What We Have Learned about Carbon Biogeochemical Cycling in the Arctic?

http://www.eaps.purdue.edu/ebdl/

Qianlai Zhuang

PURDUE UNIVERSITY

Departments of Earth, Atmospheric, and Planetary Sciences and Agronomy

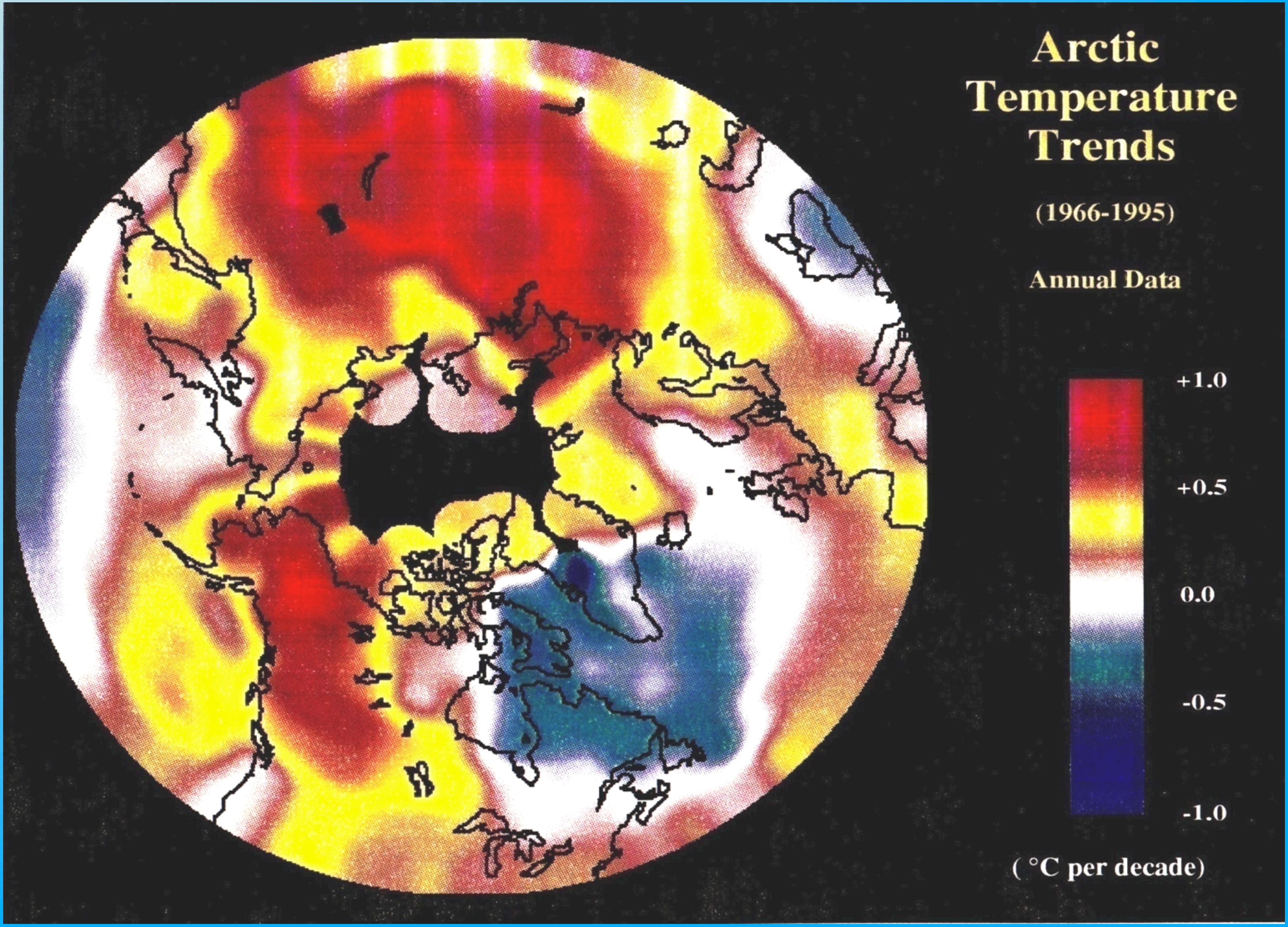
Research Team

Purdue University
Qianlai Zhuang
Zeli Tan
Xudong Zhu

Massachusetts Institute of Technology
Adam Schlosser
Xiang Gao
Erwan Monier

Marine Biological Laboratory at Woods Hole
Jerry M. Melillo
David Kicklighter

University of Alaska Fairbanks
Katey Walter Anthony
Yuri Shur
Mikhail Kanevskiy

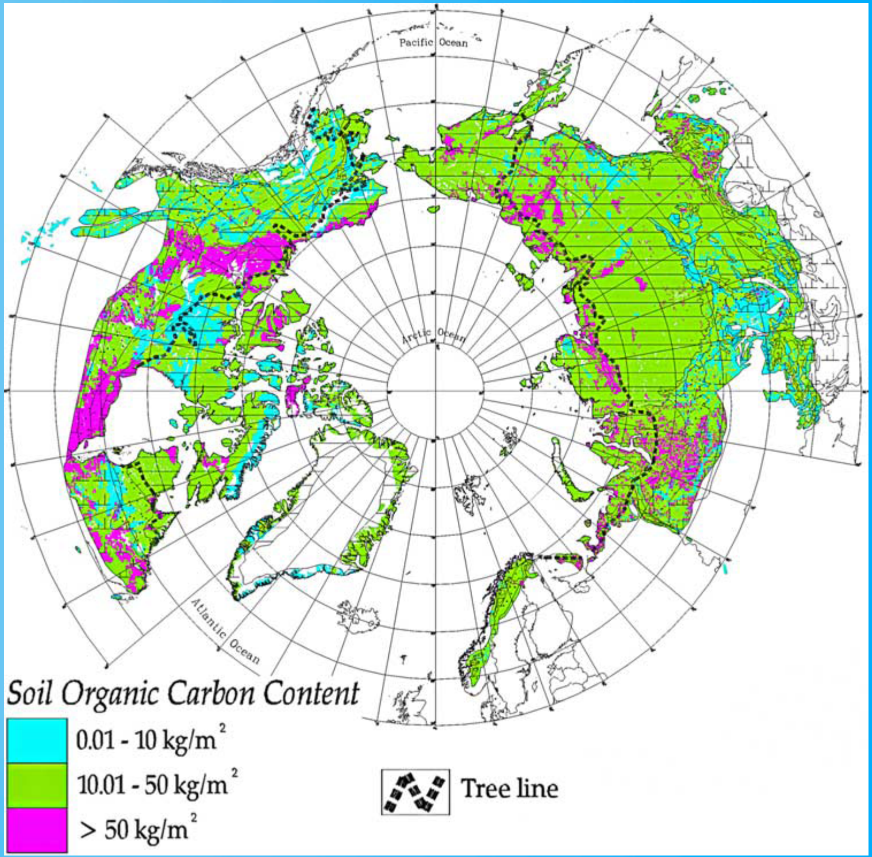


(Serreze et al. 2000, Climatic Change)

Ecosystems in the Arctic

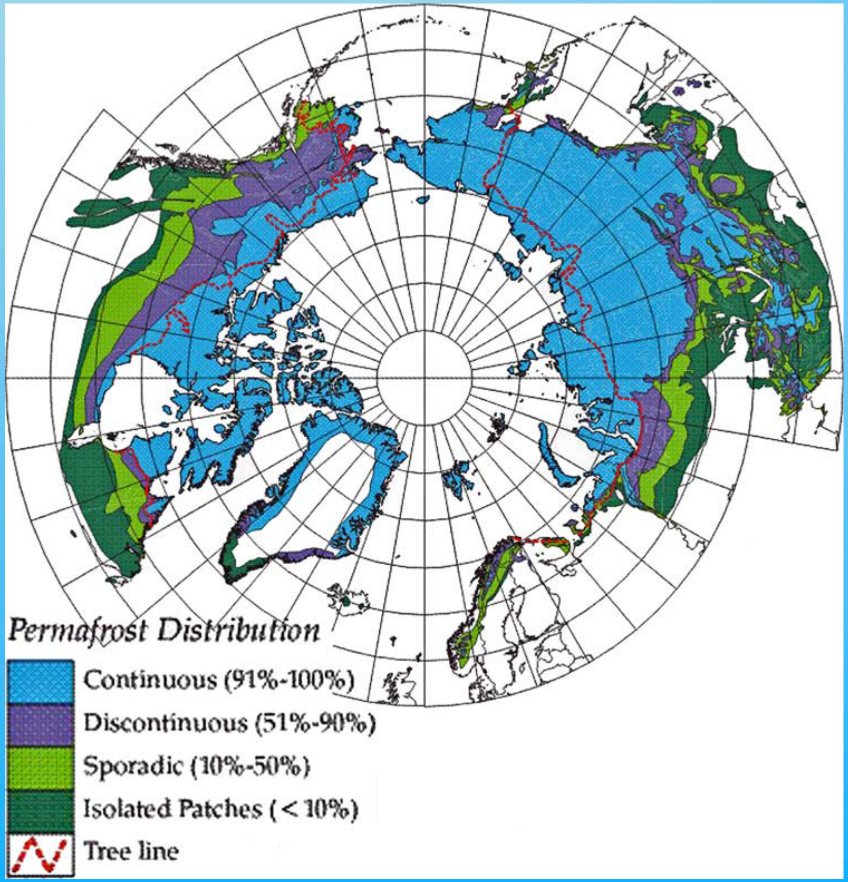
- Large vulnerable carbon pool (~1/3 of world soil C)
- Large wetland distribution (~1/2 of world wetlands)
- Longer growing season (1-4 days /decade)
- Changing vegetation (e.g., moving treeline)





1672 Pg C in soils and permafrost
or ½ the belowground organic C

(Tarnocai et al. 2009)



11.2 to 13.5 million km^2

(Zhang et al., 2000, Polar. Geogr.)

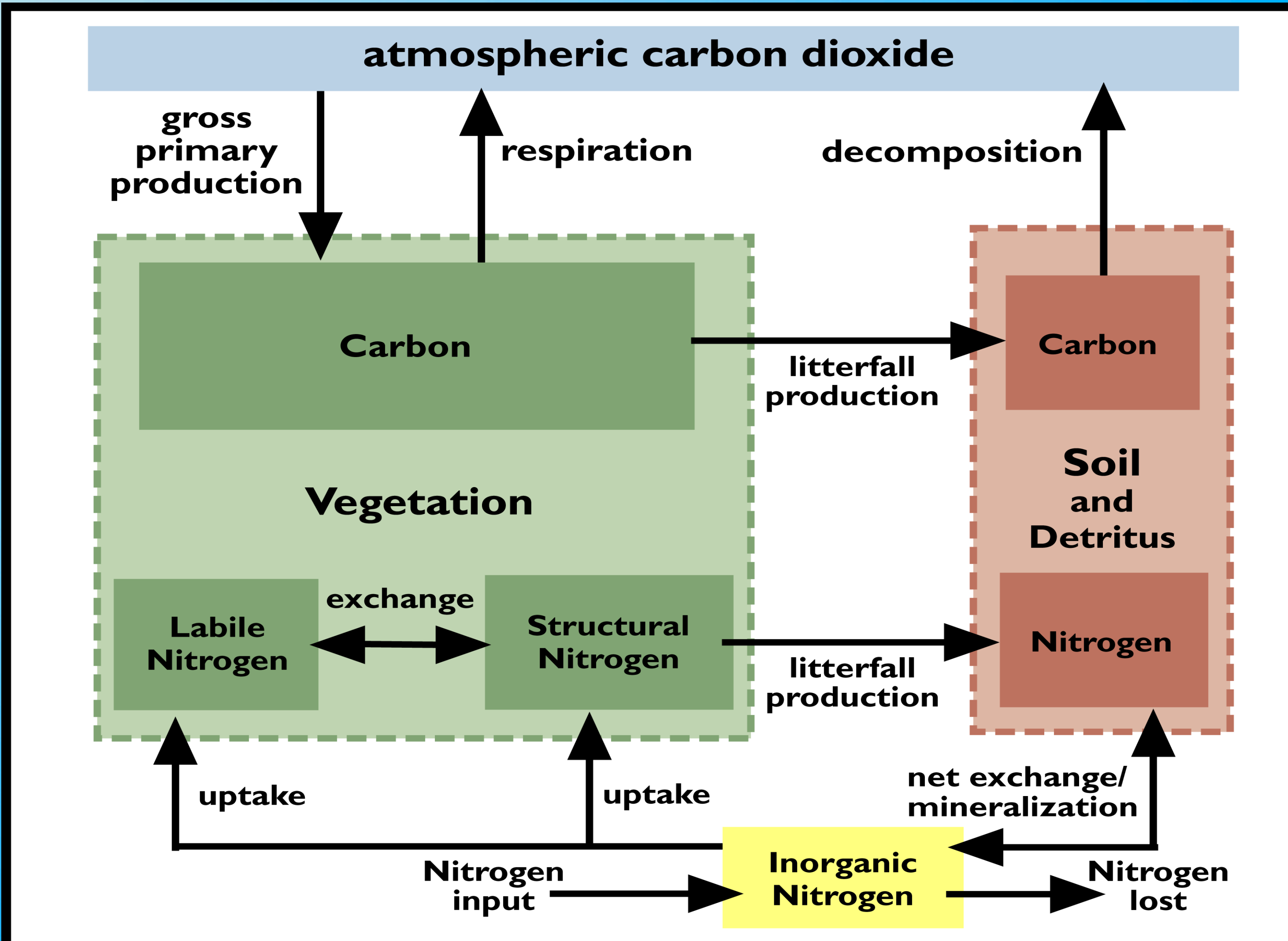
Large-Scale Processes in the Region

- Permafrost thawing (~1/4 of areas underlain by permafrost)

- Fire disturbance increase (~1% yr^{-1})

Overarching Questions

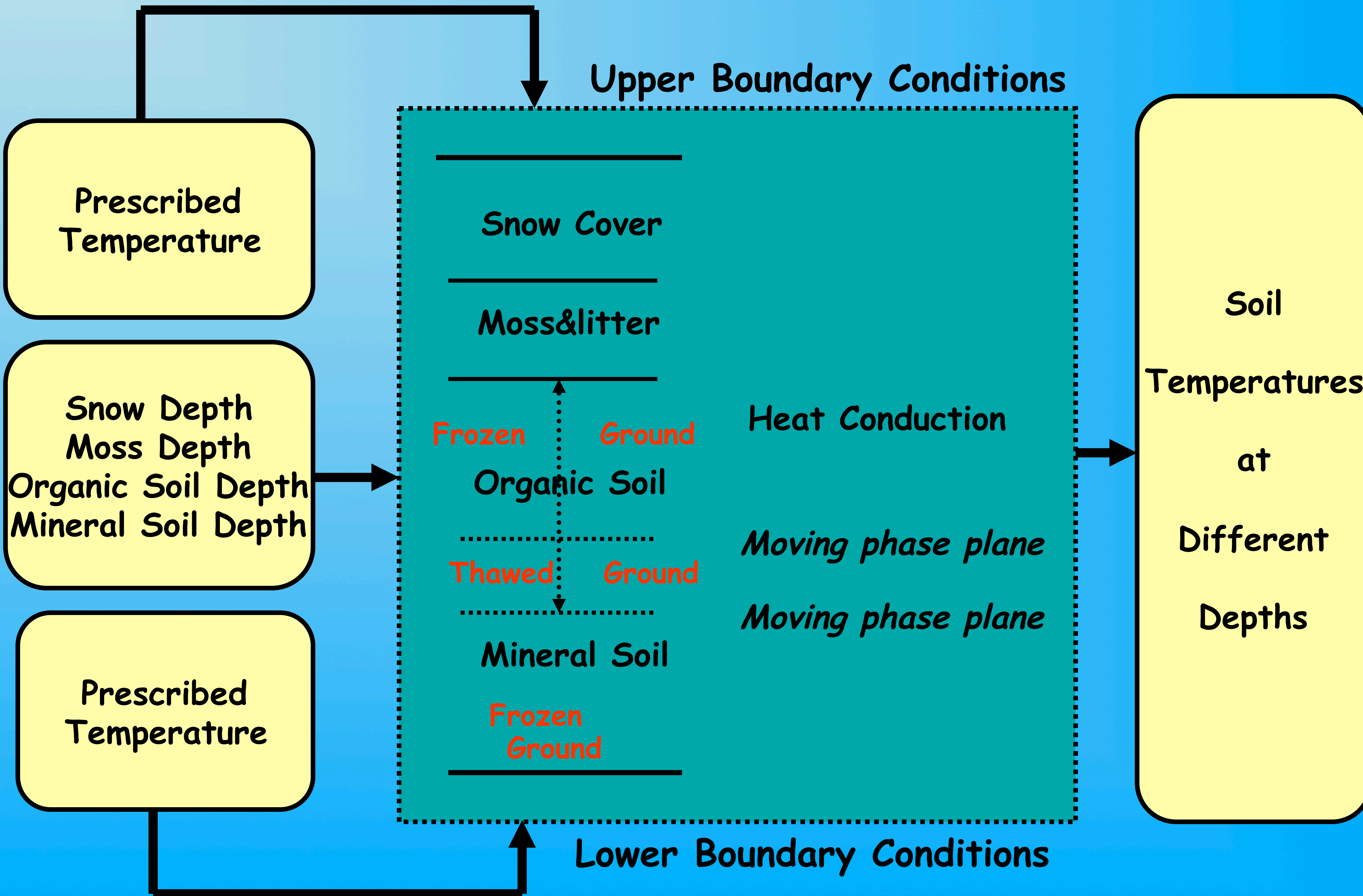
- What is the current budget of CO_2 and CH_4 for the region?
- How will the budget change over the 21st century?
- What is the impact of the budget change on climate in the 21st century?



Terrestrial Ecosystem Model (TEM)

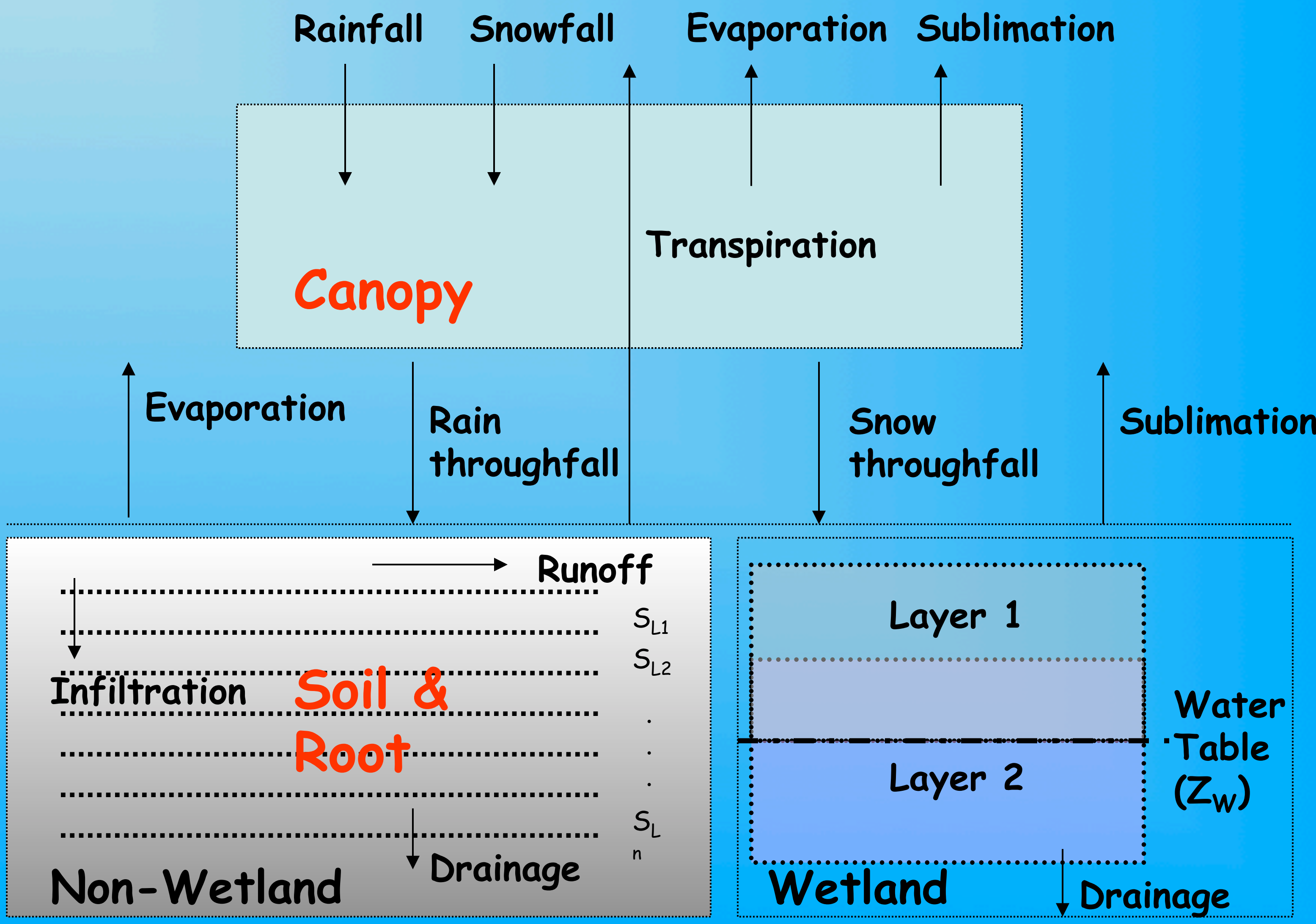
The Ecosystems Center, Marine Biological Laboratory (Woods Hole, Massachusetts)

Soil Thermal Model



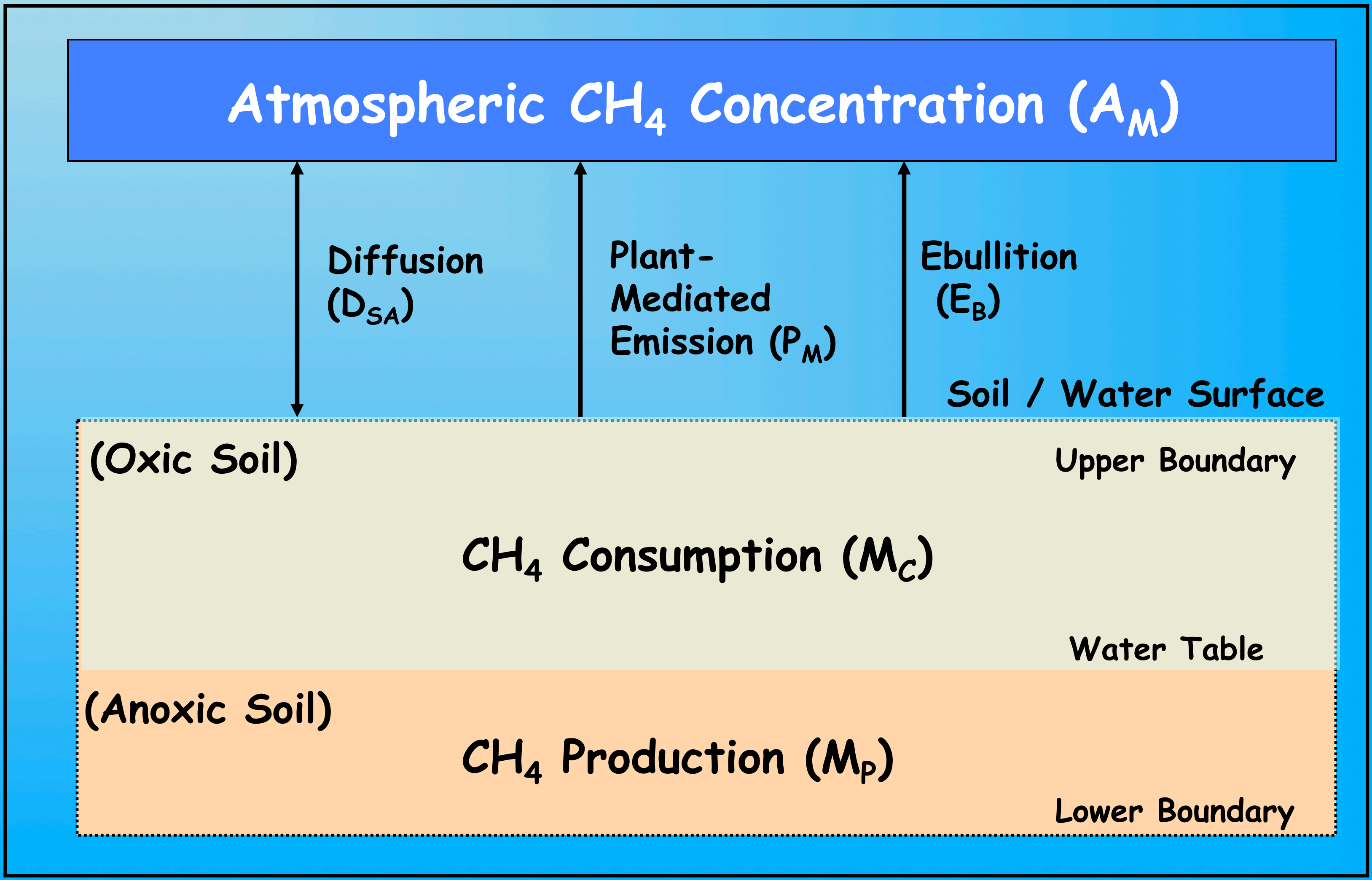
(Zhuang et al., 2001JGR)

Updated Hydrological Model



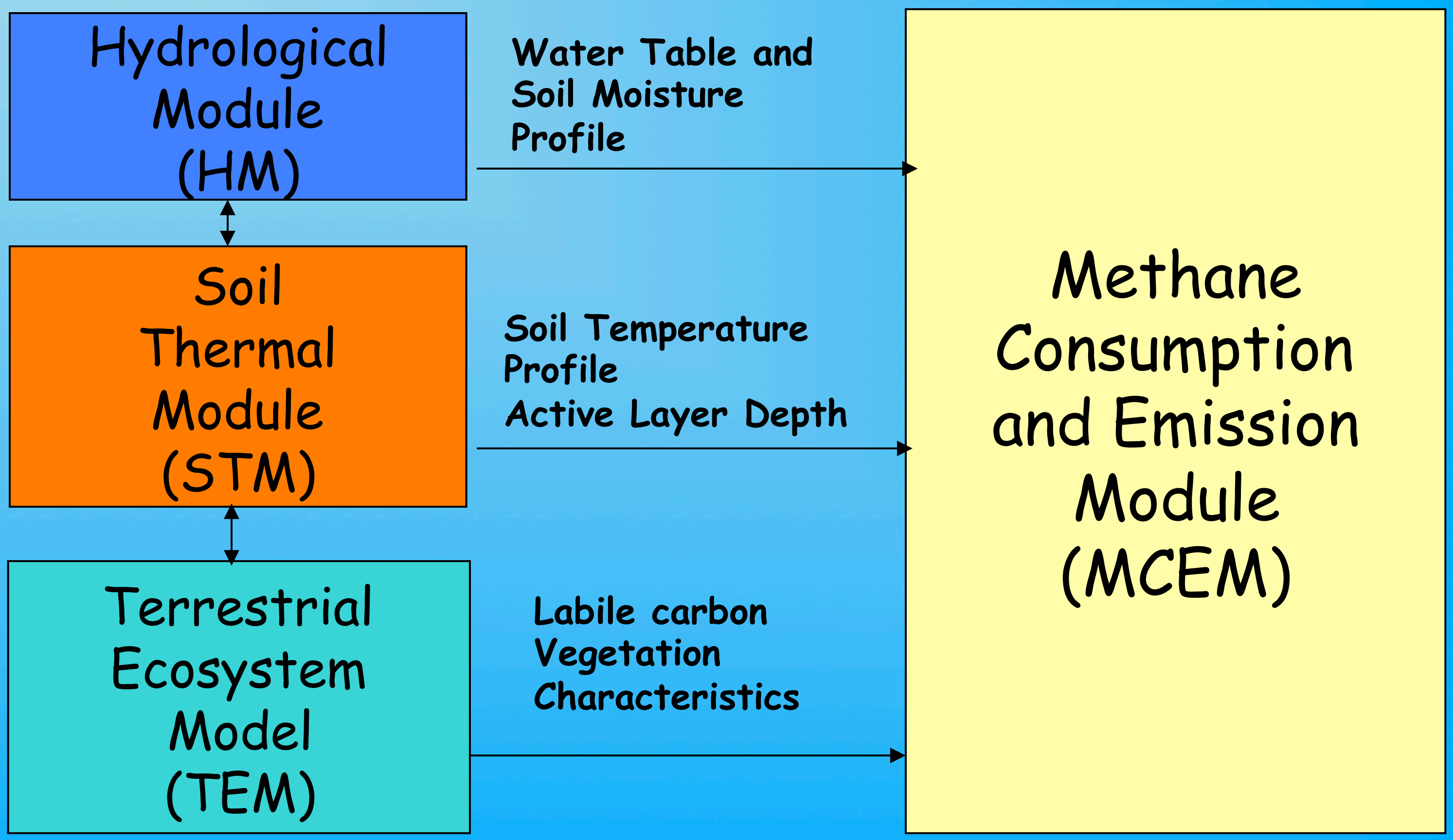
(*Zhuang et al.*, *2002JGR*)

Methane Consumption and Emission Model



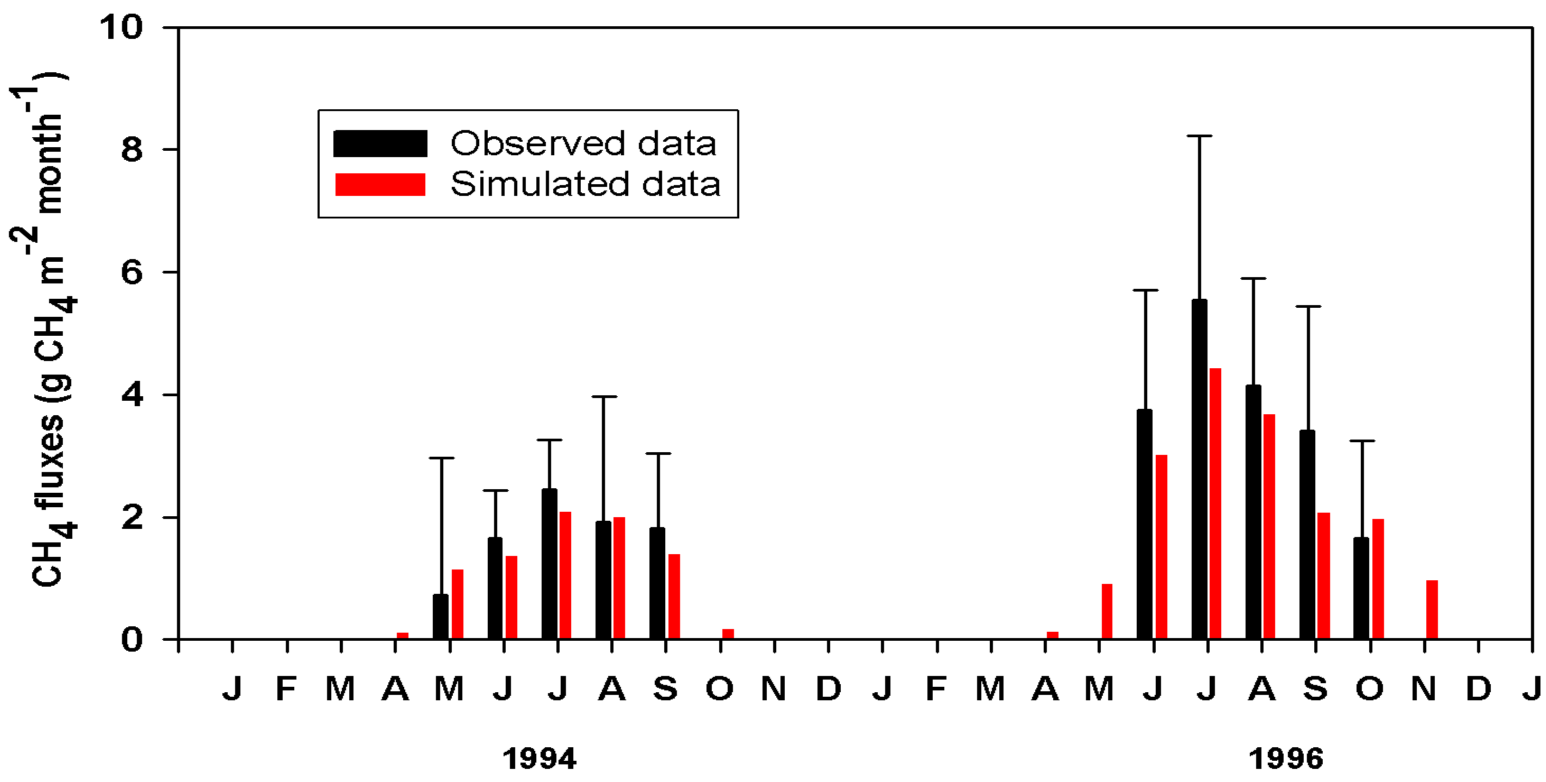
(Zhuang et al., 2004 GBC)

Methane Modeling Framework



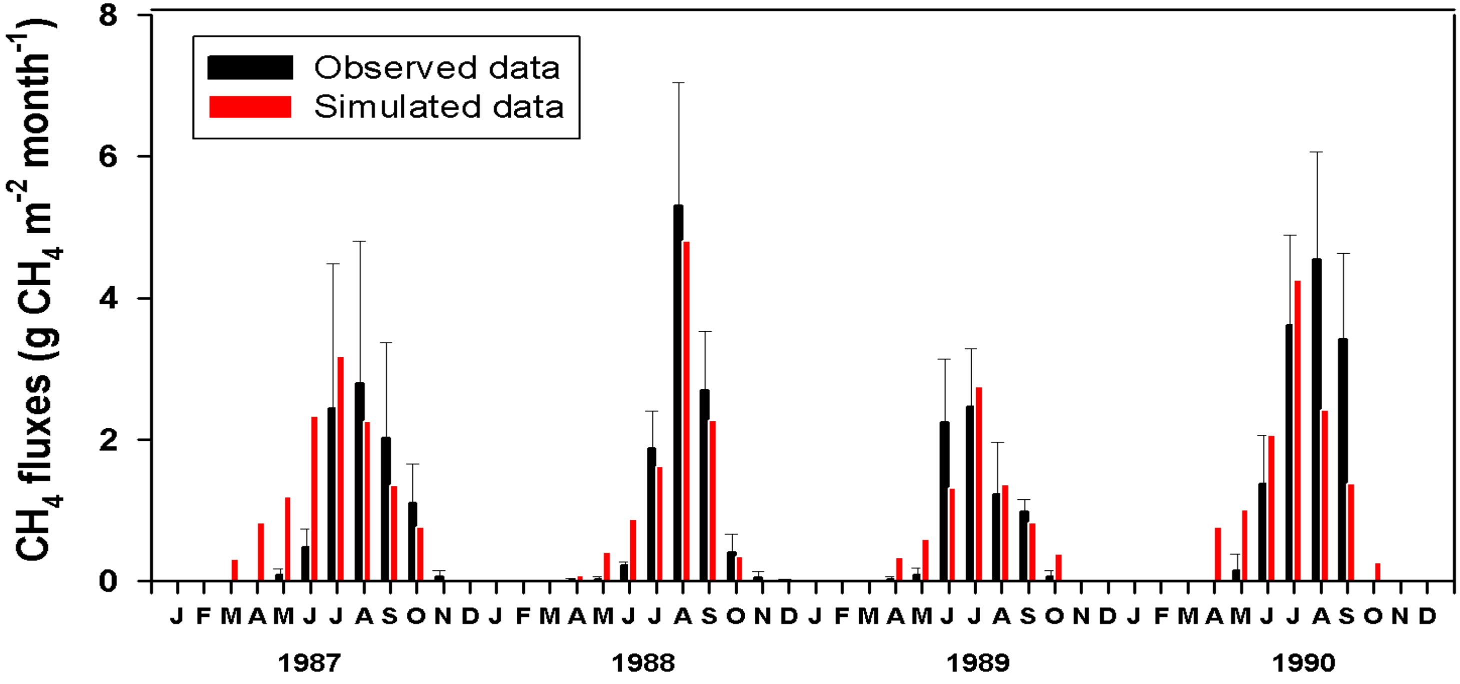
(Zhuang et al., 2004GBC)

Methane Fluxes at a Fen Site in Canada



(Zhuang et al., 2004 GBC)

Methane Fluxes of a Wet Tundra Ecosystem in Alaska



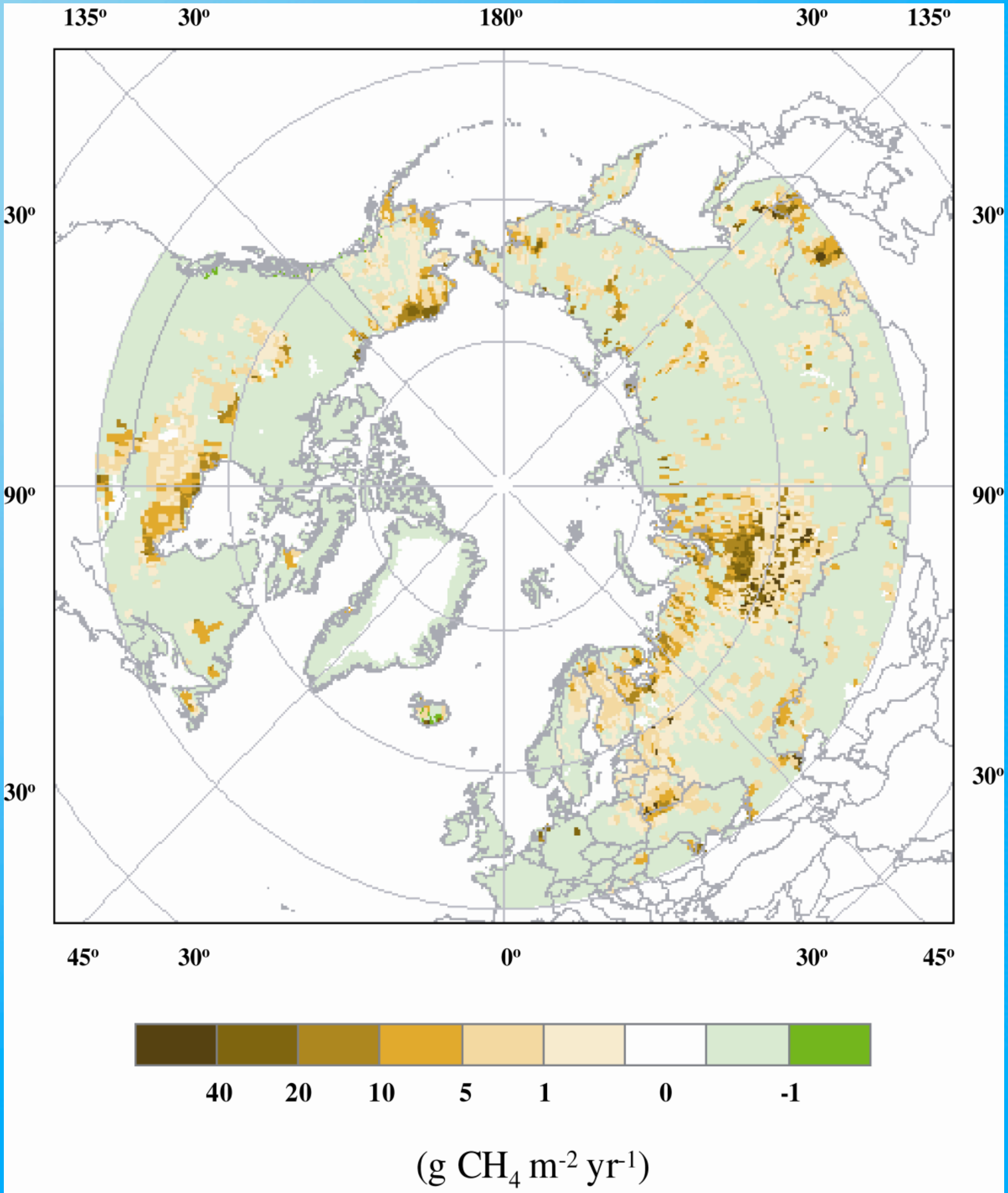
(Zhuang et al., 2004GBC)

Net Methane Fluxes in the 1990s

Emissions
= 56 Tg CH_4 yr^{-1}

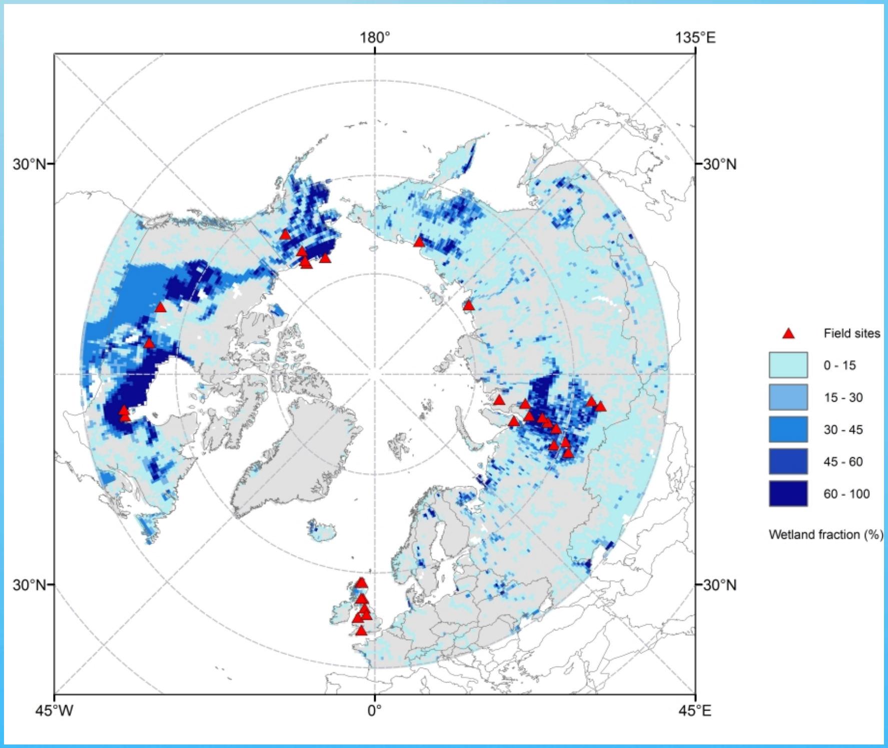
Consumption
= -7 Tg CH_4 yr^{-1}

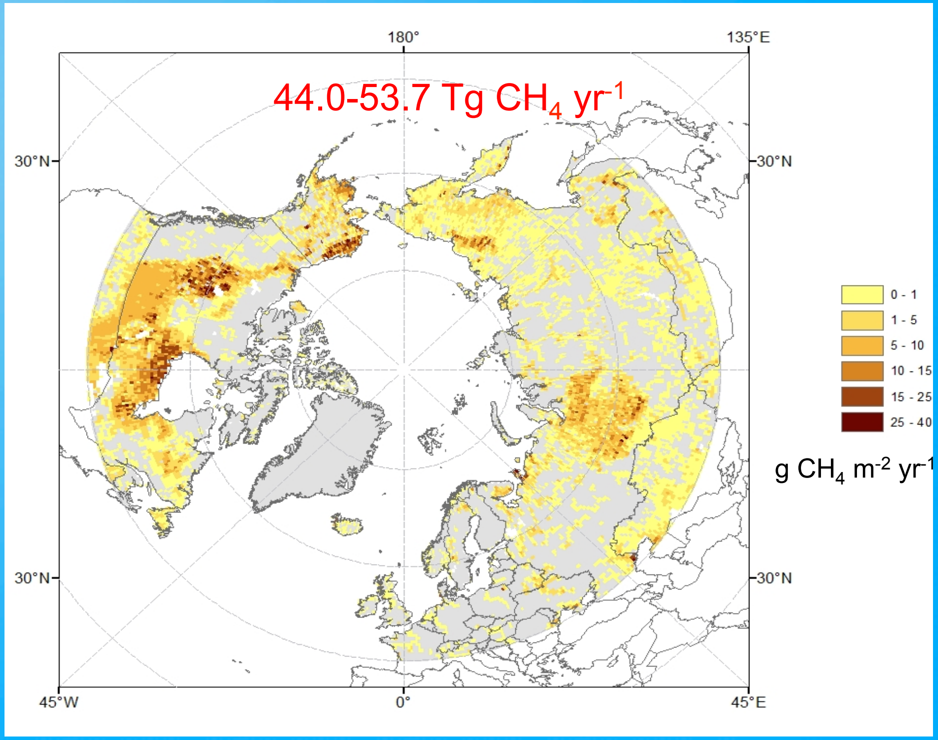
Net Methane
Fluxes
= 49 Tg CH_4 yr^{-1}



(Zhuang et al., 2004GBC)

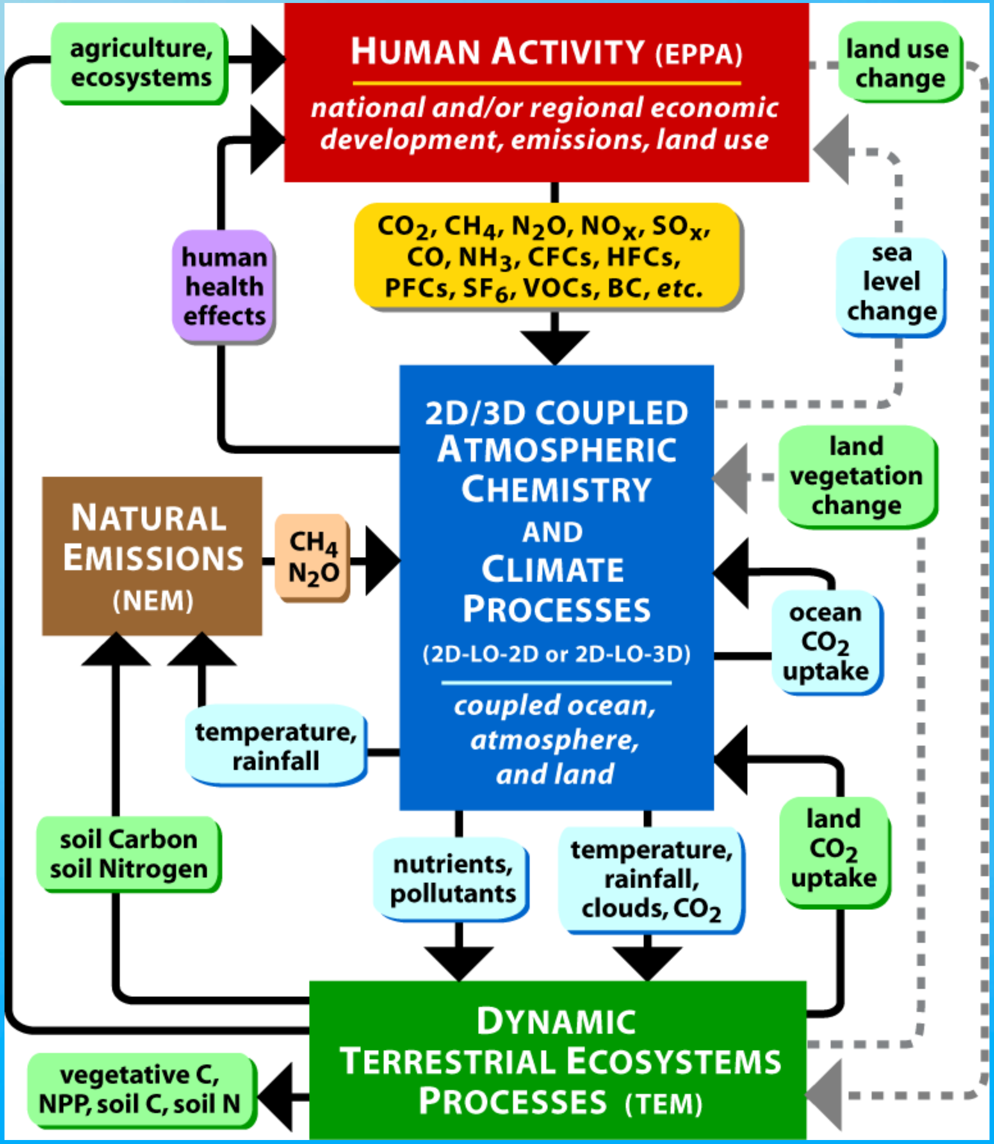
Annual wetland CH_4 emissions during 1990-2009
Based on a Neural Network Approach





(Zhu et al., 2013BGC)

MIT Integrated Global System Model (IGSM)



Changes in Atmospheric CO_2 and CH_4 and Global Radiative Forcing during the 21st Century

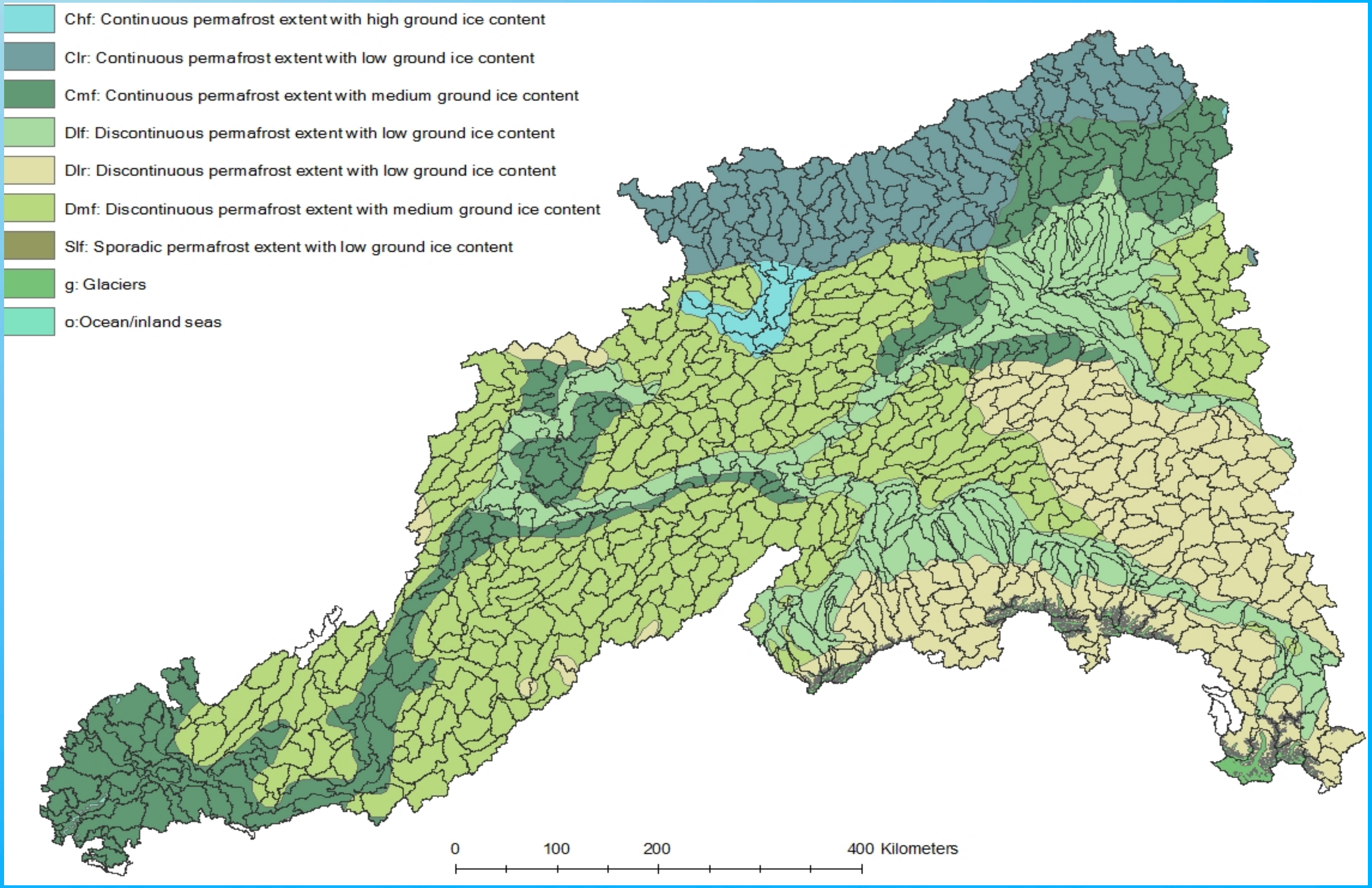
	CO_2 fertilization effect			No CO_2 fertilization effect		
Anthropogenic Emissions	**$\Delta[CH_4]$ (ppm)**	**$\Delta[CO_2]$ (ppm)**	**ΔF (W/m^2)**	**$\Delta[CH_4]$ (ppm)**	**$\Delta[CO_2]$ (ppm)**	**ΔF (W/m^2)**
High	**0.35**	**-19**	**-0.065**	**0.25**	**0.7**	**0.047**
Intermediate	**0.18**	**-5.1**	**-0.006**	**0.15**	**3.3**	**0.073**
Low	**0.06**	**-1.6**	**-0.005**	**0.05**	**2.1**	**0.044**

(Zhuang et al., 2006 GRL)

Summary #1

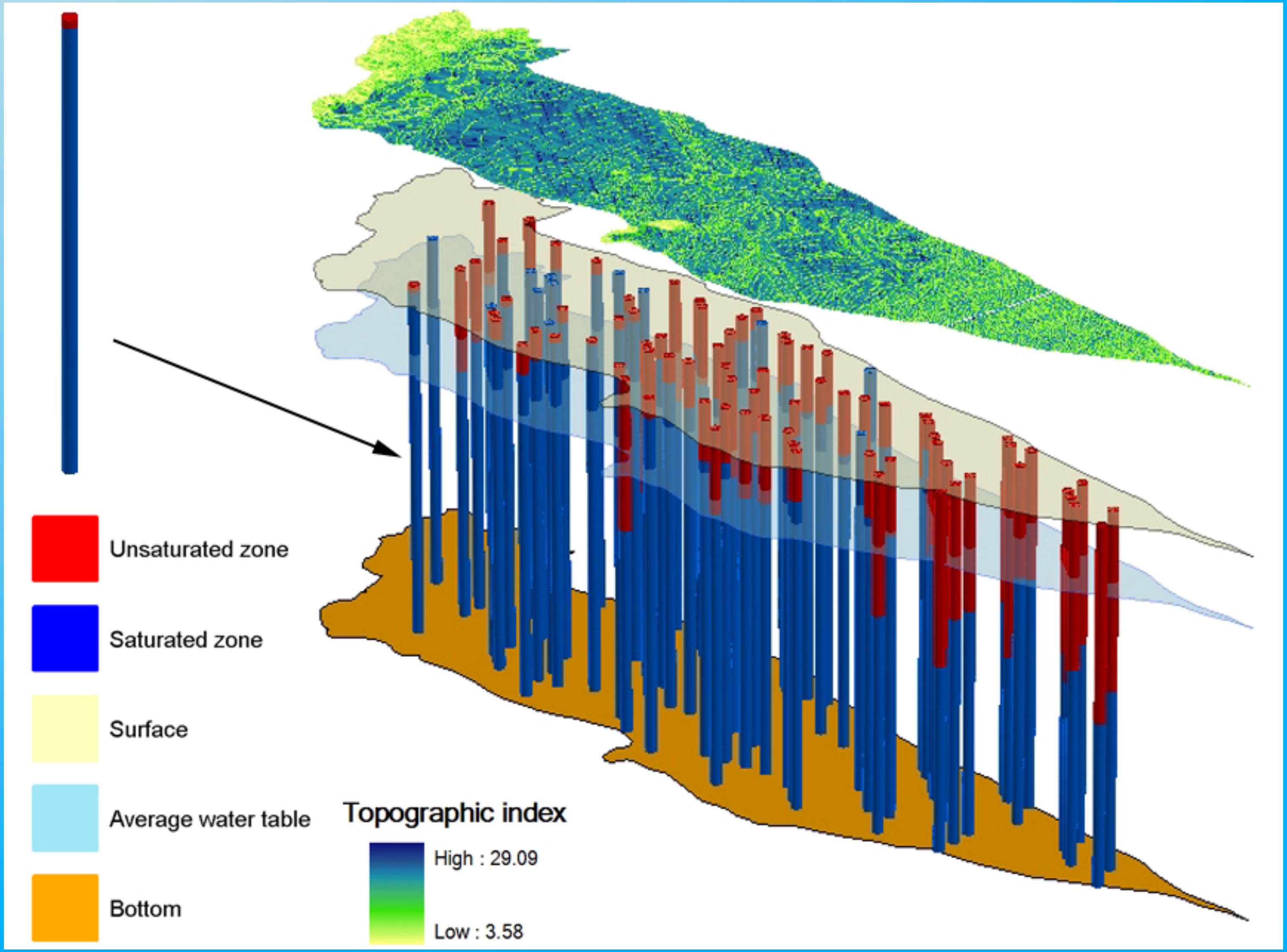
- CO_2 fertilization effects present a significant uncertainty
- Fire disturbances exert significant impacts on the regional sink and source activities
- Vegetation redistributions have minimum effects on the GHG budget during the 21st century
- Regional GHG emissions exert small radiative forcing on the global climate system

Improve Estimates of Water Table Depth With a TOPMODEL Approach

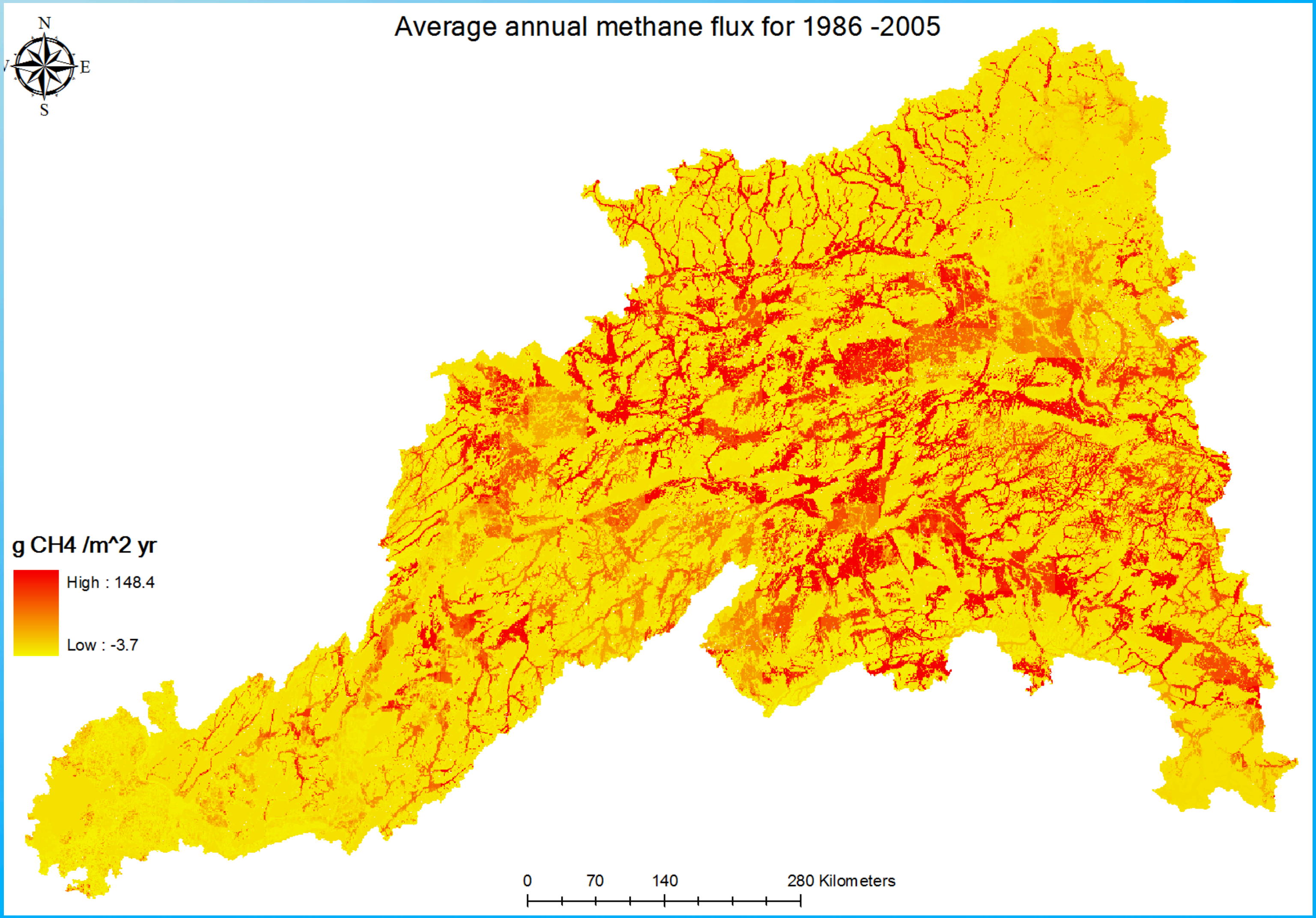


(Lu and Zhuang, 2011JGRB)

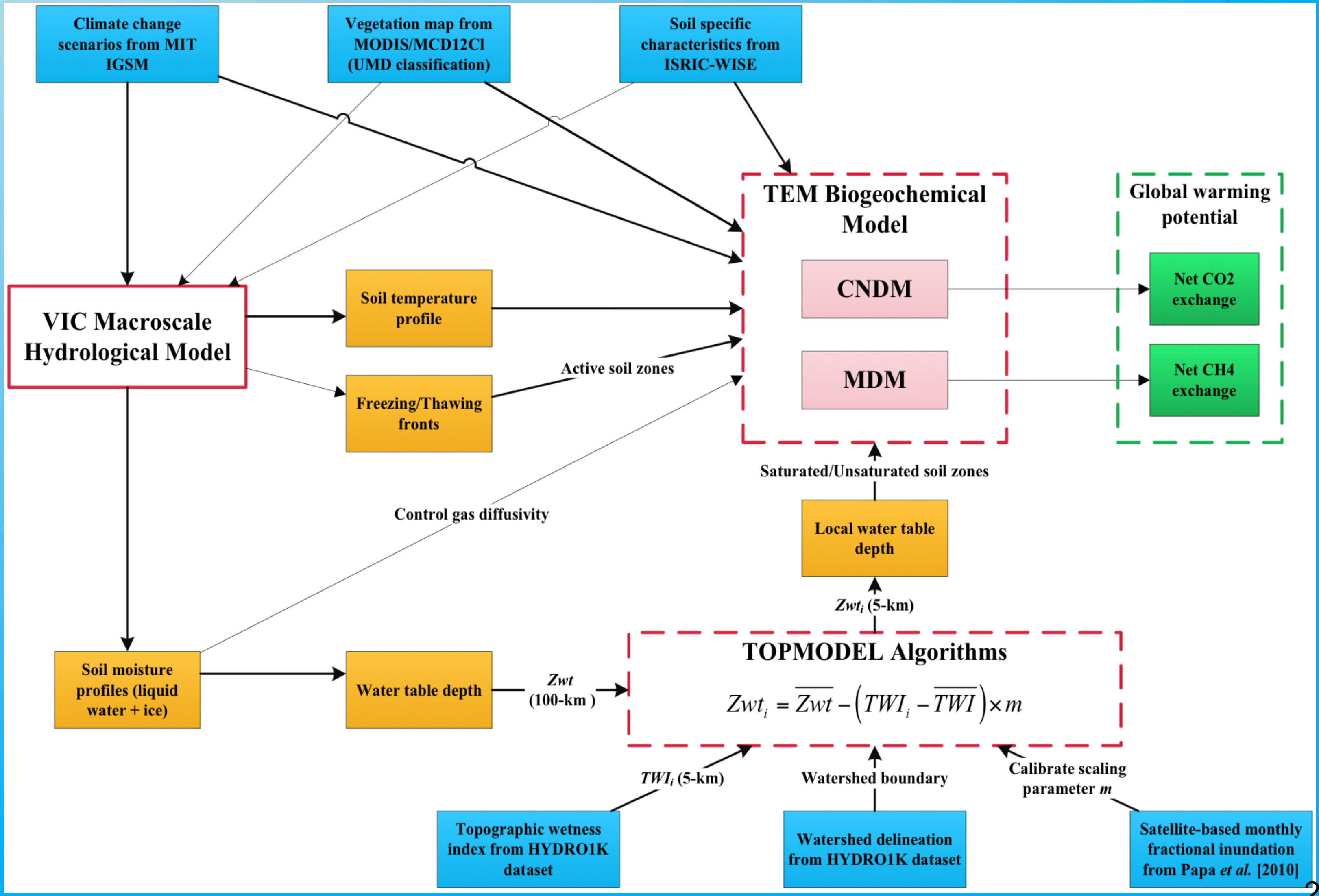
Estimated Fine-Scale Water table Depth Distribution



Estimated Fine-Scale Methane Emissions

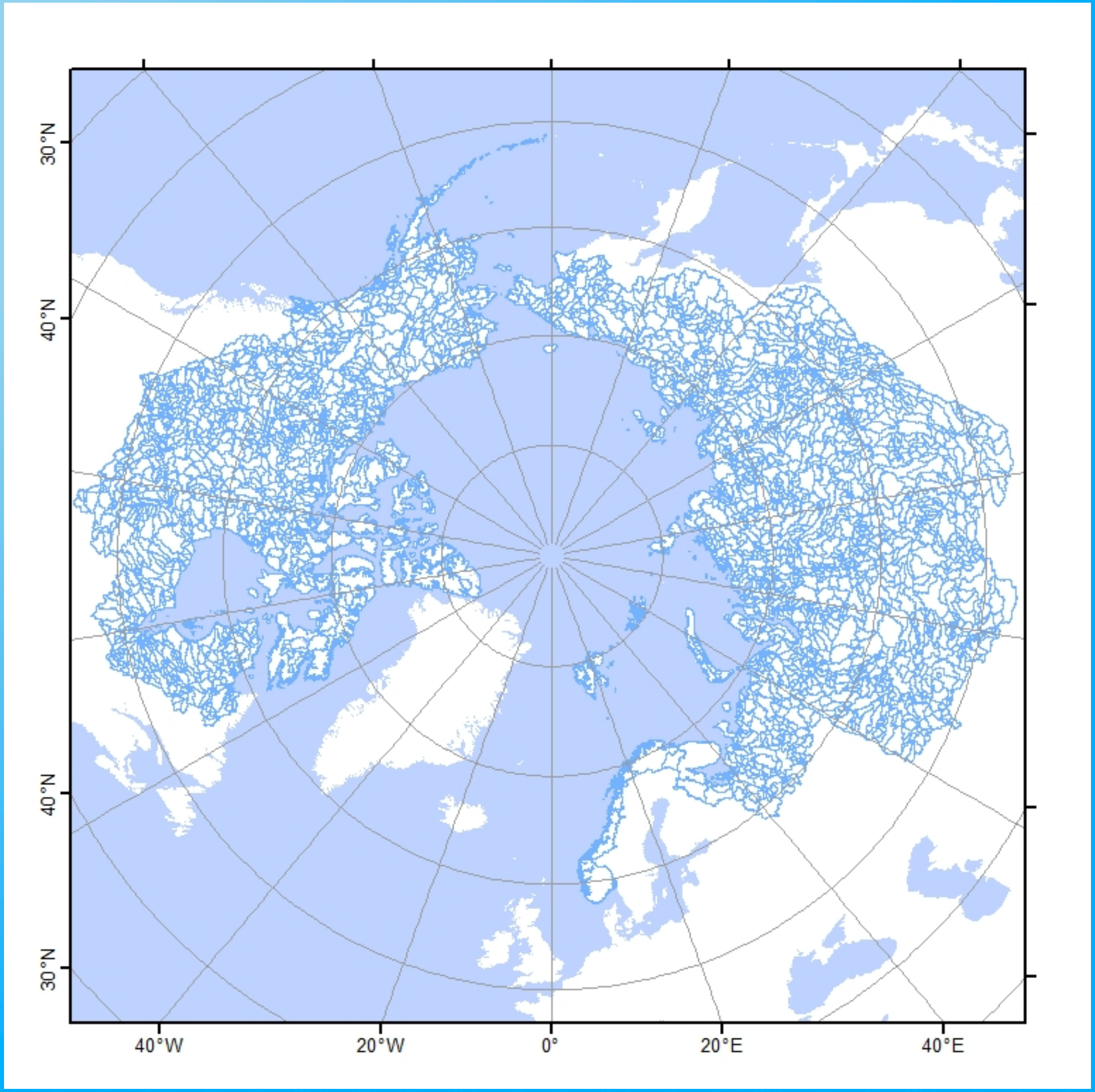


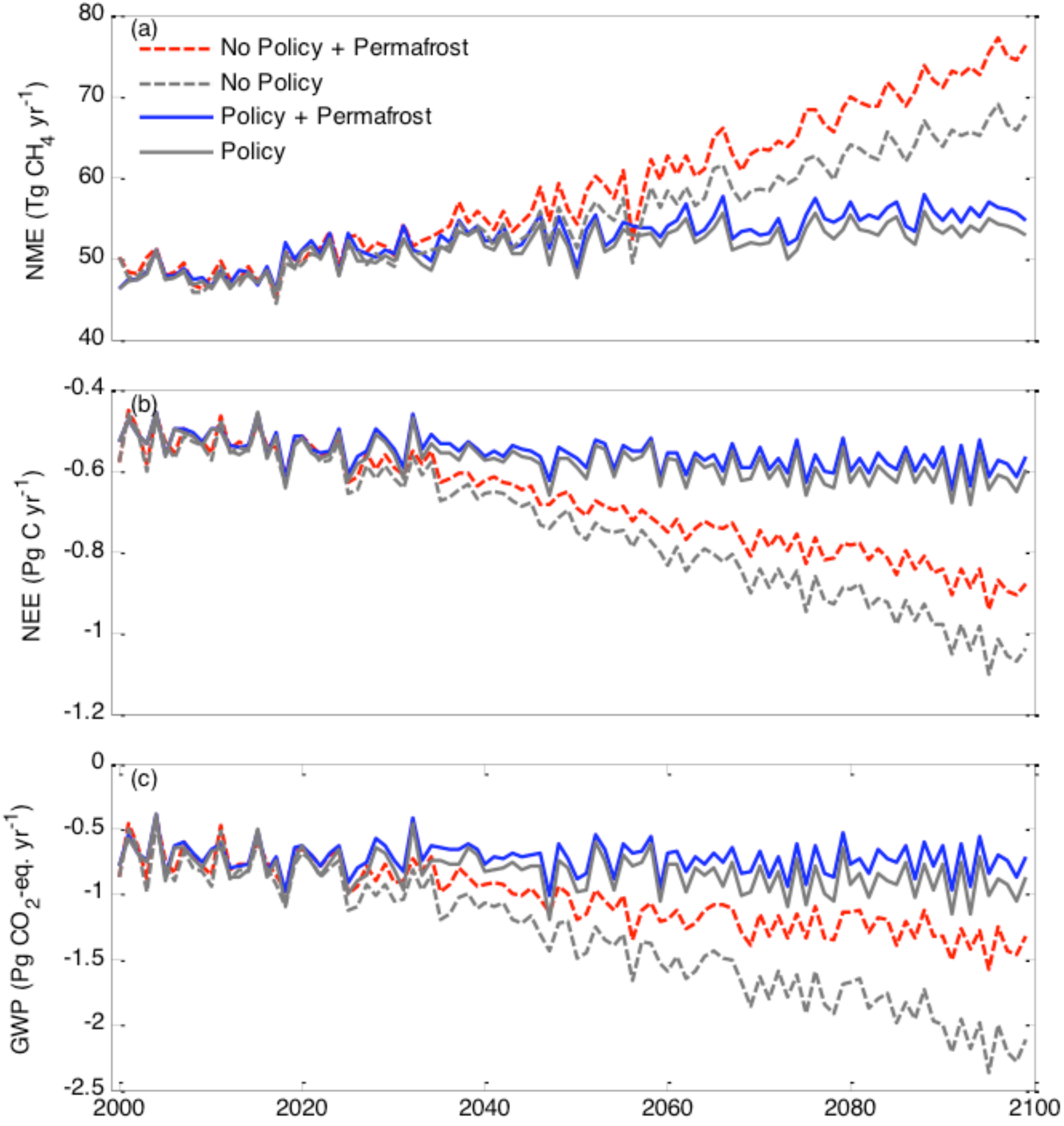
Coupled Wetland Modeling Framework with a Sophisticated Hydrological Model and TOPMODEL Approach



(Zhu et al., 2013Biogeoscience)

The delineation of the watersheds across the Pan-Arctic land region, derived from HYDRO1K dataset





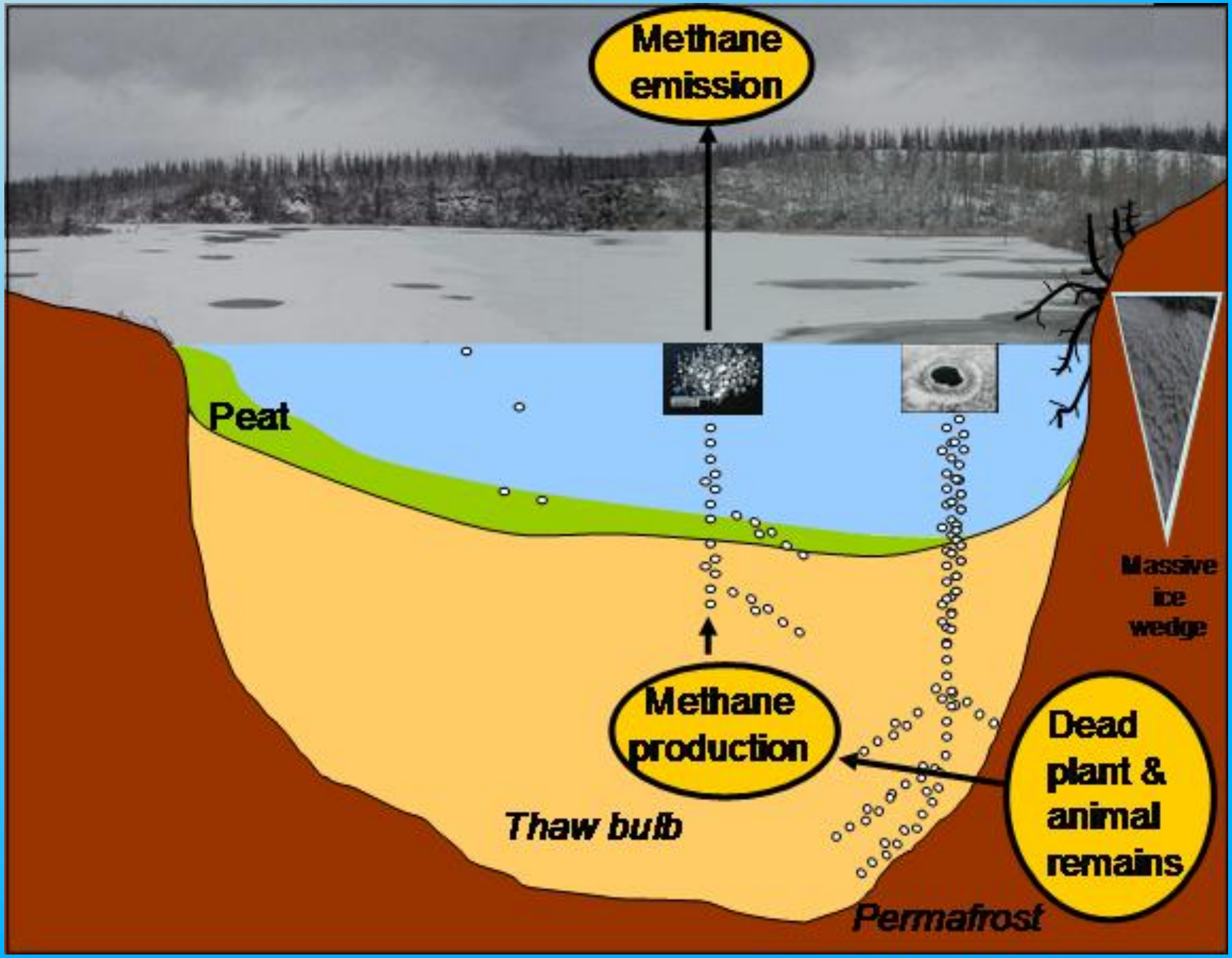
(Zhu et al., 2013ERL)

Summary #2

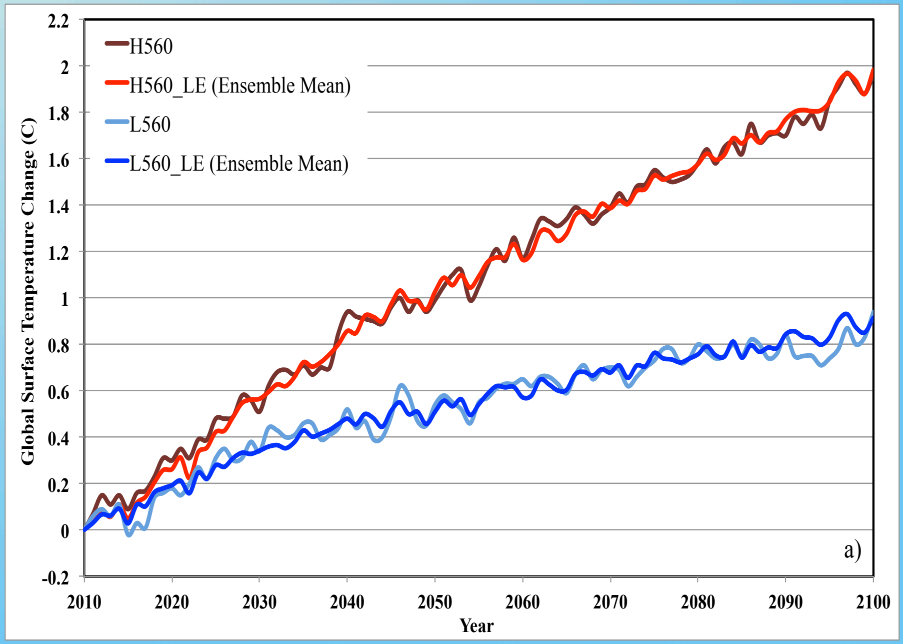
- Fine-scale water table depth dynamics estimated with TOPMODEL approach do not significantly affect the total methane emissions
- Estimated regional methane emissions still exert small radiative forcing on the global climate system in the 21st century

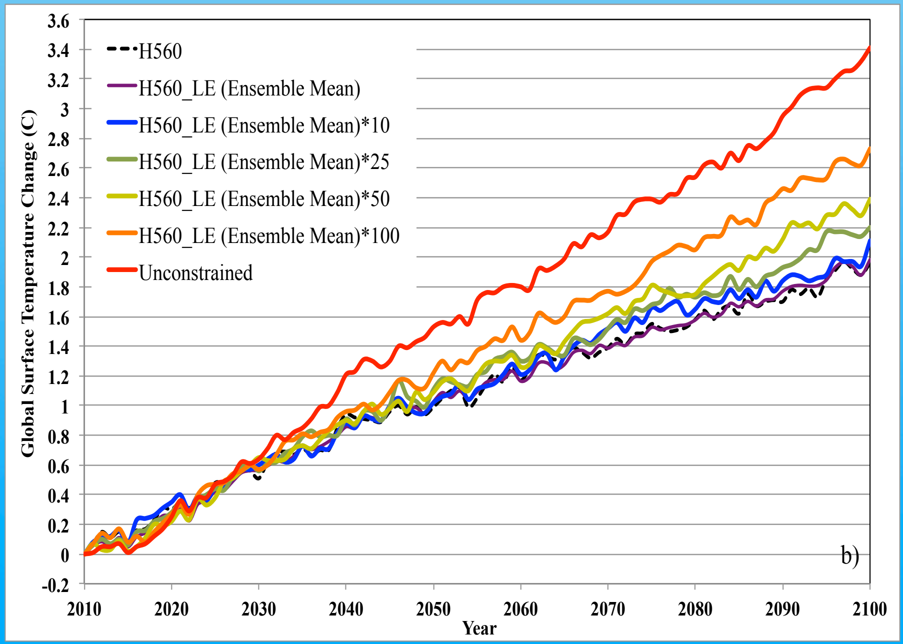
Arctic Lakes Are with Similar Emissions to Wetlands

(Walter Anthony et al., 2011Limnol. Oceanogr.: Methods)



(Courtesy of Katey Walter Anthony)





a) Global temperature feedback from the increased lake CH_4 emissions for the low and high TCR cases under the GST scenario. LE in the legend refers to the lake Emission.

b) The sensitivity of global temperature change (°C) to the increased lake CH4 emission for the high TCR case under the GST scenario. *10, *25, *50, and *100 refer to the experiments with the CH4 lake-emission increases scaled by 10, 25, 50 and 100-fold, respectively. Also shown is the global temperature change by applying only the CH4 human-emission increases of the UCE scenario.

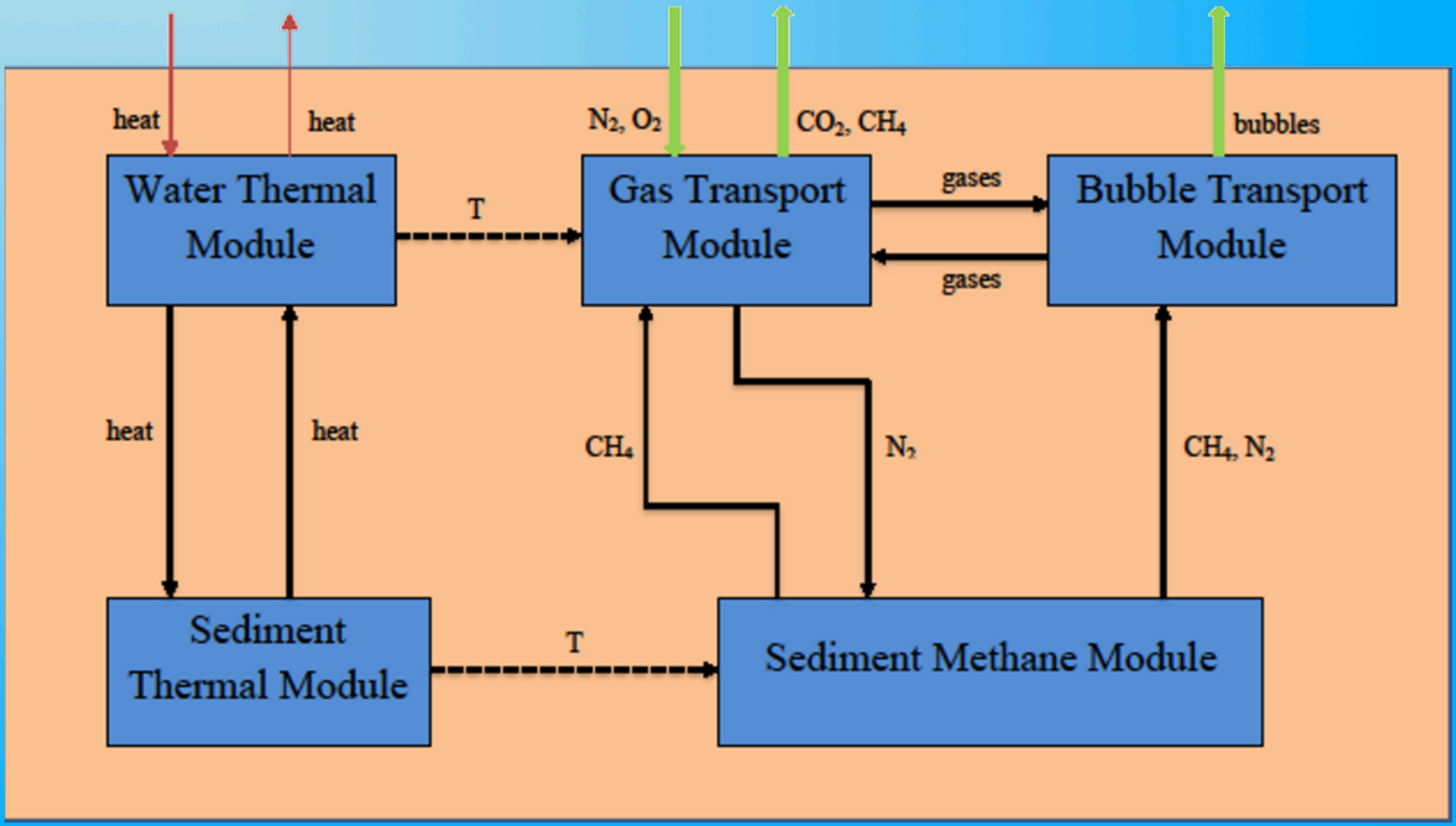
(Gao et al., 2013ERL)

Summary #3

- A simple extrapolation of observed lake emissions to the region did not result in overwhelmingly large methane emissions

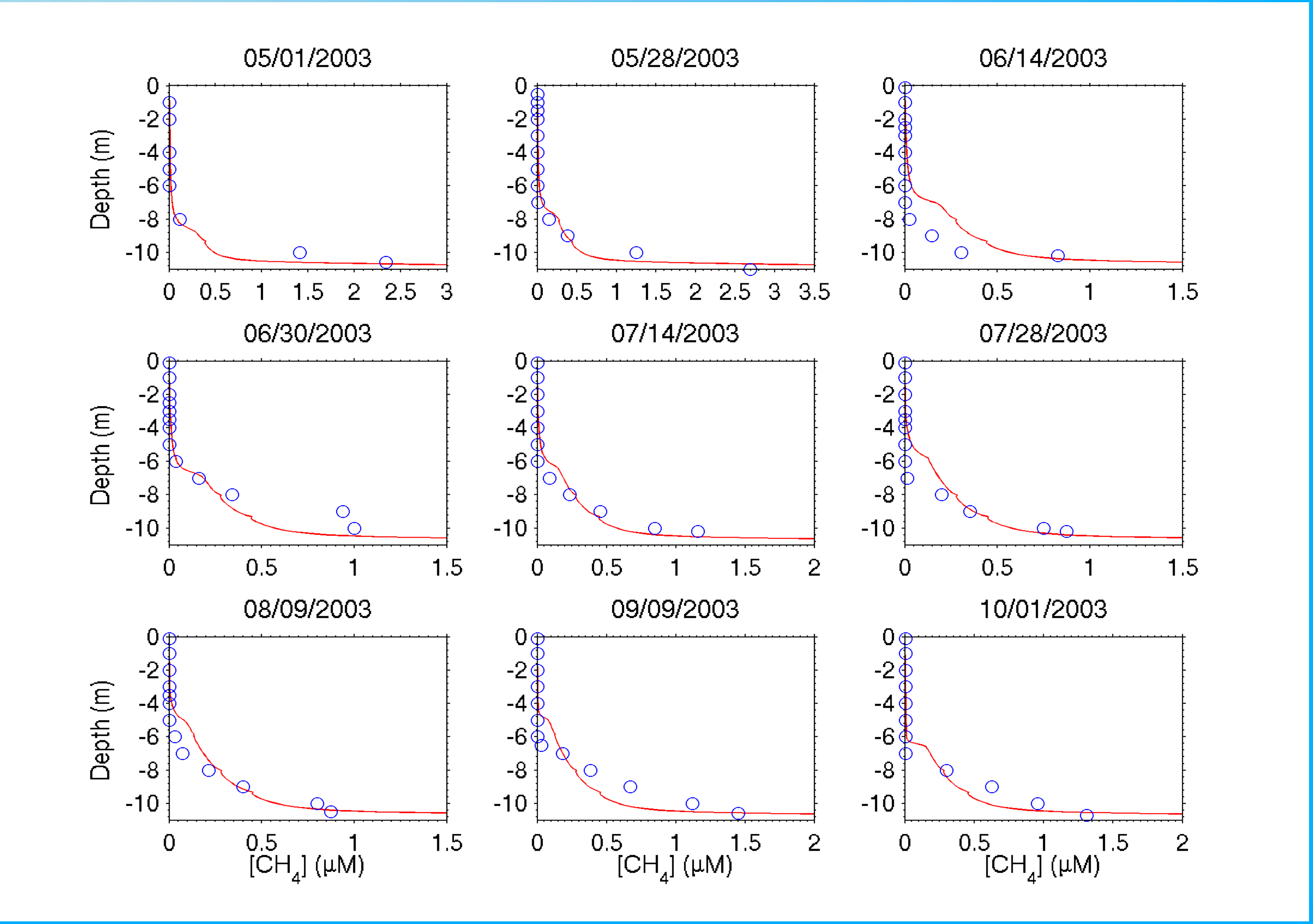
- Including lake emissions, regional methane emissions still exert small radiative forcing on the global climate system in the 21st century

Process-Based Lake Methane Emission Model

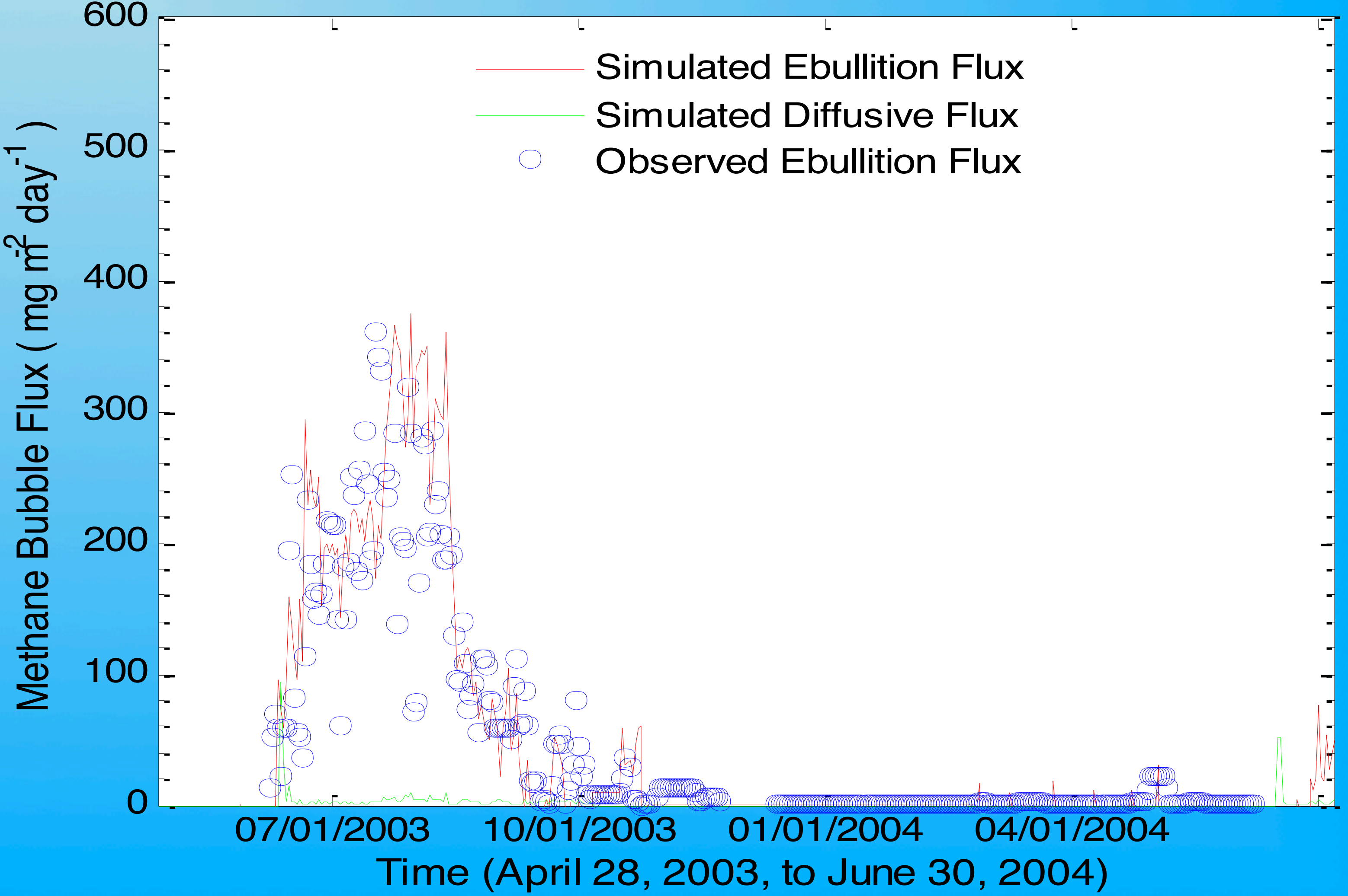


(Tan, Zhuang, and Walter Anthony, 2014JAMES)

Comparison between Observed and Simulated Porewater concentrations

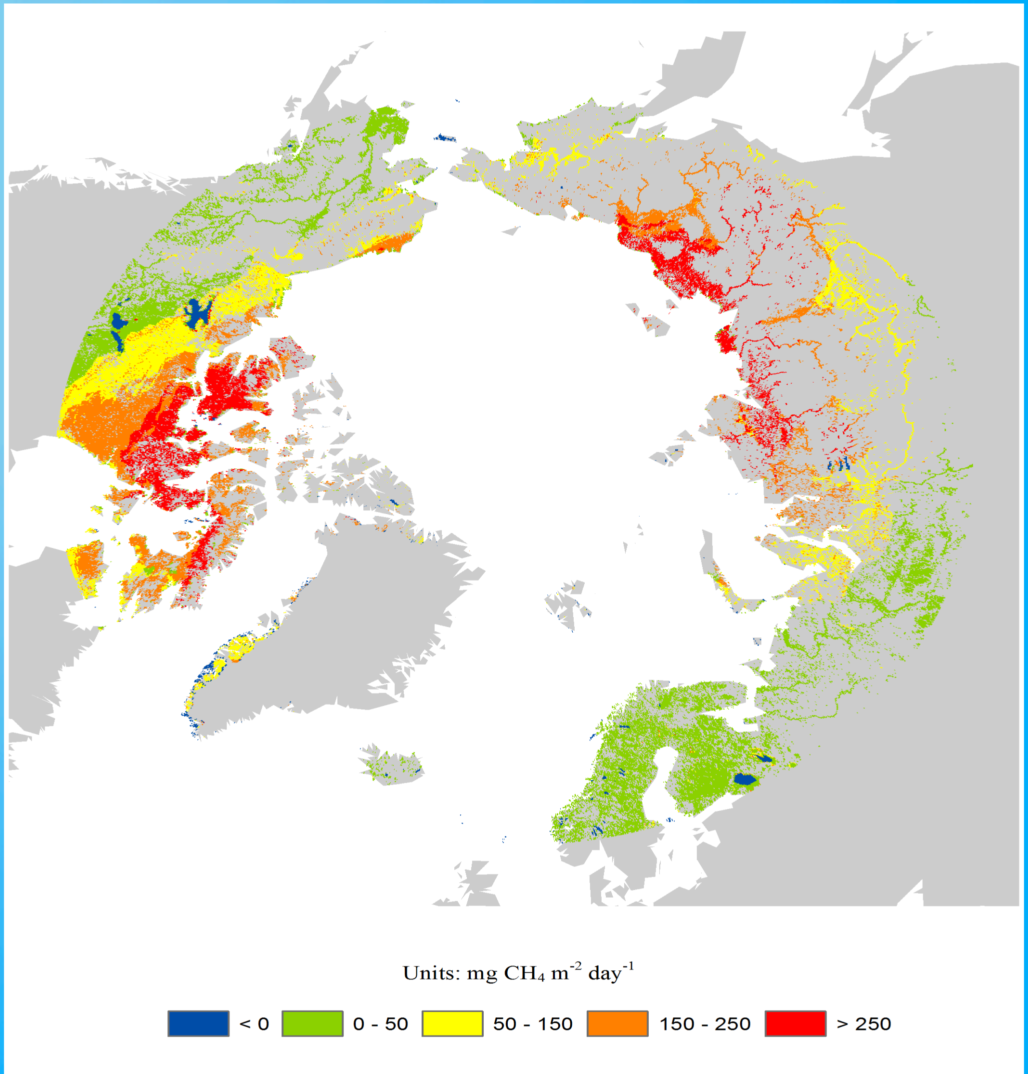


Lake Methane Emissions



Simulated Lake Emissions Based on GLWD Lake Distribution Data at 30 Second Resolution

Total current emissions: 25 Tg CH_4 yr^{-1}



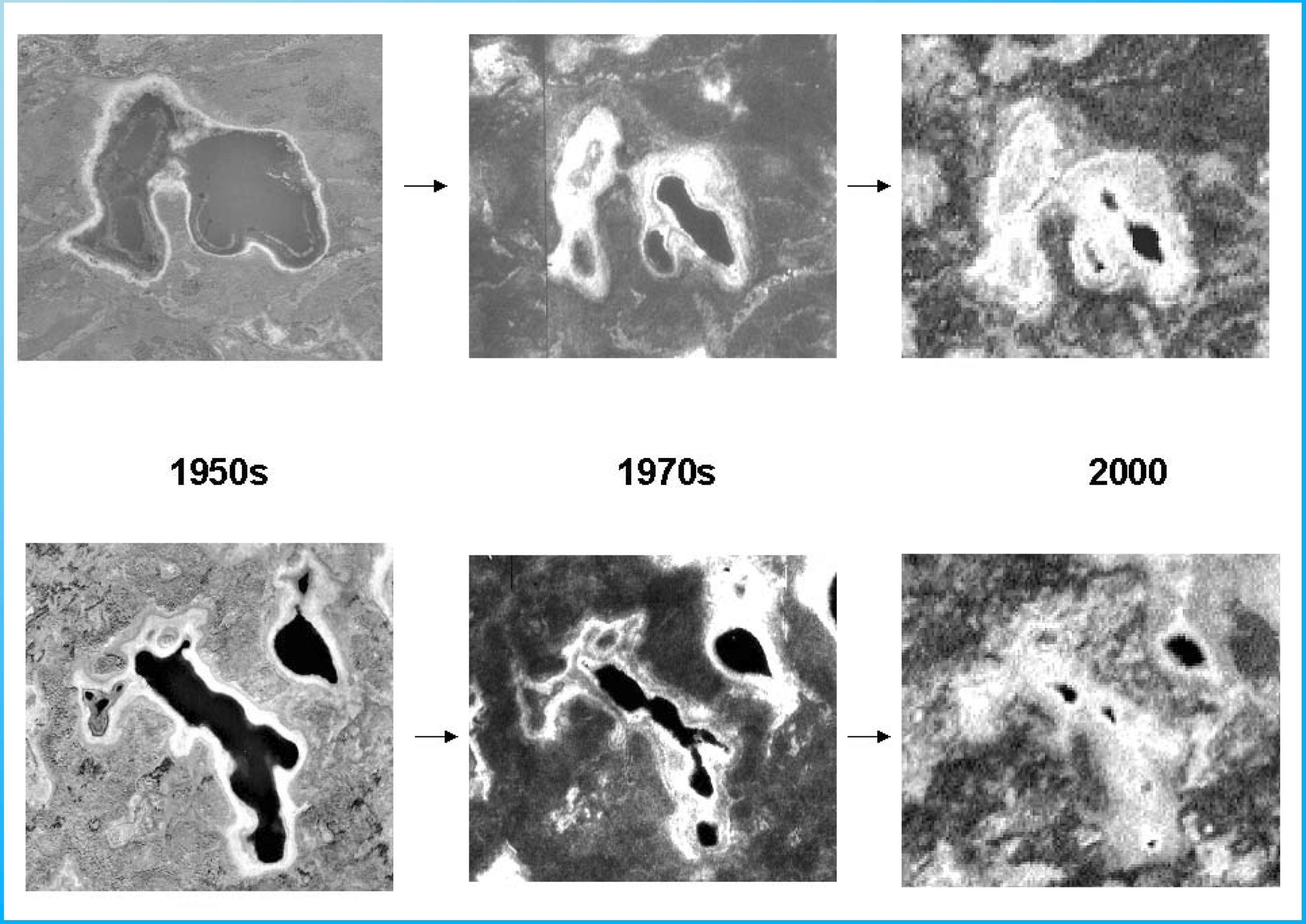
(Tan and Zhuang, 2014ERL)

Summary #4

- A process-based lake emission modeling is promising to keep track of thermal status of lake water column and sediments and permafrost and methane emissions including oxidation.

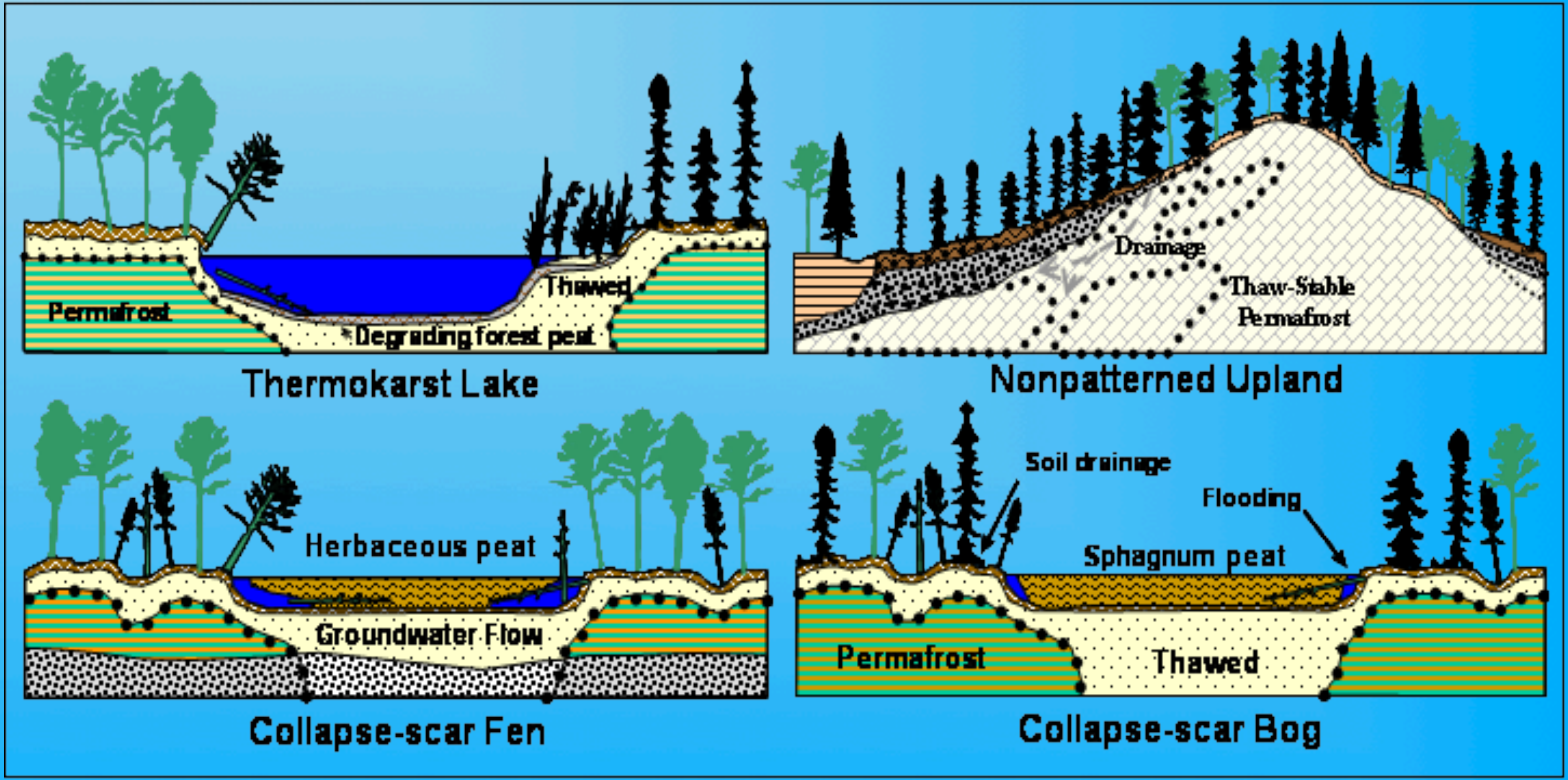
- Future extrapolation requires more sophisticated landscape modeling including lake expansion.

Changes of Water Bodies in the Arctic

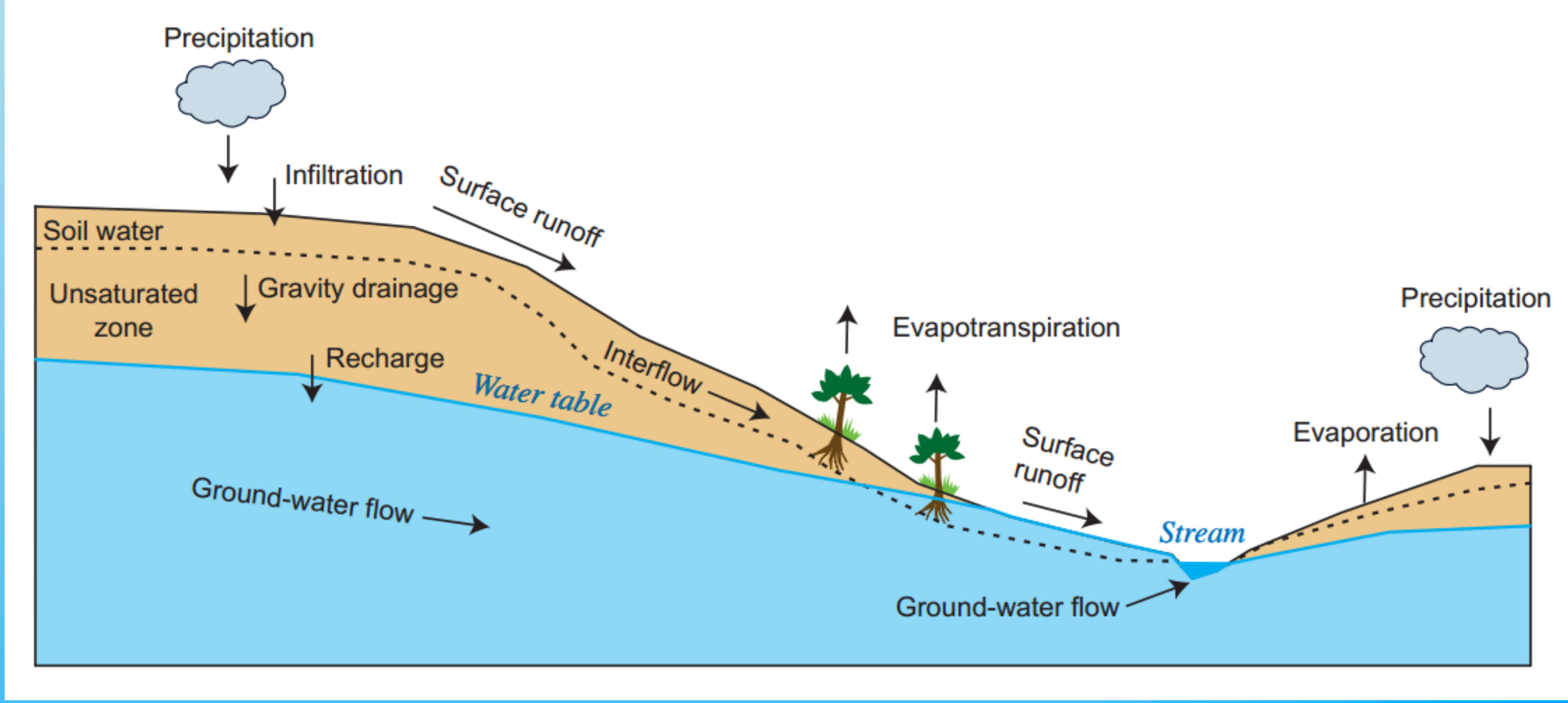


(Riordan et al., 2006)

Changes in hydrology, soils, and vegetation with varying modes of permafrost degradation



GSFLOW Model



GSFLOW simulates the coupled groundwater/surface-water flow in one or more watersheds by simultaneously simulating flow across the land surface, within subsurface saturated and unsaturated materials, and within streams and lakes. Forcing data consists of measured or estimated precipitation, air temperature, and solar radiation, as well as groundwater stresses (such as withdrawals) and boundary conditions (Markstrom, S.L., Niswonger, R.G. etc. 2008).

Spatial discretization in MODFLOW

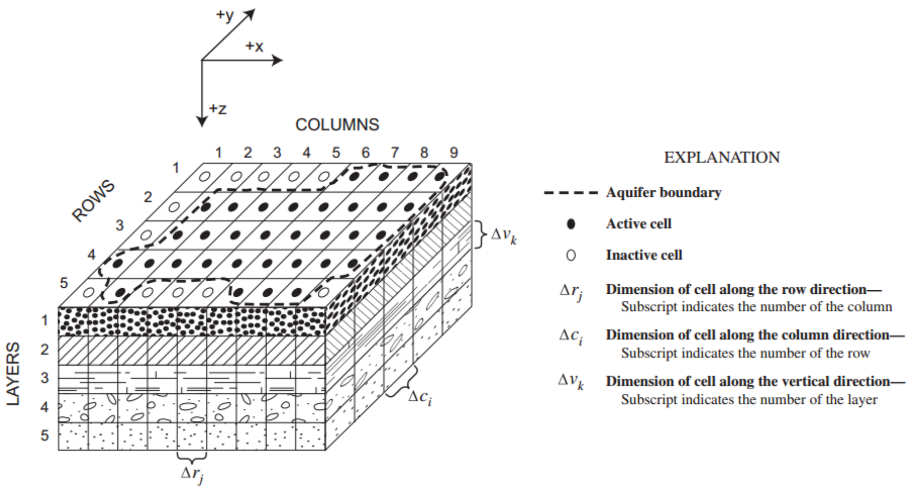
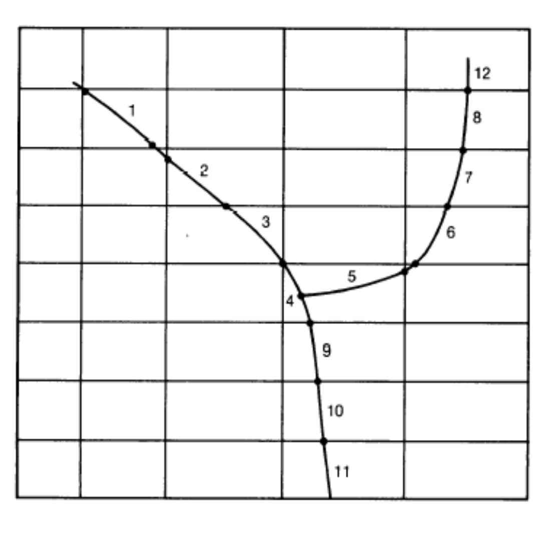
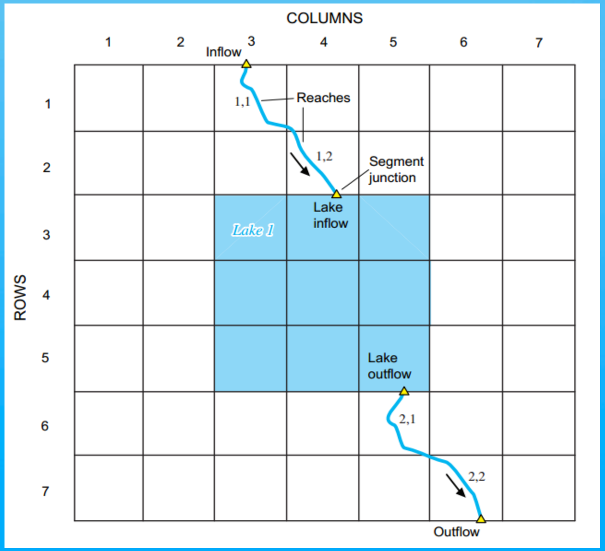


Figure 7. A discretized hypothetical aquifer system (modified from Harbaugh, 2005).

The three-dimensional movement of ground water of constant density through porous earth material can be described with the partial-differential equation:

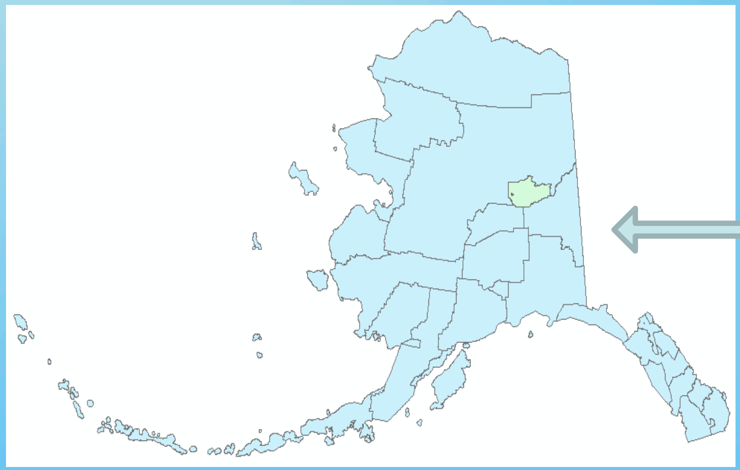
$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t}$$

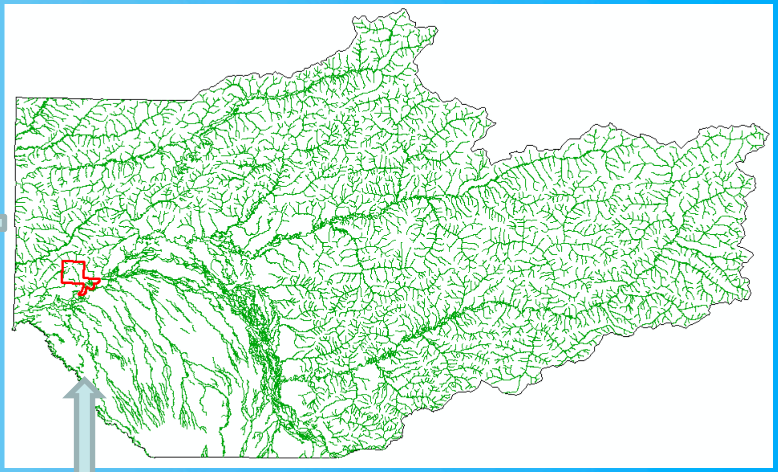




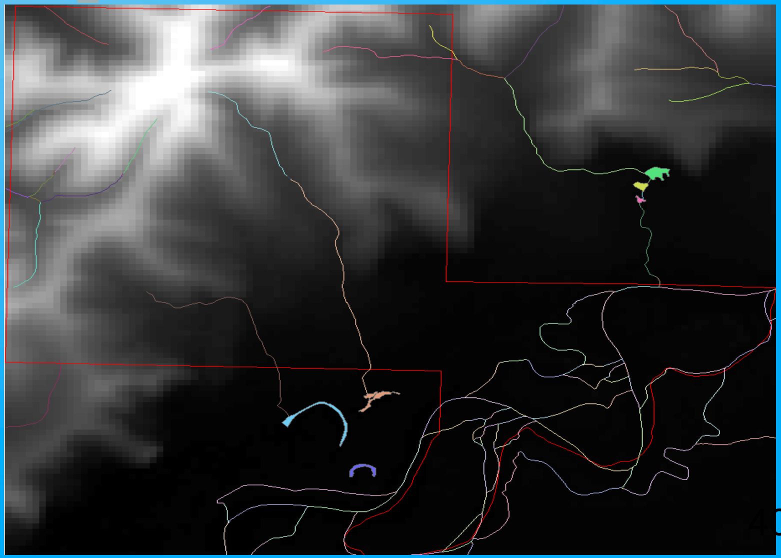
Land, rivers, streams, and lakes interact with surface-water and groundwater

Case Study in Bonanza Creek, Alaska





Bonanza Creek is located in the interior of Alaska, USA. Within the study region, hydrological features include land, rivers, streams and lakes.



Take-home Messages

1. Landscape modeling become key to biogeochemical modeling

2. 3D approaches for heat, water and material transport are needed.

(www.gibbons.de)