A Prognostic Methane Biogeochemical Model in CLM

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Boreal/Arctic-Climate Feedback

- One of the DOE IMPACTS projects
  - http://esd.lbl.gov/research/projects/abrupt_climate_change/impacts
- Potential future changes from:
  - Melting permafrost and thermokarst lakes in the Arctic
  - Changing wetland conditions from changing precipitation, temperature, and nutrients in the Tropics
  - Atmospheric feedbacks

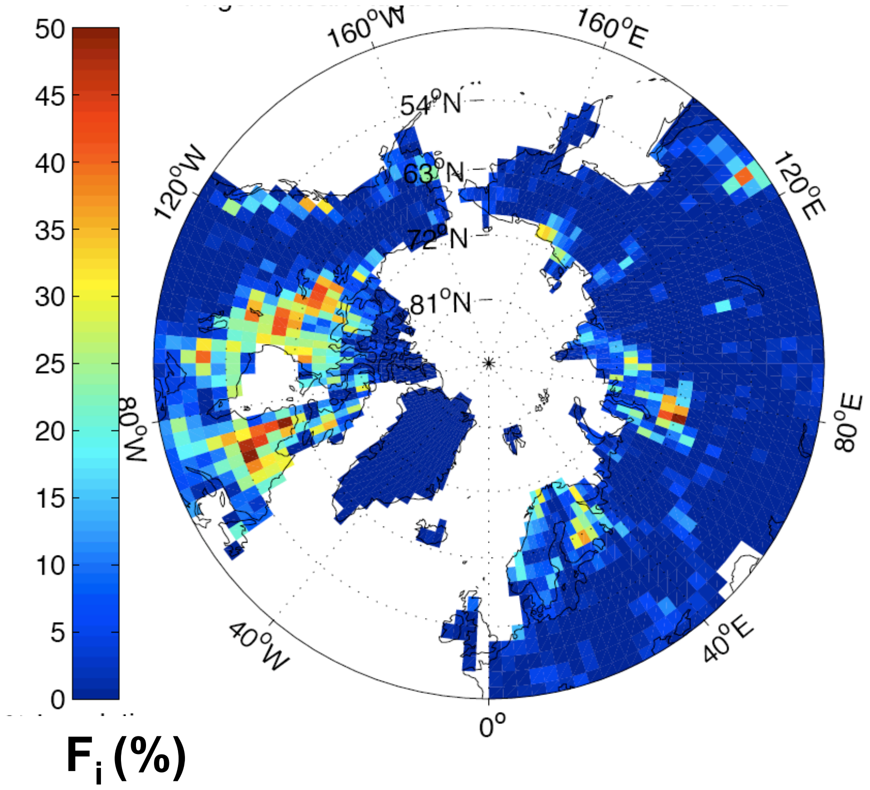
CH_4 BGC Model: Outline

- Inundated fraction (F_i)
- CH_4 BGC processes:
  - Production, oxidation, ebullition, aerenchyma, and diffusion
  - Characterization, interactions, sensitivity
- Comparison to observations
- Regional and global fluxes

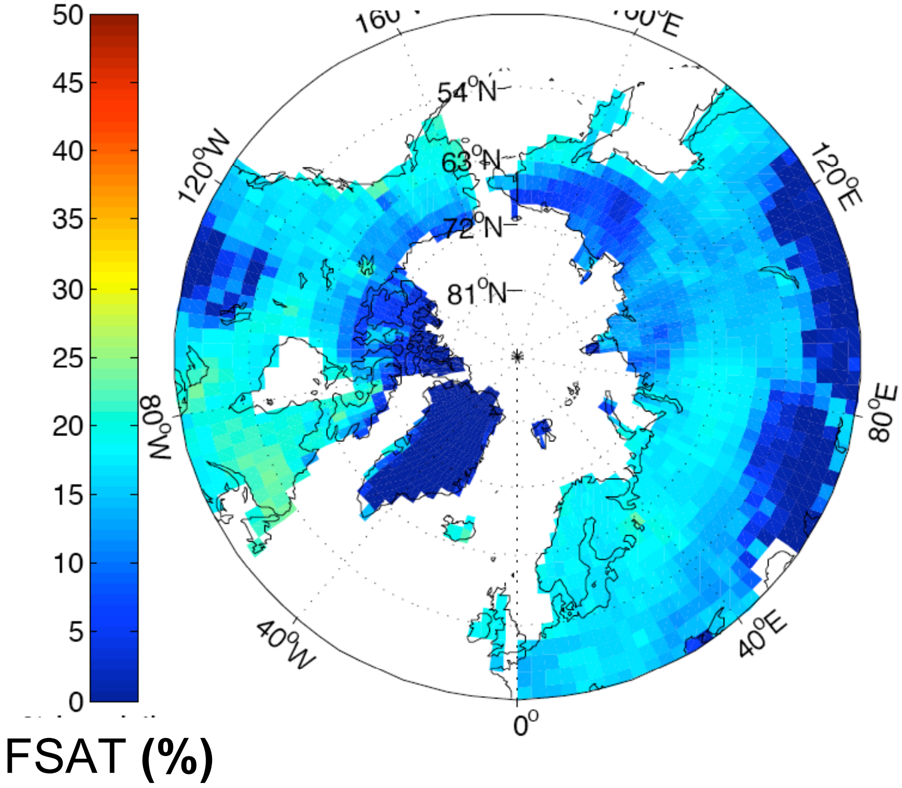
Inundated Fraction (F_i)

- Previous studies used static maps for F_i
  - Matthews and Fung (1996)
  - IGBP soils maps (Wania 2010)
- We applied a recent multi-satellite reconstruction (Prigent et al., 2007)
  - Passive microwave emissivities, ERS scatterometer, AVHRR reflectances
  - Inverted for F_i with CLM's FSAT parameterization
- Work by S. Swensen (NCAR) to develop mechanistic representation in CLM

Current CLM FSAT Prediction



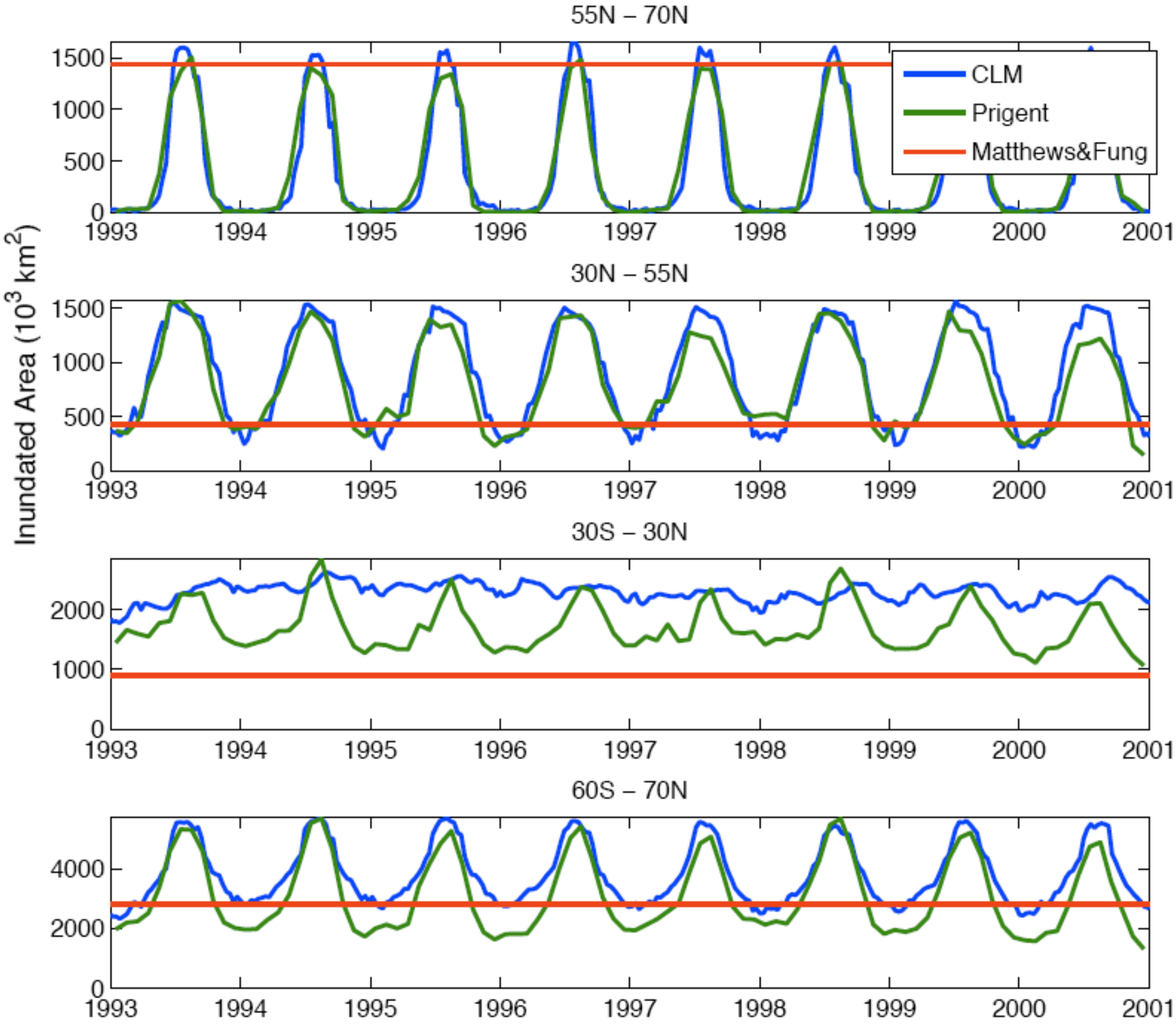
Satellite-derived August F_i



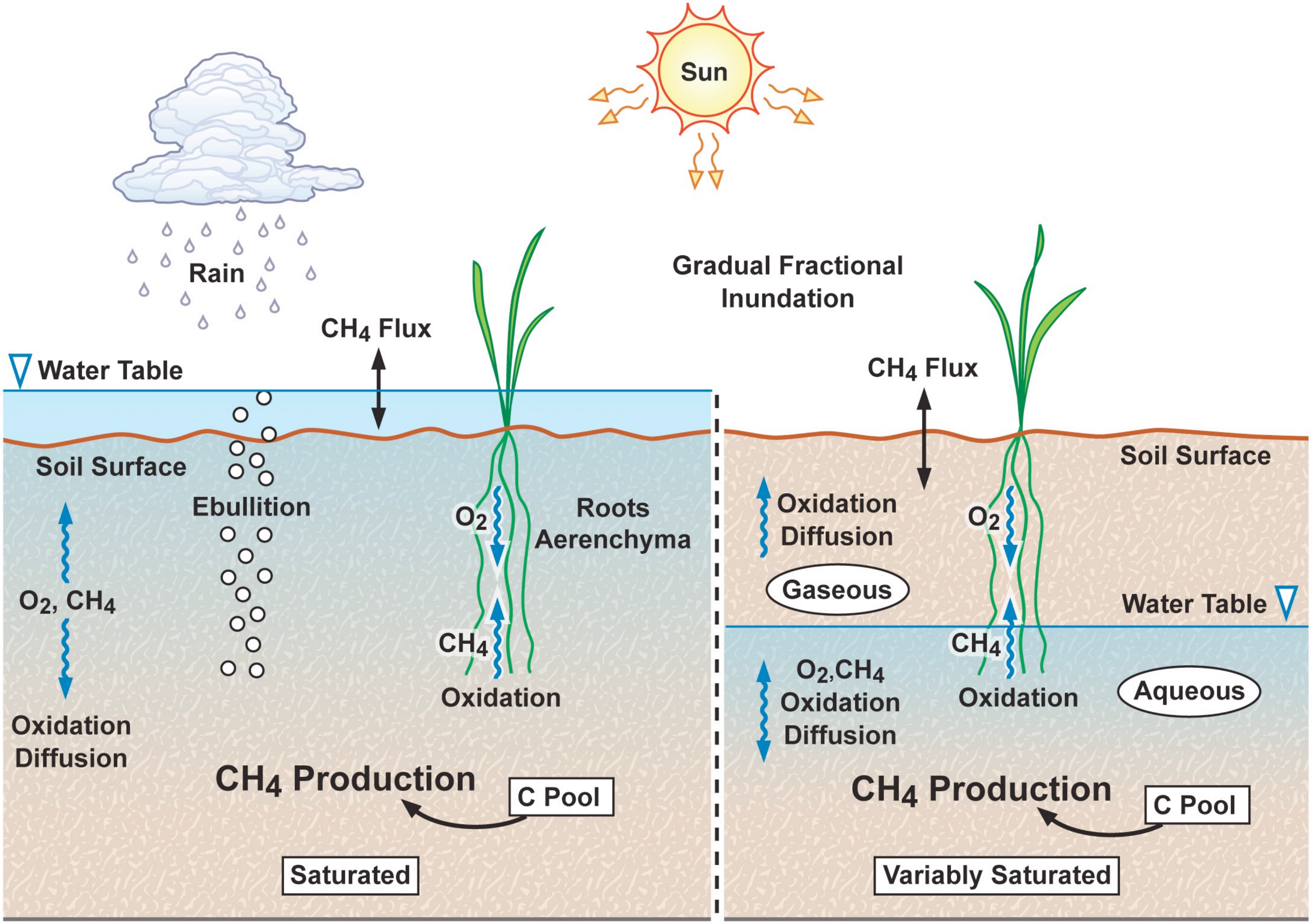
Current CLM August FSAT

- Globally integrated, current CLM FSAT over-estimates saturated area by more than a factor of 3
- Spatial heterogeneity and temporal variability poorly represented

Inverted F_i


55N – 70N
30N – 55N
30S – 30N
60S – 70N
Inundated Area (10^3 km^2)
CLM
Prigent
Matthews&Fung
0
500
1000
1500
2000
4000
1993
1994
1995
1996
1997
1998
1999
2000
2001

CLM-CH_4 Biogeochemistry



Modeling CH_4 Biogeochemistry

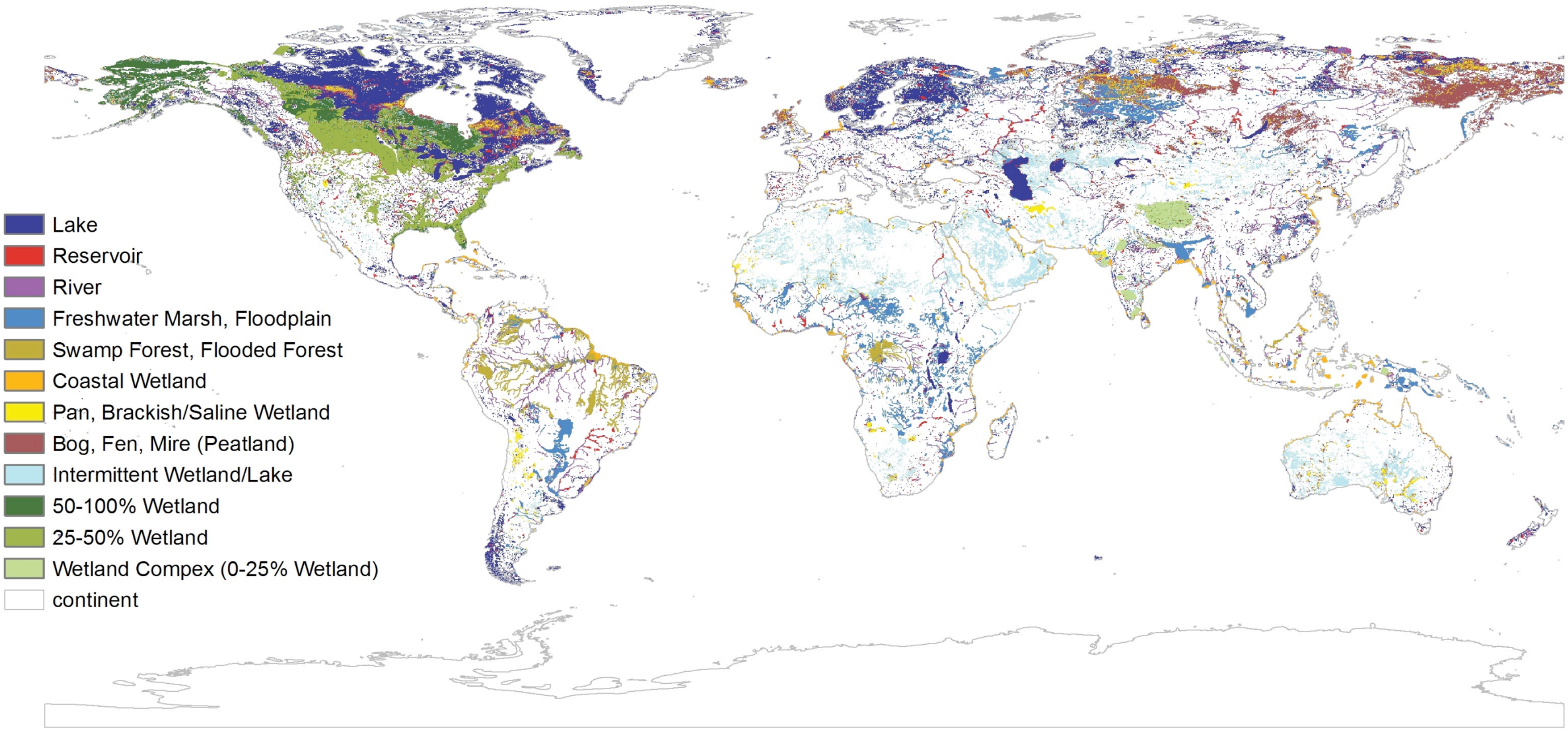
$$\underbrace{\frac{\partial(RC)}{\partial t}}_{\text{Net change}} = \underbrace{\frac{\partial F_D}{\partial z}}_{\text{Diffusion}} + \underset{\underset{\text{Production}}{\uparrow}}{P(z,t)} - \underbrace{E(z,t)}_{\text{Ebullition (bubbling)}} - \underset{\underset{\text{Aerenchyma (tissue)}}{\uparrow}}{A(z,t)}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

- Relationship applied in global, regional, and site-level models
- In CLM, solved vertically at each time step
- Competition between processes determines net surface flux

CH_4 Production

- Several interacting populations in anaerobic zone
  - Anaerobic fermentation, methanogens
  - Modeled production tied to predicted soil respiration
- Anaerobic CH_4 / CO_2 ratio varies over several orders of magnitude (Segers, 1998)
  - pH, other electron acceptors (NO_3^-, Mn_4^+, Fe_3^+, SO_4^{-2}) reduced before methane is produced
    - Adopt Zhuang et al. (2004), or analogous, approach, or
    - Integrate a global database of wetland type
- Depth dependence, seasonal inundation
- Q_{10} based on literature (values vary widely)

Global Lakes and Wetlands Database GLWD



Lehner & Doll (2004)

CH_4 Oxidation

- Sink of CH_4 and O_2 and source of CO_2
- Methanotroph CH_4 oxidation rate:

$$R_{oxic} = R_{oxid,\max}\left[\frac{C_{CH_4}}{K_{CH_4} + C_{CH_4}}\right]\left[\frac{C_{O_2}}{K_{O_2} + C_{O_2}}\right]Q_{10}$$

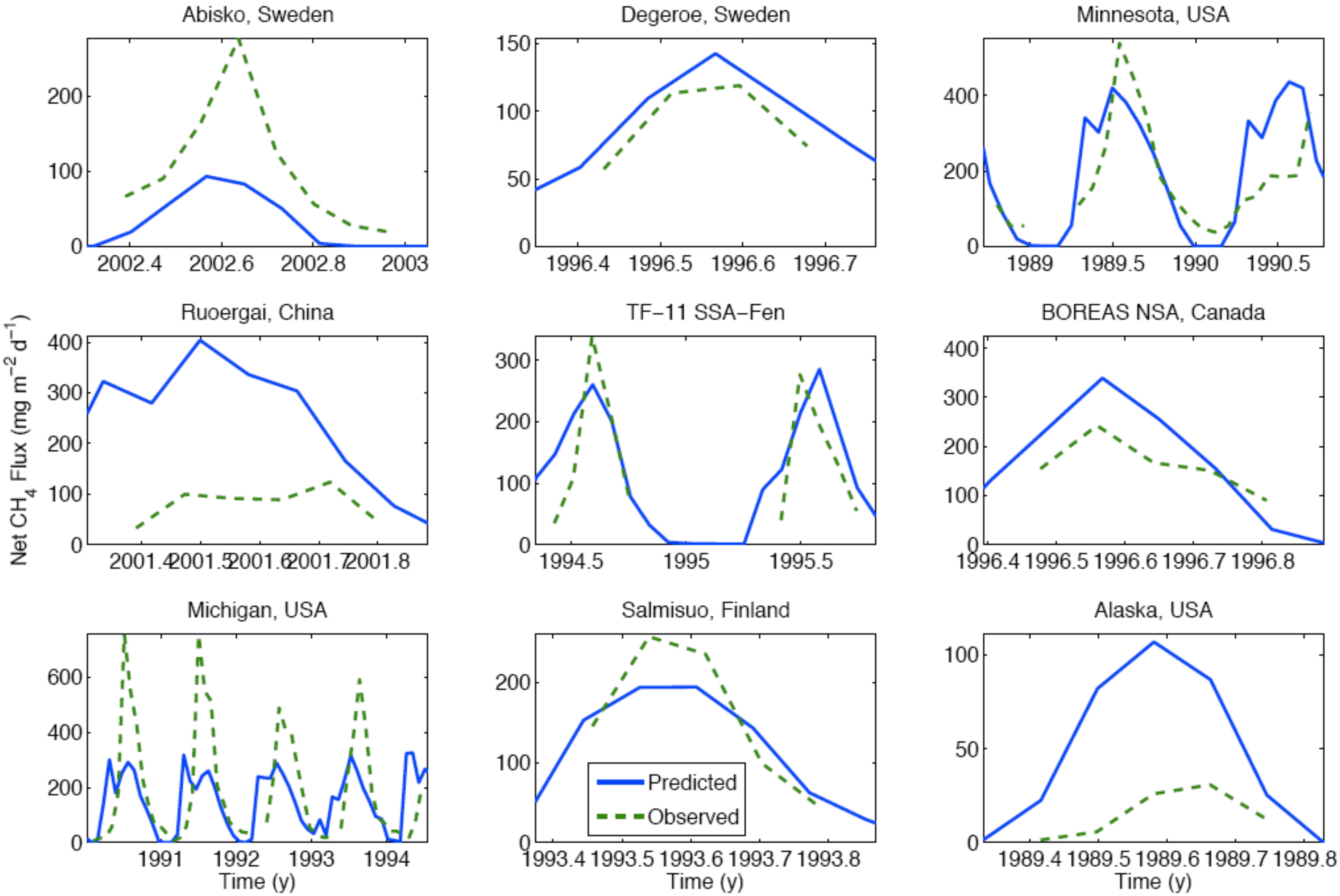
- Model includes other processes that consume O_2
  - Heterotrophic and autotrophic respiration
  - Autotrophic respiration requires much more O_2 than required by methanotrophs to remove all CH_4

Aerenchyma

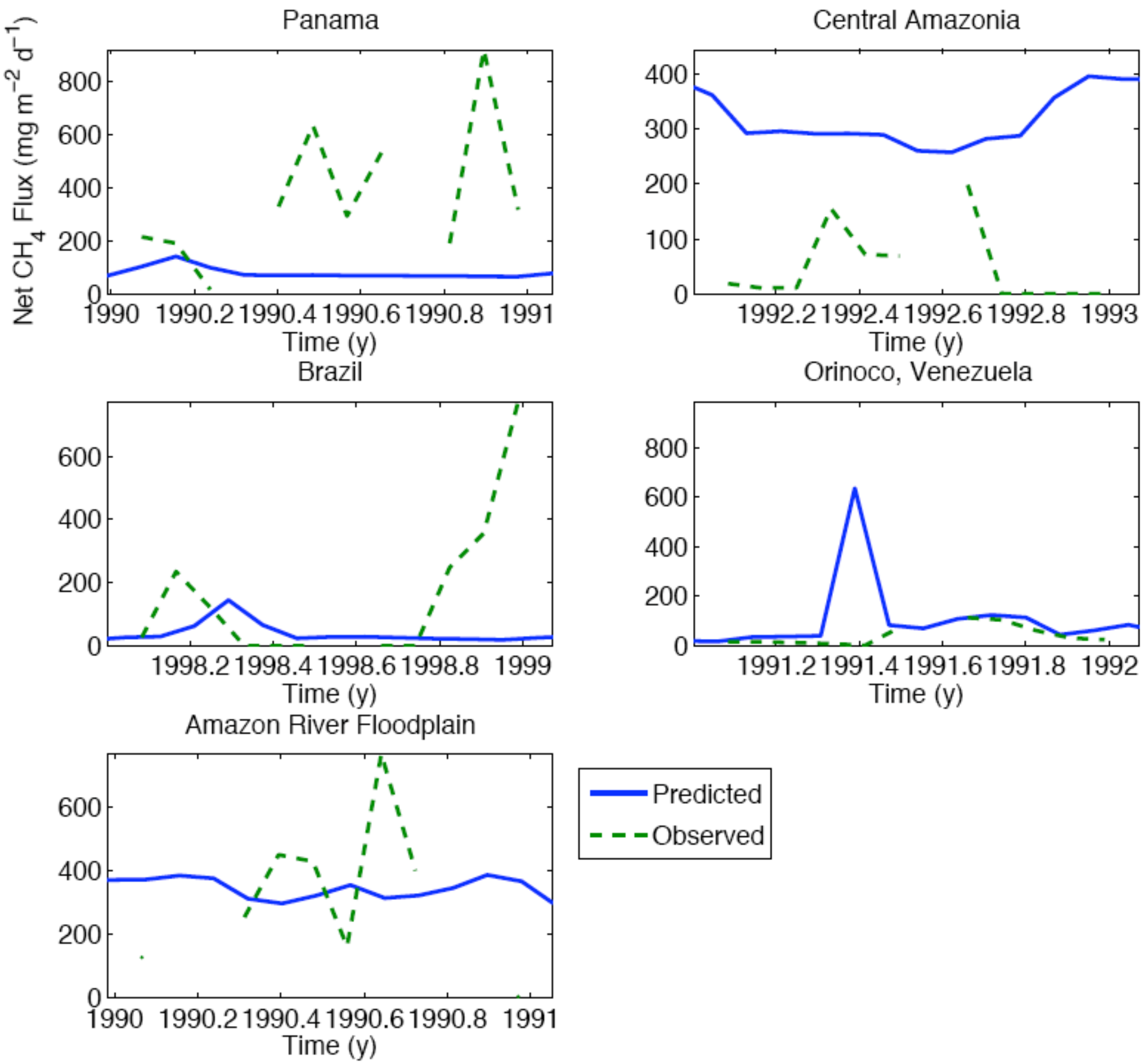
- All wetland plants need to bring O_2 to roots
  - CH_4 and O_2 can diffuse along this pathway
  - Previous models imposed constant fraction of oxidation associated with aerenchyma
- Radial and axial O_2 leakage supplies heterotrophic and autotrophic respiration and methanotrophs

$$Flux = \underbrace{D}_{\text{Diffusivity}} \underbrace{\frac{\left(C(z) - C_a\right)}{\Delta z}}_{\text{Concentration Gradient}} \overset{\text{Porosity}}{p} \underbrace{A}_{\text{Area}}$$

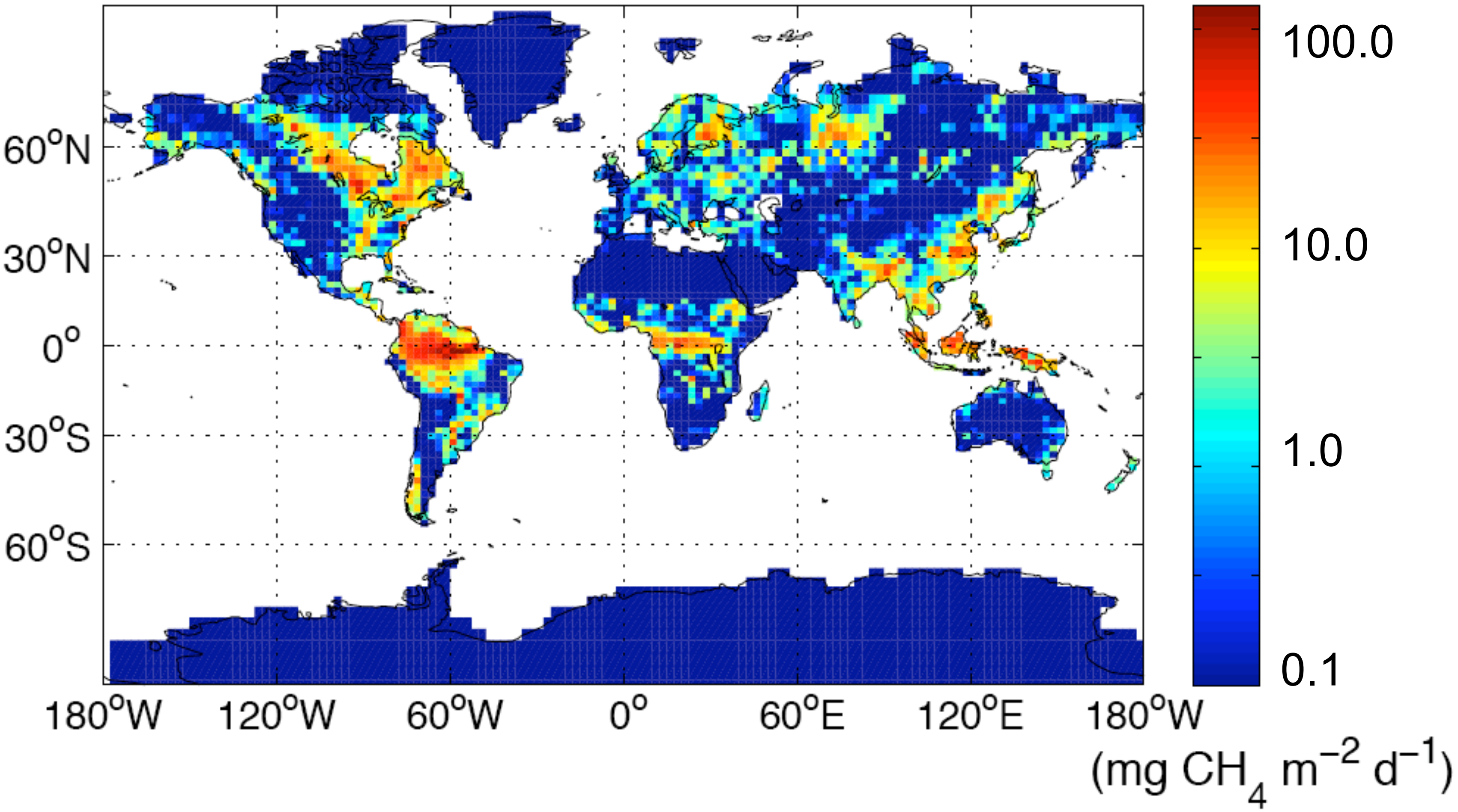
Comparison with CH_4 Observations



Comparison with CH_4 Observations

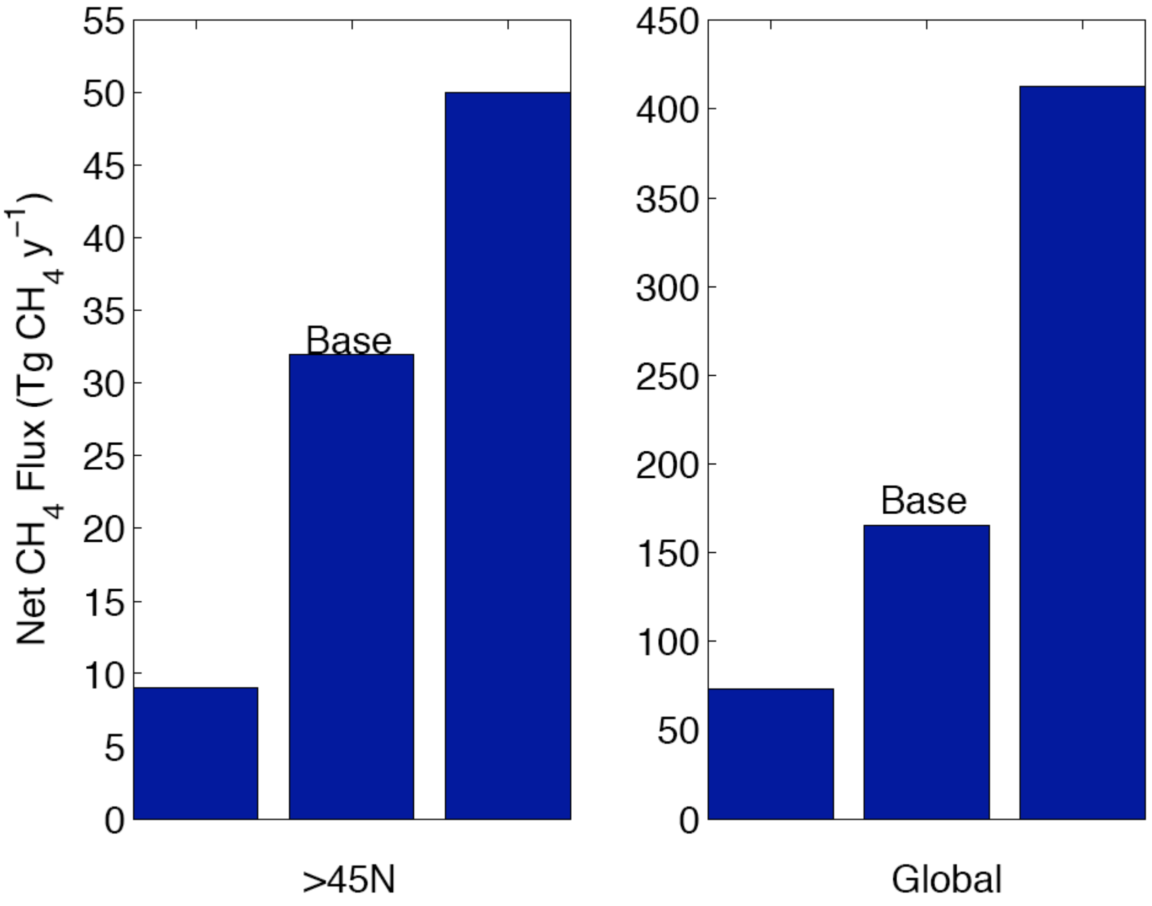


- Net CH_4 Fluxes:
  - Global: 165 Tg CH_4 y^{-1}
  - >45N: 32 Tg CH_4 y^{-1}



Sensitivity

- $K_m(CH_4)$, $K_m(O_2)$, Aerenchyma area
  - All other parameters held constant



Future Work

- Role of pH and alternative electron acceptors on CH_4 production
- Complete testing against extant CH_4 datasets
- Integration with new soil C predictions/model
- Landscape thermokarst model and CH_4 BGC
- Atmospheric coupling (regional and global) and feedback experiments
- Integration with dynamic vegetation model

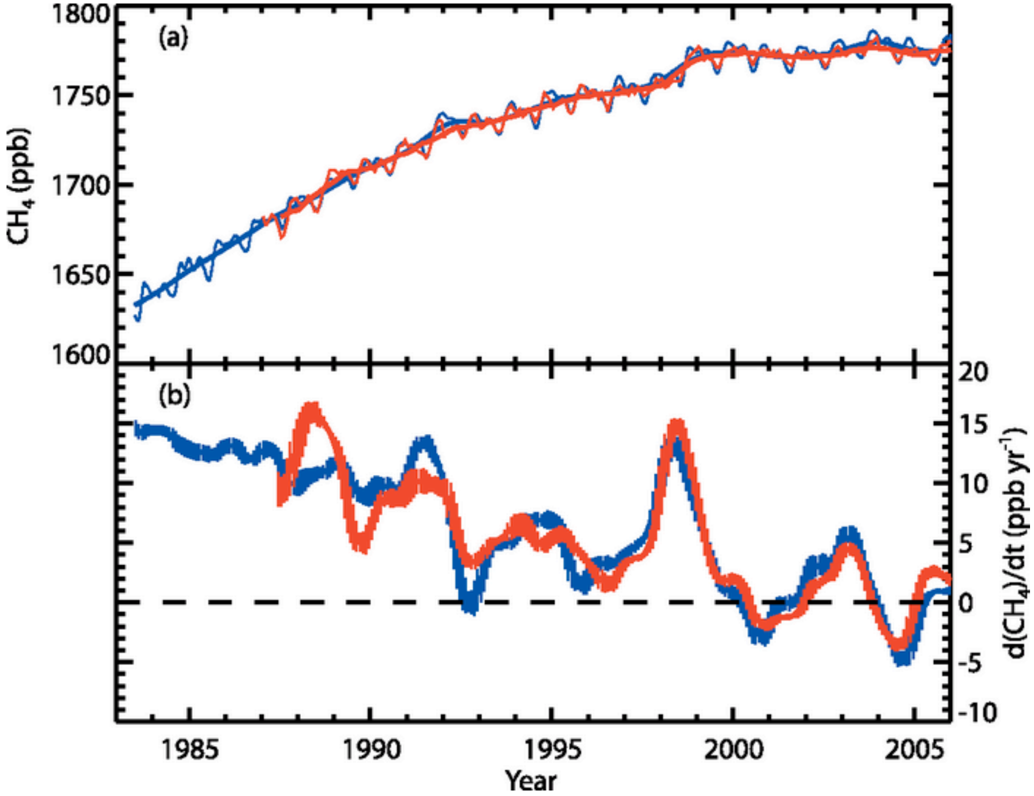
Model Discussion

- Potential improvements in current CLM-CN that would be helpful to CH_4 BGC modeling
  - No saturated, or seasonally inundated, C cycle
  - No separate C cycle by PFT
  - No wetland plants
  - No explicit depth dependence
  - No root exudation

  - Poor representation of groundwater
  - No surface water storage

Motivation

- CH_4 has second-largest RF of long-lived GHG’s
- Ice cores indicate CH_4 varied from ~400 (glacial) to 700 (interglacial) ppb
- Concentrations and emissions are increasing



IPCC FAR (2007)

Atmospheric CH_4 Budget

- Many inversion and bottom-up budgets have been developed
- Overall, ~500-600 $TgCH_4\ y^{-1}$ are emitted
  - Anthropogenic: 315-350 $TgCH_4\ y^{-1}$
  - Global wetlands: 130-194 or 100-231 $TgCH_4\ y^{-1}$
  - Northern wetlands: 31-110 $TgCH_4\ y^{-1}$
- Terrestrial fluxes are uncertain

Ebullition (Bubbling)

- Allow for bubble formation at relatively low saturation
- Bubbles rise to either atmosphere or first unsaturated layer (where it can be oxidized quickly)
- Important competition for oxidation

Subsurface Transport

- Effective diffusivity
  - Depends on water content, temperature, soil properties, and species (Moldrup et al. 2003; Millington-Quirk)
- Equilibrium assumed at WT interface
- Boundary conditions:
  - Surface conductance for top BC
  - Zero gradient for bottom BC
- Lakes
  - CH_4 and O_2 move through water based on thermal eddy diffusion and convection
  - Most atmospheric exchange via ebullition