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/a 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

- Globally integrated, current CLM FSAT over-estimates saturated area by more than a factor of 3
- Spatial heterogeneity and temporal variability poorly represented
Inverted $F_i$
CLM-CH$_4$ Biogeochemistry
Modeling CH$_4$ Biogeochemistry

\[
\frac{\partial (RC)}{\partial t} = \frac{\partial F_D}{\partial z} + P(z, t) - E(z, t) - A(z, t) - O(z, t)
\]

- Relationship applied in global, regional, and site-level models
- In CLM, solved vertically at each time step
- Competition between processes determines net surface flux
CH₄ Production

• Several interacting populations in anaerobic zone
  – Anaerobic fermentation, methanogens
  – Modeled production tied to predicted soil respiration

• Anaerobic CH₄ / CO₂ ratio varies over several orders of magnitude (Segers, 1998)
  – pH, other electron acceptors (NO₃⁻, Mn⁴⁺, Fe³⁺, SO₄²⁻) 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
• Q₁₀ based on literature (values vary widely)
Global Lakes and Wetlands Database GLWD

Lehner & Doll (2004)
CH₄ Oxidation

- Sink of CH₄ and O₂ and source of CO₂
- Methanotroph CH₄ oxidation rate:

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

- Model includes other processes that consume O₂
  - Heterotrophic and autotrophic respiration
  - Autotrophic respiration requires much more O₂ than required by methanotrophs to remove all CH₄
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

$$Flux = D \left( \frac{C(z) - C_a}{\Delta z} \right) pA$$

- Diffusivity
- Concentration Gradient
- Area
- Porosity
Comparison with CH₄ Observations

Abisko, Sweden

Degeroe, Sweden

Minnesota, USA

Ruoergai, China

TF-11 SSA—Fen

BOREAS NSA, Canada

Michigan, USA

Salmisuo, Finland

Alaska, USA
Comparison with CH$_4$ Observations
• Net CH$_4$ Fluxes:
  – Global: 165 Tg CH$_4$ y$^{-1}$
  – >45N: 32 Tg CH$_4$ y$^{-1}$
Sensitivity

• $K_m(\text{CH}_4), K_m(\text{O}_2)$, 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 $\sim$400 (glacial) to 700 (interglacial) ppb
- Concentrations and emissions are increasing
Atmospheric CH$_4$ Budget

• Many inversion and bottom-up budgets have been developed

• Overall, $\sim$500-600 TgCH$_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