CH_4 Biogeochemistry and Thermokarst Lake Dynamics in CLM

Bill Riley, Zack Subin

Collaborators: Dave Lawrence, Sean Swenson

Boreal/Arctic-Climate Feedback

Riley, Subin, Torn (LBNL); Post, postdoc (ORNL); Bonfils, Phillips (LLNL)

- This project is one of four in the DOE National Lab IMPACTS study (http://esd.lbl.gov/research/projects/abrupt_climate_change/impacts)
  - There are also 15 simultaneous University projects
- Investigate potential for abrupt climate change in the Boreal/Arctic from
  - Warming permafrost, peatlands, and lakes
    - Increases in CO_2 and CH_4 fluxes
  - Vegetation range shifts
    - Surface albedo, LH and SH fluxes, snow and surface hydrology, terrestrial carbon stocks
  - Coupling with atmosphere

CH_4 Biogeochemistry

- Previous modeling efforts
  - Walter and Heimann (2000), Zhuang et al. (2004), Wania (2008), Ridgwell et al. (1999), Potter et al. (1996)

$$\underbrace{\frac{\partial(RC)}{\partial t}}_{\text{Net change}} = \underbrace{\frac{\partial F_D}{\partial z}}_{\text{Diffusion}} + \underset{\uparrow\ \text{Production}}{P(z,t)} - \underbrace{E(z,t)}_{\text{Ebullition (bubbling)}} - \underset{\uparrow\ \text{Aerenchyma (tissue)}}{A(z,t)} - \underbrace{O(z,t)}_{\text{Oxidation}}$$

CH_4 Production

- CH_4 to CO_2 production ratio (*f*) varies from 0.001 to 1.7 in anaerobic conditions (Segers, 1998)
  - Other electron acceptors (NO_3^-, Mn_2^+, Fe_3^+, SO_4^{-2}) are reduced before methane is produced
- Other approaches:
  - Walter and Heimann (2000):

$$R = R_0\, f(z)\, f\left(NPP(t)\right) Q_{10}$$

  - Zhuang et al. (2004): added pH and redox potential
  - Wania (2008): $R = R_0(1 - f_{air}(z))$
- Plan: use the C cycle component of CLM to generate substrate availability, and scale production with this value, anaerobicity, etc.

Ebullition (Bubbling)

- W&H2000, Z2004 allow bubbling if aqueous CH_4 concentrations exceeds a set threshold (500 μM); rate constant of 1 h^{-1}
- Wania2008 uses a more complex approach allowing for bubbling at lower saturations

Aerenchyma (Tissue Transport)

- Some vascular plants (grasses and sedges) can provide conduit for CH_4 to the atmosphere (and O_2 to the root zone)

$$A = \underset{\uparrow \atop \text{Rate Constant}}{k}\,\underset{\uparrow \atop \text{Tissue Quality}}{T_v}\,\underbrace{f_{root}}_{\text{Root Fraction}}\,\underset{\uparrow \atop \text{Growth Stage}}{f_{growth}}\,\underbrace{\left(C(z) - C_a\right)}_{\text{Concentration Gradient}}$$

CH$_4$ Oxidation

- W&H2000:

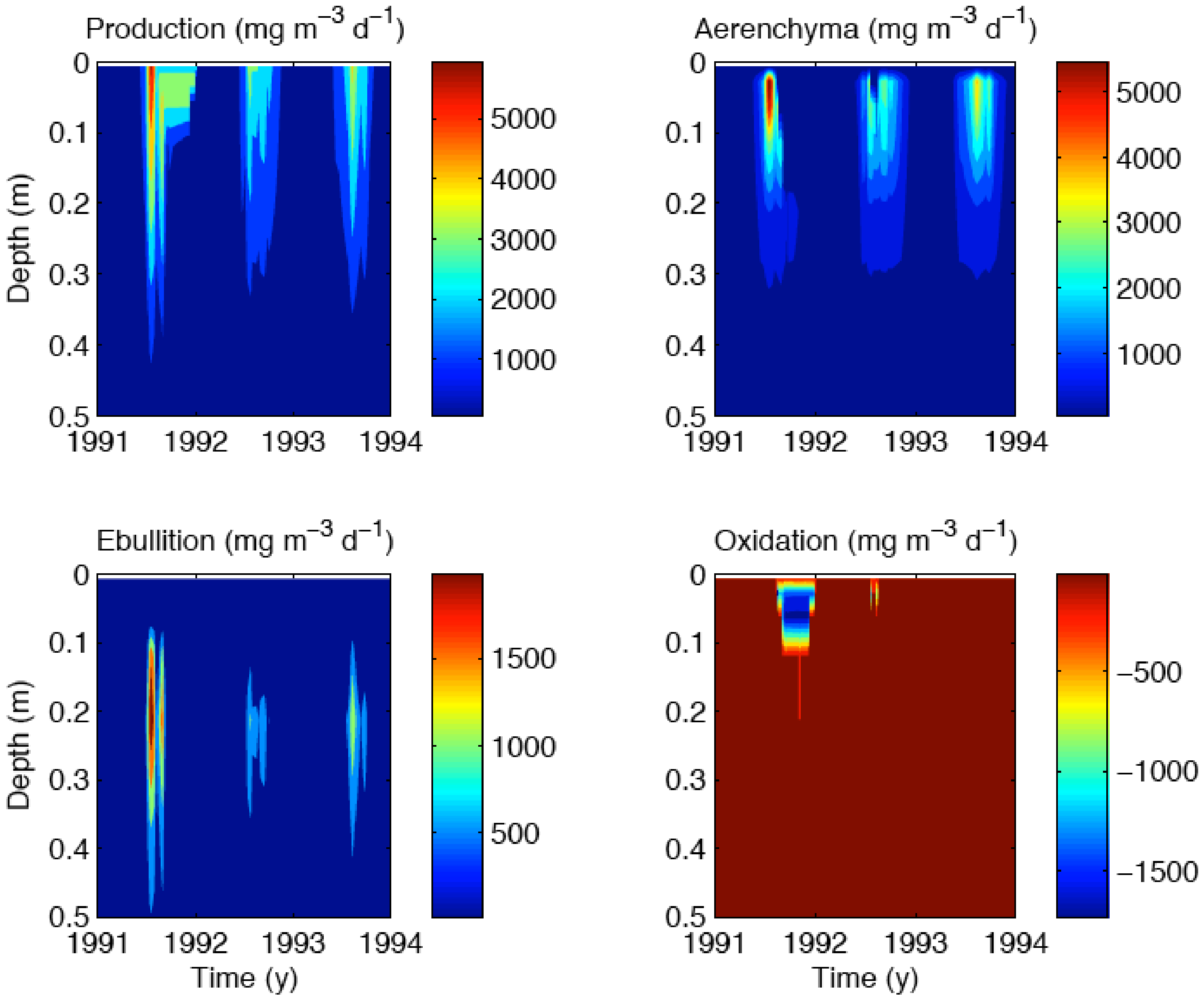
$$R_{oxic} = R_{oxid,\max}\left\lfloor \frac{C_{CH_4}}{K + C_{CH_4}} \right\rfloor Q_{10}\, f(\theta)$$

- Zhuang2004 added a factor for redox potential
- Wania2008: uses all available O$_2$ (or scaled)
- All models consider oxidation in root zone of plants that have aerenchyma (40-50%)
- Sink of O$_2$ and source of CO$_2$

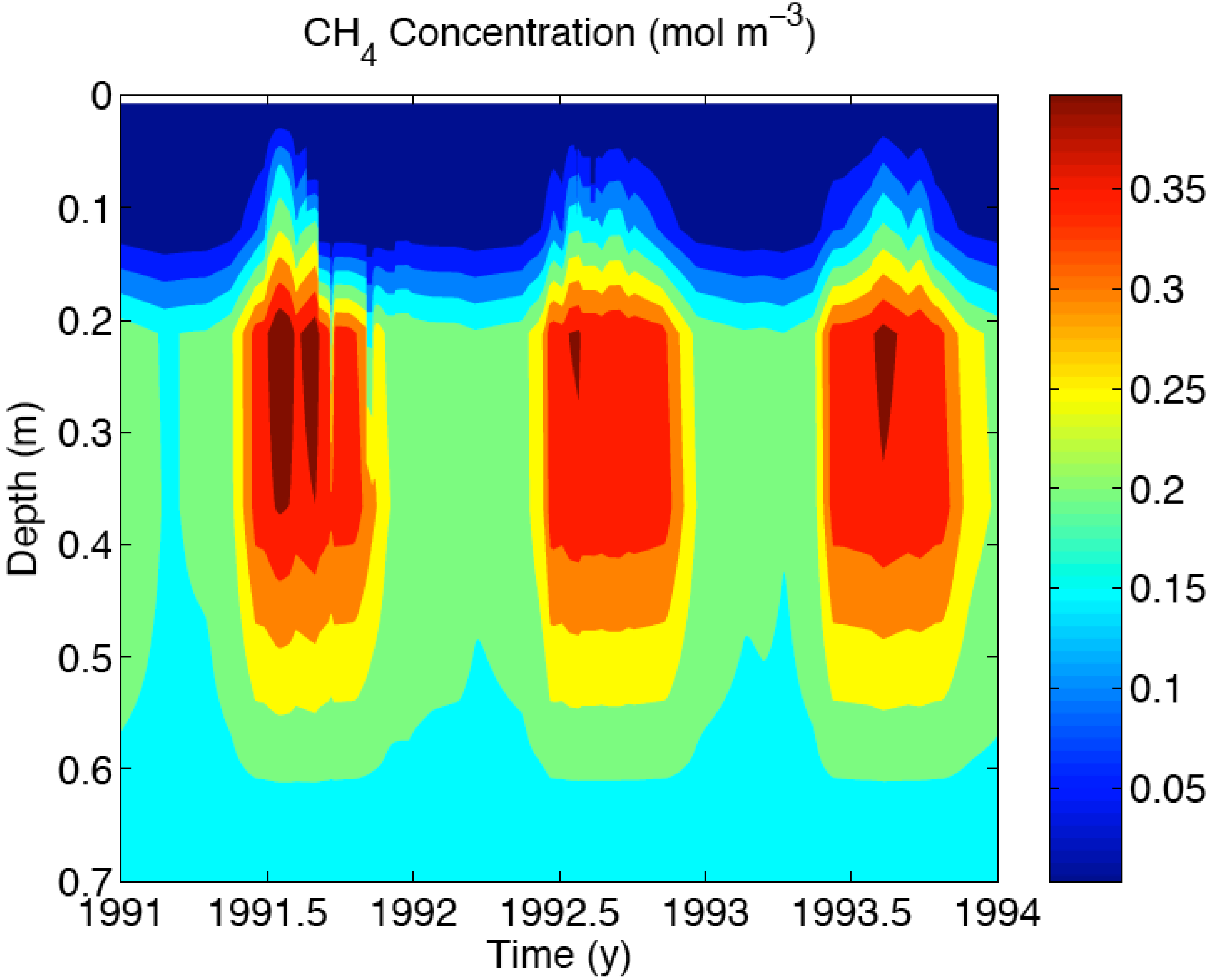
Diffusion

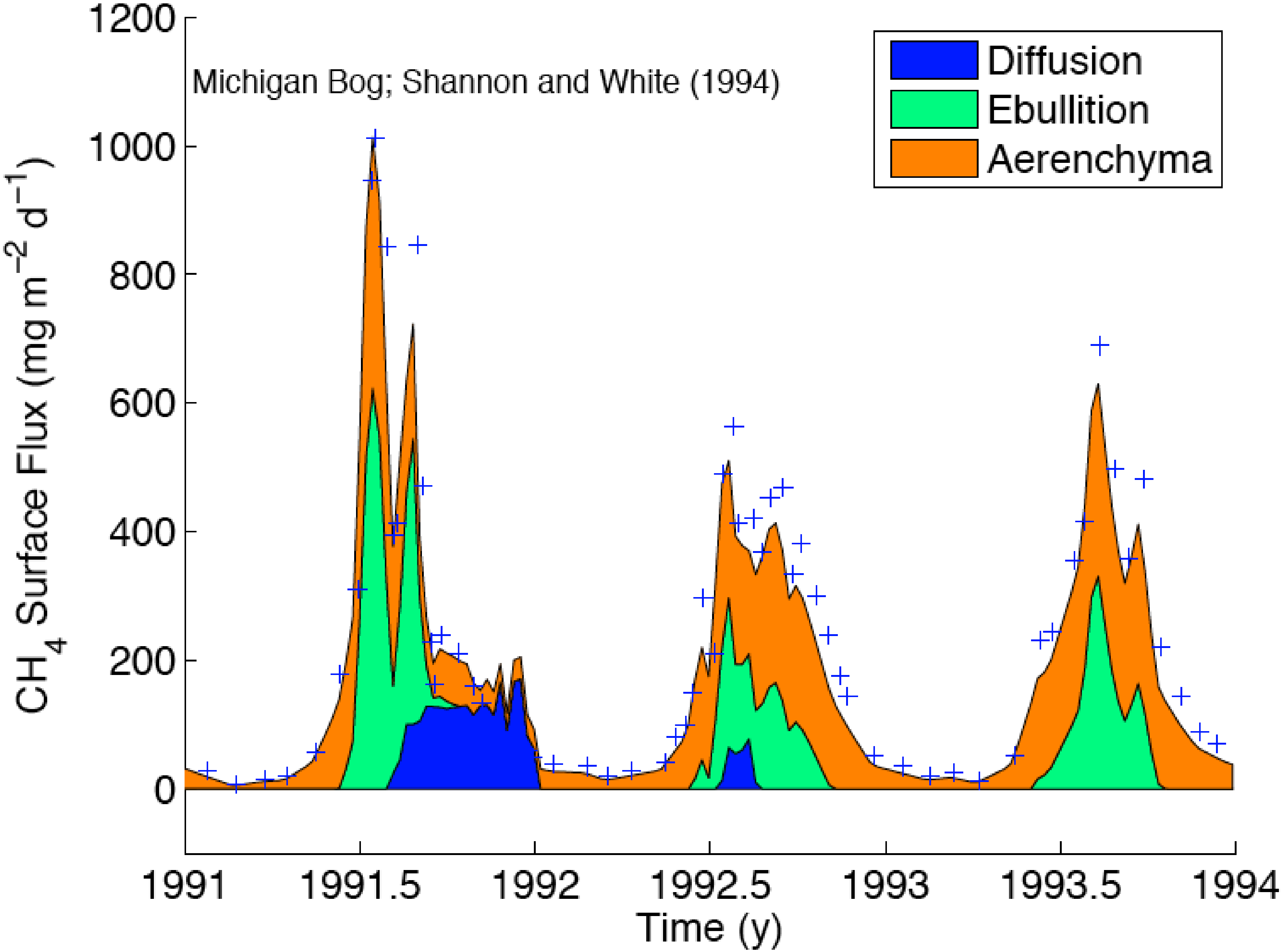
- Effective diffusivity in gas and water depends on water content, soil properties, species (Moldrup et al. 2003)
  - Test for organic soils
- Equilibrium assumed at WT interface
- Boundary conditions:
  - Surface conductance for top BC
  - Zero gradient for bottom BC

Example: Michigan Bog; Shannon and White (1994)



Example: Michigan Bog; Shannon and White (1994)




Michigan Bog; Shannon and White (1994)
Diffusion
Ebullition
Aerenchyma
CH4 Surface Flux (mg m−2 d−1)
1200
1000
800
600
400
200
0
1991
1991.5
1992
1992.5
1993
1993.5
1994
Time (y)

In-Hand Methane Data

Location	***Time range***	***variables***	***ecosystems***
North Scotland	1997-1998	CH4flux,WT, soil T	peatland
Tuzu, Sichuan, China	1988-1994 growning season	CH4flux , soil T	rice paddy
APEX site, Fairbanks, AK	2005-2006 summer	CH4 flux	peatland
Sallie's Fen, NH	1994~2001	CH4flux, soil T, air T	pealand
Jinsha, China	1994-1995 growning season	crop growth, CH4, soil T, air T, WT	rice paddy
Qingyuan, China		CH4, N2O	rice paddy
Edwin S. George Reserve,Michigan	1991-1994	CH4, WT, pore water CH4, soil T	pealand
Happy Valley, Ak	summber, 1994	CH4 and CO2 flux	peatland
Happy valley and Toolik Lake ARCSS/LAII s	1994-1996	CH4 and CO2 flux	peatland
BOREAS (Northern Study Area), Canada	1994 summer	CH4 and CO2 flux	Boreal forest including wetland
BOREAS (Southern Study Area), Canada		CH4 and CO2 flux	Boreal forest including wetland
Sweden		CH4 and N2O flux	Agriculture
Alaska, US	1986-1990	CH4 flux and profile	Tundra
Central plains experimental range, CO, US	1995~1996	CH4 and N2O flux, soil T, moisture	shortgrass steppe
Sidney, Nebraska, US	1993~1995	CH4 and N2O flux, soil T, moisture	wheat/fallow/grassland
Barkey,CO, US	May~Aug1993	CH4 and N2O flux, soil T, moisture	irrigated agriculture
Glacier lake, Wyoming, US	1992~1993	CH4 and N2O flux	spruce/wet meadow
Fort Collins Drake Road, CO, US		CH4 and N2O flux	irrigated agriculture
Durham, NH, US	1990-1996	CH4 and N2O flux	Deciduous woodland
Fam, Germany	1992-1994	CH4 and N2O flux, soil T, moisture	Rain-fed agriculture
Solling, Germany	Jun-Oct,1991	CH4 and N2O flux, soil T, moisture	spruce forest
hoglwald, Germany	May~Aug1995	CH4 and N2O flux, soil T, moisture	spruce-beech forest
New York, US	Apr~Oct 1993	CH4 and N2O flux	urban-rural oak woodland
Scottish Pasture, Scotland, UK	1992-1994	CH4 and N2O flux, soil T, moisture	grassland/pasture
Gullane, Scotland, UK	1994-1995	CH4 and N2O flux	woodland/agriculture/grass
Mallard Lake Landfill, US	1995~1996	CH4 and N2O flux, soil T, moisture	landfill
Kellogg Biological Stationi, MI, US	1995-1996	CH4 and N2O flux	Rain-fed agriculture
Mayaguez, Puerto Rico	1992-1995	CH4 and N2O flux, soil T, moisture	pasture
Lajas, Puerto Rico	1992-1996	CH4 and N2O flux	pasture
Isabela, Puerto Rico	1992-1997	CH4 and N2O flux, soil T, moisture	pasture
Mexico, Sonora	1994-1995	CH4 and N2O flux	irrigated agriculture
Banana, Costa Rica	Jul-Oct 1994	CH4 and N2O flux, soil T, moisture	agriculture
Core Experiment, Costa Rica	1990-1991	CH4 and N2O flux	forest/pasture
Pasture, Costa Rica	may-aug 1995	CH4 and N2O flux, soil T, moisture	grassland/pasture
Guapiles, Costa Rica	1992	CH4 and N2O flux	forest/pasture
Beaumont 1990/Texas, US	jun-sep, 1990	CH4 and N2O flux, soil T, moisture	Agriculture/irrigated rice

Thermokarst Lakes

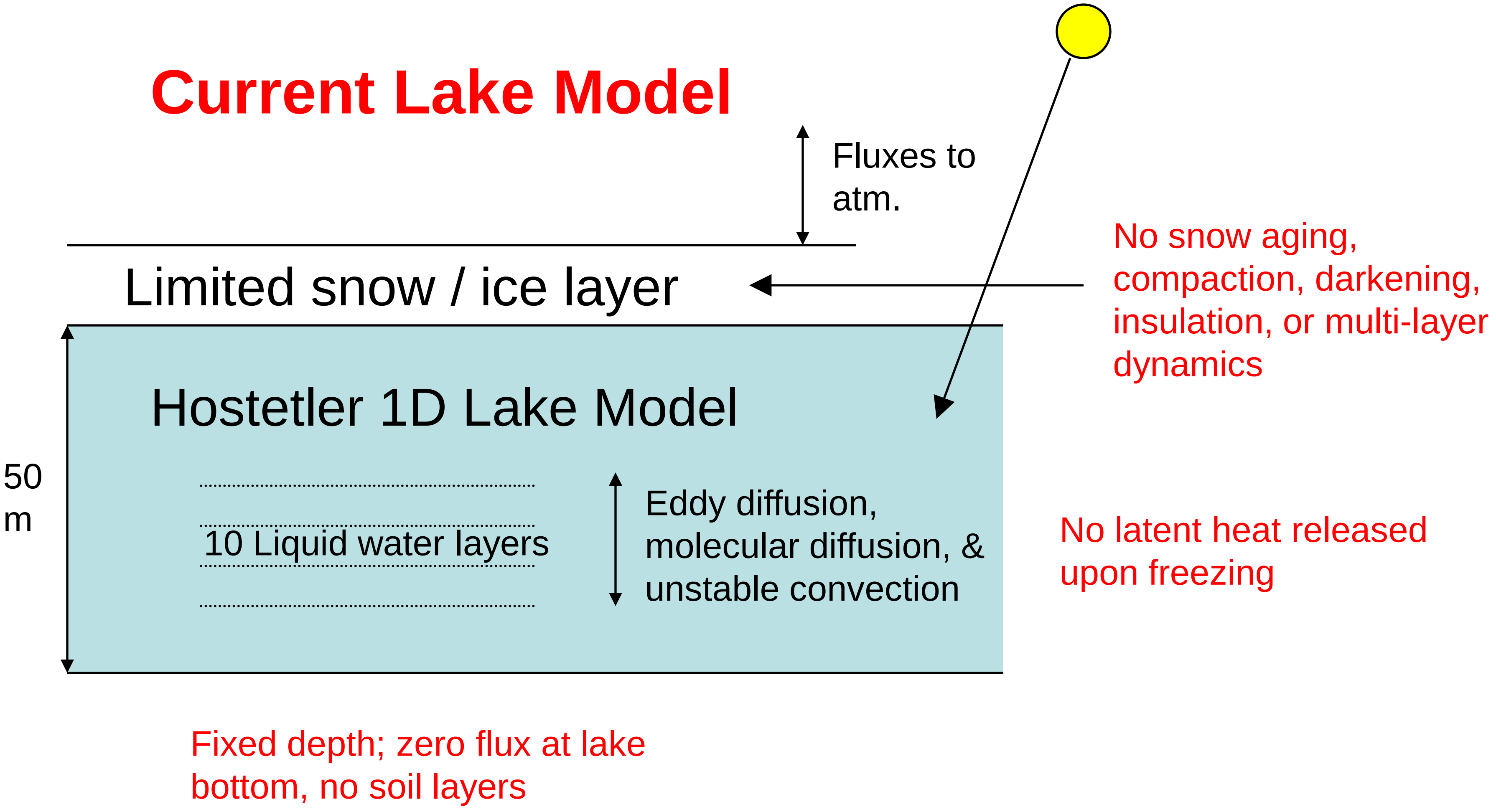
- Deepened by thaw subsidence, with expansion mediated by wind, waves, and erosion
- Expanding lakes often have an unfrozen volume of soil (talik) below them
- Cover up to 20-40% of affected landscapes in West Canadian Arctic, Siberia, Arctic Coastal Plain, and Bering Strait
- Large range of sizes and ages

Thermokarst Lakes

- Taliks can undergo extensive organic decomposition, releasing CO_2 and CH_4
  - Can produce as much CH_4 during winter as summer
- Lakes increase net radiation, seasonal thermal inertia, and ground thermal conductance, increasing thawing rates in their surroundings
- Modeling approach (just beginning)
  - Apply a representation of Lawrence Plug's (Dalhousie) 2D finite-difference thermokarst lake model to establish lake characteristic dynamics at annual time scales
  - Consider approaches to characterize heterogeneity in size and depth
  - Enhance current lake model to provide a platform for thermokarst model
  - Integrate with CH_4, O_2, & CO_2 modules (described earlier)

Lake Model Additions

Current Lake Model



Fluxes to atm.

Limited snow / ice layer

No snow aging, compaction, darkening, insulation, or multi-layer dynamics

Hostetler 1D Lake Model

50 m

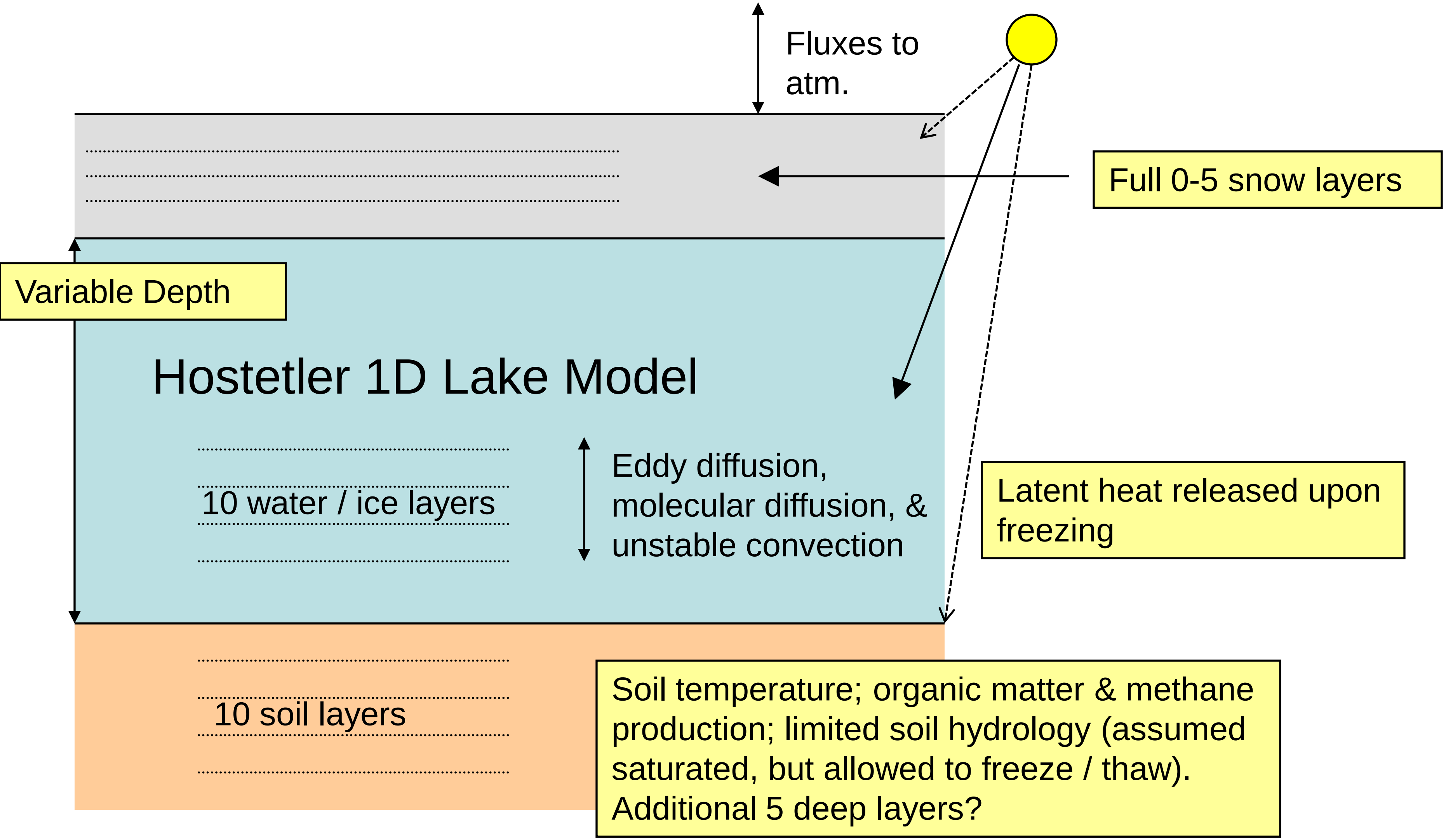
10 Liquid water layers

Eddy diffusion, molecular diffusion, & unstable convection

No latent heat released upon freezing

Fixed depth; zero flux at lake bottom, no soil layers

New “Shallow” Lake Landunit



Fluxes to atm.

Full 0-5 snow layers

Variable Depth

Hostetler 1D Lake Model

10 water / ice layers

Eddy diffusion, molecular diffusion, & unstable convection

Latent heat released upon freezing

10 soil layers

Soil temperature; organic matter & methane production; limited soil hydrology (assumed saturated, but allowed to freeze / thaw). Additional 5 deep layers?