Interrelation of Global Climate and the Response of Oceanic Hydrate Accumulations

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Project Purpose and Goals

The goals of this study 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 estimate the global quantity of hydrate-originating carbon that could reach the upper atmosphere as the greenhouse gases CH_4 and CO_2,
3. To quantify the interrelationship between global climate and the amount of hydrate-originating carbon (CH_4 and CO_2) reaching the upper atmosphere,
4. To test rapid clathrate release hypotheses, which tie large-scale hydrate dissociation and gas release to rapid warming over very short (geologically speaking) periods. Given current concerns about the possibility of global warming, there is particular urgency to investigate this aspect of oceanic hydrates.

Project Tasks

Project initiation: May/June 2008

Year 1 (FY08/09) Tasks:

✓ Task 08-1: Assessing and Quantifying Global Warming Scenarios

➢ Task 08-2: Coupling TOUGH+HYDRATE/C.CANDI/TOUGH+REACT codes

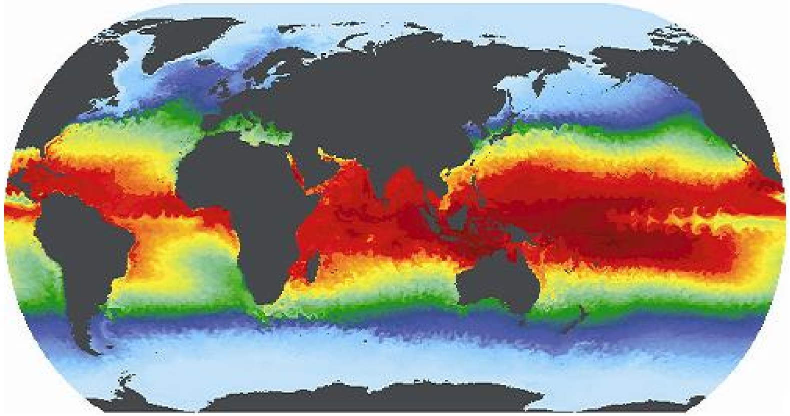
➢ Task 08-3: Studies of Greenhouse Gas Releases at the Ocean Floor on Limited Spatial Scales

- Task 08-4: Reactive Transport Enhancements to POP
- Task 08-5: Code Integration

➢ Task 08-6: Communications, Reporting and Technology Transfer

Climate, Ocean and Sea Ice Modeling (COSIM) at Los Alamos

- Develop advanced ocean and ice models for evaluating the role of ocean and ice in climate, high-latitude climate change and projecting impacts of these changes on regions throughout the globe.



- **Office of Science (DOE)**
  - — Coupled climate system models
  - — Sea ice and Arctic changes
  - — Ice sheets and sea level rise
  - — Abrupt climate change (ocean circulation changes)
  - — High latitude biogeochemical models for carbon and sulfur cycles

- Hydrates
  - — Evaluate fate of methane after sea-floor hydrate release
  - — Rapid releases hypothesized in paleoclimate records
  - — We lack a solid understanding of the fate of hydrate-originating methane from sea floor sediments

Community Climate System Model

NSF/DOE
Used for IPCC Assessments
300+ scientists

Atmosphere
CAM
(NCAR)

7 States
10 Fluxes

Once per hour

6 States
6 Fluxes

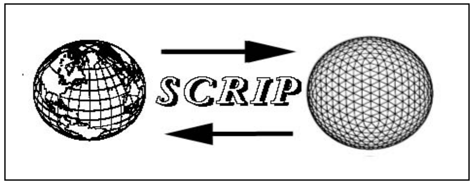
Land
CLM
(NCAR, Others)

6 States
6 Fluxes

Once per hour

7 States
9 Fluxes

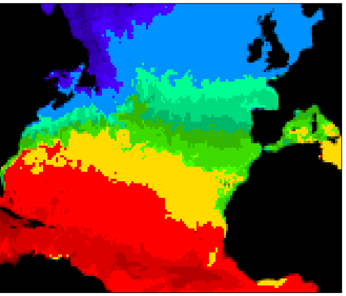
Flux Coupler
ANL/LANL/NCAR



4 States
3 Fluxes

Once per day

6 Fluxes



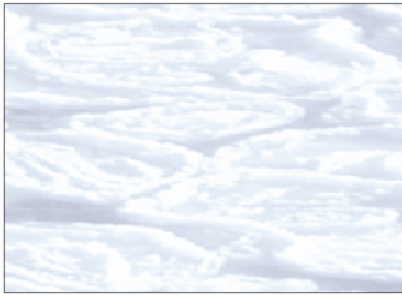
Ocean
POP
(LANL)

6 States
13 Fluxes

Once per hour

11 States
10 Fluxes

Ice
CICE
(LANL)



Hydrates and Climate

- Methane is a strong greenhouse gas
- Potential large scale release of hydrate methane due to warming scenarios
  - Proposed in past rapid climate changes
  - We lack a solid understanding of the fate of hydrate-originating methane from sea floor sediments

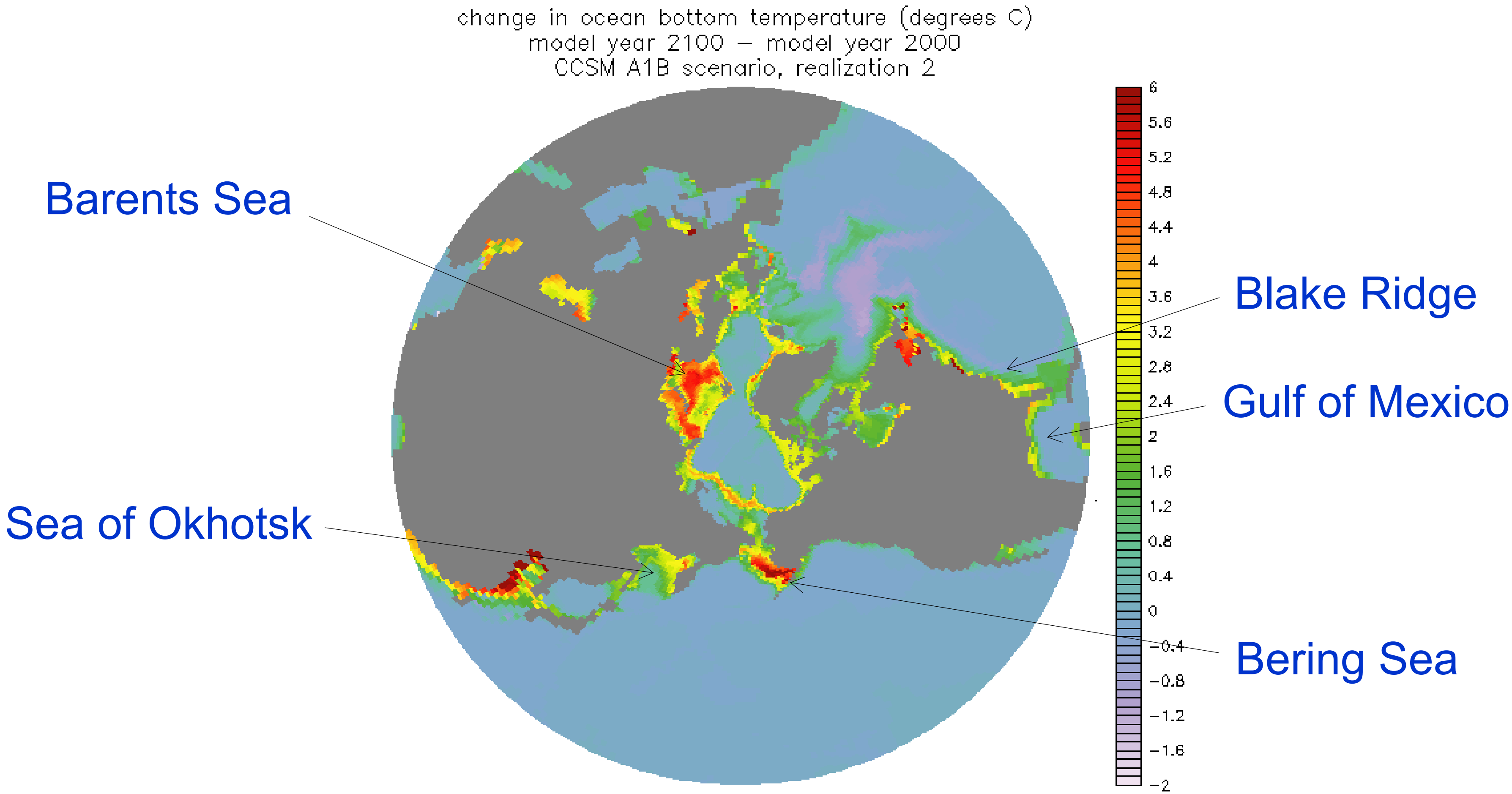
Task 1: Assessing Warming Scenarios

- Synopsis of studies on sea-floor temperature evolution

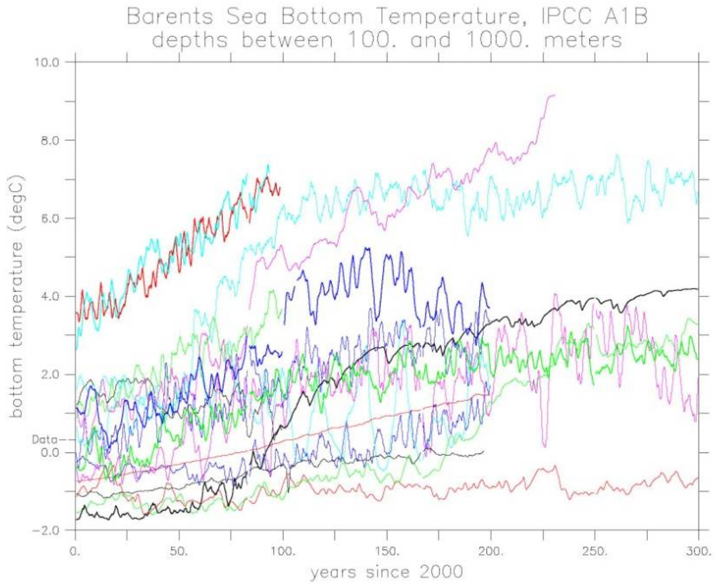
- Use existing data from IPCC projections to bracket the range of temperatures
  - A1B: mid-range scenario (850 ppm by 2100, some technology insertion from balanced sources)

- Pick likely locations based on some physical understanding and earlier studies
  - Relatively shallow
  - Areas of more pronounced warming
  - Likely position of large deposits

Task 1: IPCC Results and Locations

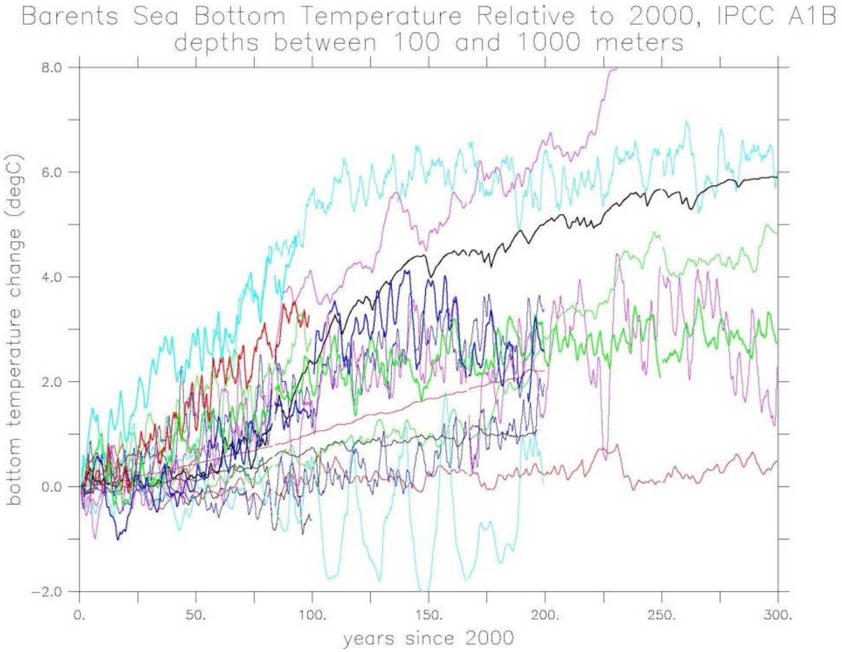


Task 1: Barents Sea



One realization from each IPCC modeling center

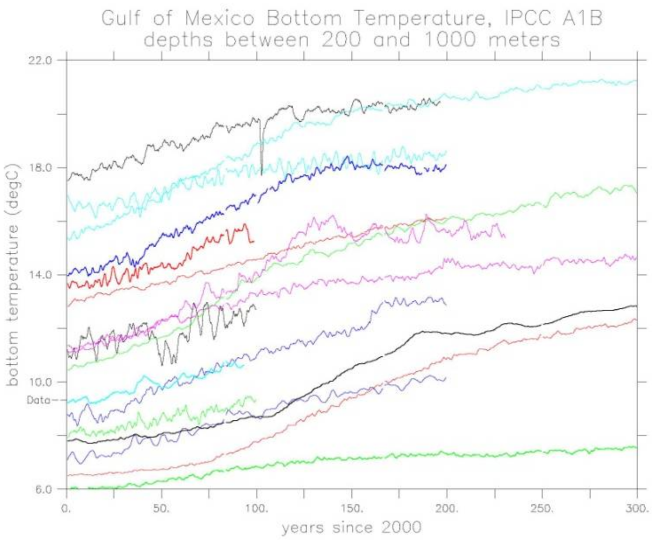
CCSM in red



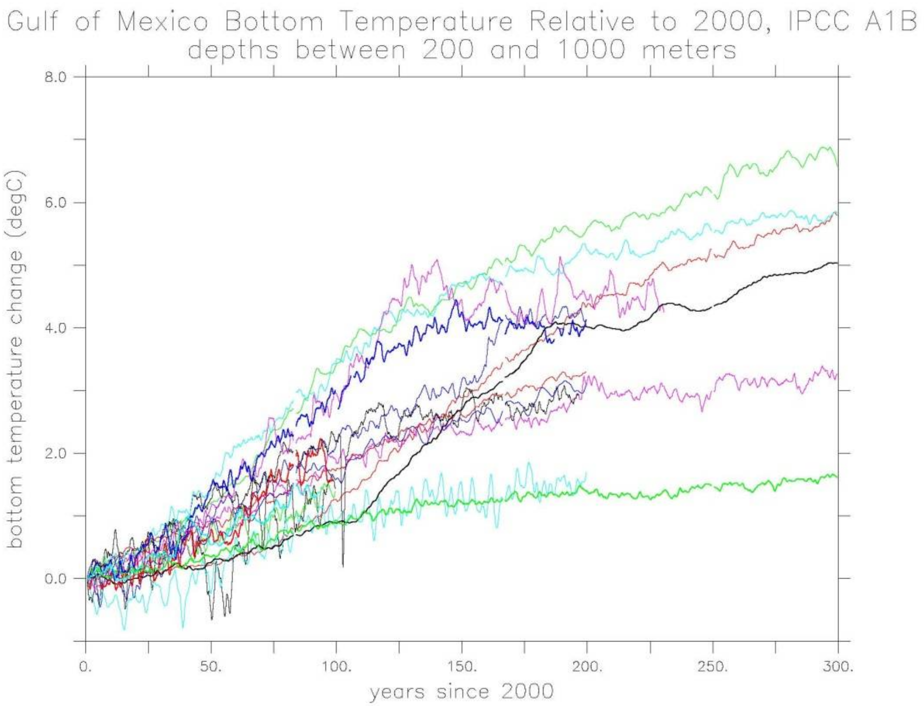
Large variability in temperature due to differences in spinup, resolution, formulation, lack of data.

Delta(T) more important

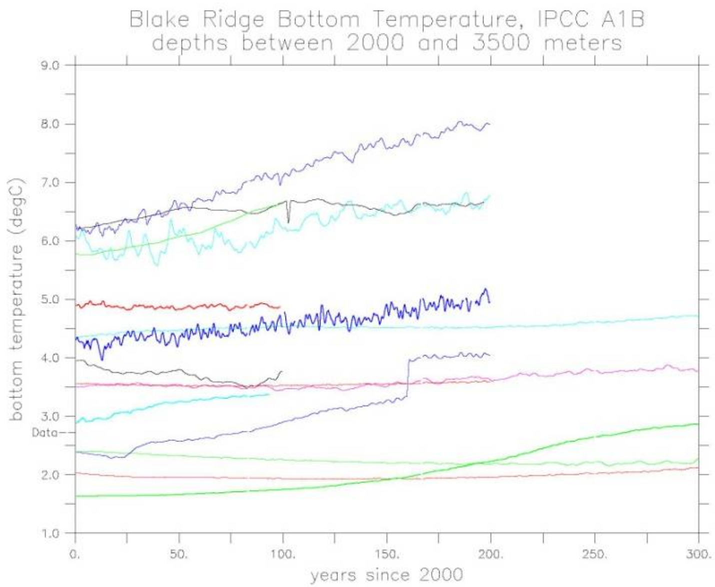
Task 1: Gulf of Mexico



Little tighter Delta(T) distribution for GoM

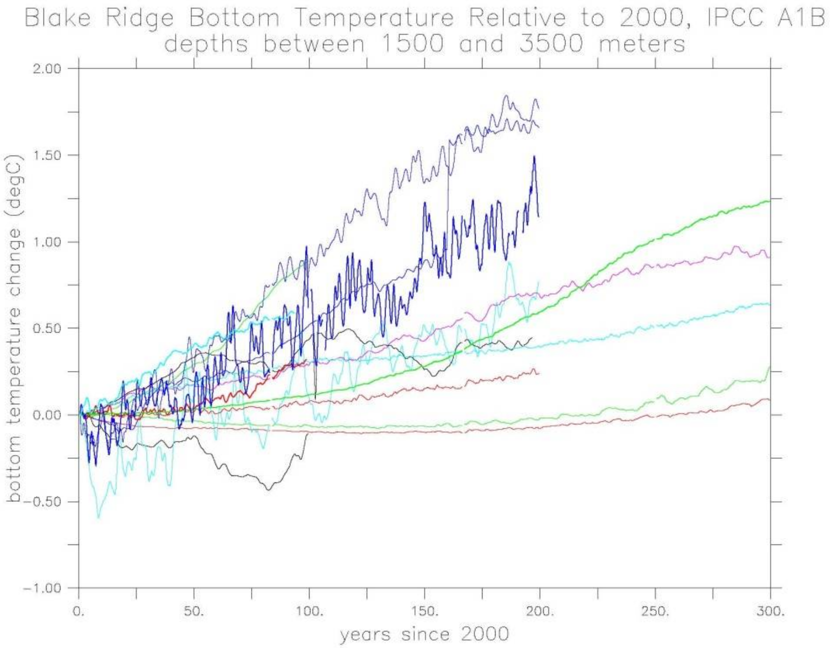


Task 1: Blake Ridge

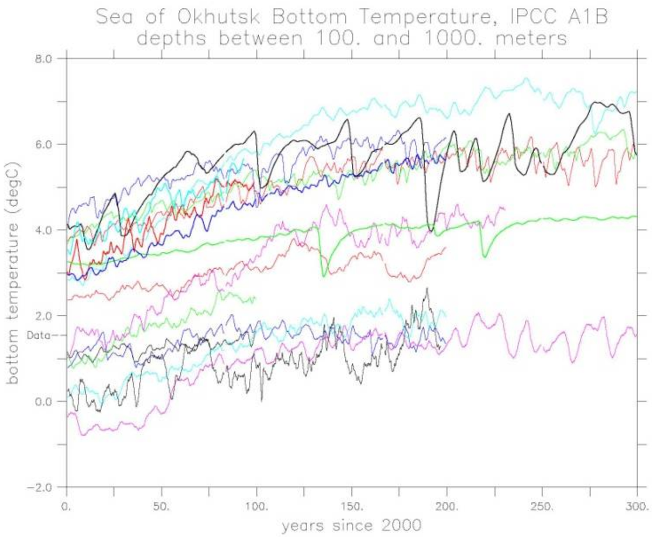


(Seafloor feature not resolved in model)

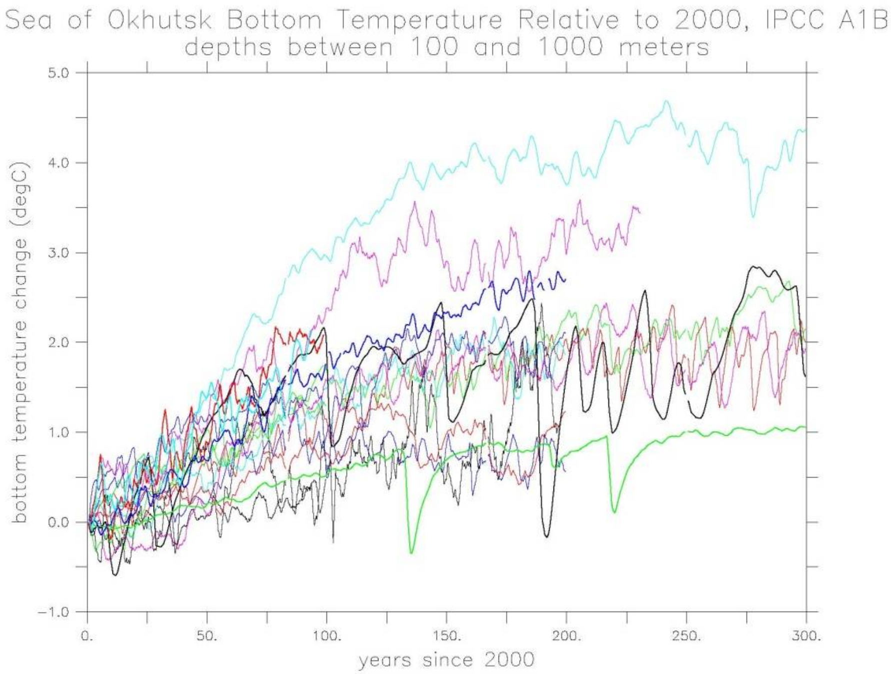
Small warming signal



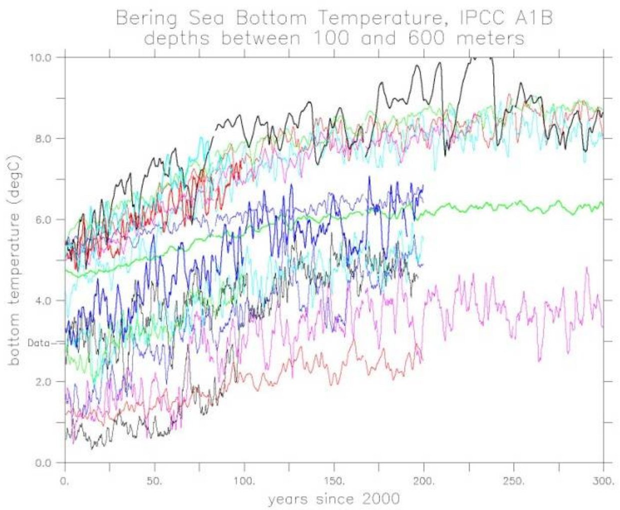
Task 1: Sea of Okhotsk

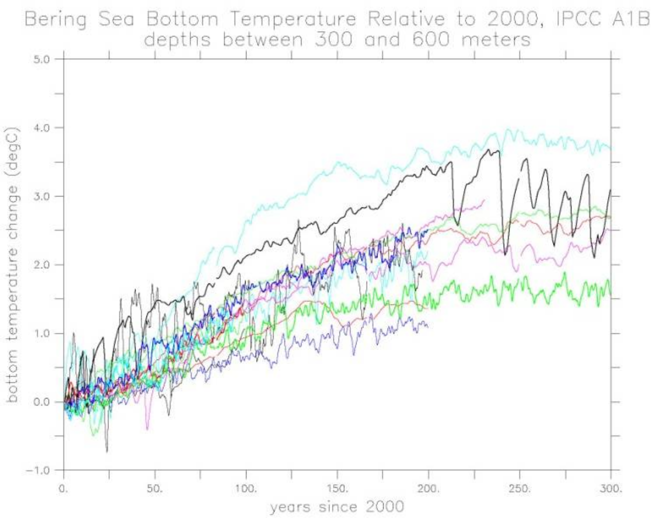


Less warming here too…

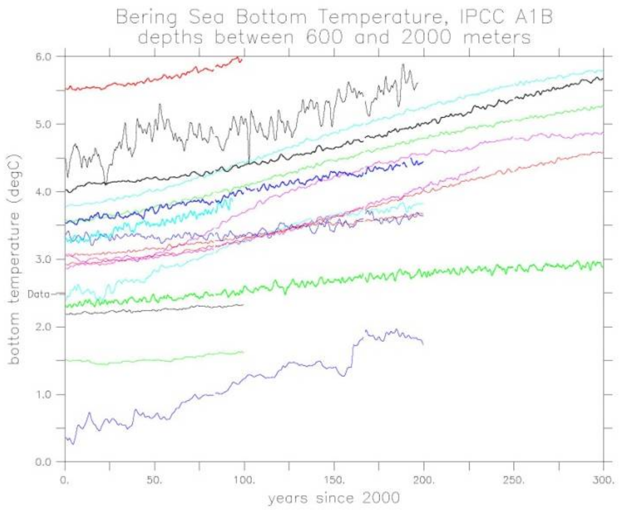


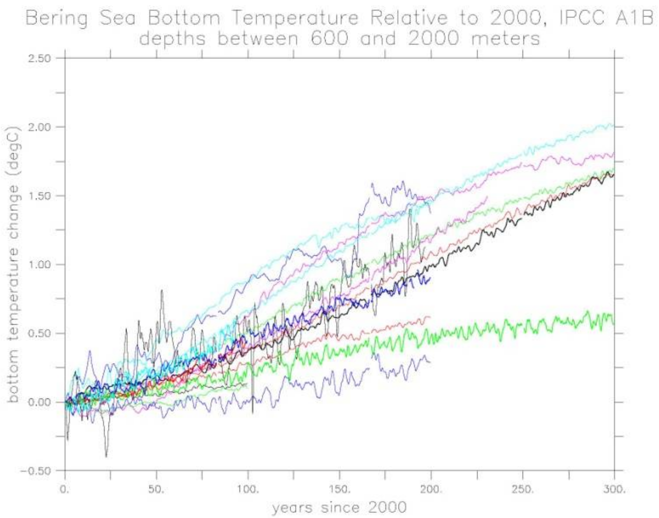
Task 1: Bering Sea





Bottom topography very different, so chose shallow and deep slices





Task 1: Conclusions and Future Work

- Ocean bottom temps
  - Highly variable between models
  - Range of 1-5 degrees is reasonable for locations of interest
- Future tasks
  - Focus on reactive transport, dissociation, partial oxidation
  - Bubble/plume model for vertical transport in column
  - Adding new biogeochemical processes for benthic organisms
  - Coupling with sea floor models

Task 3: Preliminary Studies
Methane Release from the Seafloor

Estimates of hydrates in the ocean?

- 10,000 Gton C "consensus value" (Fung, Kvenvolden, etc.) via thermodynamic modeling constrained by ODP samples and seismic studies

- ⇓ 3,000 Gton C in hydrate and 2,000 Gton in methane gas (Buffett and Archer)
- ⇑ 74,400 Gton total, 27,300 Gton on continental margins (Klauda and Sander)

- Gulf of Mexico (440m-1000m)
  - ➢ 5 Gton methane in hydrates (Milkov)
  - ➢ +4 ^{o}C change in GOM could release 2 Gton of methane (Milkov)
- Arctic?
  - ➢ "Hundreds" of Gton possible? (Kvenvolden, Archer)
  - ➢ Arctic is more susceptible to rapid temperature change
  - Distributions and depths unknown
  - Require modeling to establish extent

Task 3: Preliminary Studies

Addressing Knowledge Gaps

- Previous research used equilibrium models of hydrate inventory:
  - Stratigraphic hydrate formation (100 Kyr)
  - Hydrate deposit re-equilibration during climate changes (100 Kyr-1 Myr)
  - Changes in hydrate inventory with ocean temperature (>1 Myr)
  - ➢ No dynamic, fully coupled modeling

➢ Coupled heat and mass transport in porous media (sediments) and phase behavior over instantaneous, yearly, decadal, and century timescales

➢ Dynamic behavior impacts:

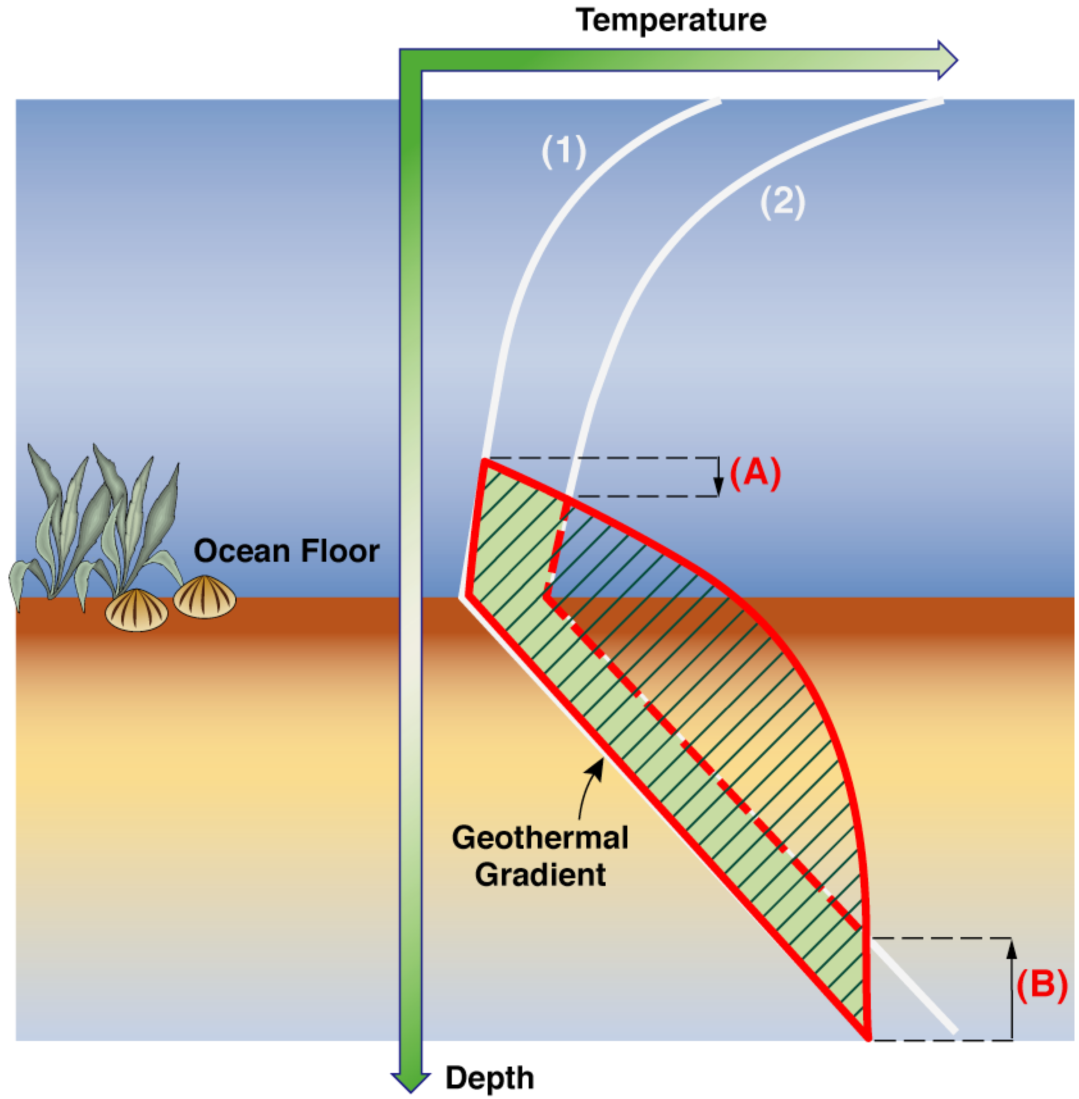
  - Rapid (catastrophic) vs. gradual (chronic) release
  - Release in aqueous vs. gaseous phase
  - Methane fluxes and fluid flow velocities
  - Short-term biochemical response
  - Feedback into local environments and global climate

Task 3: Preliminary Studies

Oceanic Gas Hydrates: Stability

- The thickness of the gas hydrate stability zone (GHSZ) is controlled by
  - Pressure (water depth), and
  - Temperature (ocean temperature profile and geothermal gradient)

- The top of the GHSZ may be above or below the seafloor



Task 3: Preliminary Studies

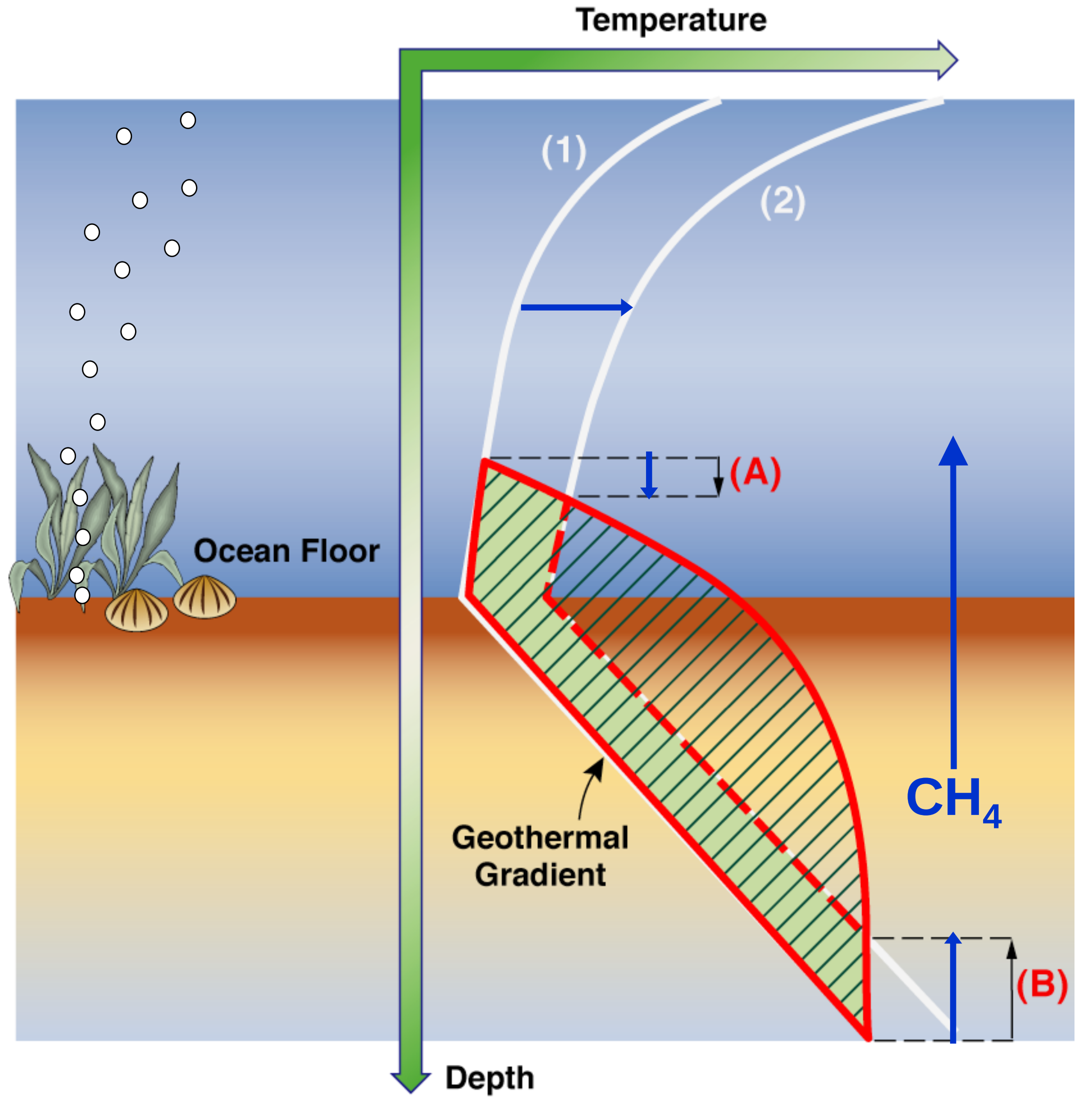
Oceanic Gas Hydrates: Dissociation

Climate change alters ocean temperature (and geothermal gradient)

Decreases hydrate stability region

Methane release to ocean by hydrate dissociation

What happens between (1) and (2)?



Task 3: Preliminary Studies

Hydrate Stability/Dissociation Model

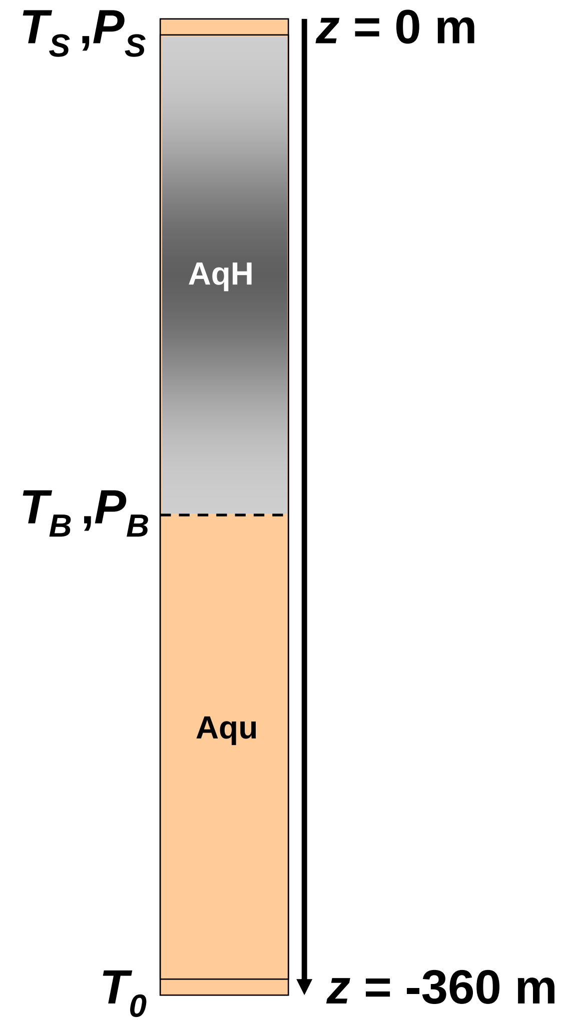
- ➢ TOUGH+HYDRATE
- ➢ 1-D sediment column, initial hydrostatic *P* gradient
- • Hydrate exists from *z* = -1 m to $T_B(z)$, $P_B(z)$
- ➢ No free gas zone included
- • Consolidated sediments (k_0 = 10^{-15} m^2)
- • ϕ = 0.3, mild capillary pressure regime
- ➢ Class 4 disperse hydrate deposit
- • S_H□= 0.03 (~1 %vol), 3.5% salinity
- • Flow and fluxes recorded at the top of the column

- ➢ Initial studies: three scenarios:

  Deep ocean - 1000 m (~100 bar), T_s = 4 °C, 3.5 °C/100m

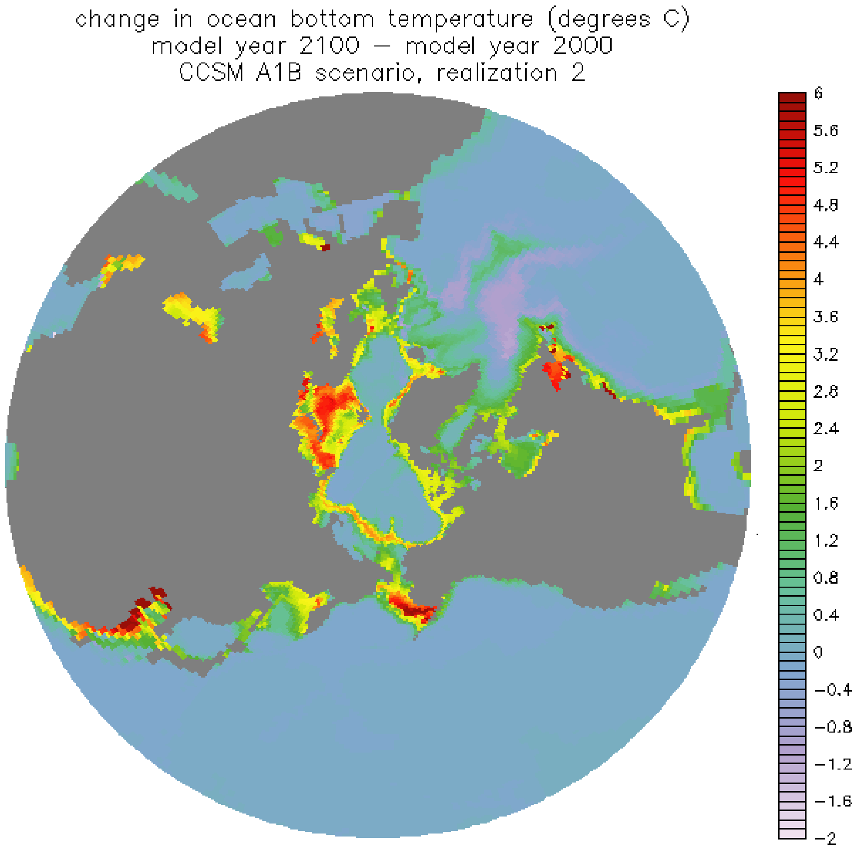
  GoM - 570 m (~57 bar), T_s= 6 °C, 2.8 °C/100m

  Arctic shelf - 320 m (~32 bar), T_s = 0.4 °C, 3 °C/100m



Task 1 + Task 3: Preliminary Studies
Climate Change Scenarios

- IPCC A1B climate simulations suggest 1-2 °C ocean warming at many shallow locations at the seafloor in the next 100 years, and perhaps an additional +3 °C by 2200.
- ΔT is location and depth dependent

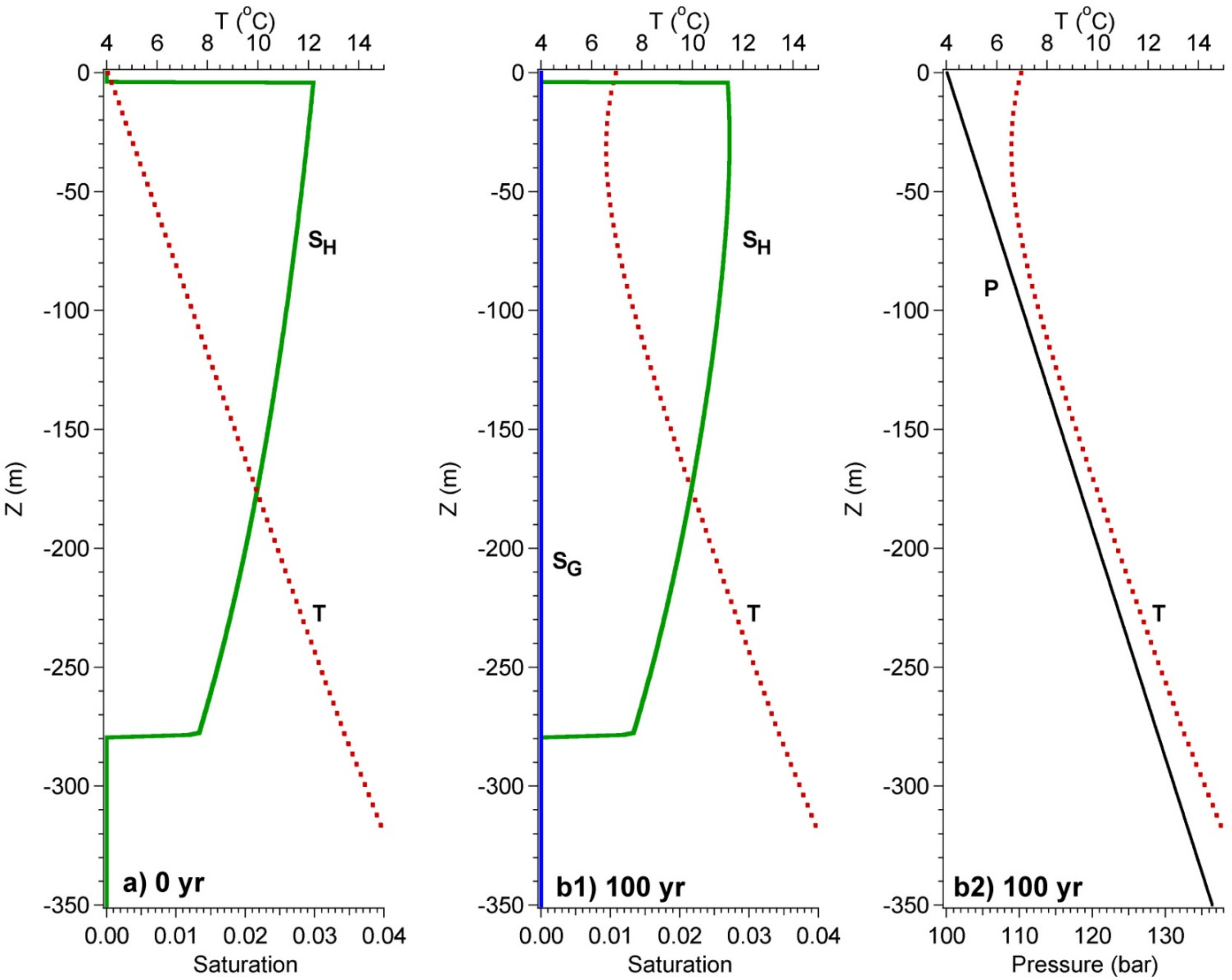


- We test 1 °C/100yr, 3 °C/100yr, and 5 °C/100yr
- Linear change in temperature at top of sediment column, T_S, at constant P_s
- Short-term changes: short-term response

Results: Deep, Cold Hydrates

ΔT = +3 °C @ 1000m

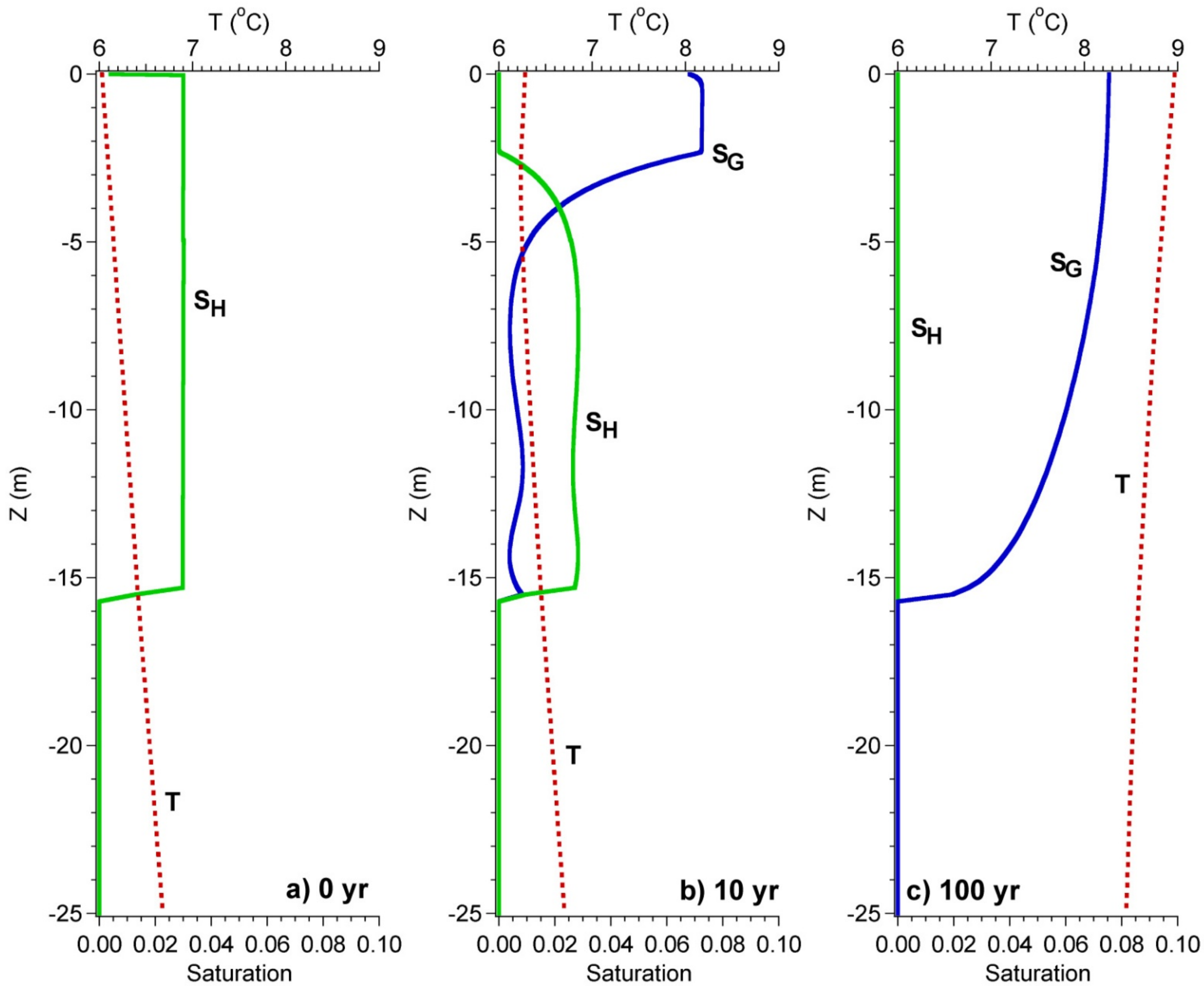
- No gas escapes sediment column
- No significant methane flux at top of sediment column
- Slight change in hydrate distribution
- Agrees with previous equilibrium models
- +10°C change required to release gas



Results: Warm, Shallow Hydrates

ΔT = +3°C @ 570m

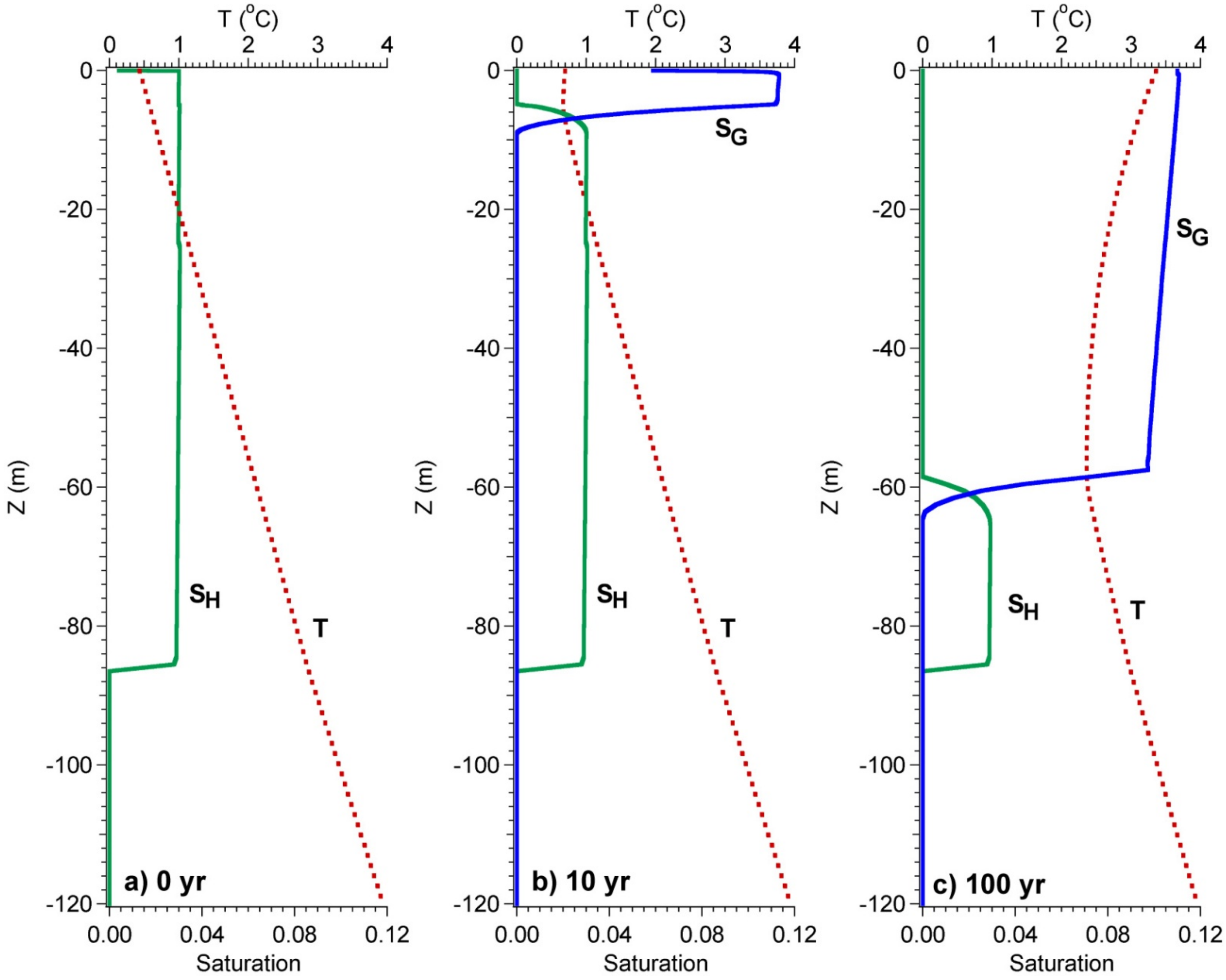
- Initial thin hydrate layer
- Close to the surface, close to the top of the GHSZ
- Rapid dissociation from the top and bottom
- No hydrate remains at t = 100 yr



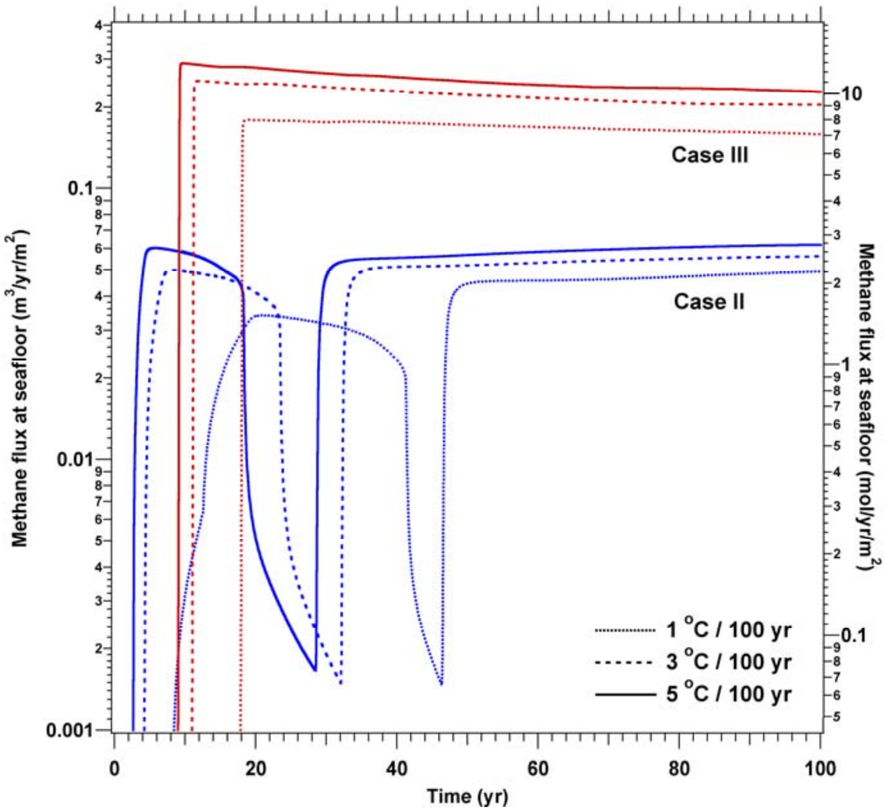
Results: Cold, Shallow Hydrates

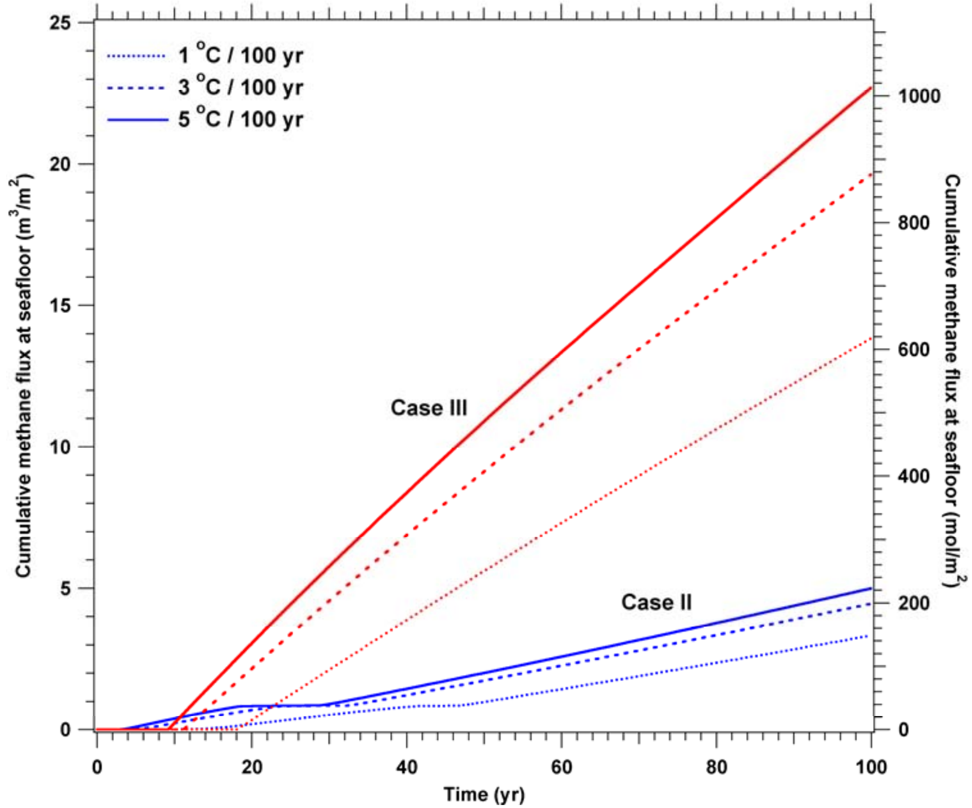
ΔT = +3 °C @ 320m

- Thick hydrate layer
- Dissociates from top
- 60m of hydrate dissociated at *t* = 100yr
- 1/3 of the deposit remains at *t* = 100 yr
- Remaining hydrate dissociates by 250-300 yr (no further change in *T*)



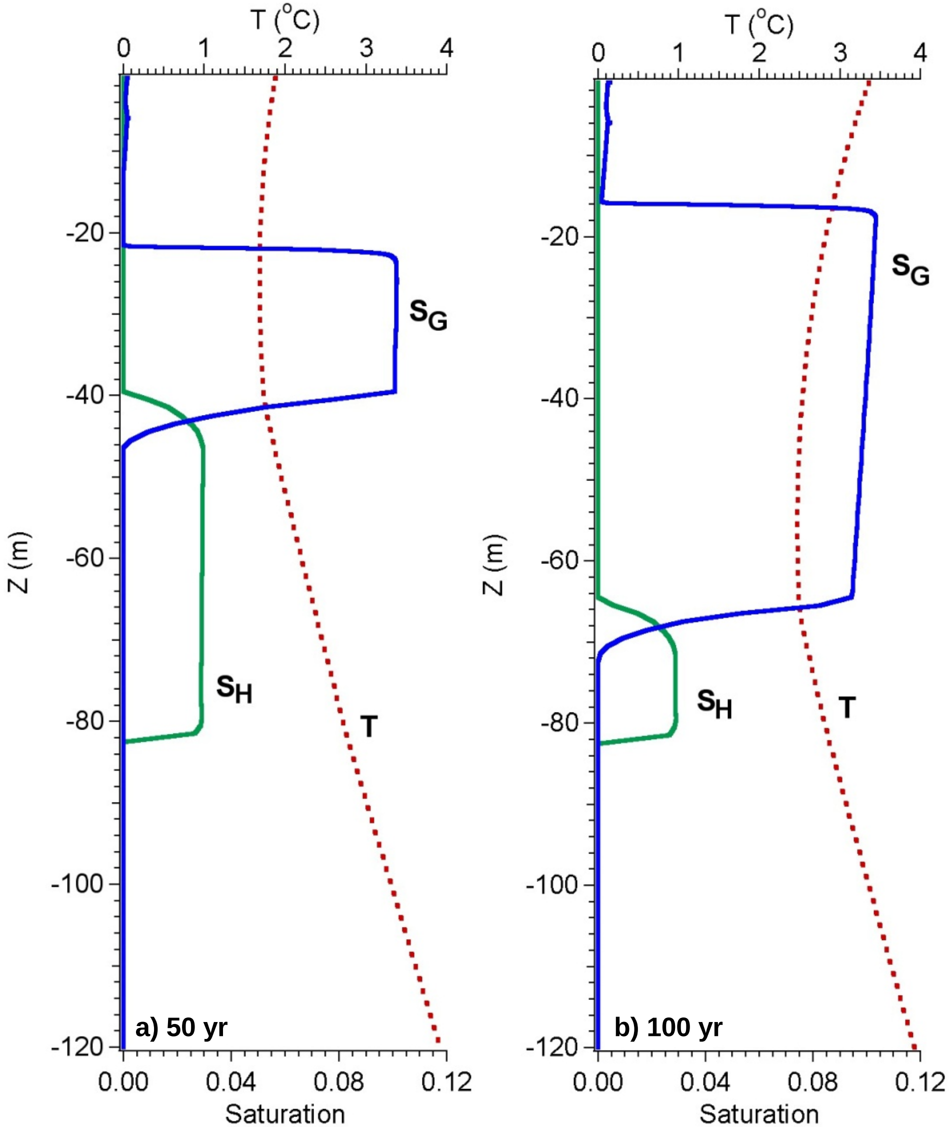
Results: Release Rates





- Peak methane fluxes: 2.5 mol/yr/m^2 (GoM, 570m), 11 mol/yr/m^2 (Arctic, 320m)
- Peak flow velocities: 6.3 cm/yr (GoM, 570m), 2.8 cm/yr (Arctic, 320m) @ +3 ^{o}C

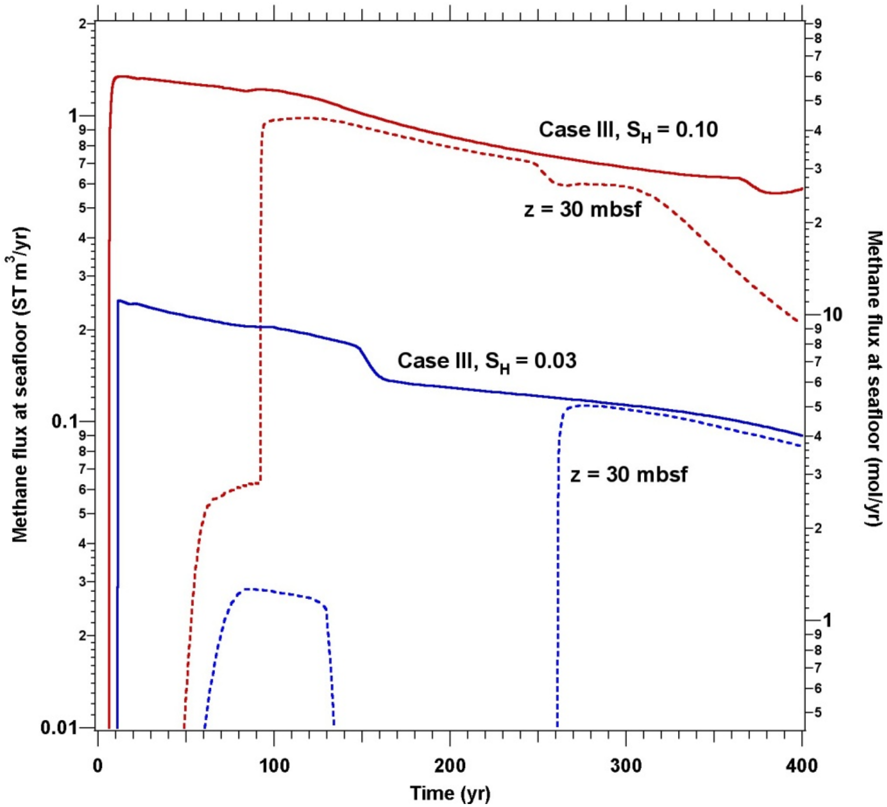
Results: Deposit Depth



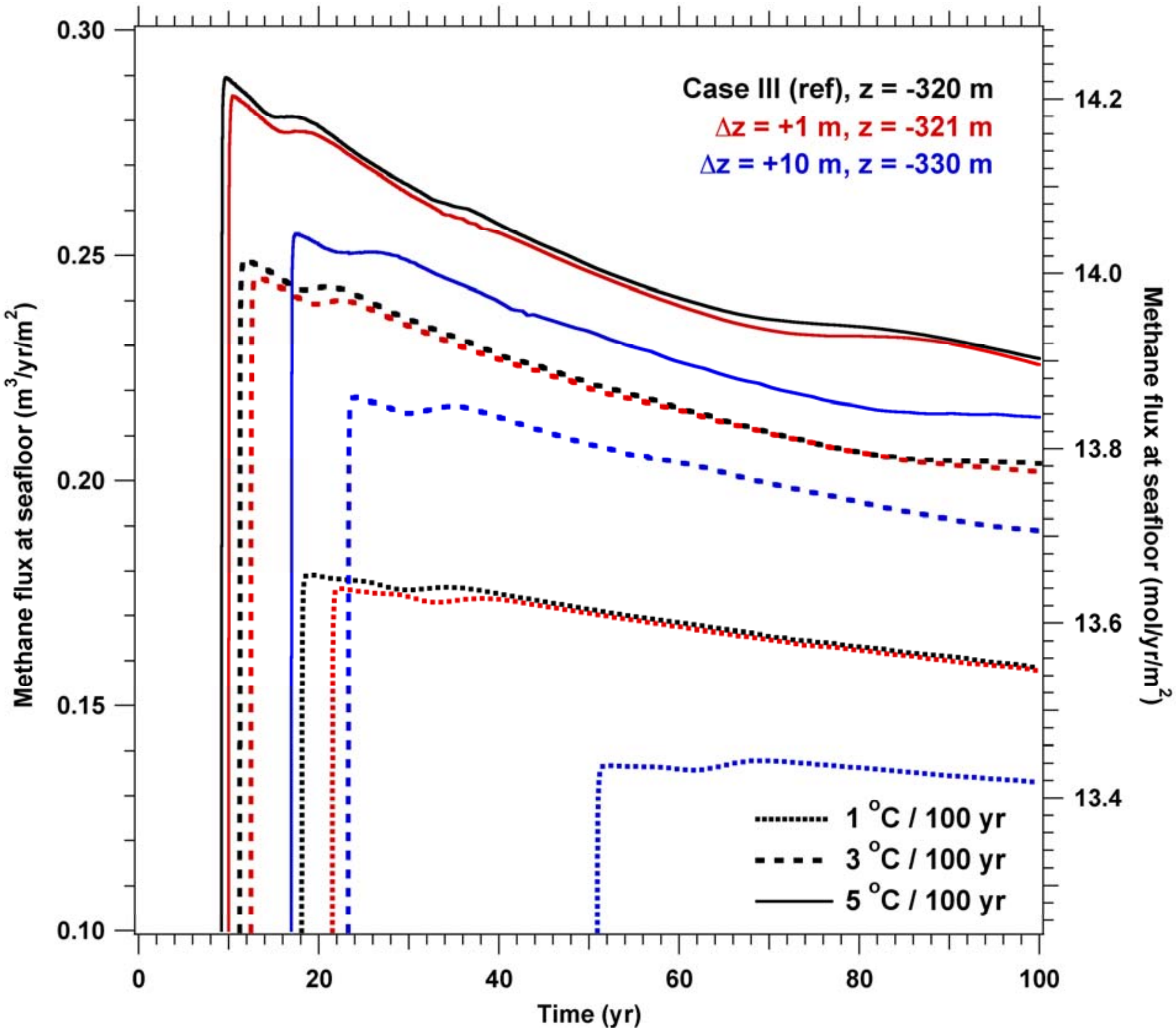
- S_H = 0.03 case
- Remove 30 m of hydrate

➢ Delay in arrival of gas plume

➢ Acceleration of *T* front



Results: Sea Level



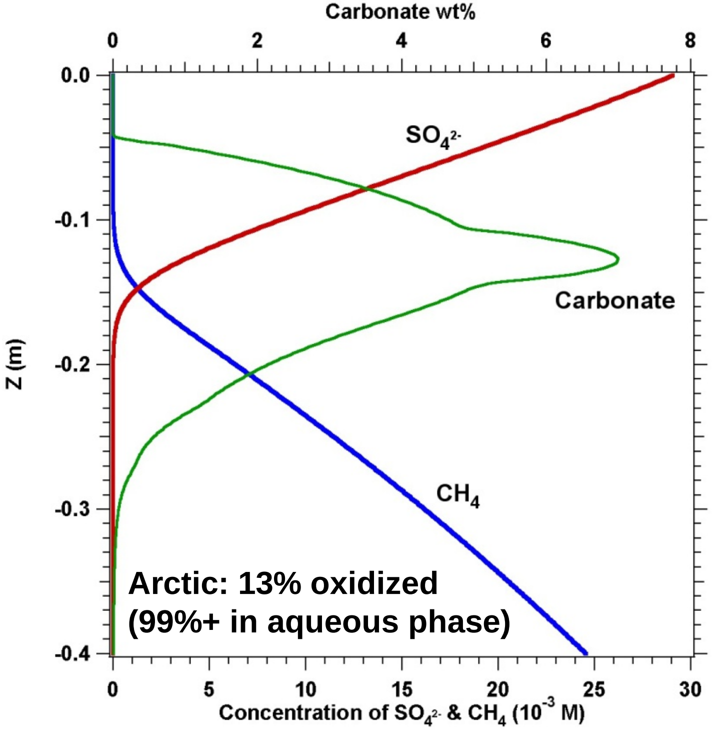
- S_H = 0.03 case
- Sea level increases (inflow of melt water) by 1 m or 10 m

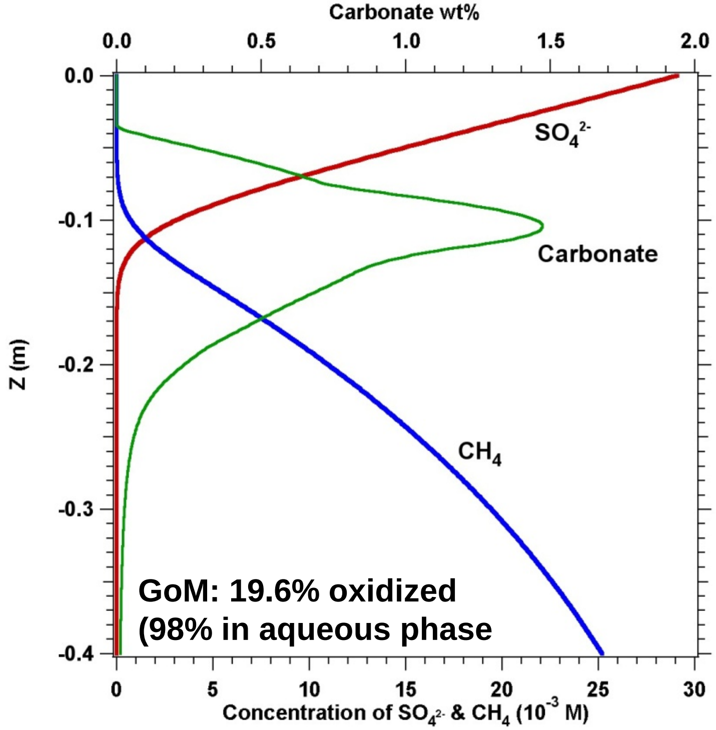
➢ Delay in the appearance of gas at the seafloor

➢ Limited mitigation of methane release

Task 2: Biogeochemical Mitigation

- Methane fluxes and fluid flow forward-coupled into C.CANDI (Luff et al.) coupled benthic chemistry and transport model
- Nearly all aqueous methane oxidized to CO_2 or bicarbonate in both cases
- Precipitation of solid carbonate (sequestration)





- Majority of methane release in gas phase
- Carbonate precipitation limited
- Gas-phase methane likely to escape
- Need fully-coupled chemistry
- Evaluating TOUGH+REACT vs. C.CANDI

Conclusions and Future Work

- Deep ocean hydrates are likely stable under short-term temperature excursions, but shallower deposits require more attention
  - Warm, shallow hydrates are readily dissociated
  - Cold, shallow arctic hydrates can release significant methane rapidly, with larger fluid velocities
  - Dissociation rate is regulated by coupled processes
  - Depth and sea level are not necessarily mitigating factors
- Examination of localized deposits, at various depths/conditions, and coupling to benthic chemistry, can create a source term for regional and global ocean and climate models

- Publications (project initiation date: LBNL - May 2008; LANL - June 2008)

Reagan, M.T. and G.J. Moridis, "The dynamic response of oceanic hydrate deposits to ocean temperature change," *J. Geophys. Res.: Oceans*, submitted June 2008, accepted August 2008.

Reagan, M.T, Moridis, G.J., Zhang, K., "Modeling of Gas Hydrate Instability and Methane Release in Response to Climate Change," *Proceedings of the 6th International Conference on Gas Hydrates*, Vancouver, BC, July 6-10, 2008.