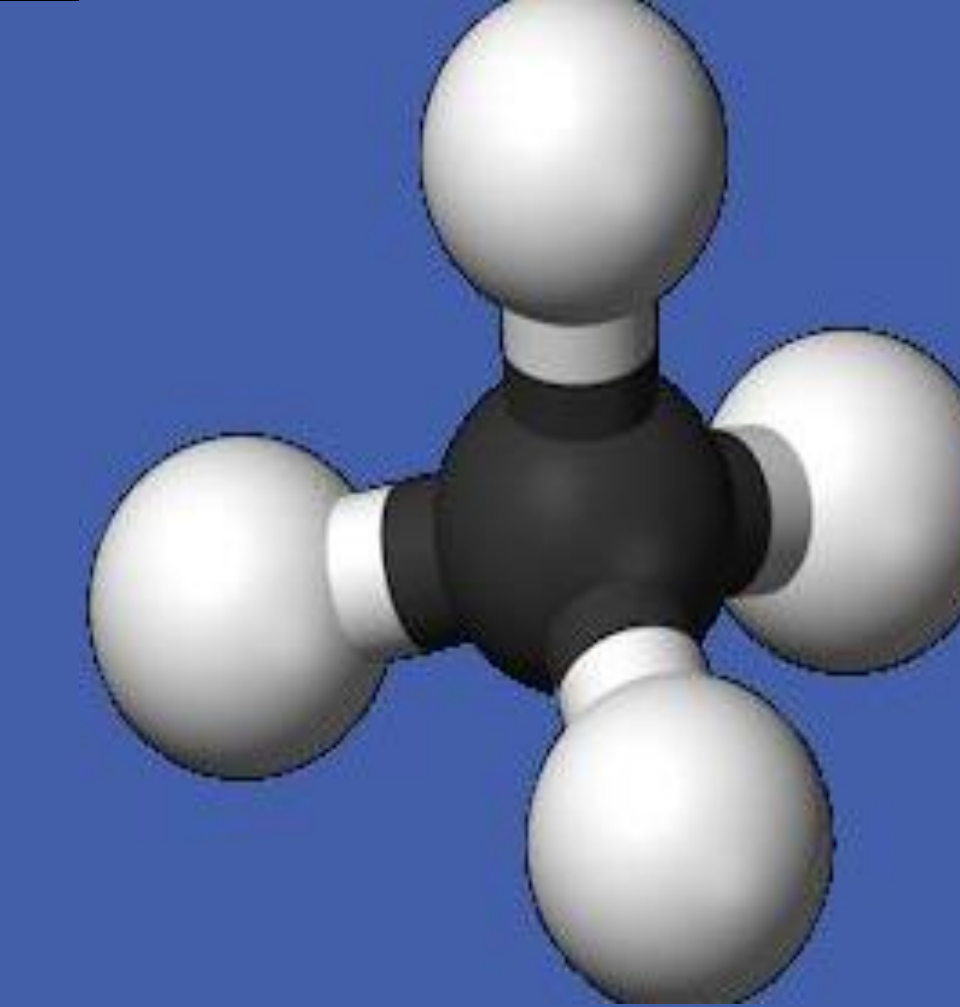# B21D-0405: Modeling CH_4 emissions from Arctic tundra:
Processes behind emissions pulses and the potential for a negative feedback

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Project Summary

Existing climate change models contain very limited considerations of greenhouse gas emissions from thawing Arctic permafrost, especially the release of methane (CH_4), a greenhouse gas 20 times more potent than CO_2 on a 100 year time scale.

The Methane Dynamics Module (MDM) by Zhuang et al. (2004) is frequently cited as evidence of a strong positive feedback between the carbon cycle of Arctic permafrost and the climate system, including in the IPCC's 2007 Report. However, the model has never been explicitly examined for effectiveness at non-Alaskan sites.

Preliminary simulations for non-Alaskan sites were performed by importing environmental variables from the ED2 model. Simulations of the MDM were run for three different sites: Happy Valley, Alaska; Axel Heiberg Island, Canada; and Zackenberg, Greenland. Results of simulated CH_4 emissions rates were then compared with on-site observations of CH_4 emissions.

Results from the preliminary simulations show that CH_4 emissions occur primarily through quick emissions pulses at the onset of surface soil freezing and thawing. Simulations indicate that these emissions pulses are due to the inhibition of CH_4 diffusion by surface soil that is saturated or frozen.

Investigations into the effectiveness of the MDM suggest that the maximum methanogenesis and methanotrophy rates are under-constrained and that the current structure of the MDM may be unable to accurately project future CH_4 emissions. Eliminating some of the modifiers and using new data to redefine maximum rates as more constrained can improve the ability of the MDM to predict current CH_4 emissions from Axel Heiberg.

Further work has focused on integrating an altered version of the MDM into the ED2 model. Most modifier functions for CH_4 production and oxidation have been replaced with functions derived from data collected from Axel Heiberg. Additionally, CH_4 in each soil layer has been divided into an air pool and water pool, with interactions between the two pools according to Henry's Law. The rates of diffusion between different layers are influenced by the relative amount of soil water in the layer, leading to a more graduate transition between saturated and unsaturated layers instead of an instant transition at a particular threshold.

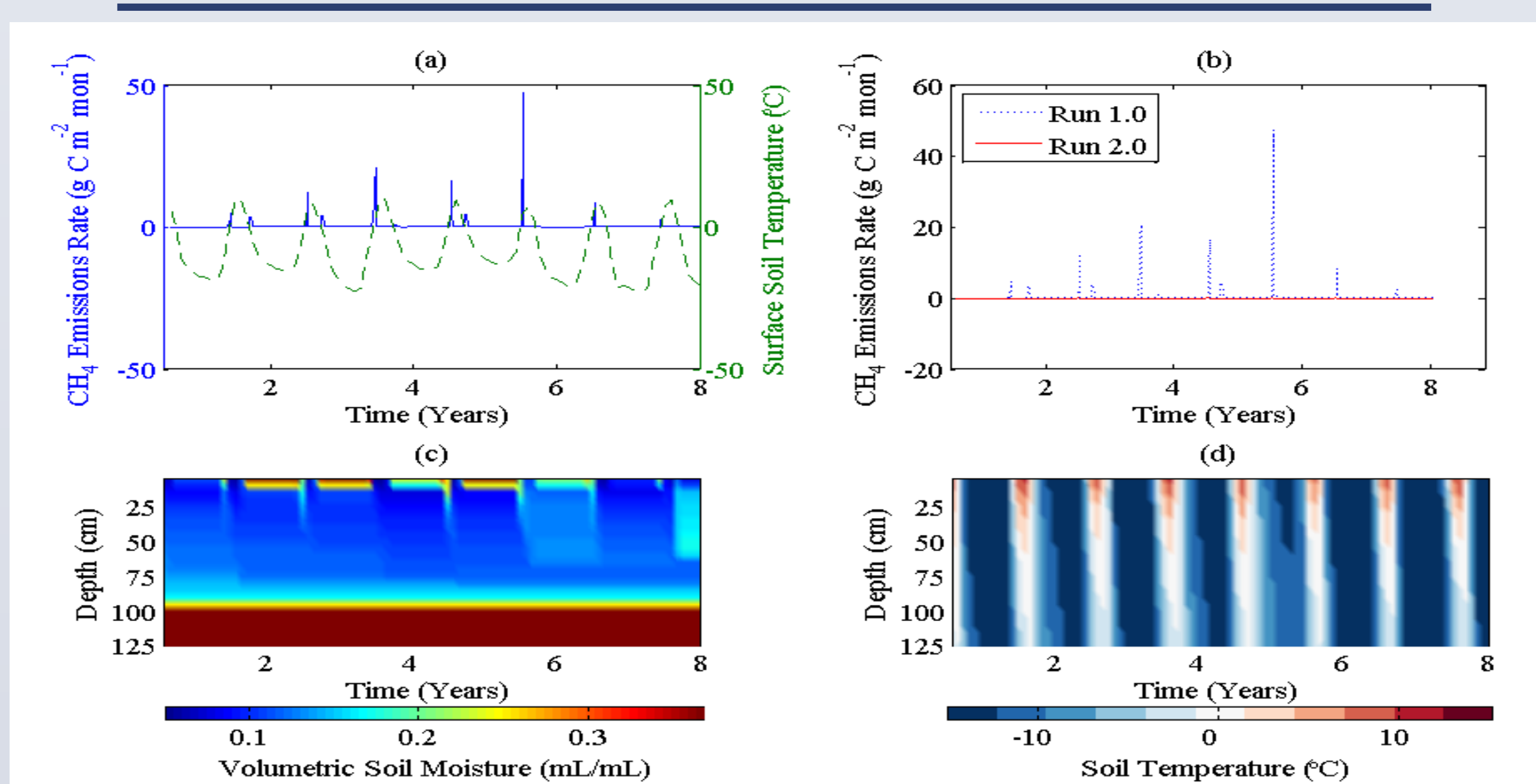## Results With Previous Versions of MDM

Figure 1: Emissions Pulses
(a) Comparison of CH_4 emissions rates and soil temperature for the surface soil layer at Axel Heiberg over simulation period with unaltered MDM. (b) Comparison of CH_4 emissions rates for runs where diffusion is inhibited by water or ice (Run 1.0) and where it is not (Run 2.0). (c) Soil moisture profile for Axel Heiberg over simulation period. (d) Soil temperature profile for Axel Heiberg.
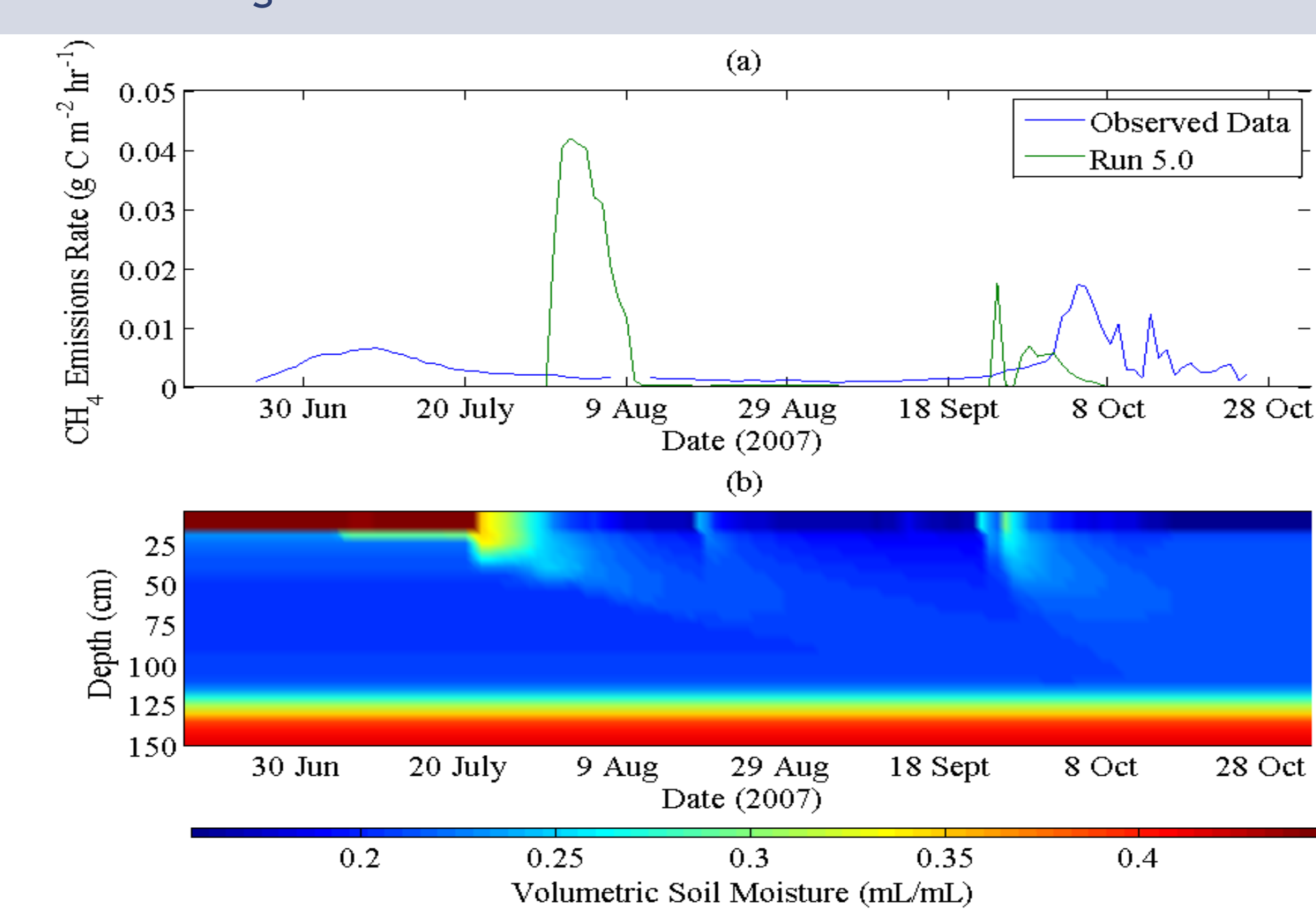

Figure 2: Zackenberg Emissions Pulses
(a) Comparison of observed and simulated CH_4 emissions rates for Zackenberg, Greenland using modified MDM.
(b) Simulated soil moisture profile for observation period.

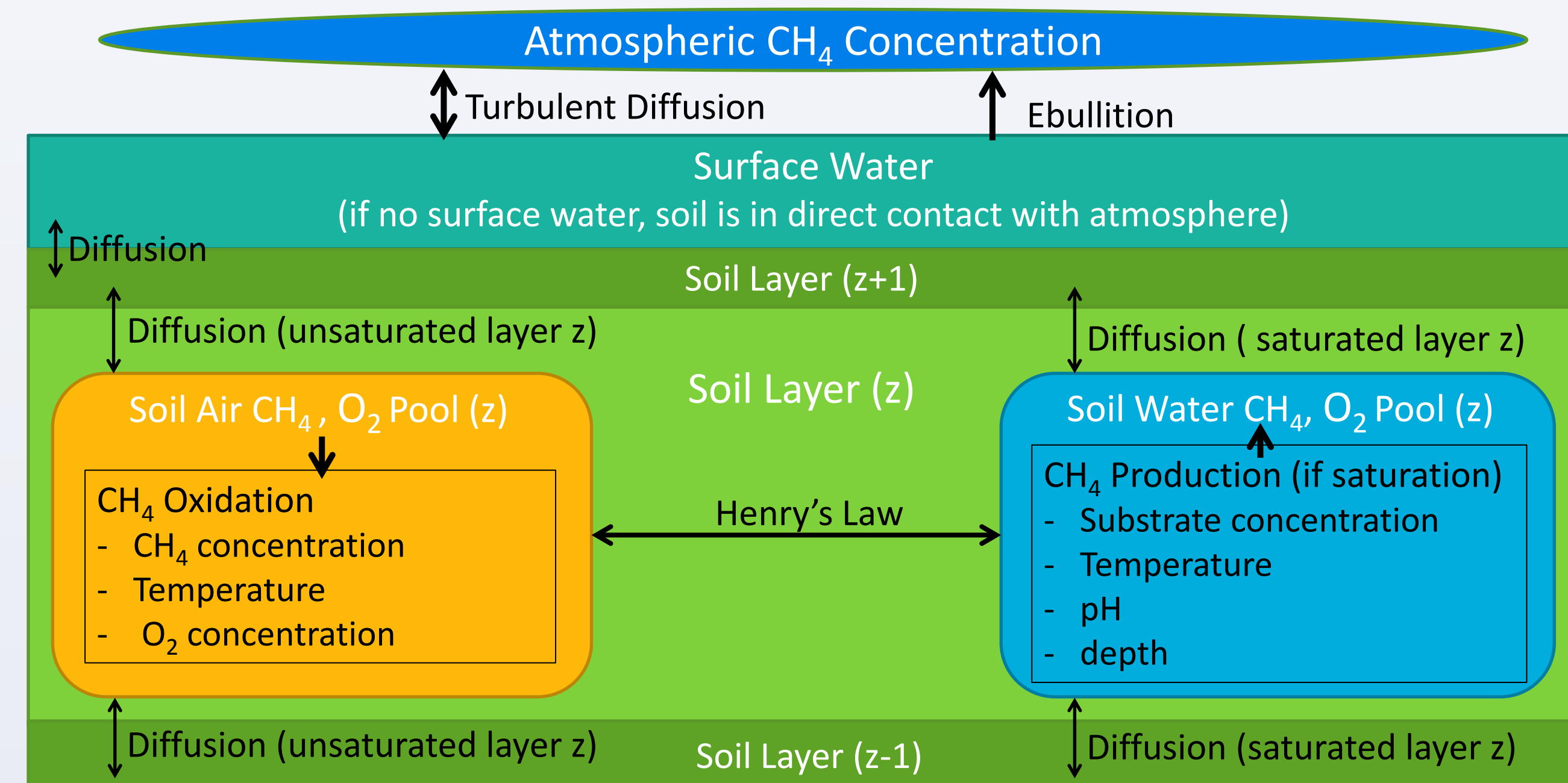## Modified Model Structure Overview

Figure 3: Structure of modified MDM The percent of water filled pore space determines where the air or water pool interacts with the surrounding layers. In the case of adjacent saturated and unsaturated layers, diffusion rates are determined by the difference between actual and equilibrium concentrations and the diffusion coefficient for the saturated layer. For adjacent unsaturated layers, increases in relative soil water decrease the diffusion coefficient.

Figure 4: Updated Methanogenesis and Methanotrophy Modifier Functions
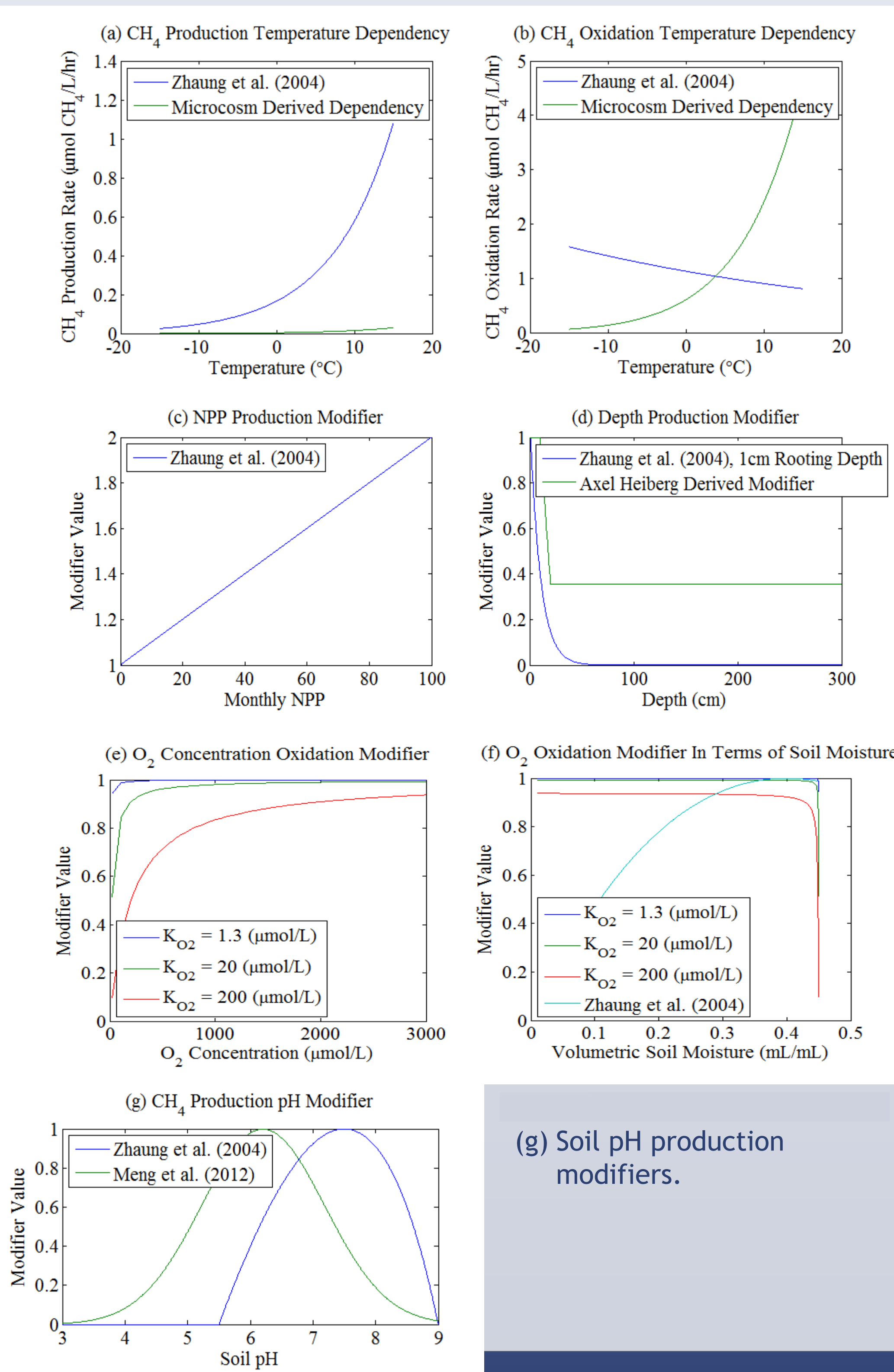
(a) Maximum CH_4 production rate for tundra multiplied by a temperature production modifier.
(b) Maximum CH_4 oxidation rate for tundra multiplied by a temperature production modifier.
(c) NPP modifier used in Zhuang et al., 2004.
(d) Depth production modifier for tundra soil without rooted plants.
(e) Methane oxidation O_2 concentration modifiers.
(f) Soil Moisture oxidation modifiers. The new modifiers are the same modifiers as in (e), but in terms of soil moisture and assuming a total O_2 concentration of 3000 $\mu mol/L$ and STP. Because of Henry's Law the oxygen concentrations in the air pool will vary with soil moisture.
(g) Soil pH production modifiers.
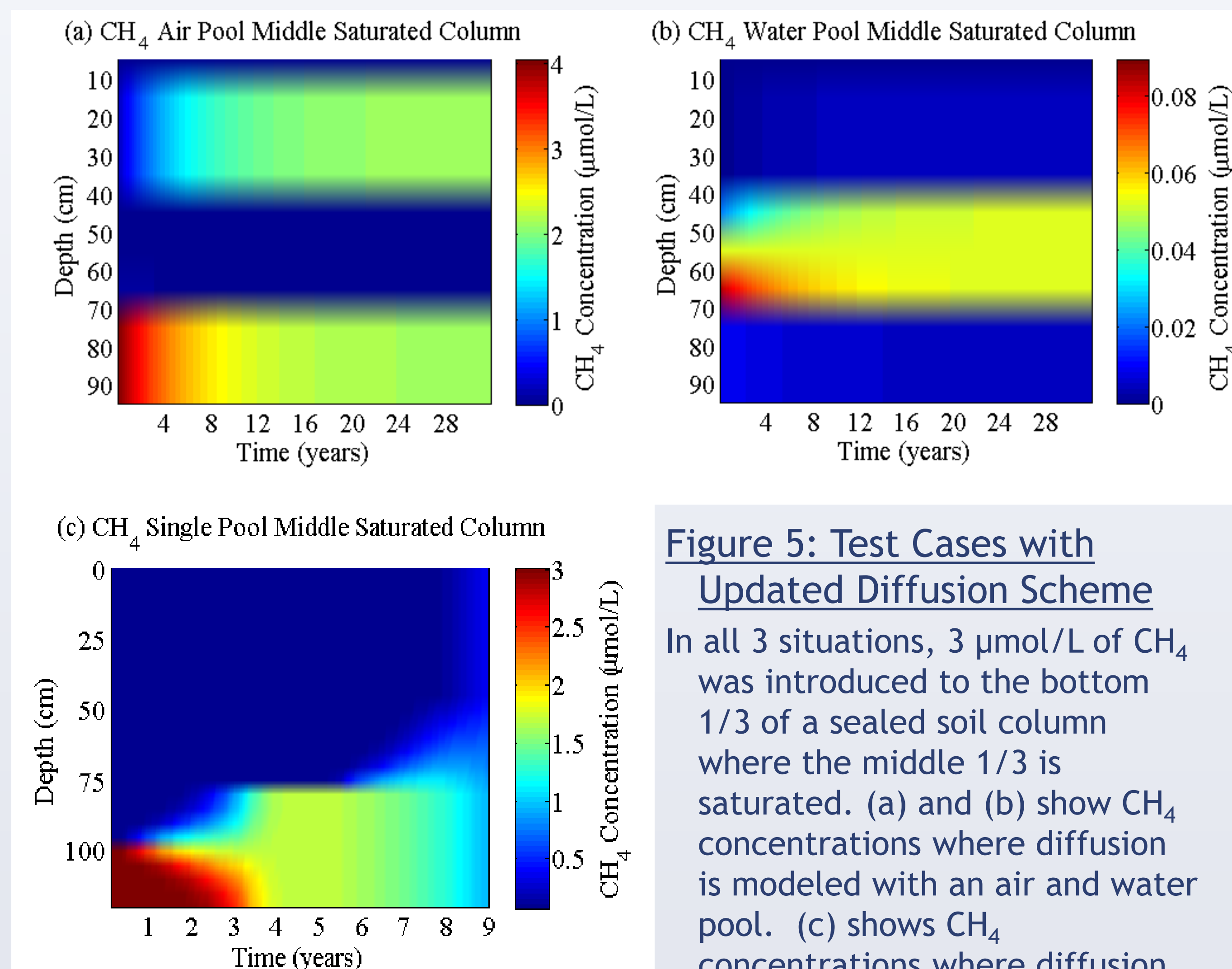
Test Case Results

Figure 5: Test Cases with Updated Diffusion Scheme
In all 3 situations, 3 $\mu mol/L$ of CH_4 was introduced to the bottom 1/3 of a sealed soil column where the middle 1/3 is saturated. (a) and (b) show CH_4 concentrations where diffusion is modeled with an air and water pool. (c) shows CH_4 concentrations where diffusion is modeled using a single soil pool as in Zhuang et al., 2004.

Conclusions

- Results suggest that CH_4 emissions from Arctic tundra occur mostly through a process of rapid CH_4 emissions pulses that occur at the onset of thawing and freezing of the surface soil.

- These CH_4 pulses are proposed to be the result of the inhibition of diffusion caused by the presence of water or ice in the surface soil, as removing this constraint on diffusion causes the CH_4 emissions pulses to disappear.

- Redefining the maximum methanogenesis and methanotrophy rates using a microcosm-derived temperature dependency from Axel Heiberg along with additional updated modifiers can improve the realism and predictability of the MDM.

- Modeling diffusion with a soil air and soil water pool can lead to different behavior than those seen in single CH_4 pool models.

- Accuracy of any new parameterization of the MDM would be greatly helped by the use of actual data documenting time series of CH_4 emissions rates.

- Overall, a warming climate may lead to CH_4 consumption by Arctic tundra soils, as a result of longer summers that extend the period of time in which CH_4 diffusion would be uninhibited and CH_4 could be oxidized more quickly than it is produced.

Future Work

Future work will continue to focus on integrating the new MDM into the ED2 model. The overall goal is to successfully simulate observed CH_4 emissions rates and project the response of CH_4 emissions to global climate change.

References

Lau, C.Y., and Stackhouse, B.T., 2012, Refined microcosm data for modeling from Axel Heiberg Soil and Axel Heiberg soil carbon profile.

Mastepanov et al., 2008, Large tundra methane burst during onset of freezing: Nature, v. 456, p. 628-630.

Meng, et al., 2012, Sensitivity of wetland methane emissions to model assumptions: application and model testing against site observations: Biogeosciences, v9, p. 2793-2819, doi:10.5194/bg-9-2793-2012.

Mykytczuk et al., 2011, GC26:Gas Flux Dynamics in high Arctic Permafrost Polygon and Ice-wedge Active Layer Soil; Microbial Feedback Implications.

Medvigy et al., 2009, Mechanistic scaling of ecosystem function and dynamics in space and time: Ecosystem Demography model version 2: J.Geophys.Res., v. 114, p. G01002, doi: 10.1029/2008JG000812.

Zhuang et al., 2004, Methane fluxes between terrestrial ecosystems and the atmosphere at northern high latitudes during the past century: A retrospective analysis with a process-based biogeochemistry model: Global Biogeochemical Cycles, v. 18, p. GB3010, doi: 10.1029/2004GB002239.