Basin-Scale Assessment of Gas Hydrate Dissociation in Response to Climate Change

Understanding Subsurface, Ocean, and Atmospheric Processes to Assess the Consequences

Matthew T. Reagan, George J. Moridis,
Lawrence Berkeley National Laboratory

Scott Elliott, Mathew Maltrud,
Los Alamos National Laboratory

Philip J. Cameron-Smith
Lawrence Livermore National Laboratory

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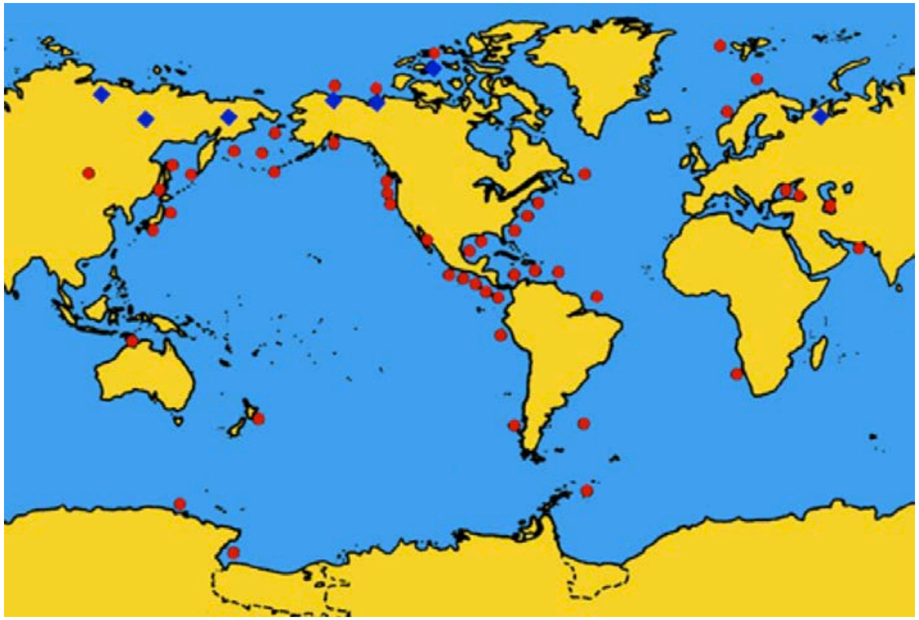
Introduction and Purpose

The goals of our research are:

1. To investigate the effect of rising water temperatures on the stability of oceanic hydrate accumulations and to determine the conditions under which methane release may occur
2. To identify geochemical effects within the water column that control the fate of hydrate-derived methane
3. To estimate the global quantity of hydrate-originating carbon that could reach the atmosphere
4. To examine, quantitatively, the possibility of hydrate-related climate feedbacks

Global Organic Carbon Distribution & Gas Hydrates

- Enormous amount of organic matter trapped in arctic systems
- Hydrates store huge amounts of methane
- Huge deposits in permafrost and in the oceans (oceans >> permafrost)
- Hydrate carbon significant on a global scale, and over long times (Archer, 2007; 2009)
- Recent studies suggest 3000 – 5000 Gt (Archer, 2009; Wallman, 2011)
- Much hydrate is deep and low-saturation
- Continental margins are the key



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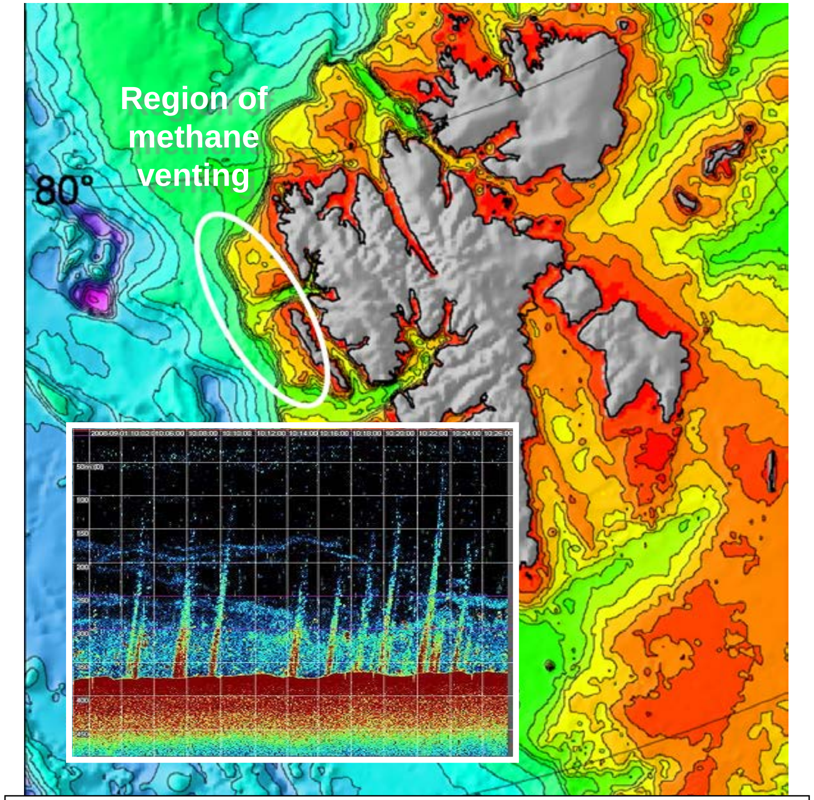
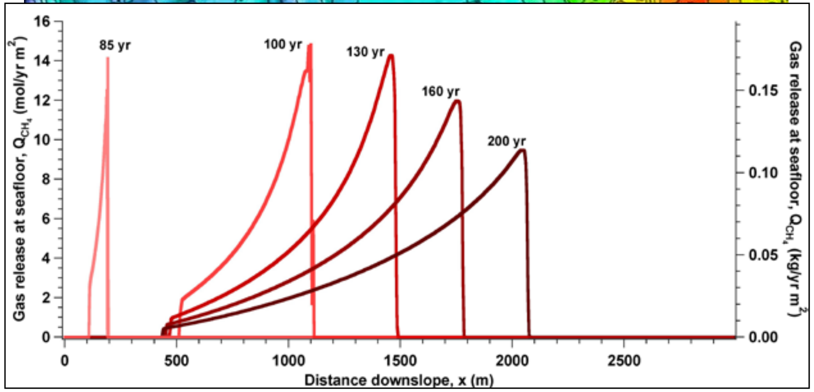
- Much hydrate is deep and low-saturation
- Continental margins are the key
- The arctic is warming
- Methane plumes are appearing near the edge of the GHSZ in regions undergoing measured ocean warming (Westbrook et al., 2009)
- Simulations of shallow hydrates subjected to warming show plumes forming at the landward GHSZ limit[1]

from NOAA/IBCAO (http://www.ngdc.noaa.gov/)





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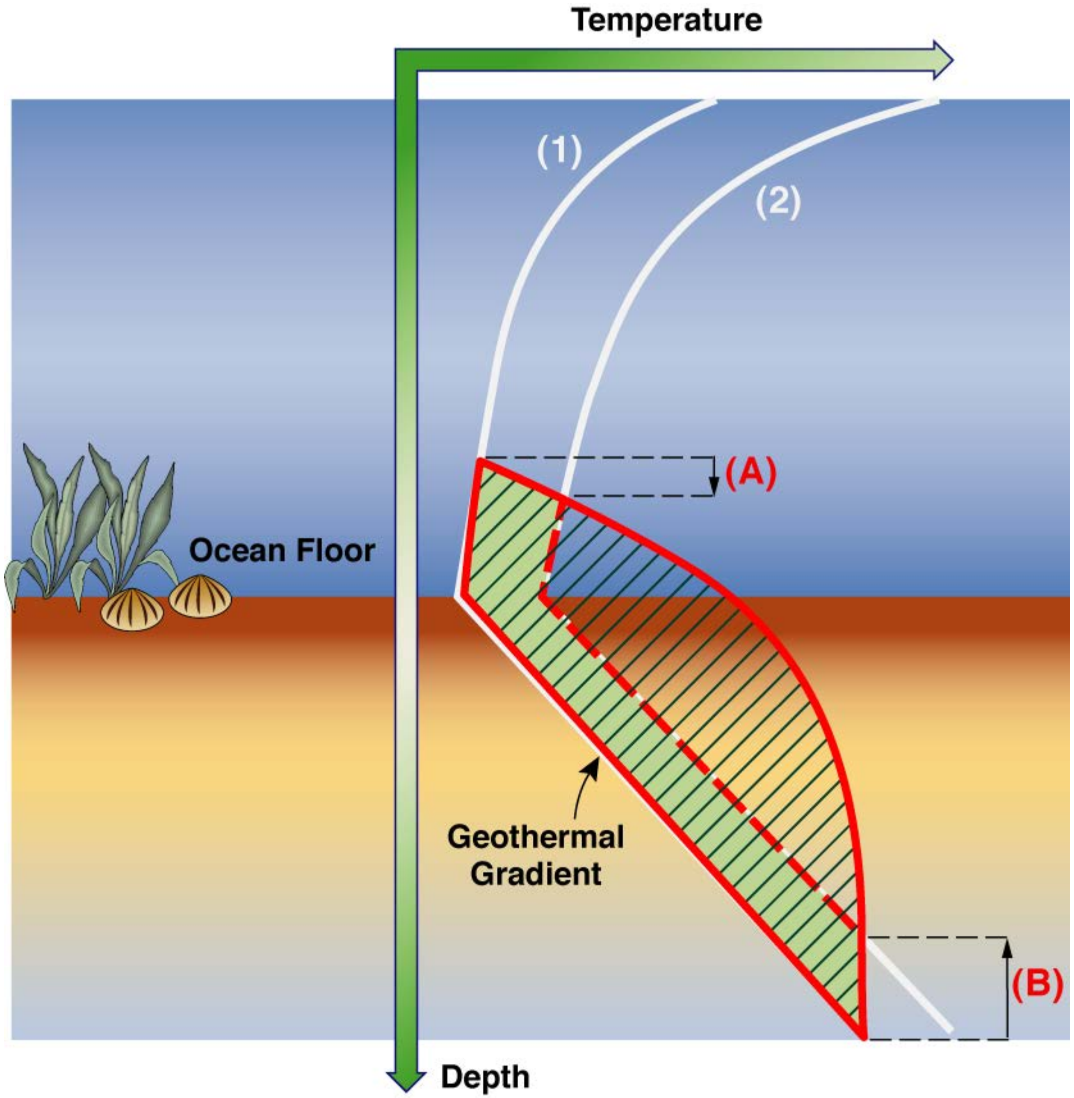
[1] Reagan, M.T. and Moridis, G.J., "Large-Scale Simulation of Oceanic Gas Hydrate Dissociation in Response to Climate Change," *Geophysical Research Letters*, **36**, L23612, 2009.

Oceanic Gas Hydrates: Dissociation

Climate change alters ocean temperature (and geothermal gradient)

Decreases hydrate stability region

Methane release to ocean by hydrate dissociation



Oceanic Gas Hydrates: Dissociation

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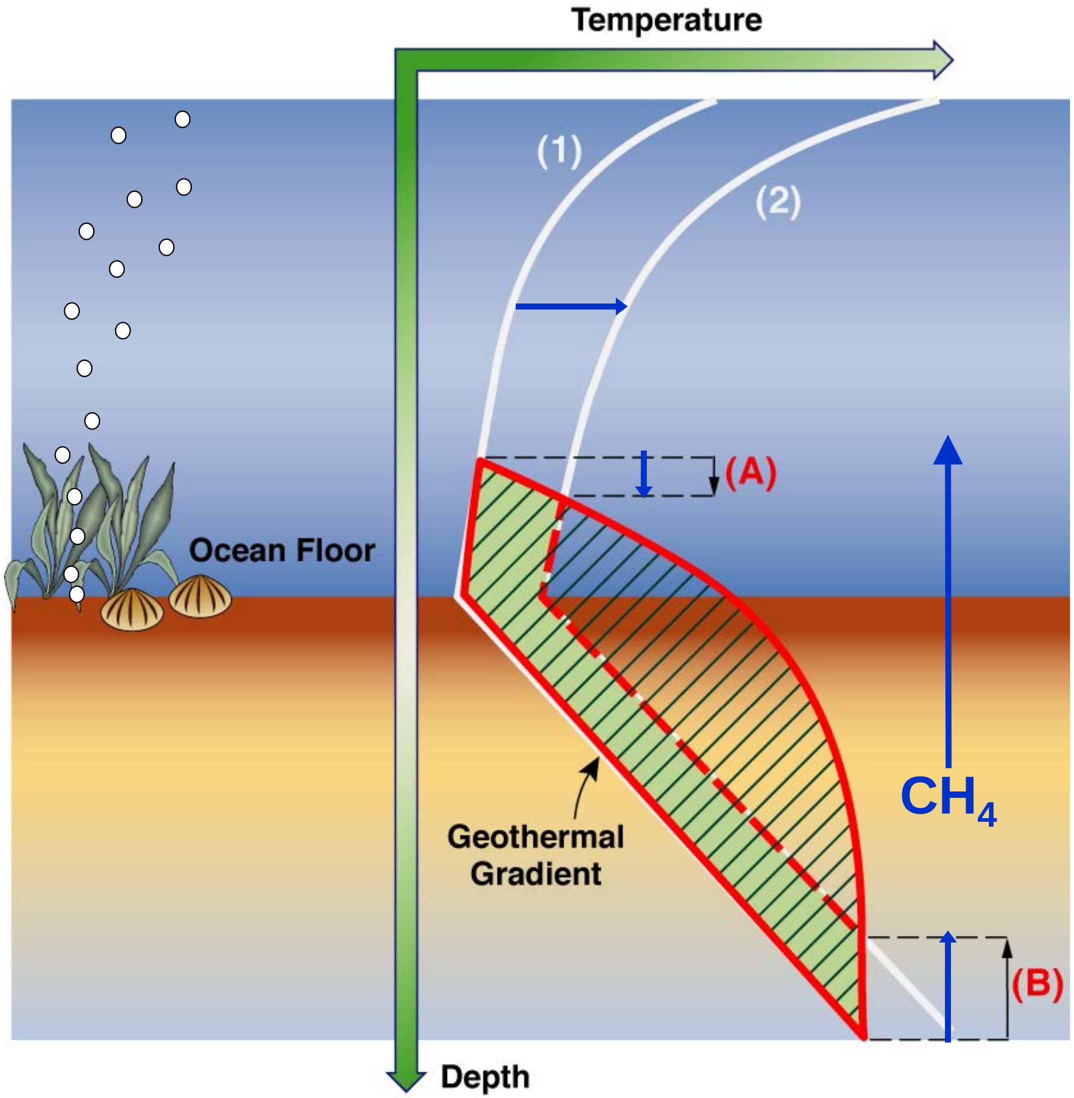
What is the fate of the methane?



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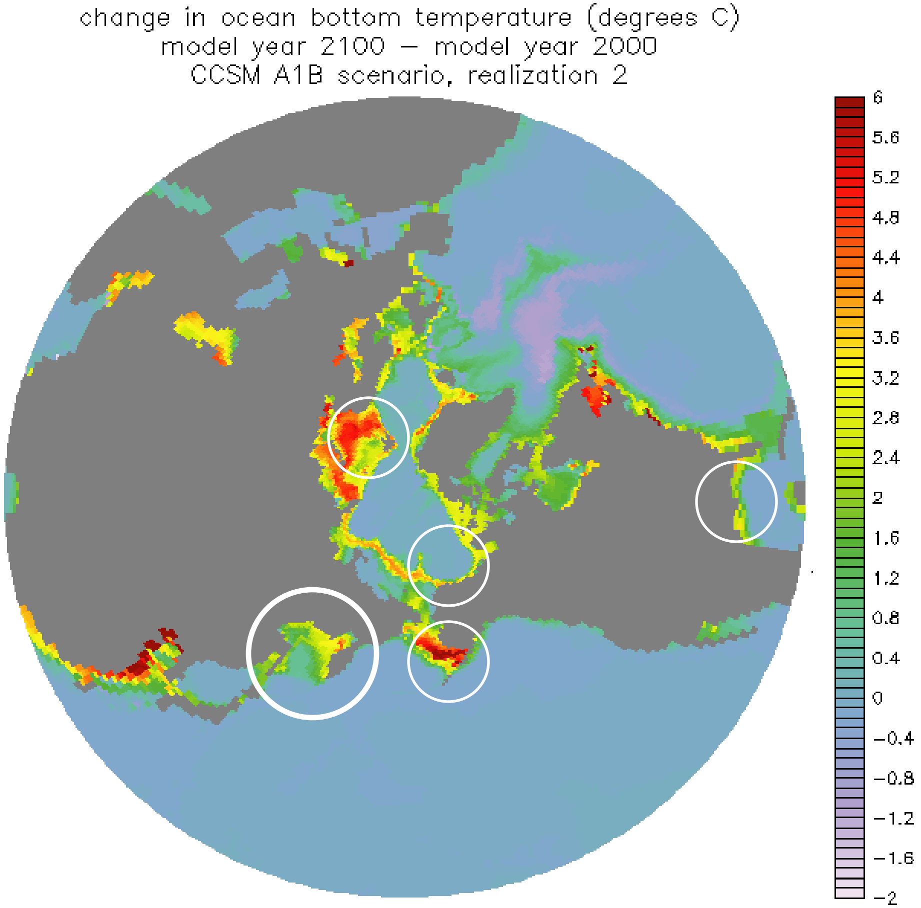
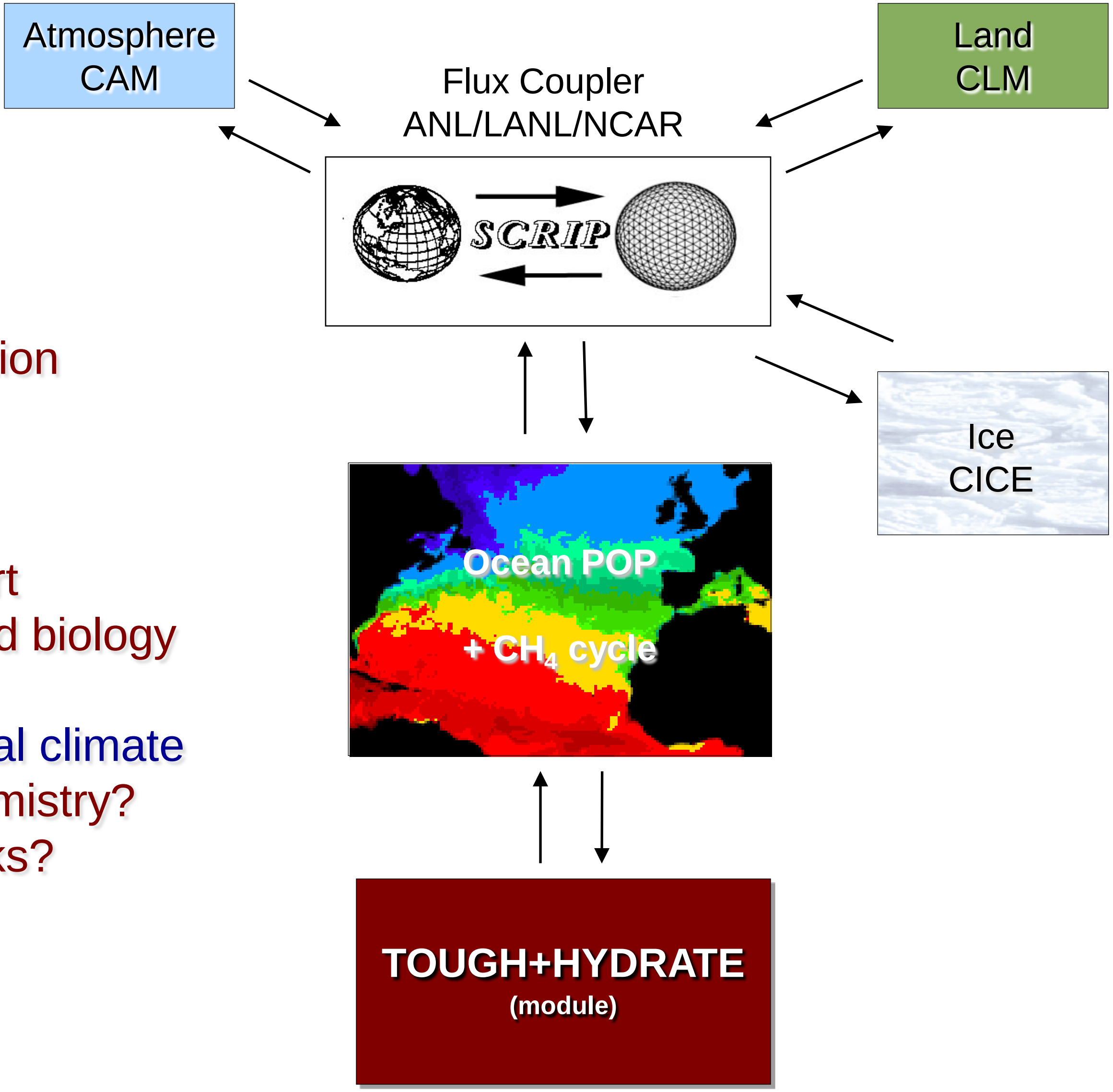


Outline

1) Sub-seafloor
    - Hydrate dissociation
    - Fluid transport
2) Ocean water column
    - Methane transport
    - Geochemistry and biology
3) Atmosphere and global climate
    - Atmospheric chemistry?
    - Positive feedbacks?



Atmosphere
CAM

Flux Coupler
ANL/LANL/NCAR

Land
CLM

Ice
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Ocean POP
+ CH_4 cycle

TOUGH+HYDRATE
(module)

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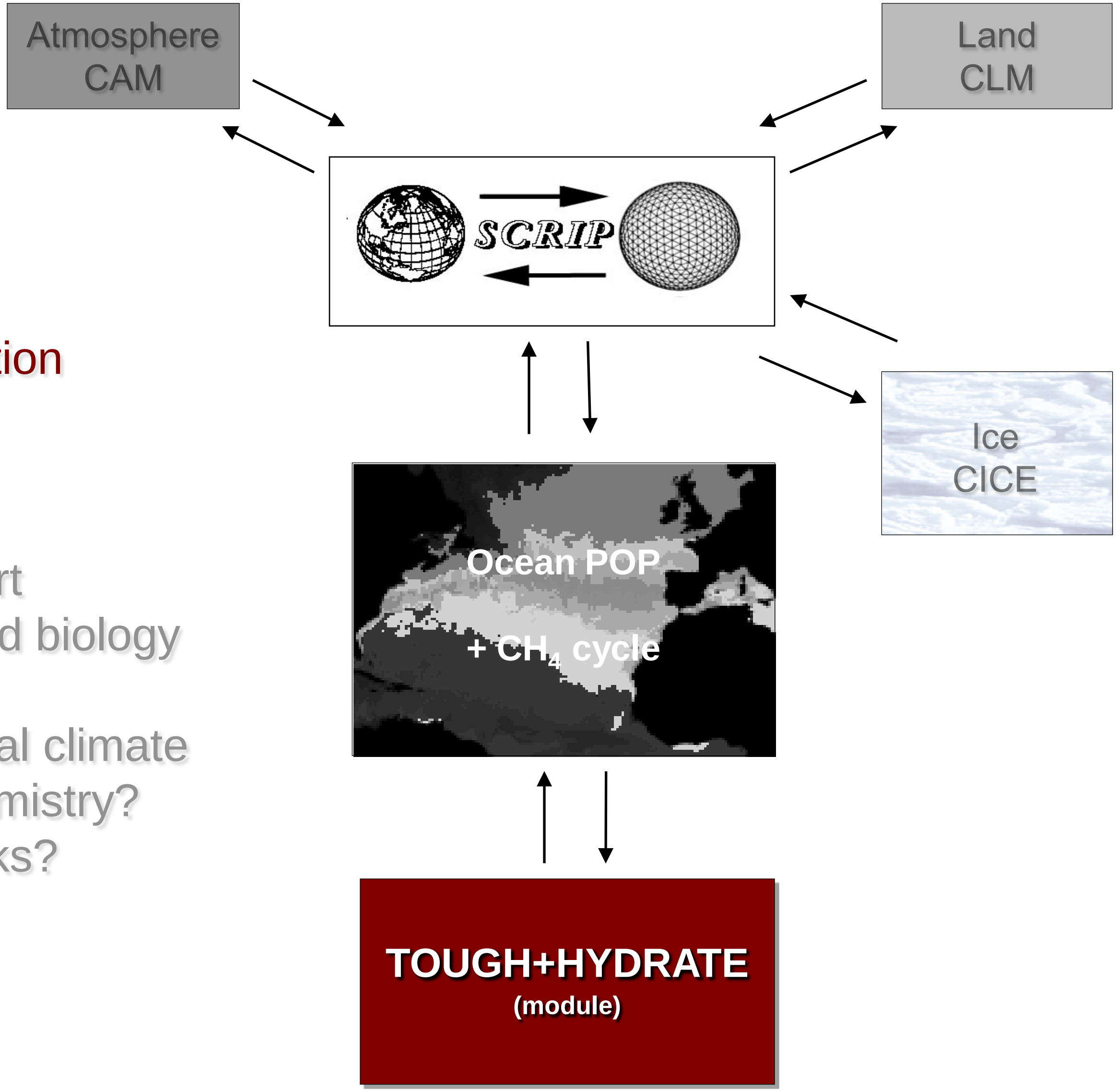

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The Numerical Model

TOUGH+HYDRATE code (Moridis *et al.*, 2008):

- Describes fully coupled non-isothermal hydrate dissociation/formation, CH_4 flow, and phase behavior in porous media
- Descendent of the TOUGH family of codes (YMP, oil & gas, CO_2 sequestration, hydrology)
- Validated by 1) analytical solutions, 2) gas production from permafrost deposits in the field, 3) dissociation and thermal behavior in lab experiments

Components

(1) H_2O
(2) CH_4
(3) Hydrate
(4) Salt
(5) Inhibitor
(6) Heat

Phases

(1) Aqueous
H_2O, CH_4, salt, I

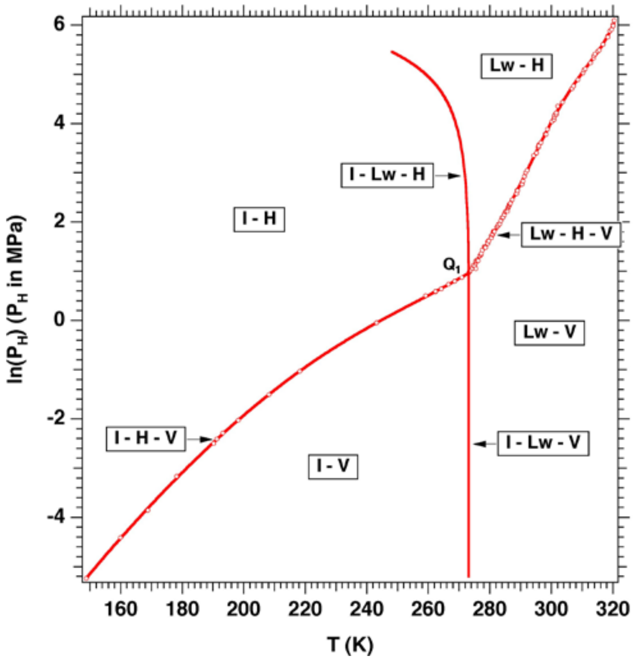
(2) Gas
CH_4, H_2O, I

(3) Solid-Hydrate
$CH_4.N_mH_2O$

(4) Solid-Ice
H_2O

30 possible phase combinations

Latest hydration *P-T* relationships



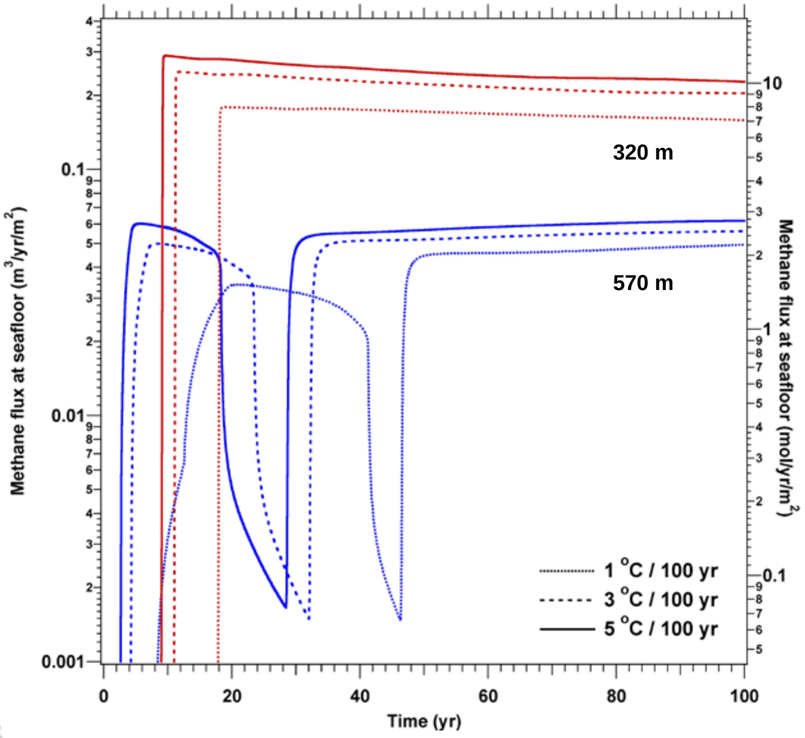
Hydrate Stability/Dissociation

- Previous work[1,2,3,4] studied Class 4 (disperse) deposits, S_H□= 0.03-0.10, 1 °C to 5 °C warming
- Provided view of GHSZ extent, localized dissociation estimates, localized fluxes, sensitivity
- 1D columns[2,3] and 2D continental slope deposits[1,4]

Multiple scenarios tested[1,2,3,4]:

- Deep ocean, 1000 m: stable
- GoM, 570 m: unstable?
- Arctic shelf, 320 m: unstable
- Barents Sea, 390 m: unstable

- Releases are sustained, but not explosive[1,2]
- Constrained by thermal effects and sediment transport properties[3,4]
- Sea level rise (10m) not mitigating[3]
- Results can be generated for any z/T/geological location via linkable subroutines



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[2] Reagan, M.T. and G.J. Moridis, oceanic gas hydrate instability and dissociation under climate change scenarios, *Geophys. Res. Lett.*, **34**, L22709, doi: 10.1029/2007GL031671, 2007.

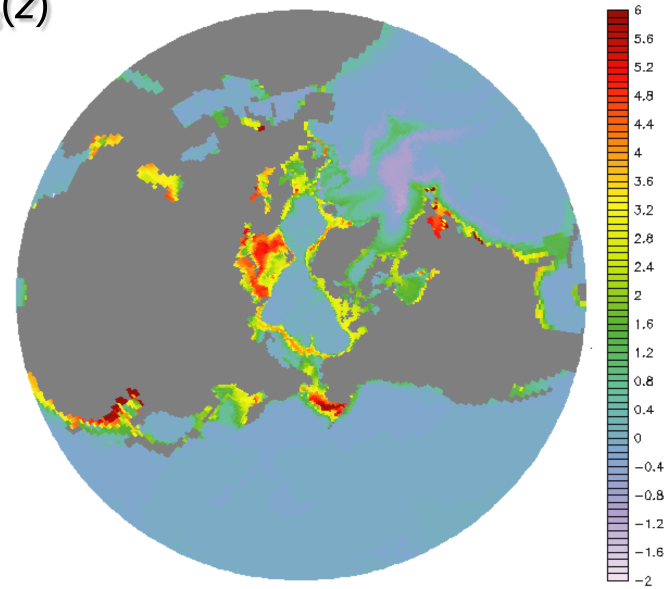
[3] Reagan, M.T. and G.J. Moridis, The dynamic response of oceanic hydrate deposits to ocean temperature change, *J. Geophys. Res. Oceans*, **113**, C12023, doi:10.1029/2008JC004938, 2008.

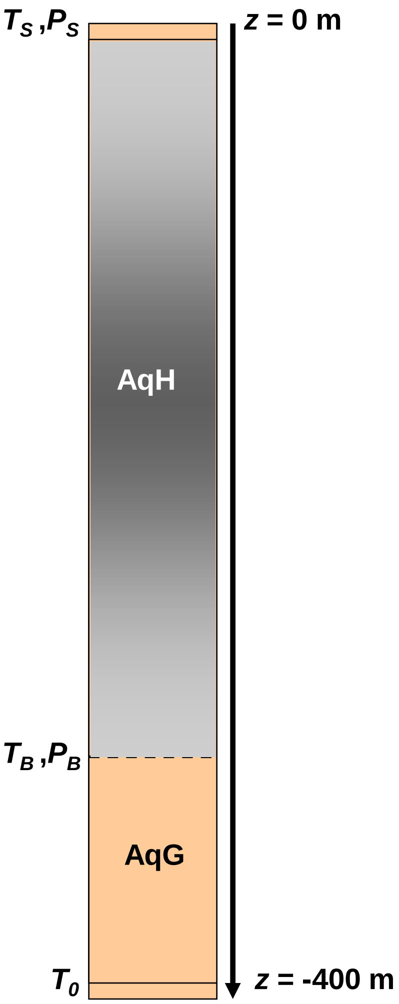
[4] Reagan, M.T., Moridis, G.J., Elliott, S.M., and Maltrud, M., "Contributions of Oceanic Gas Hydrate Dissociation to the Formation of Arctic Ocean Methane Plumes," J. Geophys. Res. Oceans, 2011JC007189, in press.

Integration: Basin-Scale Assessments

- 1D sediment column; thermal, chemical, hydrostatic equilibrium, fine discretization: dz = 10 cm – 1 m
- $k < 1$ mD, $\phi = 0.45 – 0.55$, consolidated sediments
- Hydrate exists from $z = -1$ m to $T_B(z)$, $P_B(z)$
- S_H□= 0.01-0.10 (~0.03%-3 %vol)
- Okhotsk: $T_s = 0$ °C - 2 °C
- Arctic: $T_s = 0.5$ °C - 1 °C

- $\Delta T = 1, 3, 5, 7$ °C/100 yr, or $\Delta T = f(z)$
- 100 yr warming, then T_s = constant

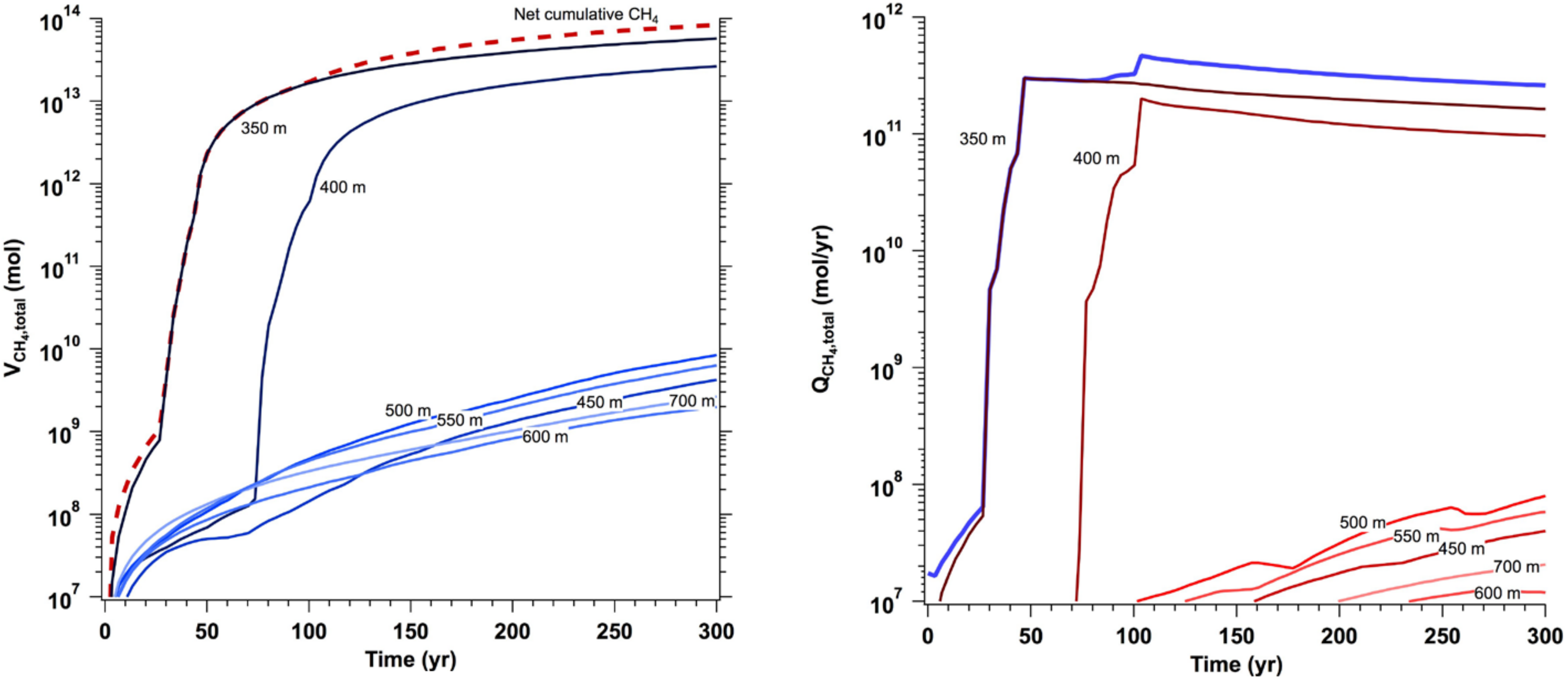




- Simulate CH_4 flux vs. t at each location
- Fluxes a function of depth, T_s, ΔT
- Perform 1-D release simulations on 40-min grid, (ETOPO2) at 25 m depth increments
- Integrate total methane release/flux over bathymetry
- Estimate basin-scale CH_4 emission

Integration: Sea of Okhotsk

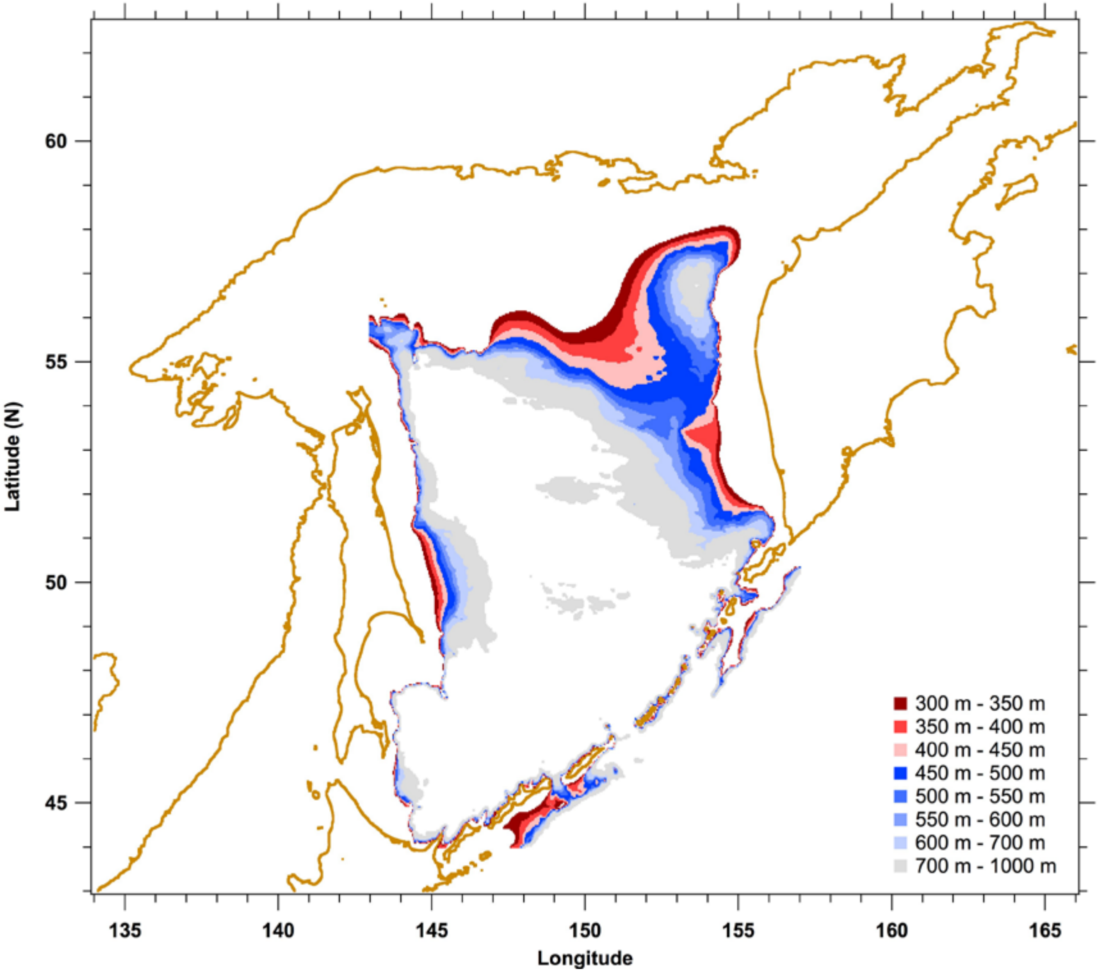
Integrated cumulative release (*V*) and net flux (*Q*)



- Adjust for 80% BSR occurrence (Ludmann & Wong, 2003)
- Instability confined to a narrow band near the top of the GHSZ
- 240 Tg released in the first century, fluxes < 5 Tg/yr

Integration: Sea of Okhotsk

Depth contours, coloring suggesting areas of potential destabilization (reds) vs. low-flux areas (blues)



- The Okhotsk basin contains extensive hydrate deposits and high methane concentrations(Obzhirov; KOMEX)
- Hydrates and free gas imaged (Ludmann & Wong, 2003; Wallmann et al., 2006)

- T+H: ~ 96 Tg (± 80) after 30 yr release (*t* = 83 yr)
- Previous estimate*: 94.4 Tg (by *t* = 30 yr)

- Only 0.1%-1% of the estimated Okhotsk methane reservoir
- Continued release may increase V_{CH4} 5×

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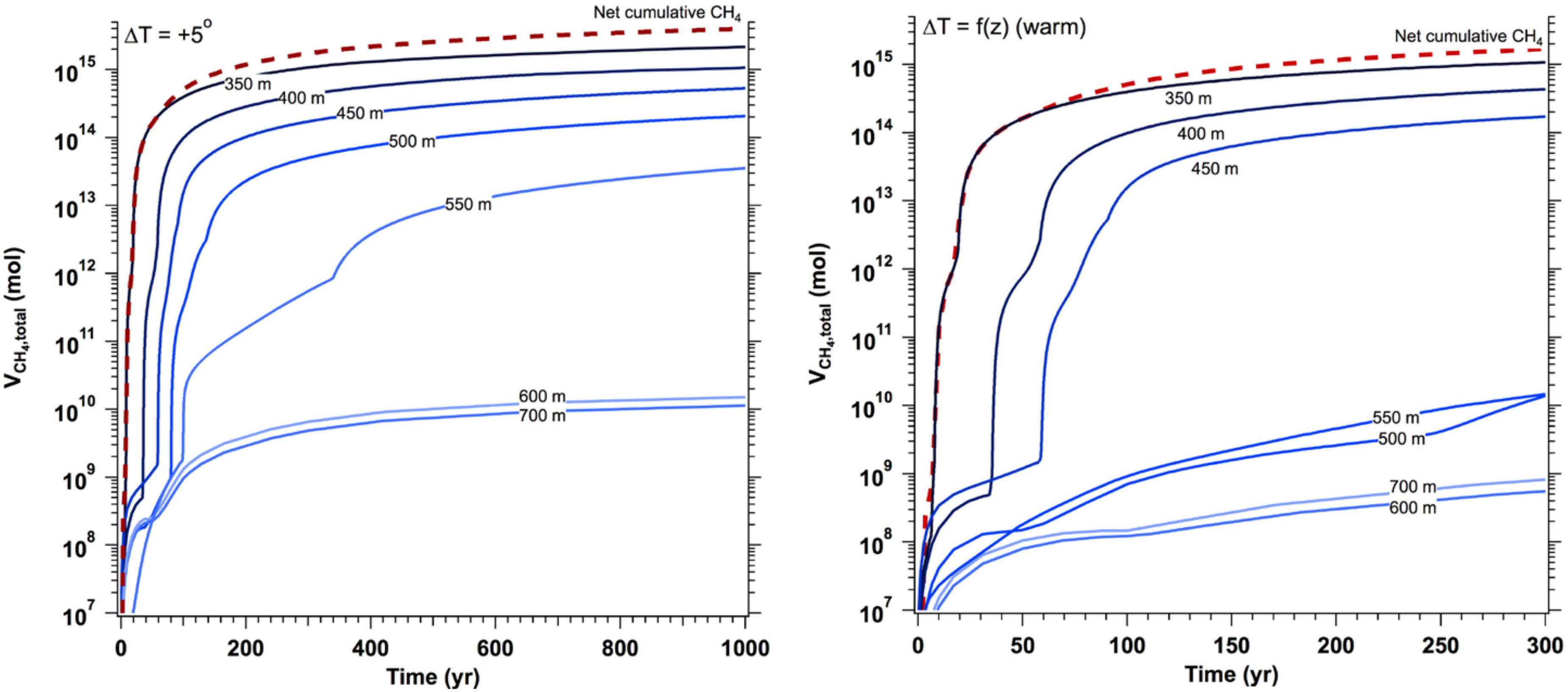
*Elliott et al., 2010

Integration: Arctic Ocean

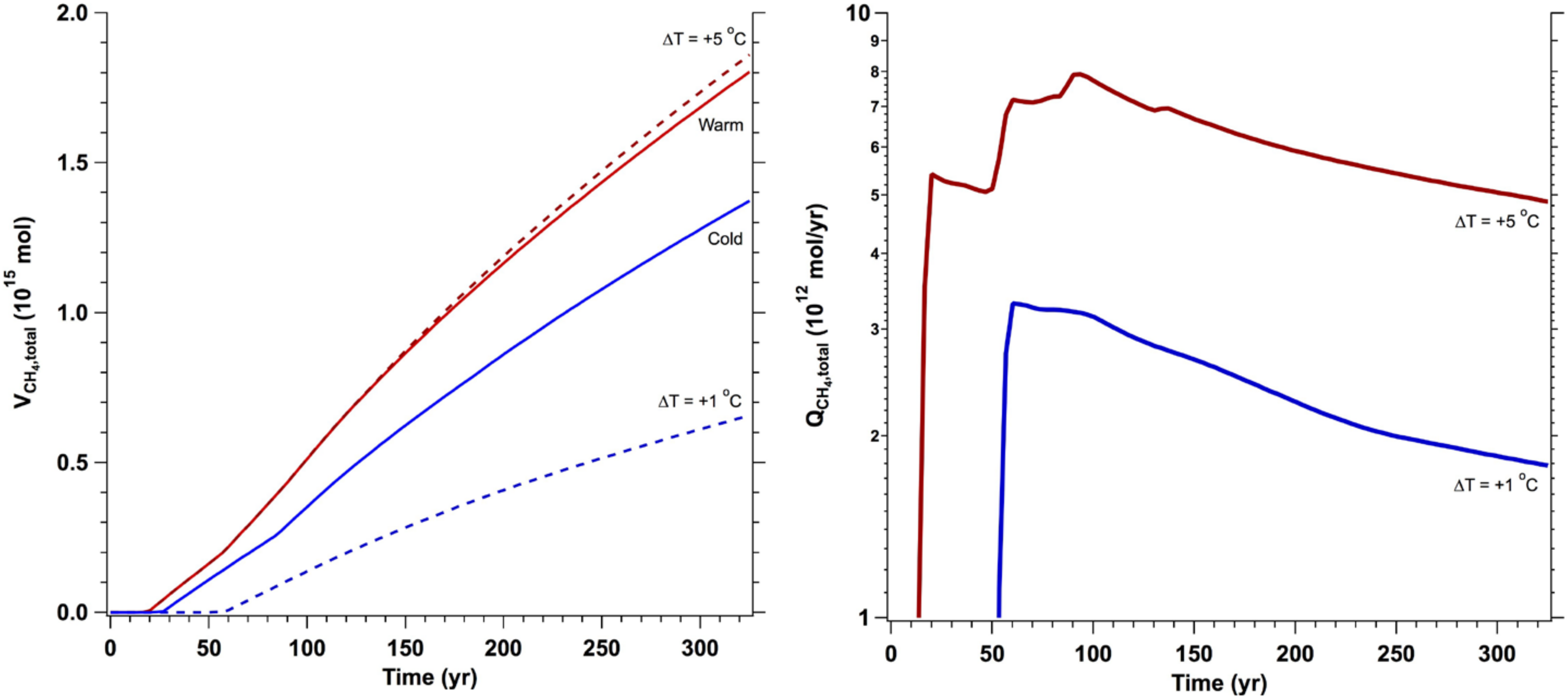
Cumulative release (V_{CH4}) vs. depth



- Instability confined to a narrow band near the top of the GHSZ
- Up to 6,400 Tg CH_4 at t = 100 yr

Integration: Arctic Ocean

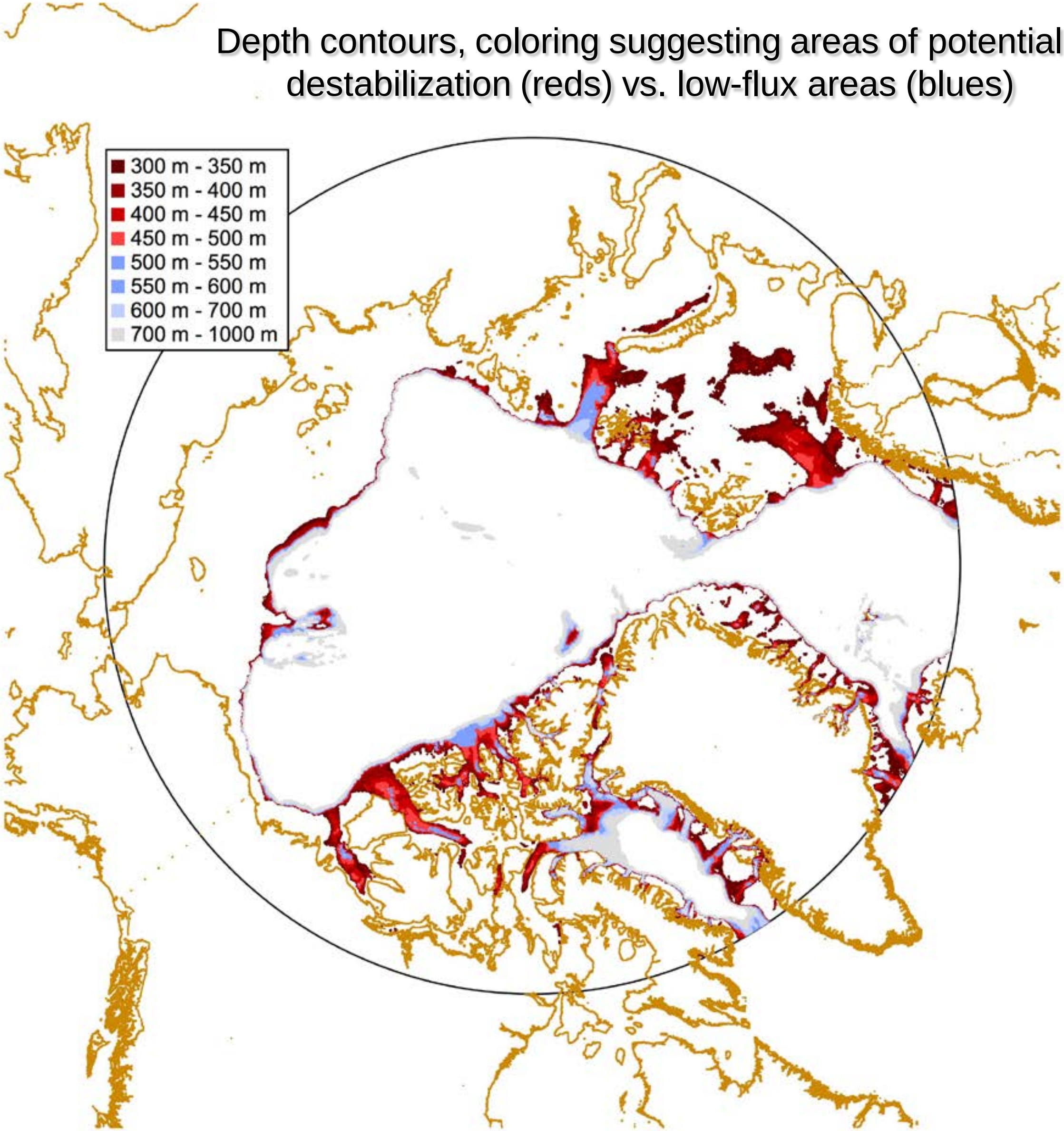
Cumulative release (*V*) and net flux (*Q*)



- Instability confined to a narrow band near the top of the GHSZ
- Scenarios: +5^{o}C, +3^{o}C, warm (1^{o}C - 5^{o}C as f(*z*)), cold (1^{o}C - 3^{o}C as f(*z*))
- Short-term: 1600 - 3200 Tg CH_4 @ 30 yr (previous assumption: 240 Tmol)
- 60 – 120 Tg/yr peak fluxes

Integration: Arctic Ocean

Depth contours, coloring suggesting areas of potential destabilization (reds) vs. low-flux areas (blues)



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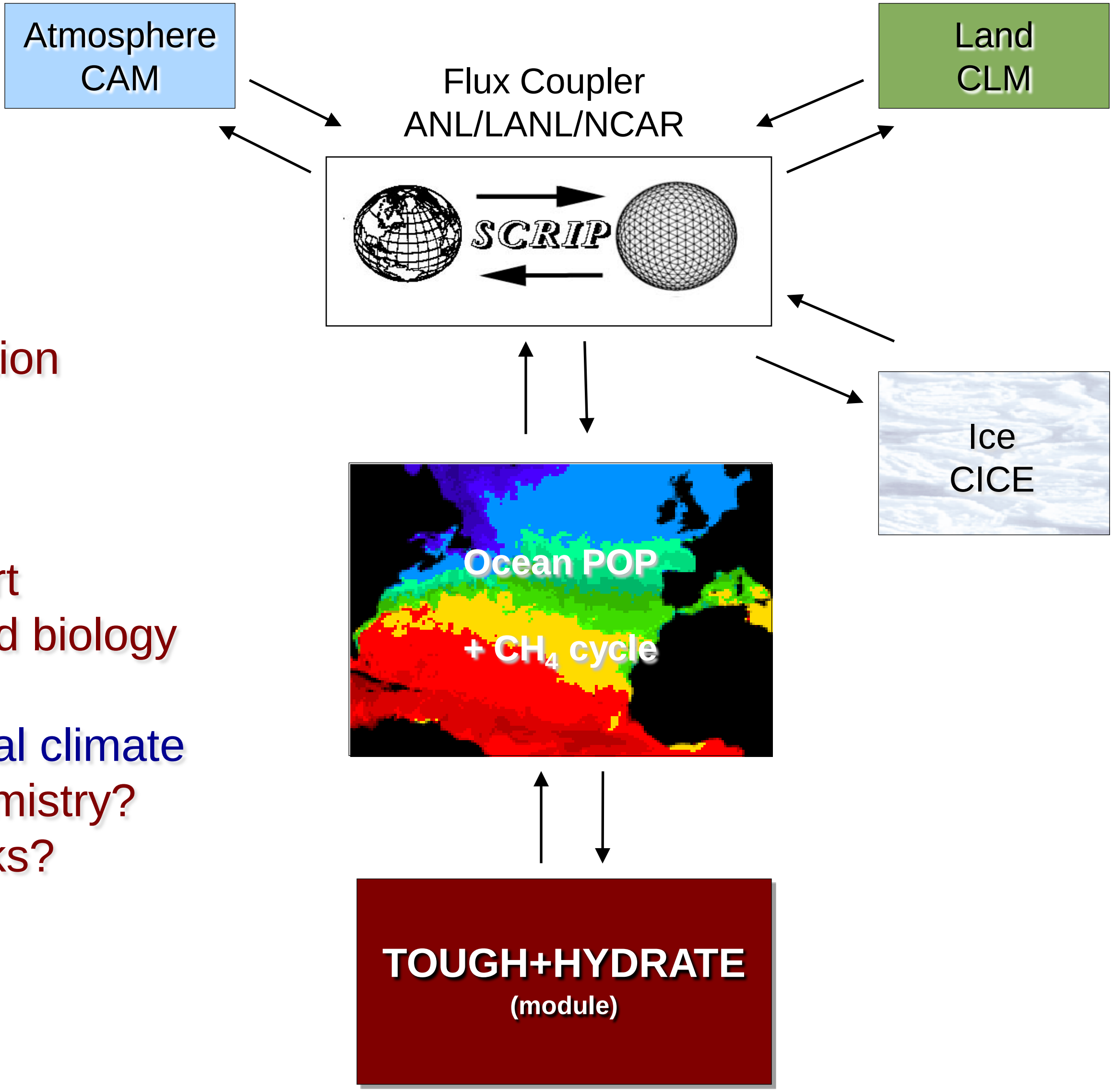

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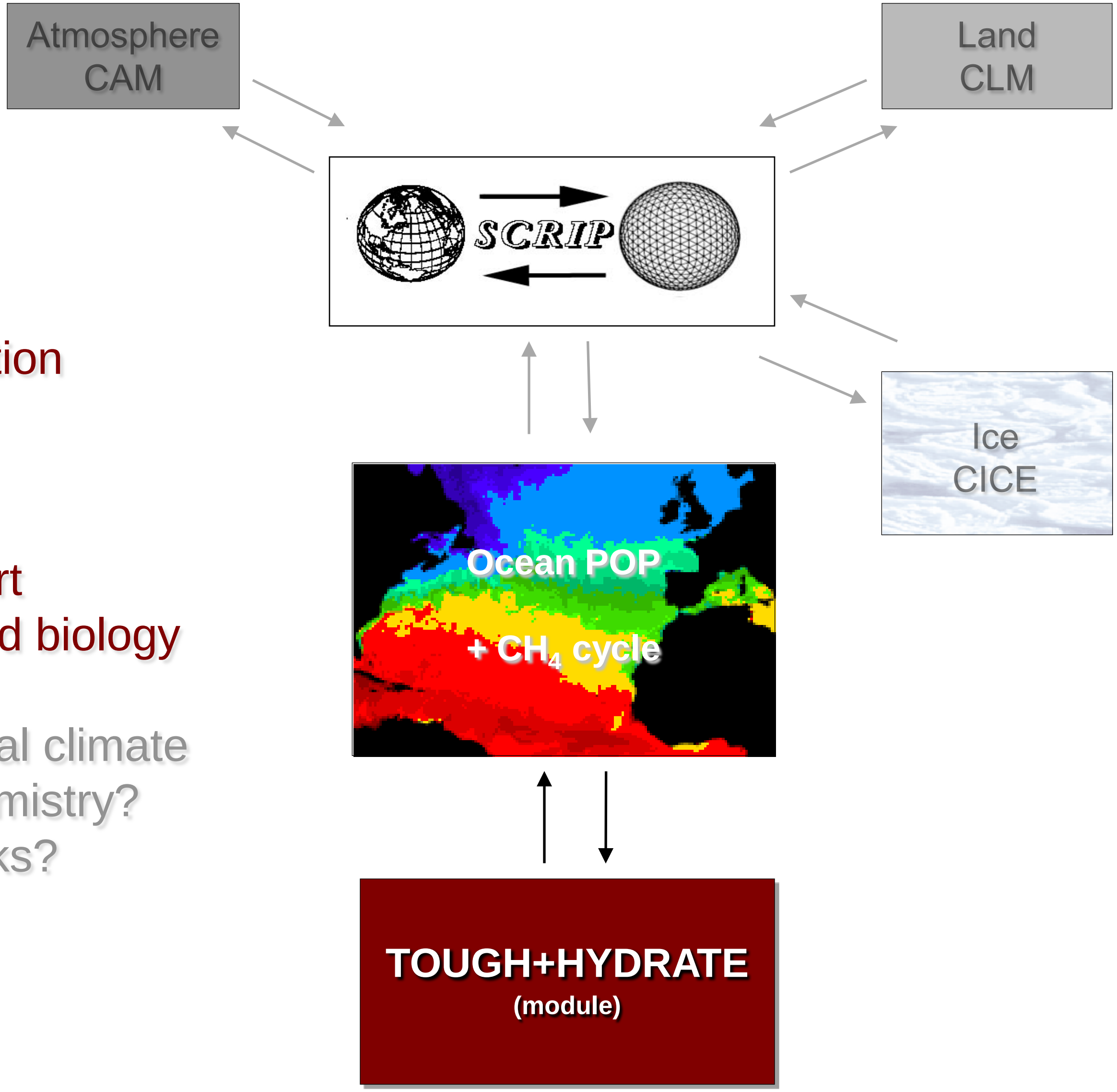

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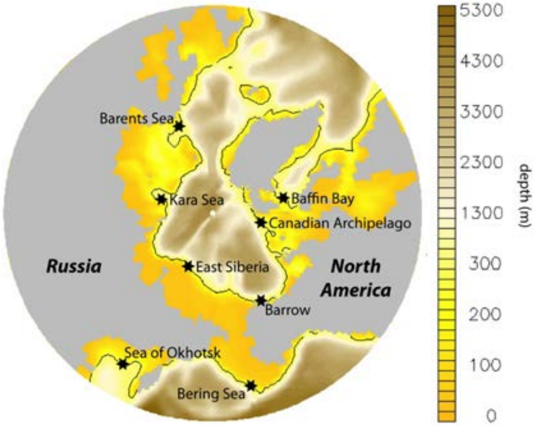
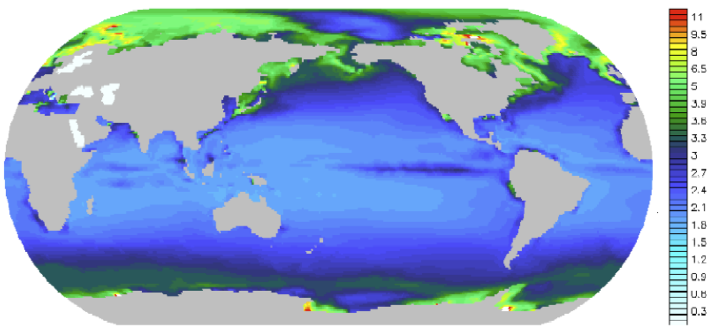
Coupled Ocean Modeling & Biochemistry

- POP extended to consider methane biogeochemistry in the water column[5,6]
- A newly generated background methane cycle creates a baseline for methane release calculations[6]
- Localized methane releases from hydrates inserted into POP[6] (fully dissolved*)

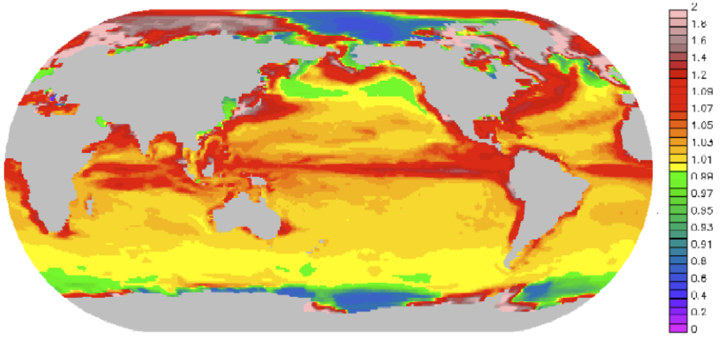
*Plume physics forthcoming



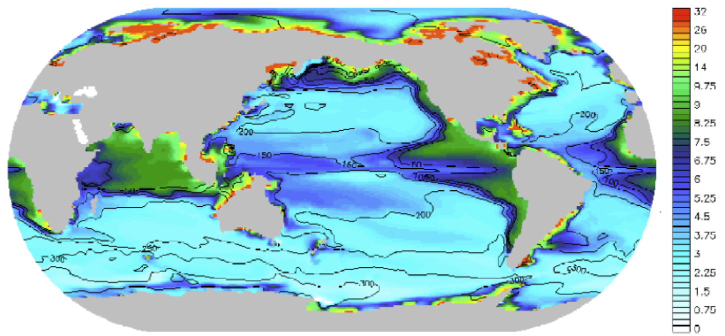
CH$_4$ Surface Concentration (nanomolar)



CH$_4$ Surface Saturation Ratio



CH$_4$ 150m Concentration (nanomolar) with O$_2$ contours



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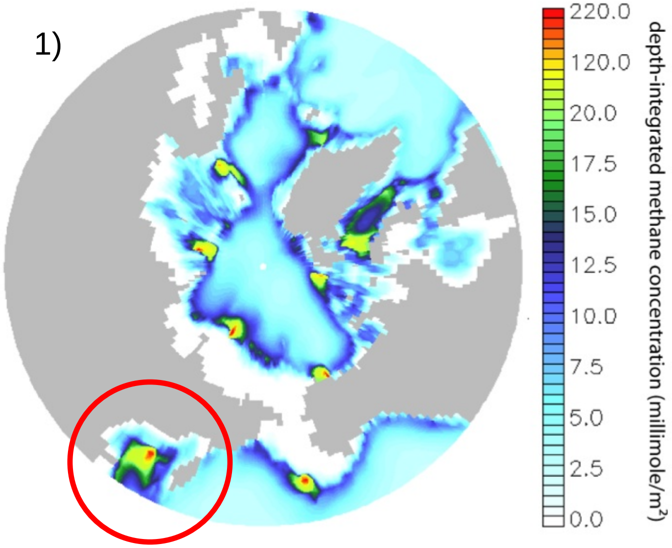
[5] Elliott, S.M., Maltrud, M., Reagan, M.T., Moridis, G.J., Cameron-Smith, P.J., "Geochemistry of Clathrate-Derived Methane in Arctic Ocean Waters," *Geophys. Res. Lett*., **37**, L12607, 2010.

[6] Elliott, S.M., Maltrud, M., Reagan, M.T., Moridis, G.J., Cameron-Smith, P.J., "Marine Methane Cycle Simulations for the Period of Early Global Warming," *J. Geophys. Res. Biog.*, **116**, G01010, 2010.

Coupled Ocean Modeling & Biochemistry

***t* = 30 yr:**

1)



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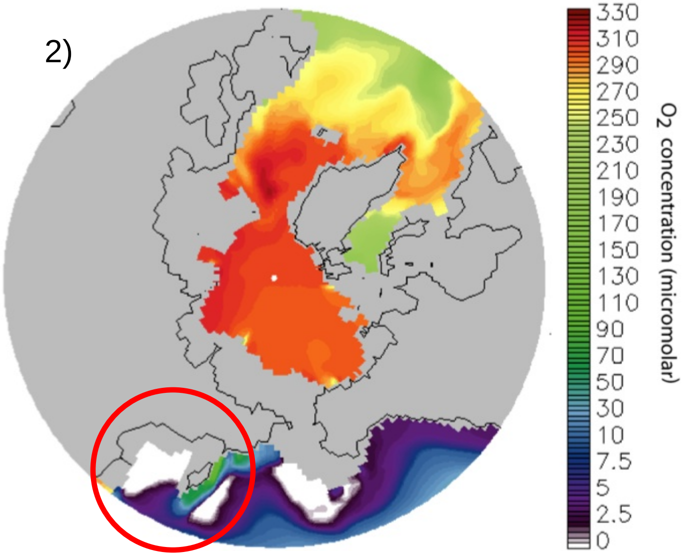

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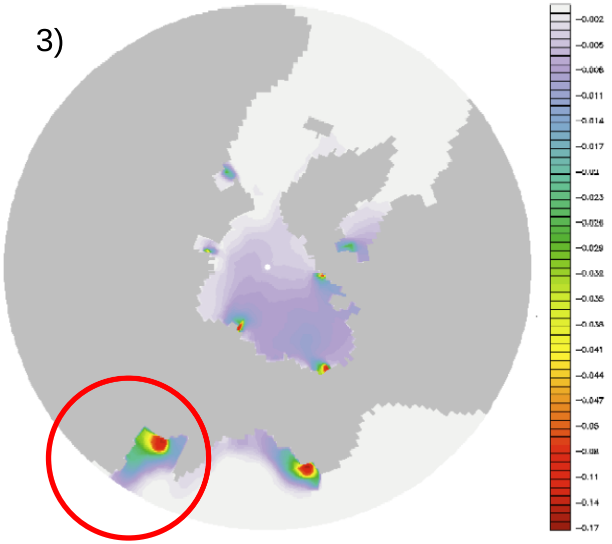

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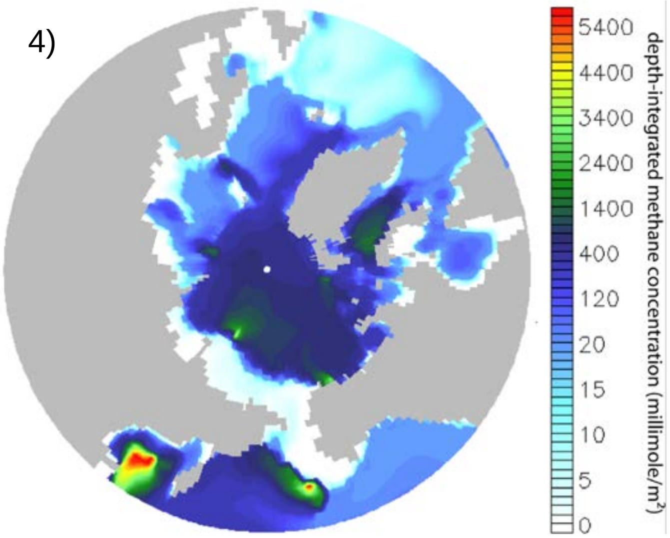

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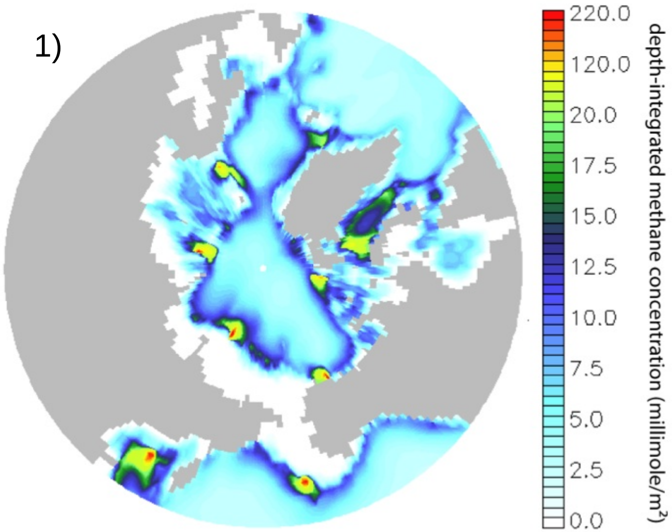

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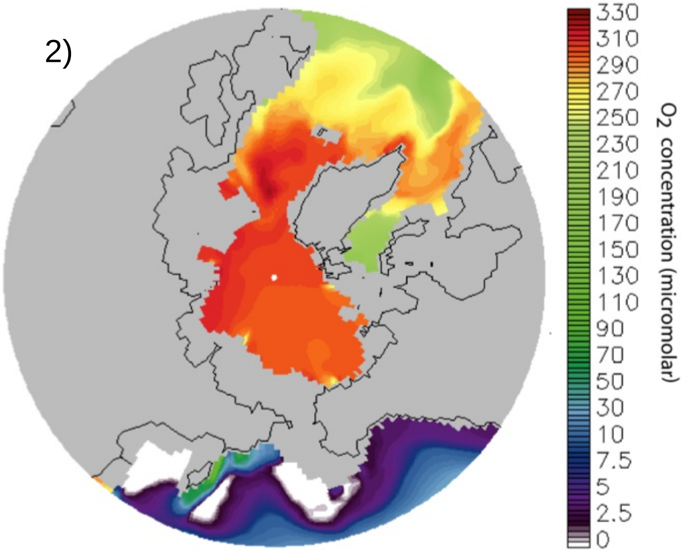

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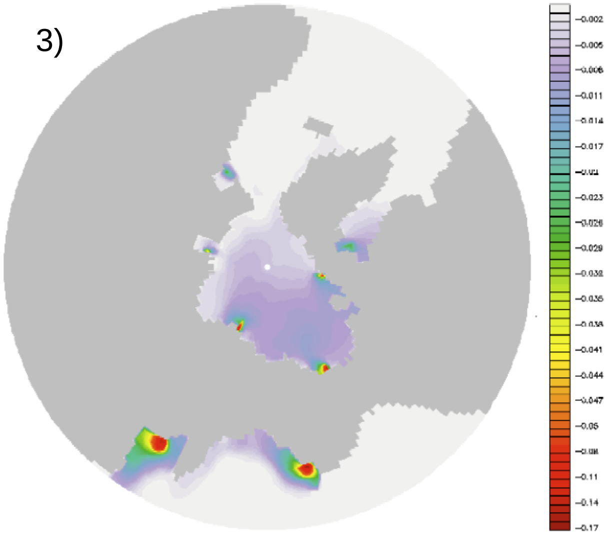

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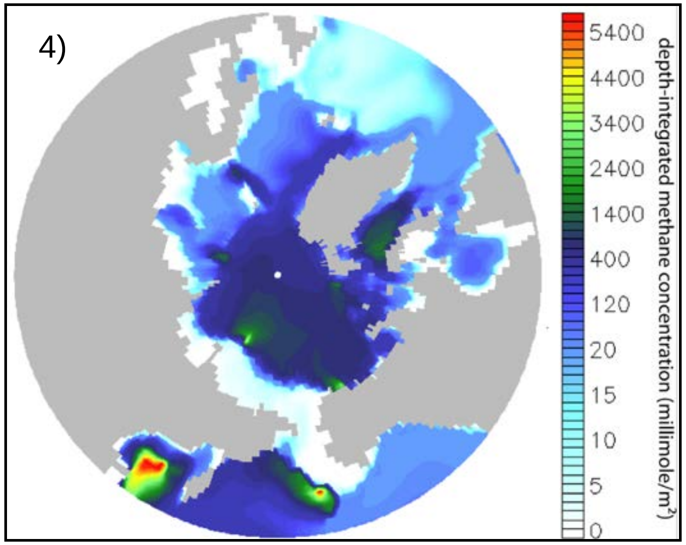

~60% Transfer to atmosphere!

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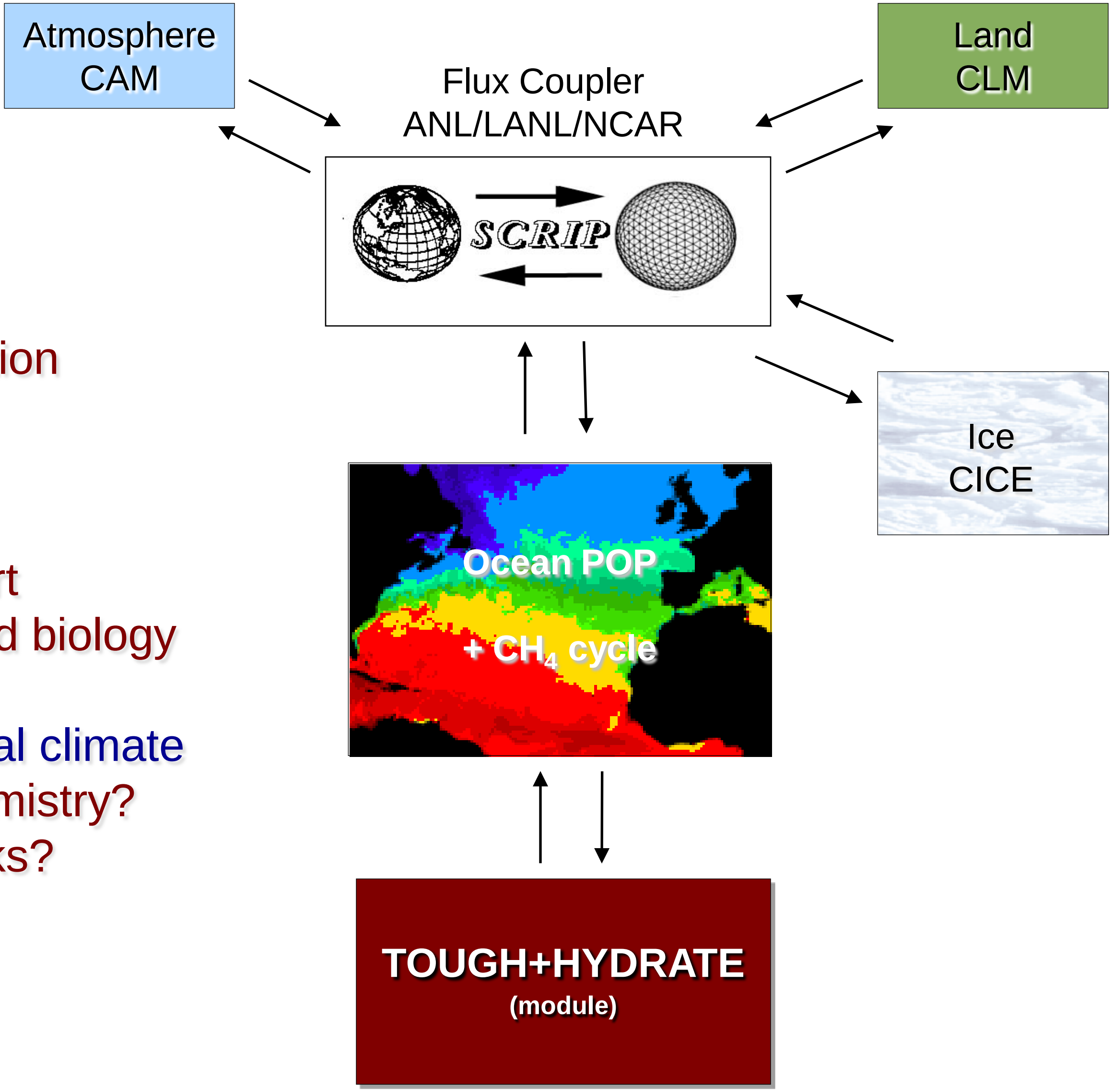

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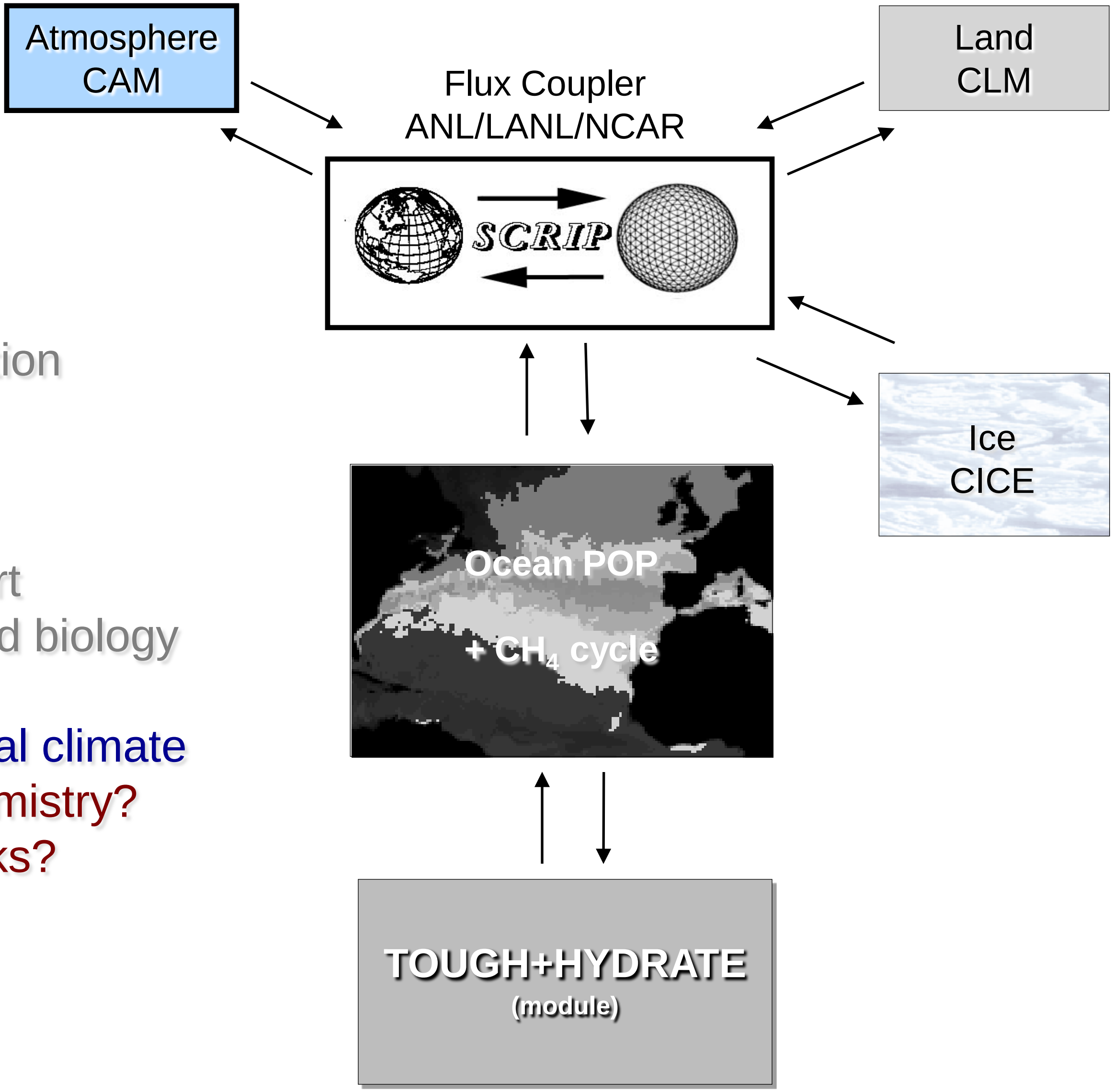

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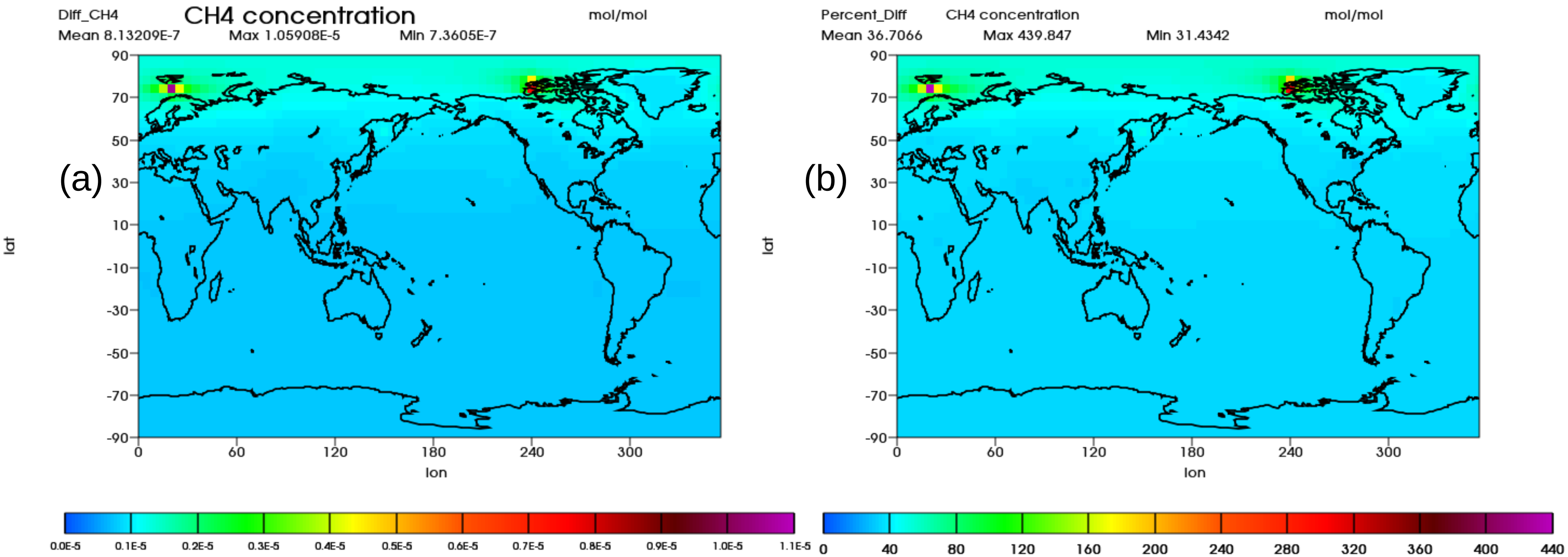
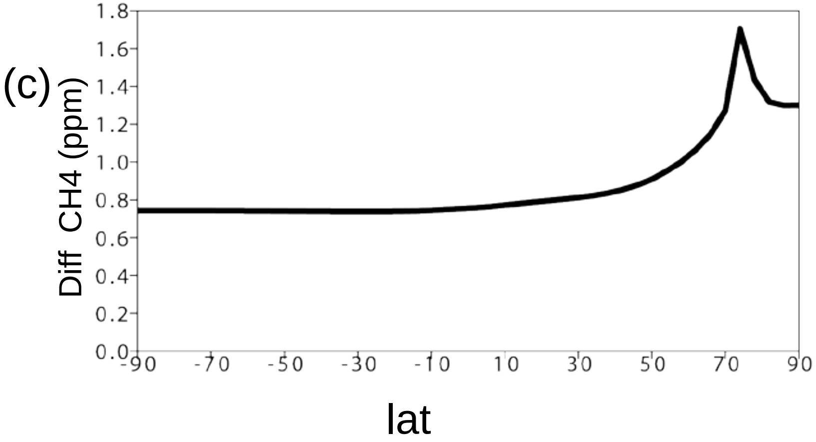
Increase in global CH_4 concentration



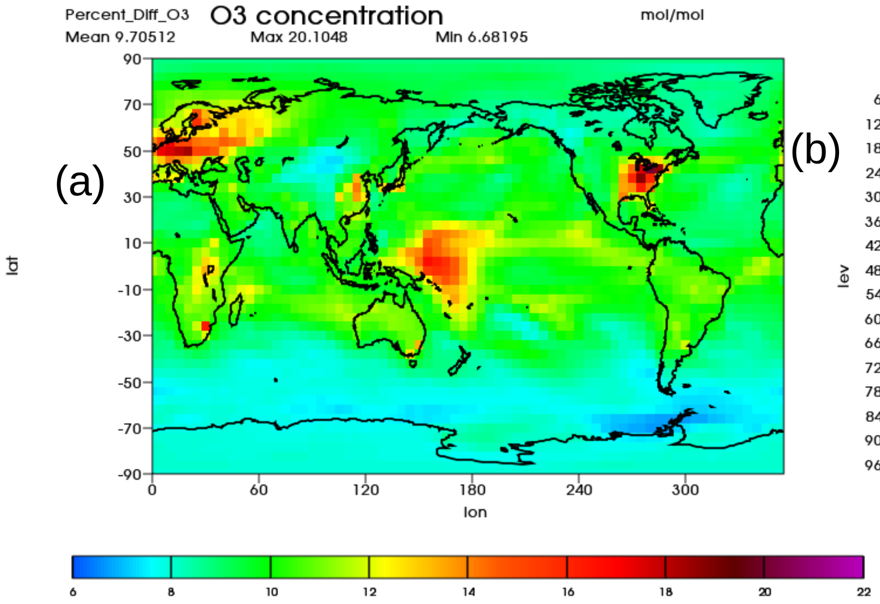


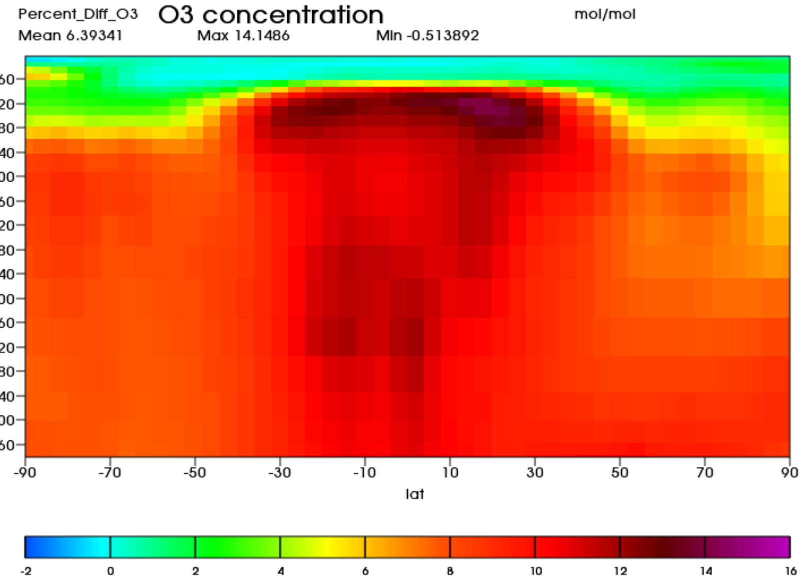
(a) Difference in surface CH_4 concentration relative to control

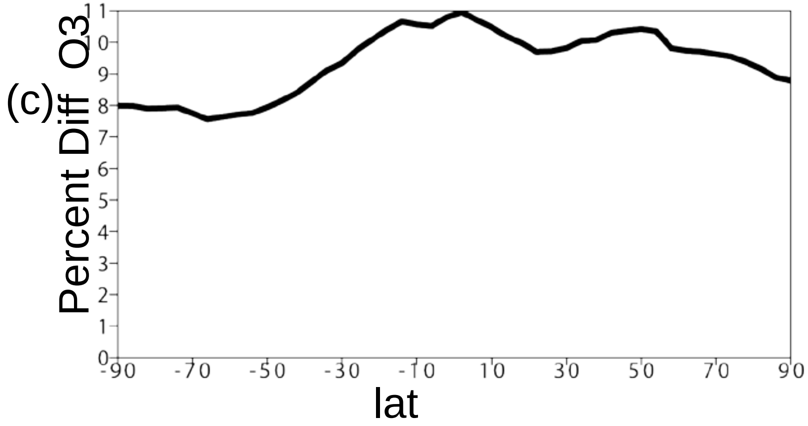
(b) Percent Difference in CH_4 concentration relative to Control

(c) Difference in surface CH_4, zonal mean

Significant Increases in Ozone







(a) Percent difference in surface ozone relative to control

(b) Percent difference in atmospheric ozone (zonal mean)

(c) Percent difference in surface ozone (zonal mean)

Conclusions

- Shallow hydrates can release significant methane rapidly, with significant methane fluxes regulated by coupled thermo-hydrological processes
- Methane is relevant to ocean (and atmospheric!) chemistry, not just as a contributor to total atmospheric CO_2

- 1-D models averaged over depth/temperature/area can estimate basin-scale release potential
- The vast majority of deep hydrates are stable, in the short term, but the methane release potential is still large
- Limited instability/release can feed biochemical/chemical changes in the ocean and atmosphere, before climate effects are considered
- Resource limitations overturn assumptions about methane oxidation
- New coupled seafloor-ocean-atmosphere calculations under way (with plume physics, extended biochemistry, higher resolution) leading to a coupled global model… and better estimates

http://esdtools.lbl.gov/info/hydrate-publications/climate/