Oil & Natural Gas Technology

FWP ESD07-014 - Lawrence Berkeley National Laboratory
FWP 08FE-003 – Los Alamos National Laboratory

Topical Report

Interrelation of Global Climate and the Response of Oceanic Hydrate Accumulations

Submitted by:
Matthew T. Reagan
Lawrence Berkeley National Laboratory
1 Cyclotron Road
Berkeley, CA 94720
e-mail: mtreagan@lbl.gov
Phone number: (510)486-6517

Prepared for:
United States Department of Energy
National Energy Technology Laboratory

Office of Fossil Energy

Interrelation of Global Climate and the Response of Oceanic Hydrate Accumulations

Task Report

Date: March 1, 2013
Period: June 1, 2012 – February 28, 2013
NETL Manager: Skip Pratt

Principal Investigator: Matthew T. Reagan, mtreagan@lbl.gov, (510) 486-6517

Acknowledgment: "This material is based upon work supported by the Department of Energy."

Task 2: Global Scale Simulations of the Interrelation Between Hydrate Dissociation and Global Climate

Abstract
It has been postulated that methane from oceanic hydrates may have a significant role in future climate, but the behavior of contemporary oceanic methane hydrate deposits subjected to rapid temperature changes has only recently been investigated. Field investigations have discovered substantial methane gas plumes exiting the seafloor at depths corresponding to the upper limit of a receding gas hydrate stability zone, suggesting the possible warming-driven dissociation of shallow hydrate deposits and raising the question of whether these releases may increase and become more common in the future. Previous work in this project has established that such methane release is strongly regulated by coupled thermo-hydrological-transport processes in the sediments and coupled biogeochemical processes in the water column. In this Task, we simulate the release of methane from oceanic deposits on a global scale, using temperature changes taken directly from the CESM global climate model—the first such simulations performed. The results show that the methane release is likely to be confined to a narrow region of high dissociation susceptibility, defined mainly by depth and temperature, and that any release will be relatively uniform and controlled, rather than explosive. However, the released quantities can be

biogeochemically and climatologically significant, as they are similar in magnitude and distribution to the estimated methane release quantities derived from earlier sensitivity studies that suggest significant chemical changes in the water column and significant changes in atmospheric chemistry. Moreover, the methane fluxes shown here are also within the range of potential climate sensitivity, such that recent developments in bubble-plume modeling and nutrient limitation effects in the water column biochemical filter will be necessary to fully understand the consequences.

Models and Methods

The TOUGH+HYDRATE code [Moridis et al., 2008] used in this study describes multiphase flow and transport in hydrate-bearing geologic media. It includes coupled mass and energy transport within porous and fractured media, and also describes the full phase behavior of water, methane, solid hydrate, ice, and inhibitors (i.e. salts). This code was used in previous studies of hydrate dissociation in oceanic sediments [Reagan & Moridis, 2011a]. The global ocean simulations are based on a one degree resolution, global Parallel Ocean Program (POP), part of the Community Earth System Model (CESM), a fully-coupled, global climate model that provides state-of-the-art computer simulations of past, present, and future climate states [Gent et al., 2011]. The CESM model is the same described in earlier work in this project [Elliott et al., 2011].

As in previous studies, we simulate disperse, low-saturation deposits from a water depth of 300 m, above the top of the likely GHSZ for any non-permafrost-associated hydrates, down to a water depth of 1000 m. The representation of each depth/location involves a vertical, 1-D domain describing the sediment column from the seafloor downward [Reagan & Moridis, 2008]. Initial seafloor temperatures are taken from the bottom (seafloor) gridblocks of the POP model—thus T and P vary with depth and location—and we assume a sediment geothermal gradient of 3˚C /100m. We use a uniform initial hydrate saturation of 3% reflecting the high end of the estimated global average saturation for stratigraphic deposits [Reagan & Moridis, 2008]. This, of course, is an assumption that all regions that allow stable hydrate actually contain stable hydrate, and as such we are calculating upper limits for hydrate dissociation and methane release. However, the global distribution of hydrates has been assessed mainly through thermodynamic modeling and the spatial distribution within sediments, globally, is still an open question. With this in mind, the initial condition is at steady state, and at complete thermal, chemical, and hydrostatic equilibrium at the selected depth and temperature. The top of the sediment column is an open boundary, allowing heat and mass transfer between the sediment and the ocean. A detailed description of the column-simulation methodology, the sourcing of the common parameters, parametric sensitivity studies, and justification of assumptions can be found in Reagan & Moridis [2008].

We calculate methane fluxes at the seafloor using the RCP8.5 (radiative forcing of 8.5 W/m^2 by 2100), one of the more strongly forced climate change scenarios (van Vuuren et al., 2011) that has recently received greater attention as a possible viable outcome. After 2100, the temperature is held constant (as predicting temperature change beyond this point becomes increasingly speculative), and the system is allowed to find a new equilibrium. We also use the "Historical" dataset, a set of climate simulations used to "hindcast" the period from 1855-2010, to establish the potential location of stable hydrates in the pre-warming ocean.

We remove from the integration CESM/POP gridblocks where 1) shallow hydrate could not have existed prior to 1855, 2) climate simulations show no temperature increase by 2100, and 3) hydrates are deep enough that the largest temperature changes indicated in the RCP8.5 scenario ($\Delta T = + 6^{\circ}C$ for locations remaining after criteria 1 and 2 are applied) would not cause hydrate dissociation at the top of the column (i.e., the seafloor remains within the GHSZ). This limitation gives very similar results to the exclusion of systems shallower than 300 m and deeper than 1000 m, as discussed in early publications, with the additional of excluding systems not expected to experience temperature changes. As the POP ocean model component uses a relatively coarse depth discretization, we use the ETOPO2 database [USDC, 2006] to convert the longitude and latitude of each CESM/POP gridblock to an accurate value for seafloor depth. We use a coarse integration discretization in depth and temperature for this initial study, grouping initial temperatures and ΔTs into 1˚ bins, and depths into 50 m bins. While this may "smooth out" some of the z/T dependences, previous studies [Reagan et al., 2011b] lead us to expect that only a few depth zones with similar average fluxes will play a role. Future integrations may refine this discretization (resulting in a much larger ensemble of simulations) if it is necessary to reduce the uncertainty and refine the estimates to constrain possible releases.

The results currently include a preliminary global estimate of the potential quantity of methane that could be released due to the RCP85 climate scenario. However, we also present an analysis of the temperature change scenarios themselves, as the *location* of the release may be as important as the magnitude of the release. Previous work in this project has focused on hypothetical scenarios in the Arctic and Sea of Okhotsk, with notable biogeochemical consequences [Elliott et al., 2011].

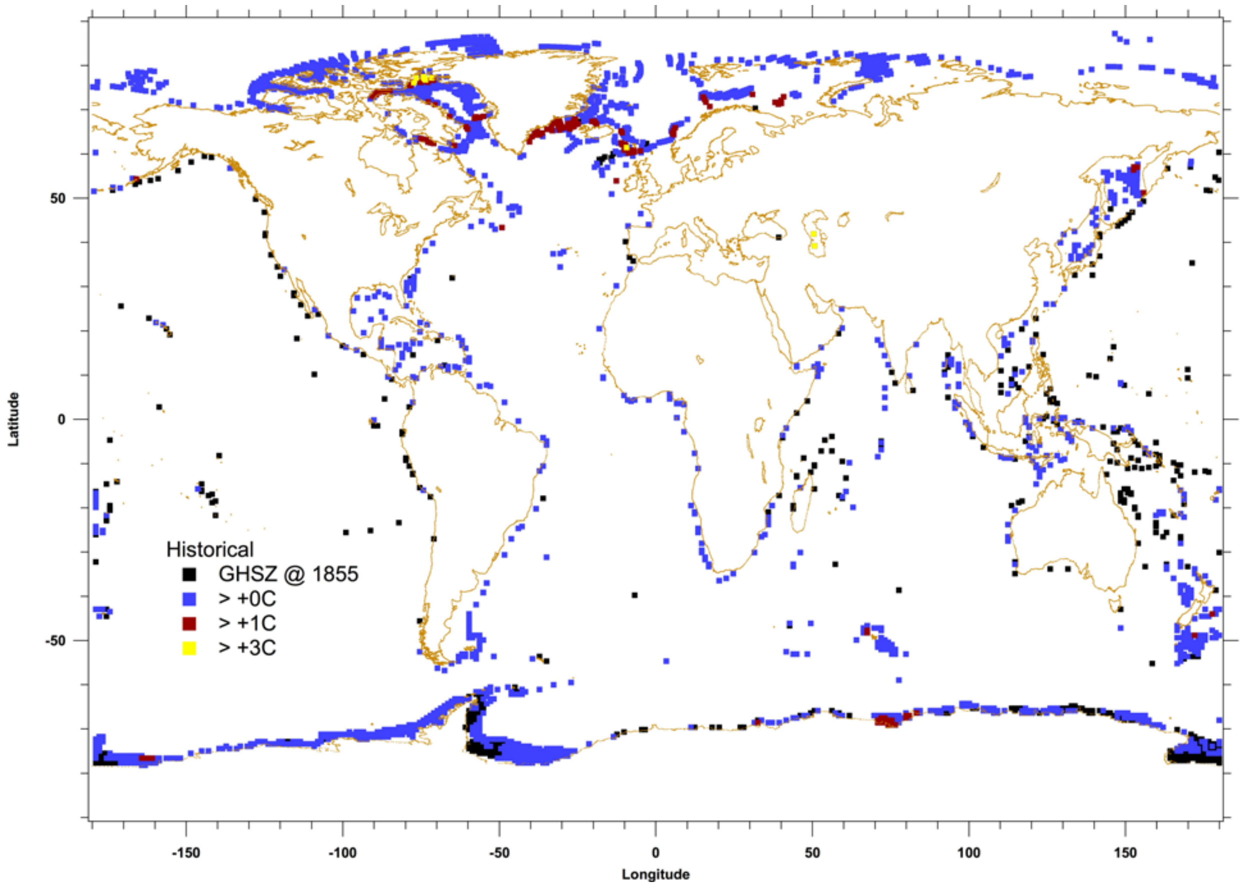

Figure 1: Map of seafloor temperature change for the "Historical" CMIP5 scenario (1855-2010). The dots indicate CESM gridblocks within the GHSZ at 1855. Within that set, black dots are those that experience no warming, blue dots those that experience 0-1˚C warming, red dots those that experience 1-3˚C warming, and yellow dots those that experience 3-4˚C warming.

Results

1. Distribution and Magnitude of Temperature Change at the Seafloor

We first look at the location of climate-sensitive hydrates. Figure 1 present a map of the seafloor, with points representing gridblocks in the CESM 1-degree mesh that meet the following criteria:

1) The seafloor was within the GHSZ at year 1855 (all dots), plus
2) The seafloor experienced no significant positive temperature change (black dots)
3) The seafloor experienced 0-1˚ warming (blue dots)
4) The seafloor experienced 1-3˚ warming (red dots)
5) The seafloor experienced 3-4˚ warming (yellow dots)

It is clear that the bulk of the seafloor that 1) could have had shallow hydrates and 2) could have climate-sensitive hydrates is located in the polar regions, with the currently poorly understood Antarctic continental slope having quite a bit of potential hydrates in addition to the better-understood (and often studied) Arctic basin. However, it appears that most of these hydrates have experienced less than +1˚C of warming between 1855-2010 (most of it during the interval 1910-2010), with only a few regions experiencing greater warming. (This temperature assessment suggests that perhaps the Greenland coast and areas North Sea may be worthy of investigation).

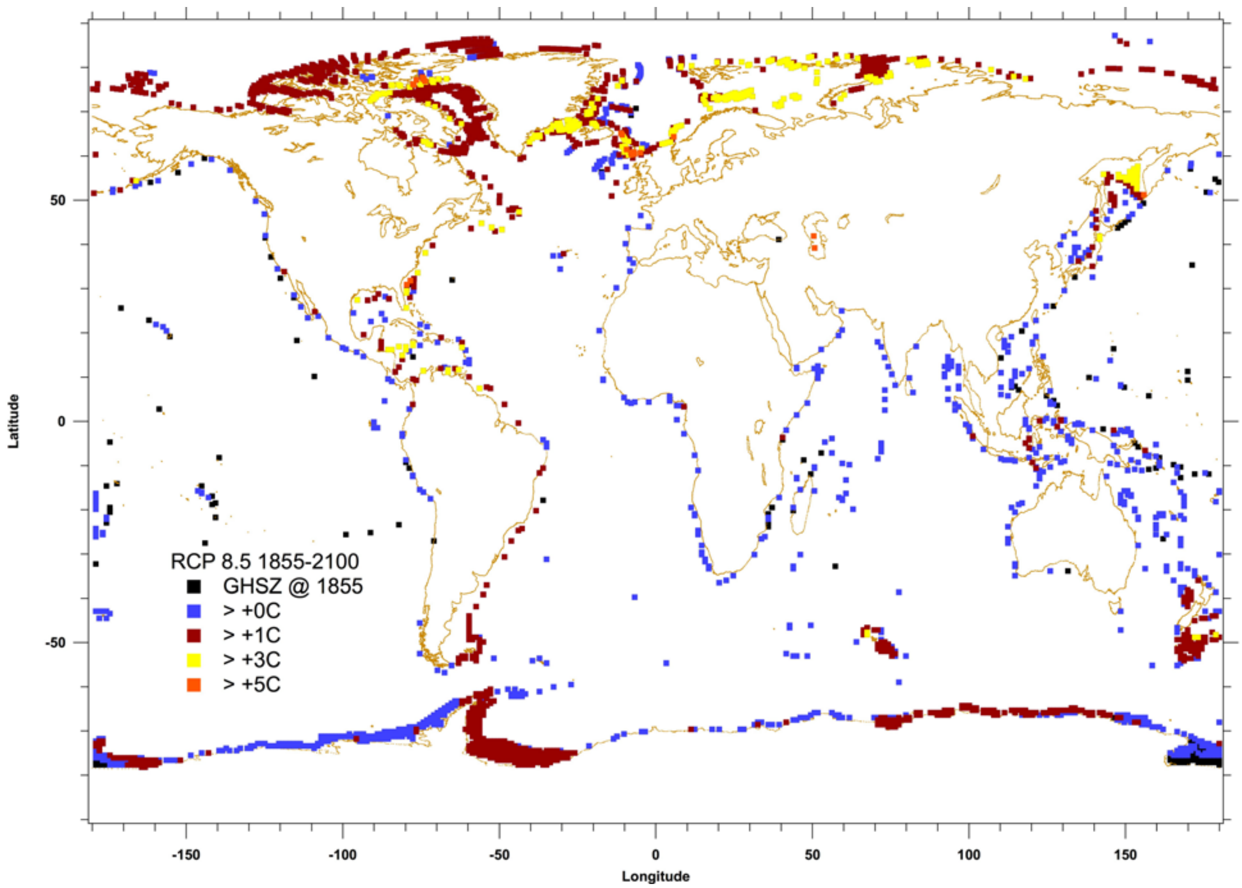

Figure 2: Map of seafloor temperature change for the RCP8.5 scenario (1855-2100). The dots indicate CESM gridblocks within the GHSZ at 1855. Within that set, black dots are those that experience no warming, blue dots those that experience 0-1˚C warming, red dots those that experience 1-3˚C warming, and yellow dots those that experience 3-5˚C warming, and orange dots those that experience 5-6˚C warming.

Figure 2 shows an analogous map for the RCP8.5 scenario, tracking total temperature change from 1855-2100. An additional criterium:

6) The seafloor experienced 5-6˚ warming (orange dots)

is included to reflect the great warming in this scenario. Again, we have a strong bias towards polar regions for the location of climate-sensitive hydrates. This is in close agreement to the assumptions made earlier in the study, where we chose to focus on Arctic systems.

Figure 3 shows histograms of susceptible hydrates vs. latitude and depth, using the same depth-temperature criteria as in the previous figures. In the left panel, we see that, by areal percentage, the bulk of the climate-sensitive hydrates (based on the RCP8.5 scenario) exist in high northern latitudes regions, moreso than even in Antarctic waters. In the right panel, we see that shallow hydrates in the 300 m – 600 m range make up the bulk of sensitive hydrates, with hydrates deeper than 1000 m not expected to be affected. As a result, we do not expect the global-scale integrations to differ drastically from the estimated temperature scenarios studied in early work on this project.

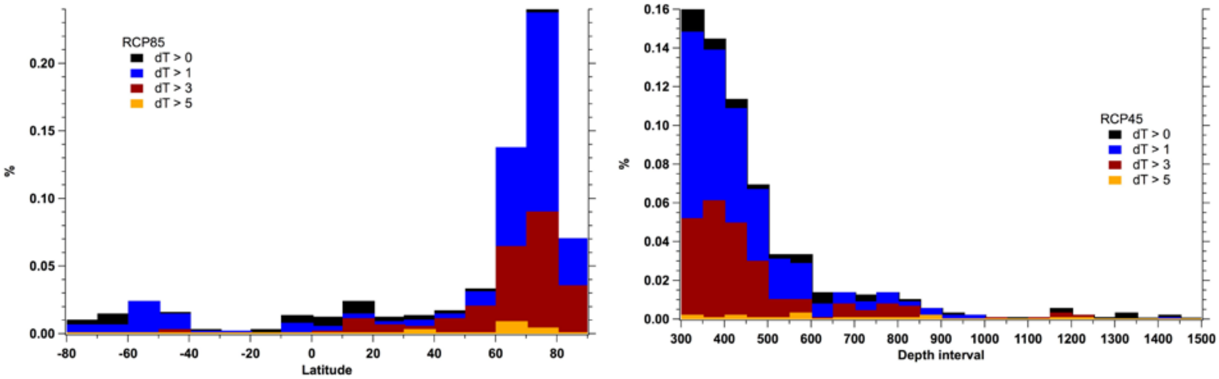

Figure 3: Histogram of the distribution of temperature changes by latitude (left) and depth interval (right), for the RCP8.5 scenario (1855-2100).

2. Global Integration of Sediment Flux Calculations

We then integrate the depth-temperature driven sediment column releases, forced by the RCP8.5 derived temperature changes at the seafloor, and integrate across the coarse depth, temperature, and 1-degree spatial grid to estimates methane flux into the water column as driven directly by the CESM climate model. Figure 4 shows the evolution of instantaneous flux (red line) vs. time, with $t = 0$ placed at the transition between the historical and RCP8.5 temperature profiles and continuing 300 years into the future. Note that we hold the seafloor temperature constant after $t = 100$ yr, since longer-term warming trends are increasingly speculative. Figure 4 also shows the cumulative release of methane (blue line) into the environment from 2011 onward.

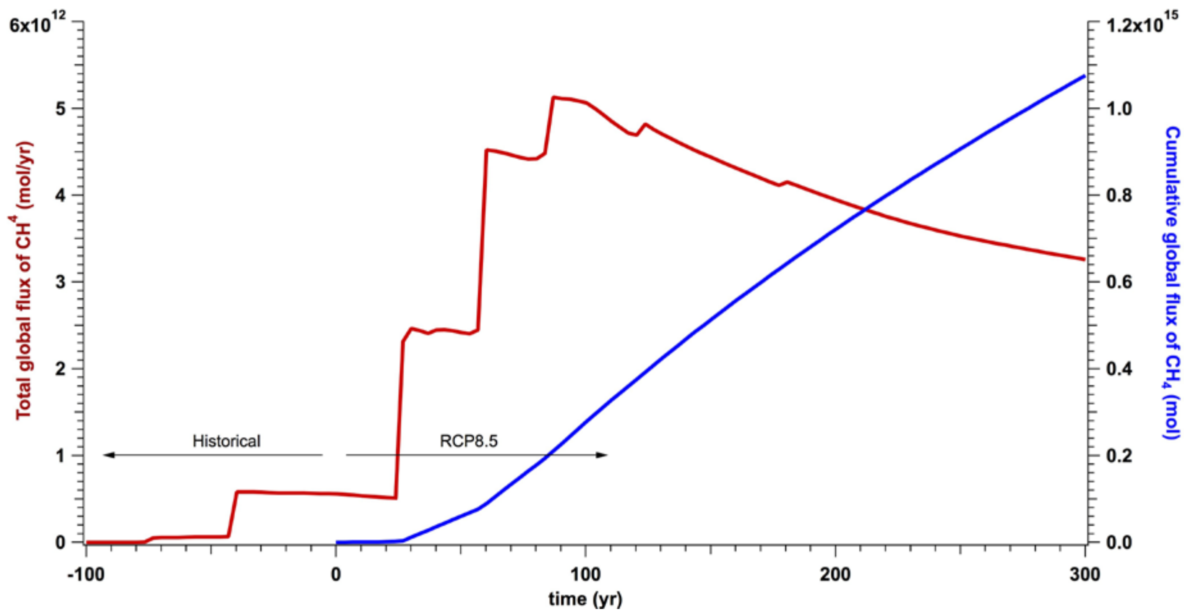

Figure 4: Methane flux into the water column (red) and cumulative release of methane (blue) vs. time for the RCP8.5 scenario.

Previous work using hypothetical Arctic temperature scenarios (ranging from +1°C everywhere to +5°C everywhere) estimated cumulative release at t = +100 yr of about 0.15 – 0.55 $\times 10^{15}$ mol (2,400 – 8,800 Tg) CH_4. Here, the global integration for the RCP 8.5 scenario gives an estimate of 0.25×10^{15} mol (4,000 Tg) CH_4. Despite the coarseness of these initial simulations, this is within the magnitude range computed in the hypothetical scenarios. The estimated global flux peaks at t = +93 yr at 5.1×10^{12} mol/yr (82 Tg/yr). Combined with the strong weighting of the releases in the Arctic basin (as well as Okhotsk), the previously assessed biogeochemical consequences (oxygen depletion, pH increases, and possible stressing of the water column biogeochemical "filter") hold for the global-scale assessment. Furthermore, colleagues at LLNL have reported that methane releases into the atmosphere of order 100 Tg/yr, localized around the Arctic basin, are significant enough to be a small but noticeable contributor to warming, but not necessarily a runaway feedback mechanism (unpublished research, personal communication). Related work has also shown the possibility that methane releases potentially lead to increased surface ozone (at levels equal to urban smog at some locations) and decreased stratospheric ozone (due to chemical pathways that lead to increased stratospheric cloud formation). Therefore this first global assessment maintains the potential significance of hydrate-derived methane to global climate, suggesting further investigation of climate and ecological consequences is warranted.

Conclusions, Current Work, and Future Directions

The next stage of the project, evaluation of the Clathrate Gun hypothesis, is already under way, including more detailed global assessments. For this next task, the global-scale evaluations need to be refined. First, increased resolution in the *x*-*y*-*z*-*T* integration, particularly in the binning of depths, is expected to capture more of the behavior of hydrates in the critical 300 m - 400 m zone (where most of the sensitive hydrates would likely exist). The "steps" seen in the plot of flux vs. time reflect the activation of different depth-temperature regimes by warming, and these curves are expected to smooth out considerably as we subdivide the depth ranges. This is particularly important as we move closer to making meaningful time predictions for the appearance of methane plumes, as these steps add significant uncertainty to the locating of past and future localized release events. We will also repeat the integration for the RCP4.5 ("middle of the road") forcing pathway and thus estimate the sensitivity of the hydrate reservoir to different temperature outcomes. As our results to this point sit quite close to the boundary between less significant and quite significant, and thus a more detailed assessment, with sensitivity studies, is necessary.

Current and upcoming CESM simulations also include the additional of a novel bubble-plume component. Using observations [Rehder et al. 2002; Leifer and MacDonald, 2003] and existing plume models [Leifer and Patro, 2002], a parameterization has been developed, accounting for methane flux, bubble size, methane dissolution and fugacity effects, and surfactant effects. Preliminary results suggest that the inclusion of bubble transport may increase transport to the atmosphere by an order of magnitude compared to transport of dissolved gas through a well-oxygenated water column. This, coupled with the biochemical resource limitations discussed in Elliott et al. [2011] is expected to lead to greater transport of released methane into the mixed layer and to the atmosphere compared to other previous and recent global-scale assessments.

The results of these more sophisticated experiments will be part of future reports, and upcoming publications.

Communications and Tech Transfer

Two papers are currently in preparation:

Scott Elliott (LANL), "Systems Model Representation of Ocean Bubble Plumes Over Decomposing Arctic Clathrates"

Matthew Reagan, "Constraints on the Release of Hydrate-Derived Methane in Response to Climate Change"

References

Elliott, S.M., Maltrud, M., Reagan, M.T., Moridis, G.J., Cameron-Smith, P.J. (2011), Marine Methane Cycle Simulations for the Period of Early Global Warming. *J. Geophysical Res. Biogeo*., *116*, G01010.

Gent, P. R., G. Danabasoglu, L. J. Donner, M. M. Holland, E. C. Hunke, S. R. Jayne, D. M. Lawrence, R. B. Neale, P. J. Rasch, M. Vertenstein, P. H. Worley, Z. –L. Yang, and M. Zhang (2011). The Community Climate System Model Version 4. *Journal of Climate*, 24 (19), 4973-4991.

Leifer, I. and I. McDonald (2003). Dynamics of the gas flux from shallow gas hydrate deposits: Interactions between hydrate bubbles and the oceanic environment. *Earth Planet. Sci. Lett.* 210, 411-424.

Leifer, I. and R. Patro (2002). The bubble mechanism for methane transport from the shallow sea bed to the surface. A review and sensitivity study. *Cont. Shelf. Res*. 22, 2409-2428.

Moridis, G.J., Kowalsky, M.B., Pruess, K. (2008) *TOUGH+HYDRATE v1.0 User's Manual: A Code for the Simulation of System Behavior in Hydrate-Bearing Geologic Media*, Report LBNL-0149E, Lawrence Berkeley National Laboratory, Berkeley, CA.

Reagan, M.T., Moridis, G.J., Elliott, S.M., Maltrud, M. (2011a), Contributions of Oceanic Gas Hydrate Dissociation to the Formation of Arctic Ocean Methane Plumes, *J. Geophys. Res. Oceans*, *116*, C09014, doi: 10.1029/2011JC007189.

Reagan, M.T., Moridis, G.J., Elliott, S.M., Maltrud, M., and Cameron-Smith, P.J., (2011b). Basin-Scale Assessment of Gas Hydrate Dissociation in Response to Climate Change, *Proc*. 7th International Conference on Gas Hydrates, Edinburgh, Scotland, UK, 17-21 July 2011.

Reagan, M.T., Moridis, G.J. (2008), Dynamic response of oceanic hydrate deposits to ocean temperature change, *J. Geophys. Res*., *113*, C12023, doi:10.1029/2008JC004938.

Rehder. G., P. Brewer, E Peltzer and G. Friederich (2002) Enhanced lifetime of methane bubble streams within the deep ocean. *Geophys. Res. Lett*. 29, 10.1029/2001GL013966.

U.S. Department of Commerce (2006). National Oceanic and Atmospheric Administration, National Geophysical Data Center, 2-minute Gridded Global Relief Data (ETOPO2v2).

van Vuuren et al. (2011). The Representative Concentration Pathways: An Overview. *Climatic Change*, 109 (1-2), 5-31.