CLM4Me, a Methane Biogeochemistry Model Integrated in CESM

W. J. Riley
(Lawrence Berkeley National Laboratory)

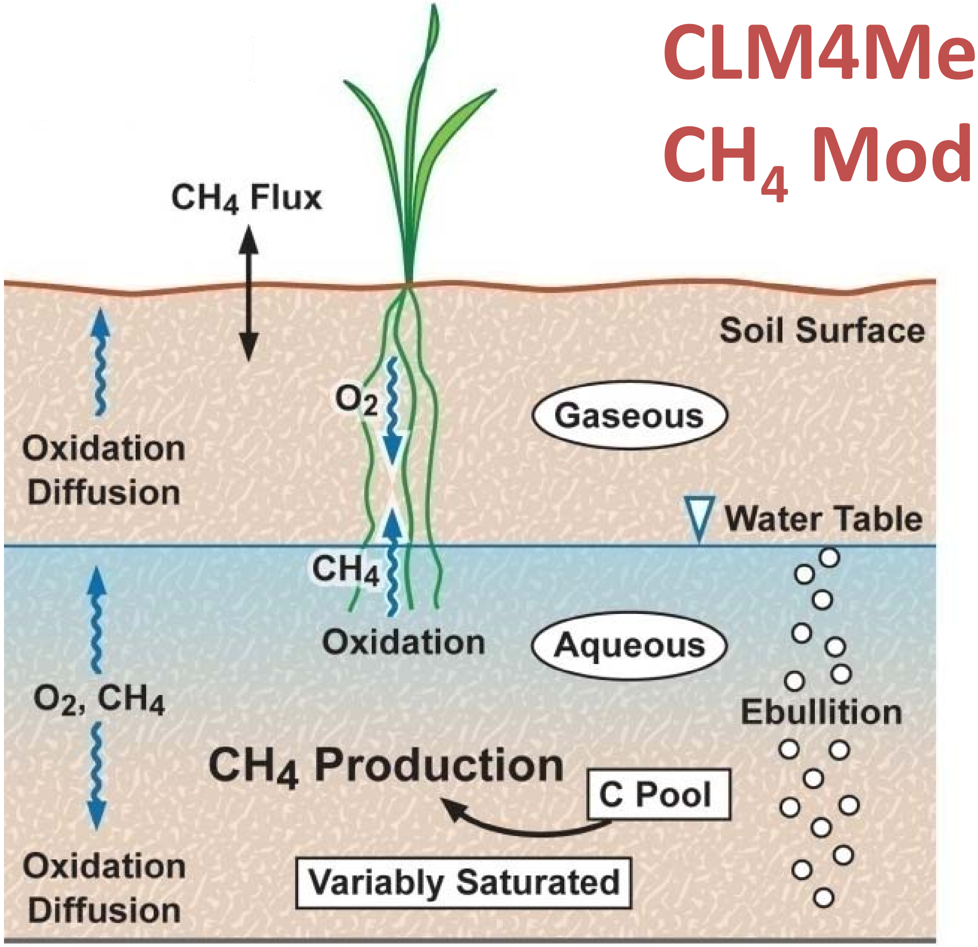
Z. M. Subin, D. M. Lawrence, S. C. Swenson, M. S. Torn,
L. Meng, N. M. Mahowald, and P. Hess


CLM4Me
COLORADO

Subtitle: Barriers to Predicting Changes in Global Terrestrial CH_4 Fluxes

- Goals
  - Develop a ‘mechanistic’ representation of the coupled microbial, vegetation, reaction, and transport processes affecting CH_4 exchanges
  - Use CLM4Me to
    - Predict large-scale net CH_4 exchanges with the atmosphere
    - Characterize uncertainty and sensitivity
    - Inform future measurements and modeling efforts
    - Estimate climate sensitivity of CH_4 emissions
    - Perform atmospheric simulations

CLM4Me - CH$_4$ Model



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

CH_4 Production

- Several interacting populations in anaerobic zone
  - Anaerobic fermentation, methanogens
  - Modeled production tied to predicted respiration
  - Proposed model improvements
- Measured 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
- Depth dependence, seasonal inundation
- Q_{10} based on literature (values vary widely)

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

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

Aerenchyma

- Inundated plants must supply O_2 to their roots and remove toxics
- Aerenchyma: conduits for gases to diffuse and advect
- O_2 in aerenchyma
  - Consumption by cells within the root tissue
  - Diffusion toward the root tips
  - Diffusion radially to the rhizosphere
- Methanotrophs may exist inside the root tissue
- Radial diffusion to the rhizosphere can supply other O_2 consumers (e.g., methanotrophs, heterotrophs)

Aerenchyma

- Modeled as gaseous diffusion between the soil layer and atmosphere
  - Pressure driven flow not yet included

Area

$$A = \frac{C(z) - C_a}{{r_L z}/{D} + r_a} \, p T \rho_r$$

Area

Rooting density

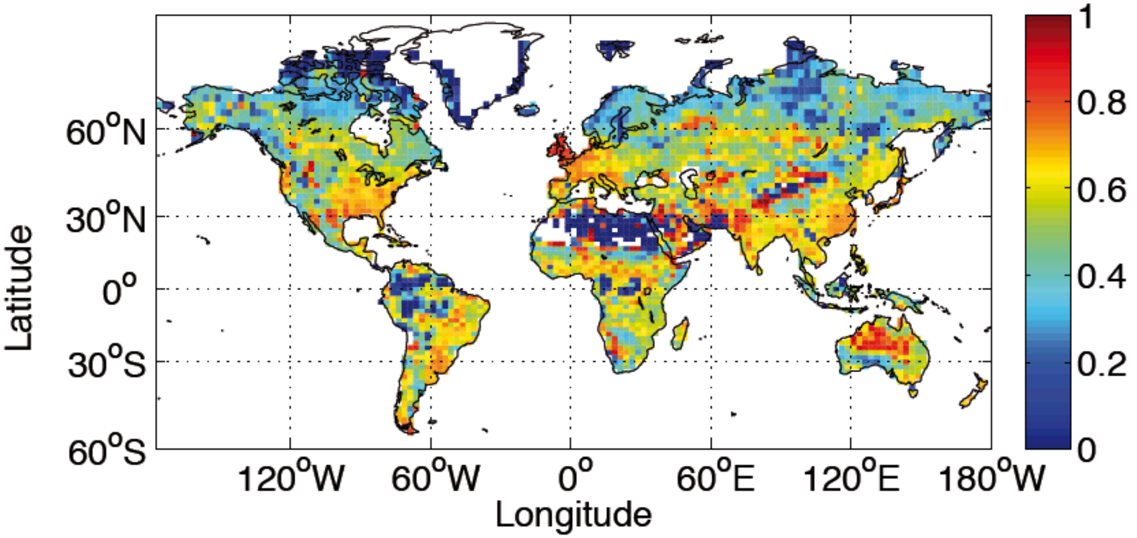
Porosity

- Porosity varies widely:
  - Across species
  - Between genotypes within a species
  - Between root types (e.g., seminal versus adventitious)
  - Along roots
- Aerenchyma area varies over the growing season as a function of NPP and LAI (Wania et al. 2010)

Aerenchyma Oxidation

- Globally, predicted annual aerenchyma oxidized fraction was ~0.6
- Spatially and temporally heterogeneous
  - E.g., north of 45°N, fraction of produced CH_4 oxidized before it reached the surface was 0.35 -0.75
  - Minimum in May and maximum in October.

Predicted Aerenchyma Oxidation Fraction

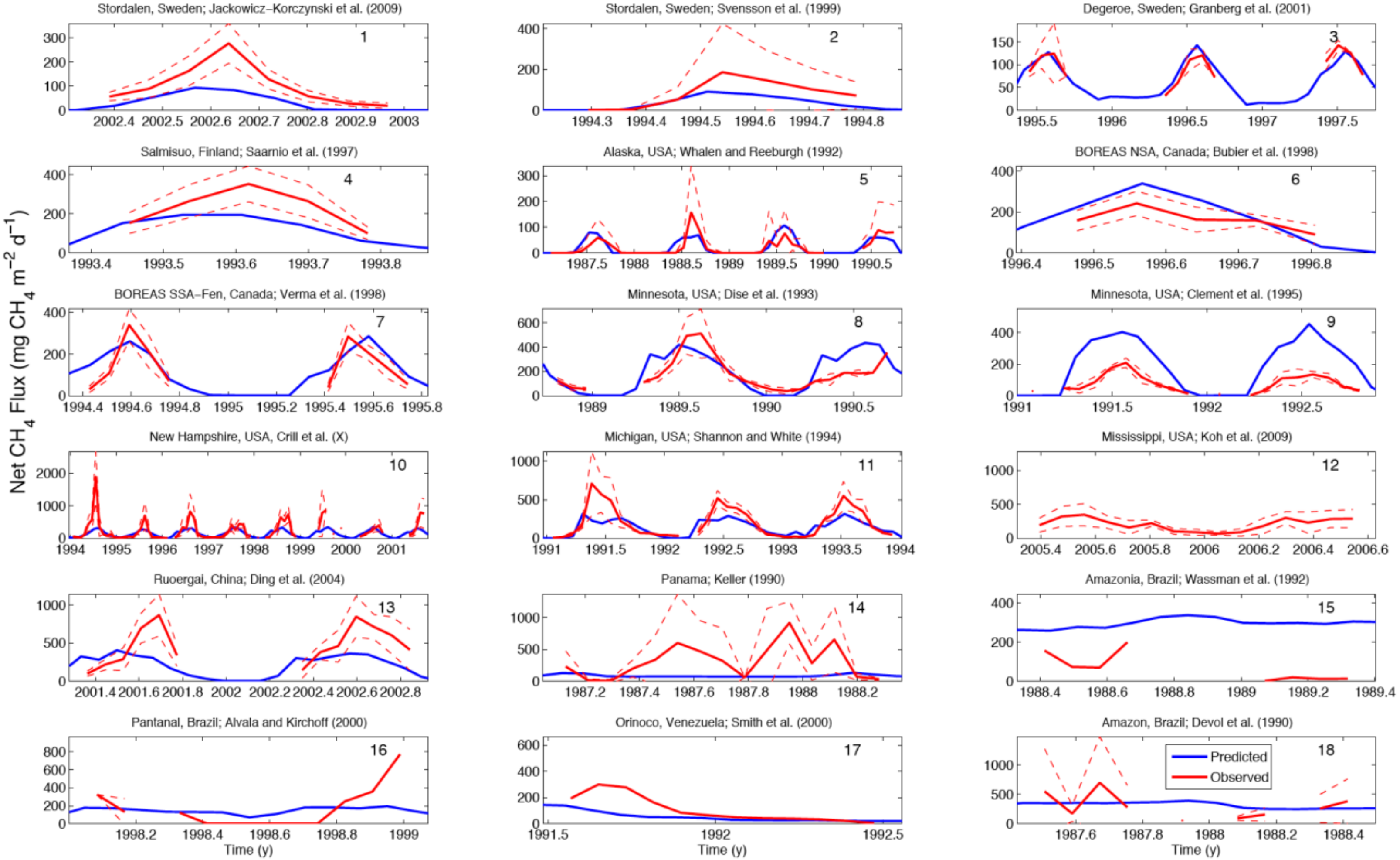


Solution Method

- 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
- Competition for O_2 by heterotrophs, autotrophic respiration, and methanotrophs
- Crank-Nicholson for transport solution
  - Sources and sinks are explicit

Comparison to Site Observations

- Insufficient observations to develop and test models

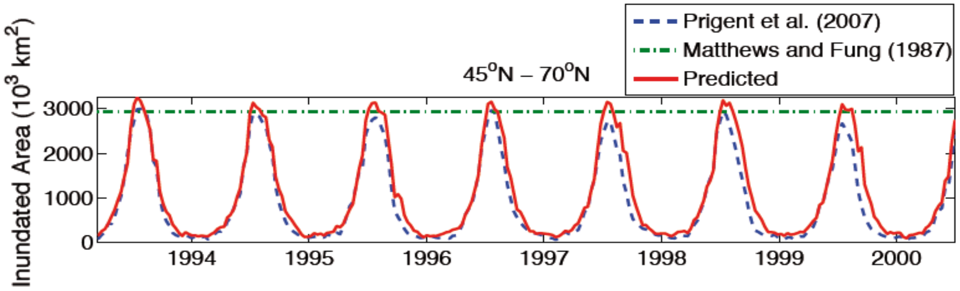


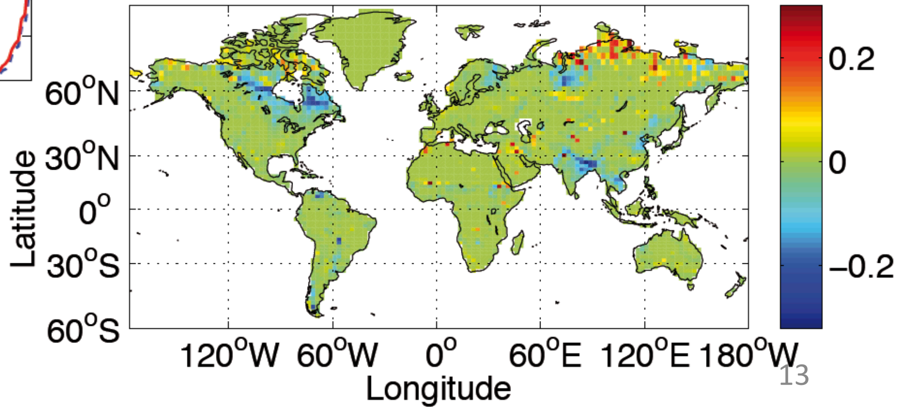
Inundated Area

- Fit to satellite data (Prigent et al. 2007)

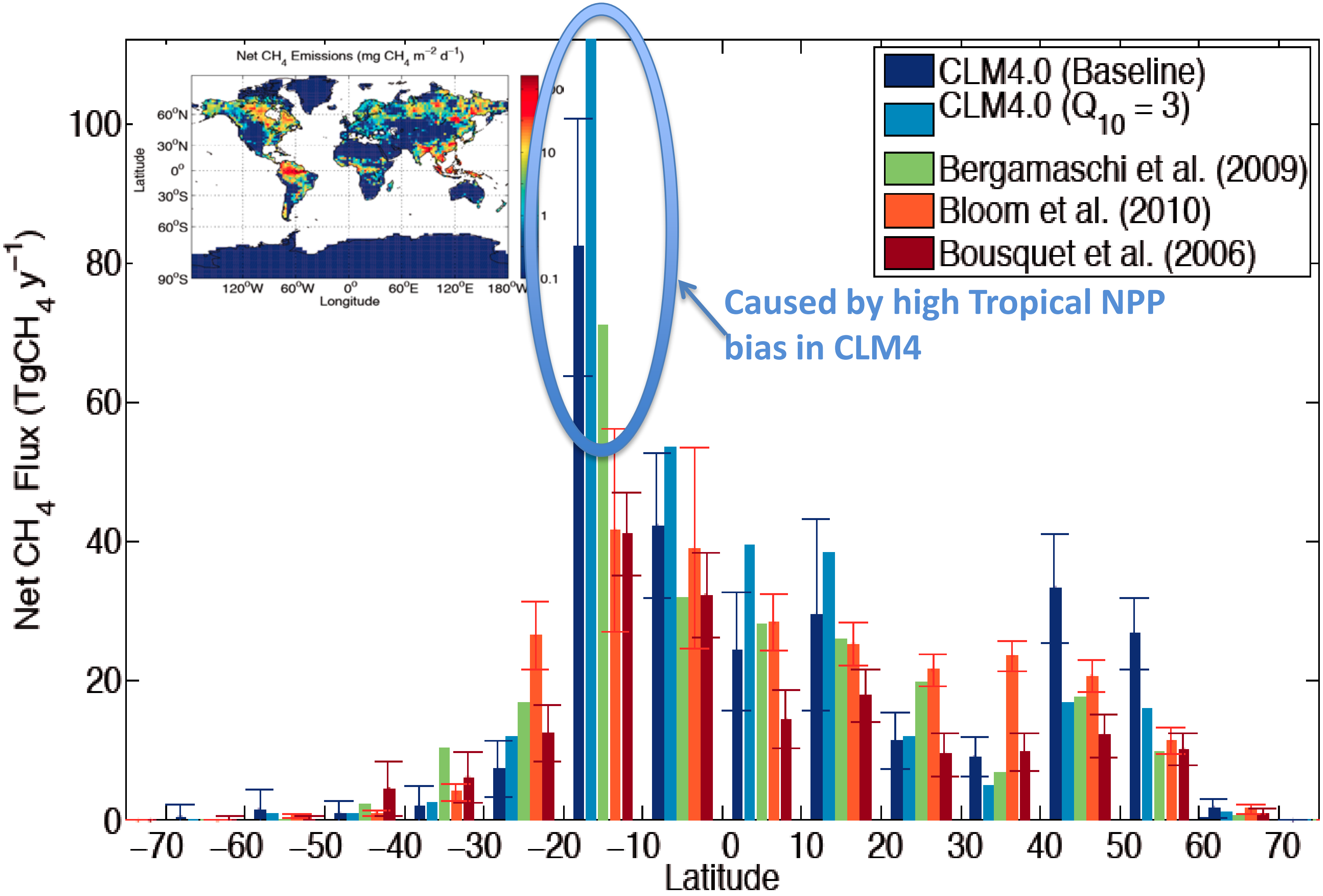
$$f_s = P_1 e^{-z_w/p_2} + p_3 Q_r$$

- Large source of uncertainty
- Satellite inundated area may not accurately represent the area responsible for CH_4 emissions



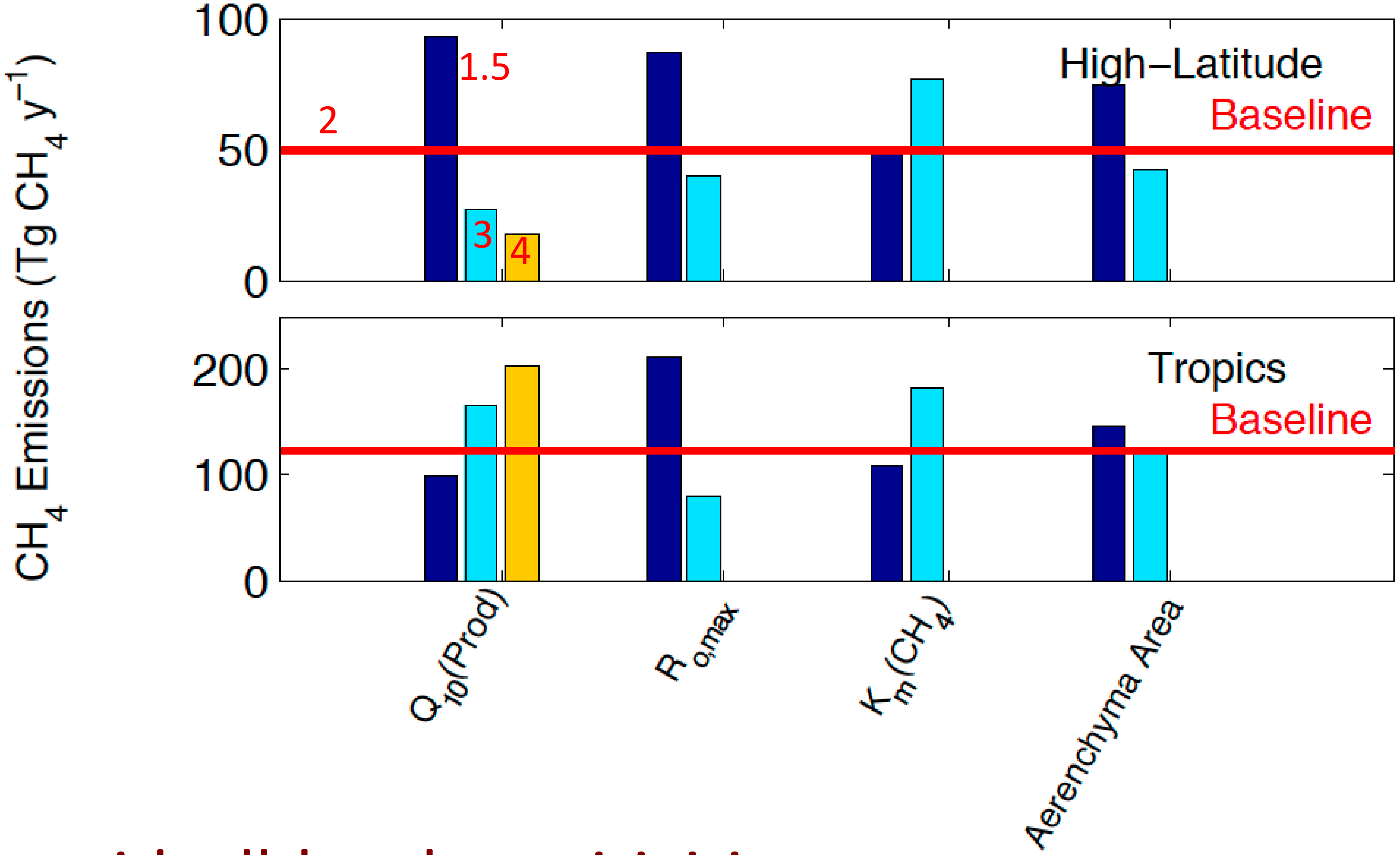


Comparison to Atmospheric Inversions



Caused by high Tropical NPP bias in CLM4

CH_4 Emission Sensitivity



- gridcell-level sensitivities are often an order of magnitude

End-of-Century Predictions

- Used CLM4Me to evaluate CH_4 emissions over 21st century
- Predicted a 20% increase in high-latitude, temperate, and tropical emissions
  - Compare to previous estimates of ~100% increase for high-latitude systems
- Predicted overall loss of inundated area in continuous permafrost and some increase in discontinuous regions
  - Emissions increase in the area surrounding Hudson's bay and northern Europe
  - Emissions decrease in much of Alaska and areas of continuous permafrost

Conclusion (1)

- Sensitivity analysis shows large uncertainty in CH_4 emissions
  - Temperature sensitivities; differences between production and oxidation
  - Vegetation properties (e.g., aerenchyma)
  - Landscape scale representations
- Many important processes for high-latitude CH_4 emissions require improvement

Planned Future Work

- Improvements planned
  - Vertically-resolved SOM pools and dynamics
  - Peatlands (soil and vegetation)
  - Thermokarst and 3-D hydrology
  - Fractional inundation
  - N cycle and interactions with C
- Improvements needed
  - Type of inundated system (marsh, bog, estuary, …)
  - Aqueous chemistry (pH, redox)

Conclusion (2)

Two Classes of Studies Could Benefit CH_4 Models:

1. Those to better constrain model structure and parameterization shown on previous slide
2. Those to improve the spatial representation of relevant surface properties

- Experiments should be designed with model structures in mind, **and inform mechanisms represented in the models**