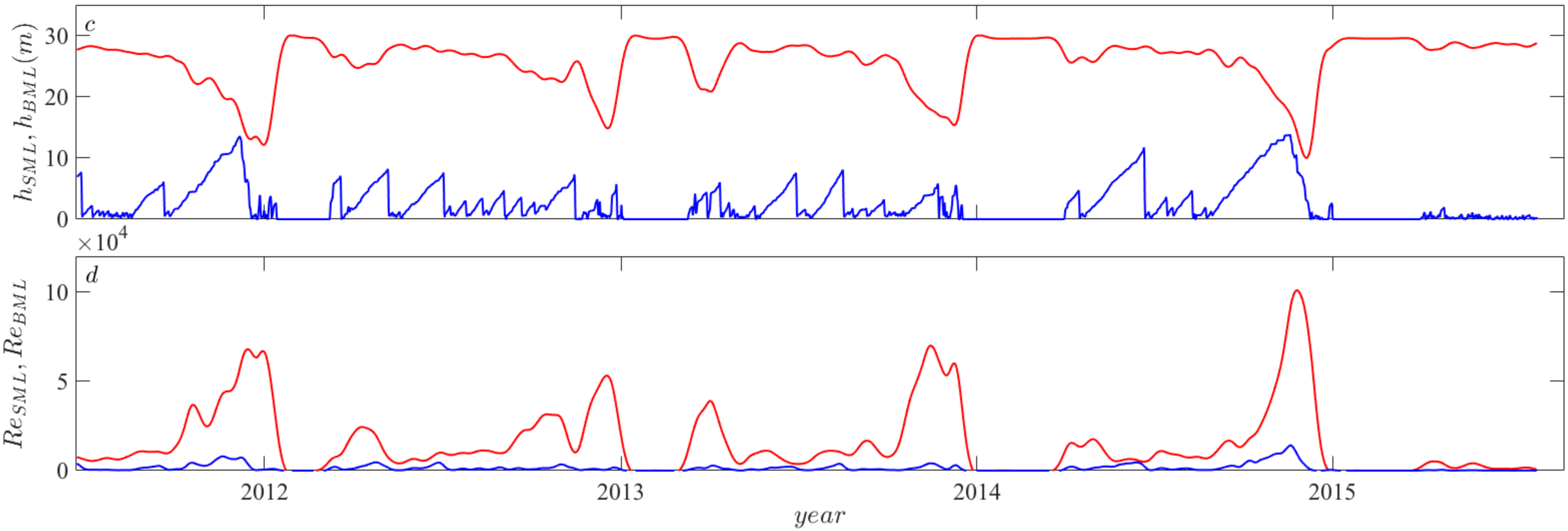
Ivey and Patterson (1984, L&O)

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
- $Re_{SML} \geq$ 10,000; higher turbulence at the surface

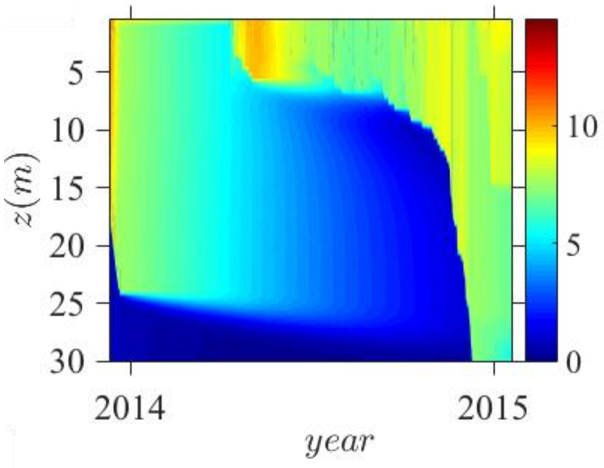
Results: Eagle Lake *Re* and mixed layer height

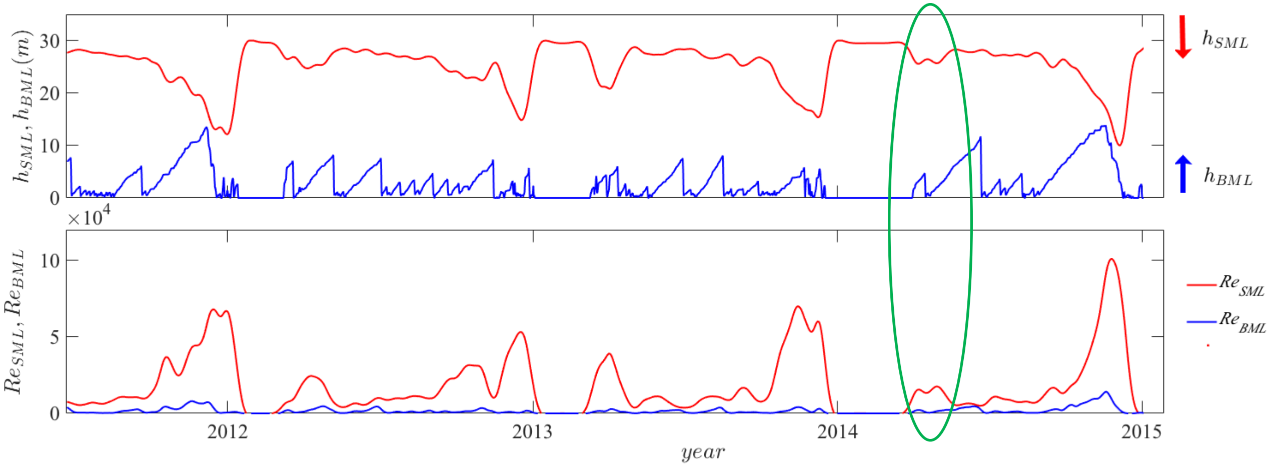


- $h_{SML} > h_{BML}$; h_{BML} <10 m
- $Re_{BML} < Re_{SML}$; Re_{BML} barely exceeds 10,000
- $Re_{SML} \geq$ 10,000; higher turbulence at the surface

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

Summary and Conclusions

- The best DO predictions are from the simple Fickian flux sub-model at the BBL, but a mixed layer approach in the surface
- In small lakes: $Re_{BML} < Re_{SML}$; $Re_{SML} > 10{,}000$ (Re_{BML} barely exceeds 10,000)
- Reynolds number dependence for mixed layer development
- 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