IMPACTS:
Investigation of the Magnitudes and Probabilities of Abrupt Climate TransitionS

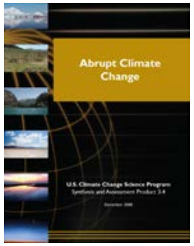
William D. Collins

Lawrence Berkeley Lab and UC Berkeley

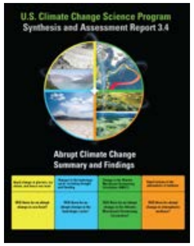
And the IMPACTS Team

Background to the IMPACTS Project
Abrupt Climate Change

- **Abrupt climate change** is a large-scale climate shift that occurs quickly, persists for decades to millennia**, and can cause substantial disruptions in human and natural systems.**
- **Abrupt climate change (ACC) is evident in the geologic record.**
- **Four types of ACC that would pose a major challenge to society are:**
  - *Rapid change in glaciers, ice sheets, and sea level*
  - *Widespread changes to the hydrologic cycle, including droughts*
  - *Abrupt change in the Atlantic Meridional Overturning Circulation*
  - *Rapid release to the atmosphere of methane*
- **BER launched IMPACTS to advance our understanding and to project the risks of all four types of ACC.**





IMPACTS: Investigation of the Magnitudes and Probabilities of Abrupt Climate TransitionS

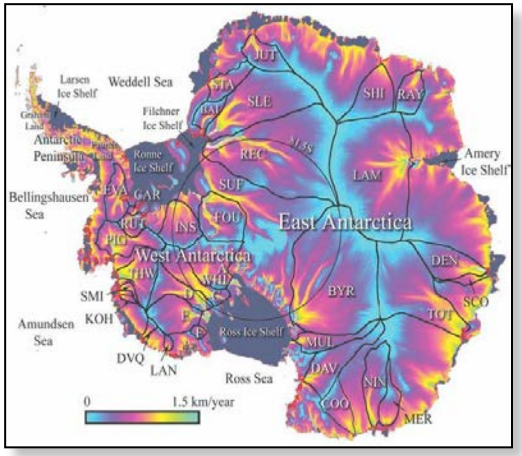
The IMPACTS Team

- **Xylar Asay-Davis**
- **Dan Bergmann**
- **Celine Bonfils**
- **Philip Cameron-Smith**
- **William Collins**
- **Scott Elliott**
- **Samson Hagos**
- **Maoyi Huang**
- **Stacy Jackson**
- **Robert Jacob**
- **Phil Jones**
- **Jong Kim**
- **Ruby Leung**
- **Bill Lipscomb**
- **Xiaohong Liu**
- **Mat Maltrud**
- **Tom Phillips**
- **Mac Post**
- **Steve Price**
- **Mat Reagan**
- **Bill Riley**
- **Todd Ringler**
- **Zack Subin**
- **Margaret Torn**
- **Chun Zhao**
- **Qianlai Zhuang**

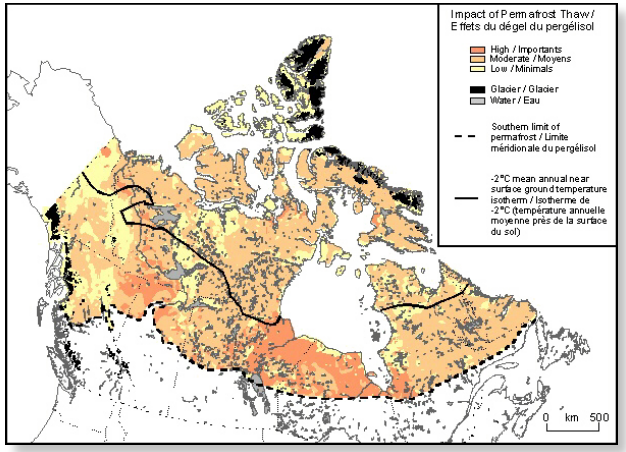
IMPACTS: Investigation of the Magnitudes and Probabilities of Abrupt Climate TransitionS

Physics-based projections of abrupt climate change

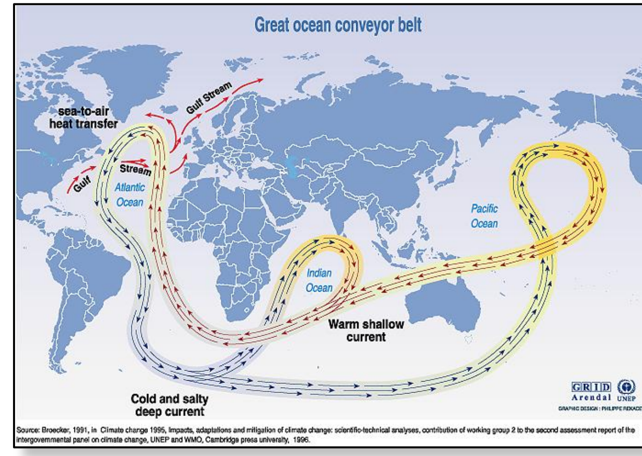
Marine ice sheet instability



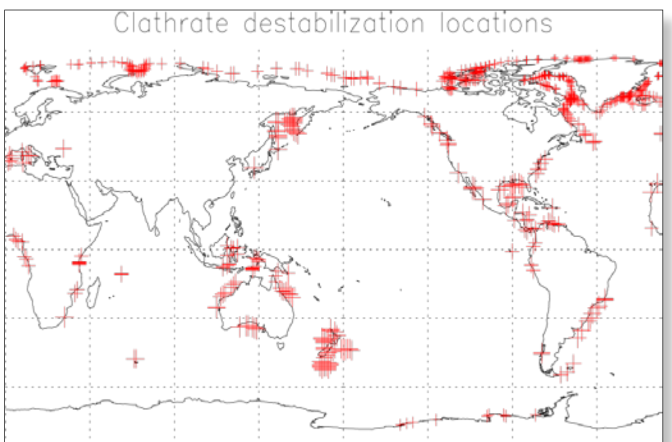
Boreal/Arctic climate feedbacks



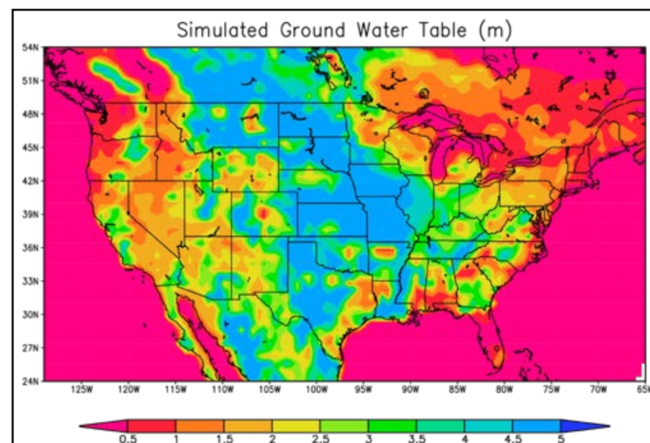
Stability of Global Ocean Circulation



Methane hydrate destabilization



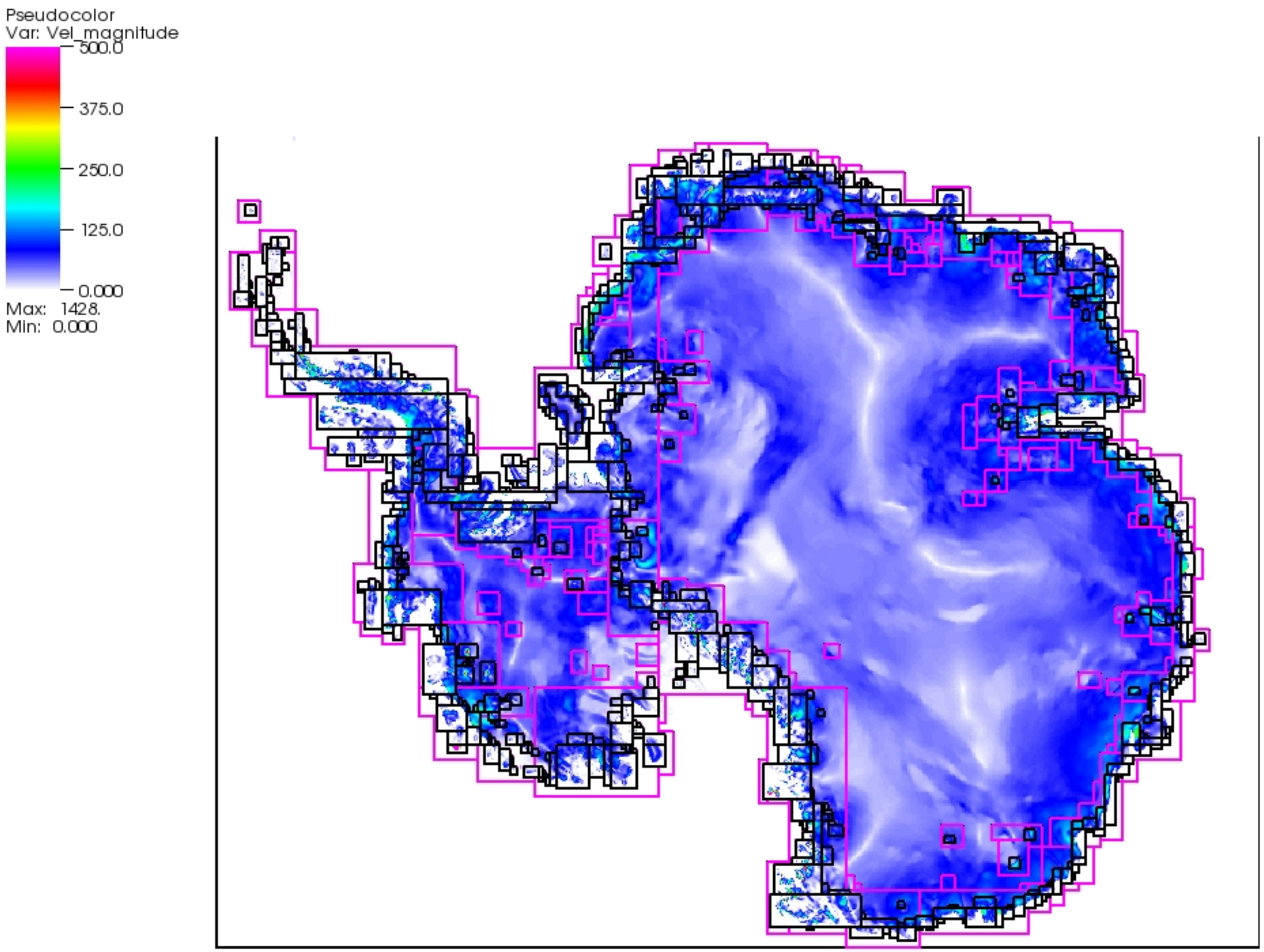
Mega droughts in N. America



IMPACTS: Investigation of the Magnitudes and Probabilities of Abrupt Climate TransitionS

Future of Greenland and Antarctic Ice Sheets

Dynamics of Antarctica and Sea-Level Rise



IMPACTS: Investigation of the Magnitudes and Probabilities of Abrupt Climate TransitionS

Implementation of Land-Ice/Ocean Interface in POP

Objectives:

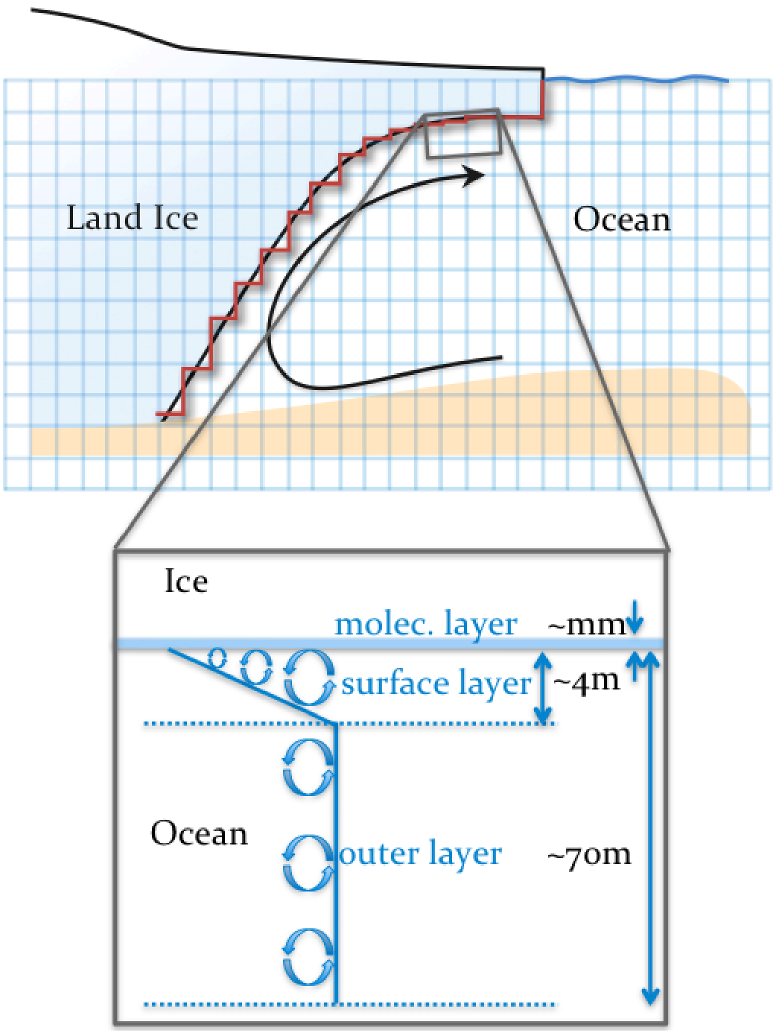
- Projections of sea-level rise due to Antarctic and Greenland ice sheets
- Examine abrupt climate feedbacks related to land-ice/ocean interactions

Implementation:

- Adding *dynamic* land-ice/ocean interface to POP
    - partial cells
    - immersed boundaries
- Developed efficient algorithms for representing turbulent ocean boundary layers under ice shelves

Experiments:

- Underway: expts. with fixed, idealized geometries for model comparison
- Next: expts. with fixed, realistic geometries for data comparison



top: land-ice/ocean interface (using partial cells)
bottom: turbulent boundary layer under the ice

IMPACTS: Investigation of the Magnitudes and Probabilities of Abrupt Climate TransitionS

New POP Grid with Sub-ice-shelf Bathymetry

Objectives:

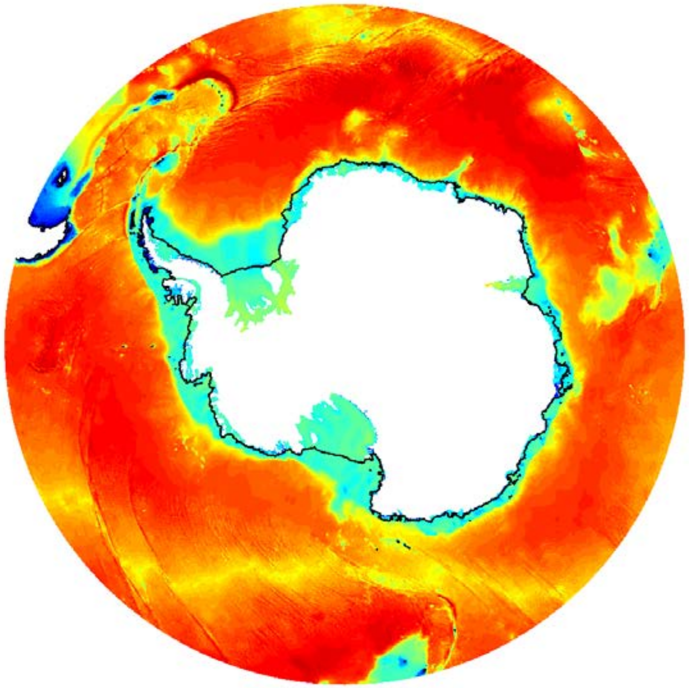
- Global ocean simulations including cavities under Antarctic ice shelves

Implementation:

- Extended POP grid to the south
- Below 60°S, used RTOPO-1 data (Timmermann et al. 2010)
    - Bedrock/bathymetry
    - Land mask from ice sheet grounding line
- Above 60°S, used existing POP bathymetry and land mask

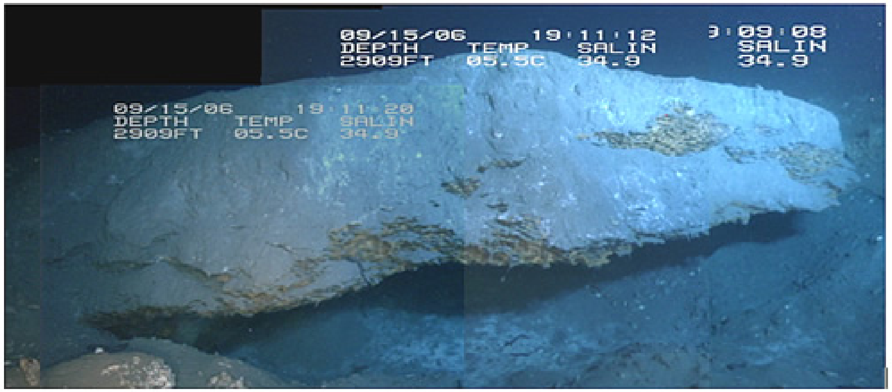
Experiments:

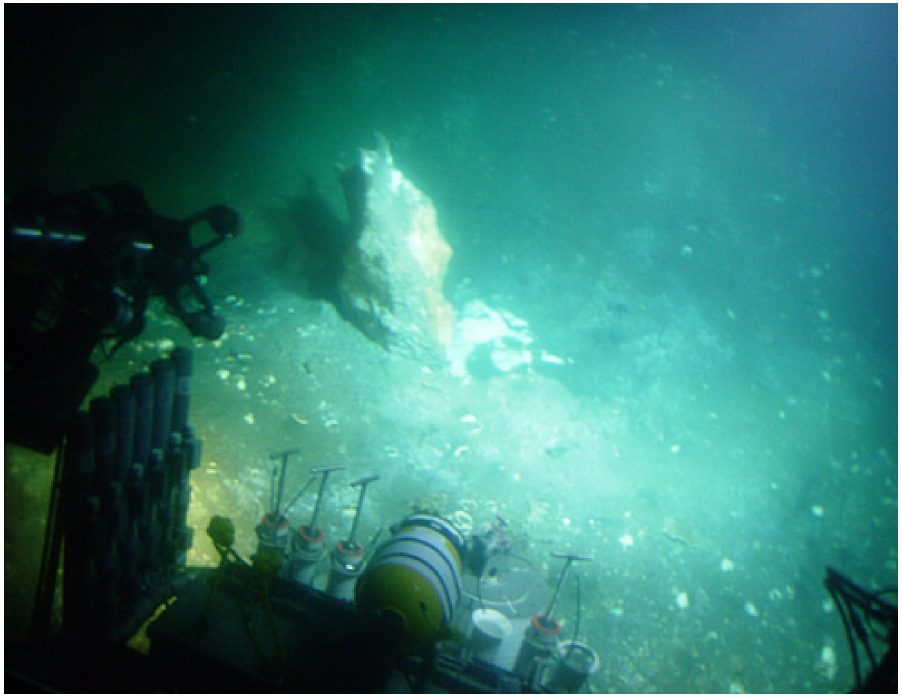
- Underway: Ocean spin-up without ice shelves
- Next: Ocean spin-up with static ice shelf geometry and no melt/freeze



New POP bathymetry
White region: new land mask (excluding ice shelves)
Black line: border of original land mask

The fate of oceanic clathrates and atmospheric CH4





IMPACTS: Investigation of the Magnitudes and Probabilities of Abrupt Climate TransitionS

Dissociation of Methane Clathrates: Basin Scales

Objectives:

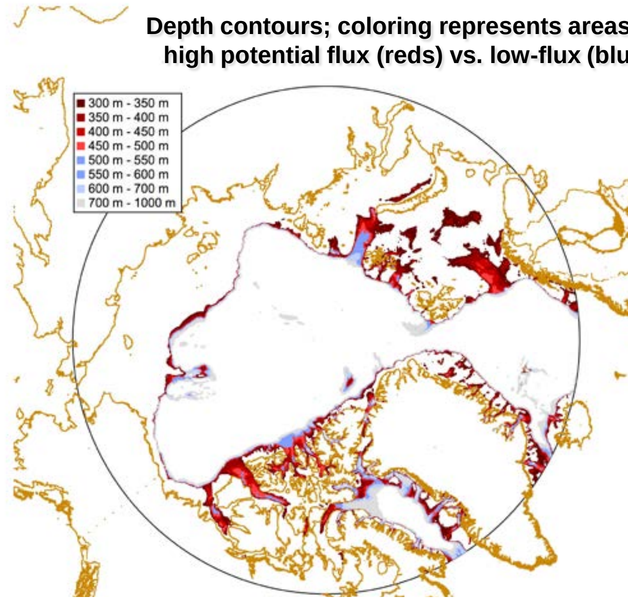
- Establish the sensitivity of subsea methane clathrates to climate change
- Estimate the total quantity of CH_4 that could be released into the water column

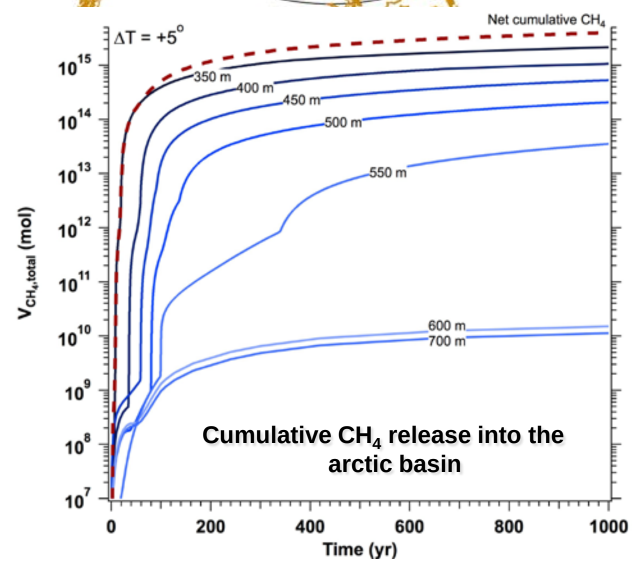
Implementation:

- Use TOUGH+HYDRATE to model coupled flow, transport, phase changes, and heat flow in sediments
- Apply temperature changes at the seafloor
- Model dissociation and the aqueous and gaseous CH_4 flux for each depth, location, and ΔT
- Integrate across ocean basins to estimate maximum potential release

Results:

- CH_4 release a strong function of depth/T/location
- Fluxes significant on century timescales
- Coupling CH_4 flux to the water column





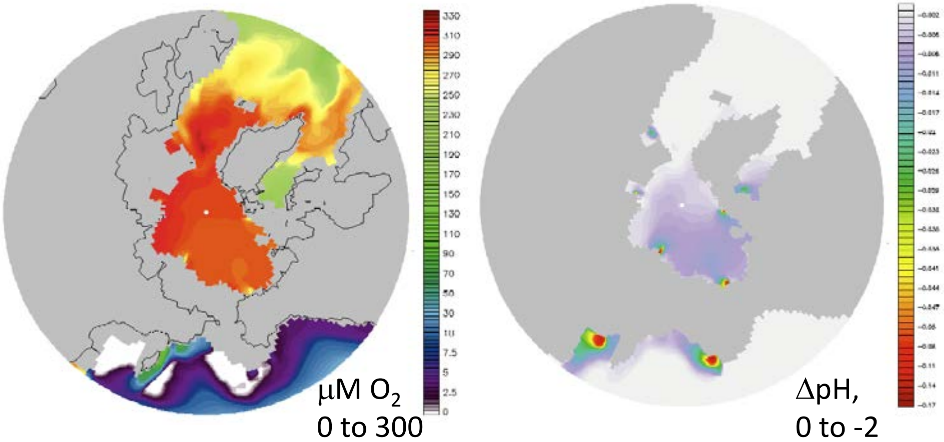
IMPACTS: Investigation of the Magnitudes and Probabilities of Abrupt Climate TransitionS

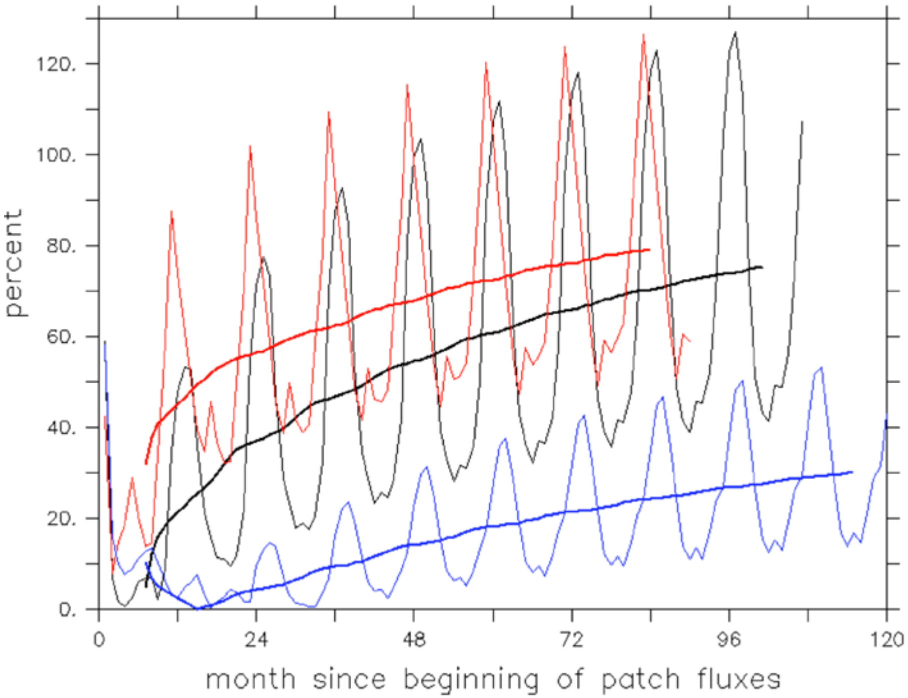
Chemistry of clathrate CH_4 *in* the Arctic Ocean

Objectives:
- Assess potential for sea floor hydrate to alter water column geochemistry
- Also compute gas reaching surface

Implementation:
- Background sources are sinking particles, global upward sea bed flow
- Add reactions with O_2, N, Fe, Cu as mediated by marine methanotrophs
- Run natural ocean cycle as background
- LBL patches at 300 meters, bubble rise

Experiments:
- Arctic fate/effects over 30 year runs
- Results: hypoxia, acidification, nutrient depletion and strong rise to interface
- Some cases tens of percent to surface
- See *Elliott et al. GRL 2010, JGR 2011*





Oxygen loss and acidification in POP, fraction to surface for bubble heights 50, 100, 150 meters

IMPACTS: Investigation of the Magnitudes and Probabilities of Abrupt Climate TransitionS

Clathrate CH_4 *in* the Arctic Ocean: Uncertainties

Objectives:

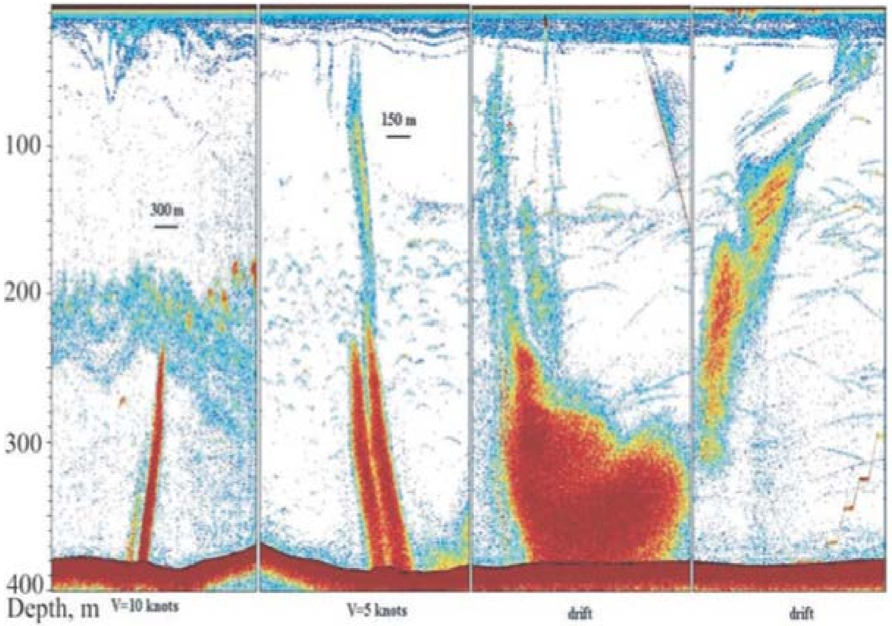
- Preliminary simulations of sea floor release, hypoxia, acidification and nutrient depletion now complete
- See *Elliott et al. GRL 2010, JGR 2011*
- Add physical chemistry of bubble rise, full microbial ecology with trace metals

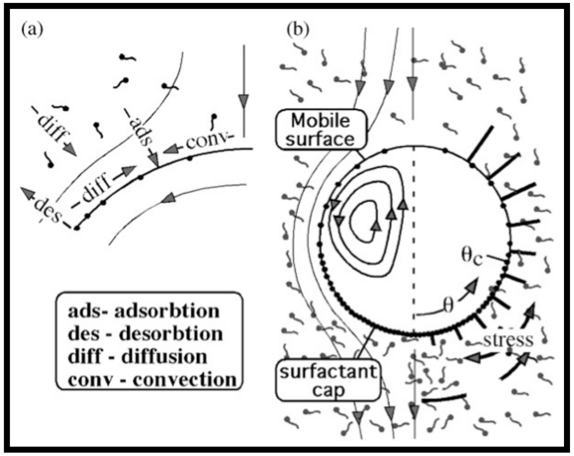
Implementation:

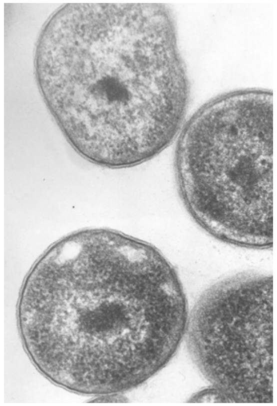
- Parameterize bubble dynamics with organic/surfactant chemistry
- Then nitrate, iron, copper consumption
- Emphasize resource restrictions on methanotrophs at true injection level

Experiments:

- Offline CH_4 vertical rise and dissolution
- Offline nutrient interplay (O_2, N, Fe, Cu)
- Tests in POP, production runs CESM







Methane plumes off Sakhalin (Obzhirov), bubble coating scheme (Leifer), marine methanotrophs

Atmospheric Impact of Methane Clathrate Emissions

Objective:

- Study the impact of methane clathrate emissions on the atmosphere.

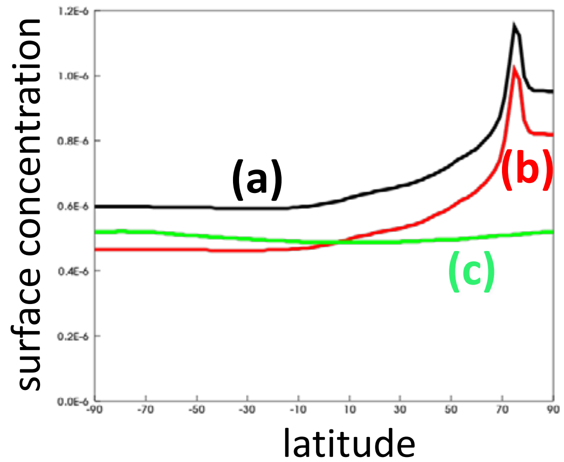
Implementation:

- Implemented Fast Methane Chemistry in CESM1_0_beta14, using CAM4 physics and RRTMG radiation.

Simulation Experiments :

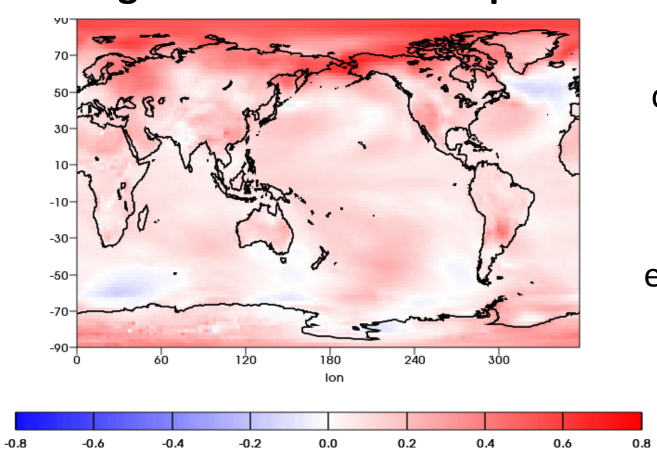
- **Control Case:** CESM, full ocean, fast methane chemistry, 2 degree resolution.
- **Arctic Methane Emission Case:** Simulating Arctic Methane Emission (22% increase),
  - Impacts CH_4, T, rainfall, air-quality.
- **Uniform Methane Emission Case:** 22% increase in emissions spread uniformly,
  - Impacts depend on emission location.

Methane Increase from Arctic Clathrates



(a) 100 year zonal mean
(b) 20 year zonal mean
(c) 20 year Uniform Emission Case

Change in Surface Air Temperature



100-year difference between Arctic methane emission & control cases

IMPACTS: Investigation of the Magnitudes and Probabilities of Abrupt Climate TransitionS

Interaction of high-latitude regions and climate change

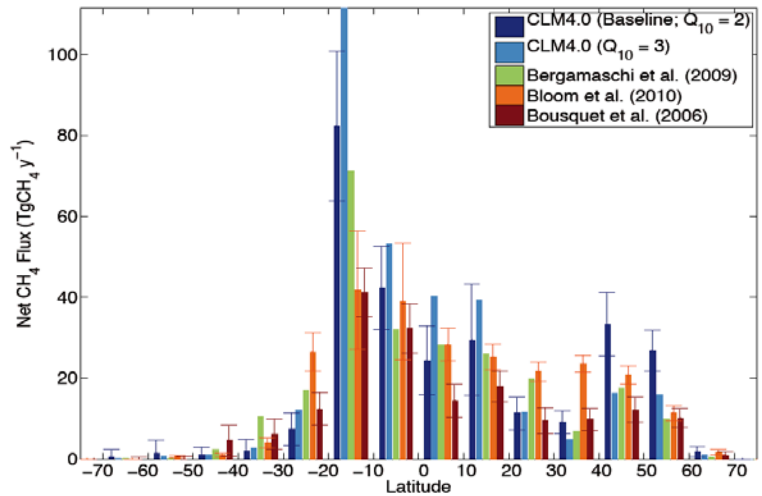
Inclusion of a Terrestrial CH_4 Model into CESM1 (CLM4Me)

Objectives:
- Identify uncertainties
- Predict 21st century CH_4 emissions
- Quantify potential for abrupt feedbacks.

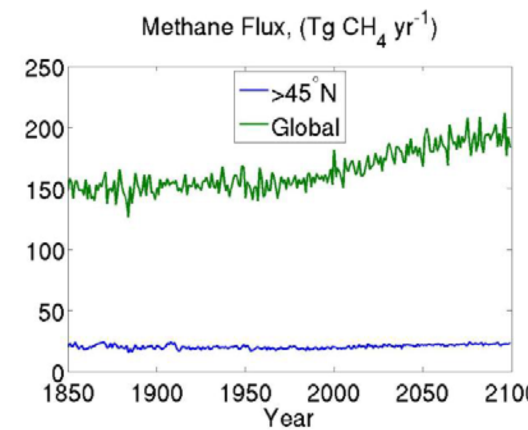
Implementation:
- Vertically resolved biochemical model
- 2 reactions and 3 transport processes
- Implementation designed to integrate with future land model improvements.

Experiments:
- Compared present CH_4 emissions to 15 sites and 3 atmospheric inversions.
- Identified critical uncertain parameters
- Showed declines in high-latitude inundation may limit 21st century increases in emissions
- Developing subgrid peatland ecosystem model

Comparison of CH_4 emissions from CLM4Me and several atmospheric inversions.



RCP 4.5 emissions from vegetated ecosystems without old soil carbon source.



IMPACTS: Investigation of the Magnitudes and Probabilities of Abrupt Climate TransitionS

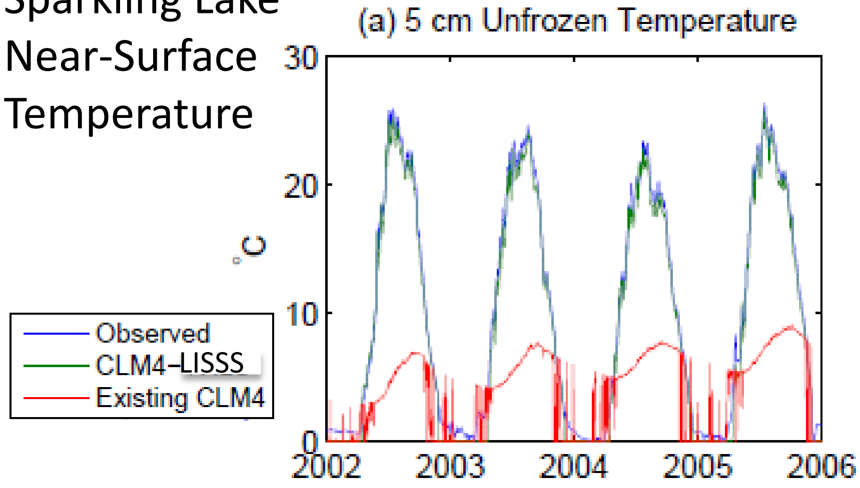
Improved Lake Model in CESM1 (CLM4-LISSS)

Objectives:
- Correct deficiencies in CLM4 lake model
- Integrate processes required for modeling high-latitude shallow lakes.
- Determine atmospheric response to altered Boreal lake distribution

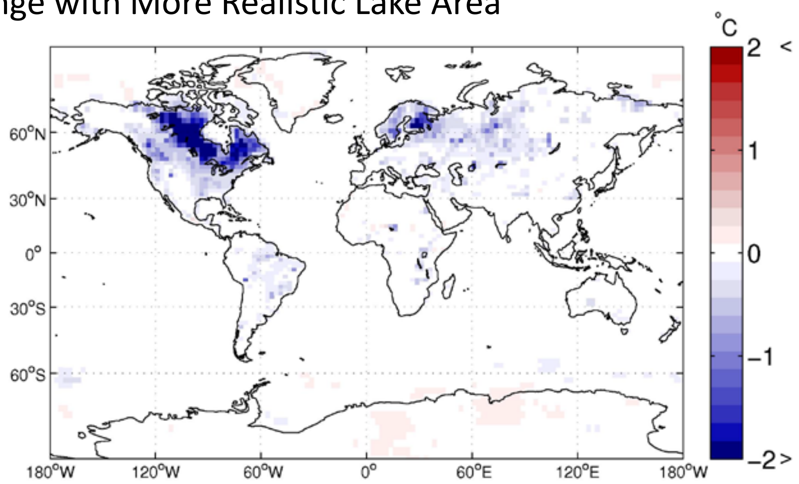
Implementation:
- Extended the Hostetler parameterization
- Included ice, snow, and sediment

Experiments:
- Evaluated predictions at 13 lakes
- Tested regional surface flux sensitivity to 14 processes and parameters
- Three CLM4 offline and CCSM4 slab-ocean experiments with altered lake area
- Idealized aqua-planet experiments explored extra-tropical terrestrial surface forcing
- Will predict 21st century thaw under thermokarst lakes

Sparkling Lake Near-Surface Temperature



Change in JJA Diurnal Surface Air Temperature Range with More Realistic Lake Area



IMPACTS: Investigation of the Magnitudes and Probabilities of Abrupt Climate TransitionS

On the influence of the height of expanding shrub vegetation on boreal climate

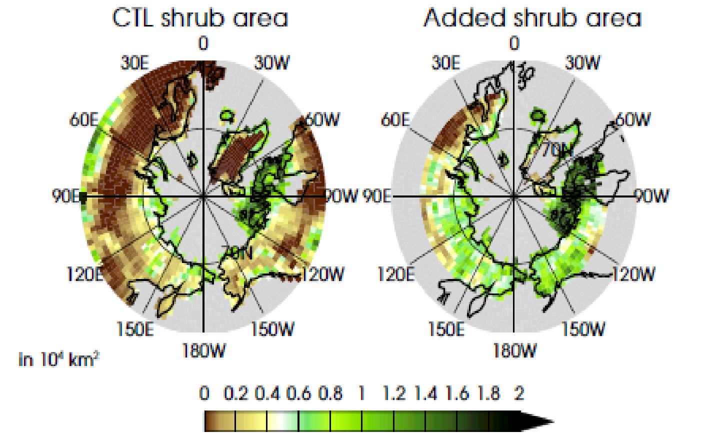
C Bonfils, T Phillips, D Lawrence, P Cameron-Smith, W Riley, Z Subin

Objectives:

- Assess the biophysically-induced effects of shrub expansion on boreal climate and permafrost
- Investigate their sensitivity to shrub height

Results:

- Shrub expansion leads to atmospheric heating through two feedbacks (albedo and ET)
- The strength and timing of these feedbacks are sensitive to shrub height
- Tall shrubs invasion destabilize the permafrost more substantially than short shrubs



(a) Default deciduous shrub distribution; (b) bare ground area north of 60°N converted to deciduous shrubs.

Experiments performed with CESM1:

	Default vegetation	short shrubs	tall shrubs
1xCO_2 / fixed ocean	Effect of adding shrubs		
1xCO_2 / interactive ocean	Added effect from indirect ocean / sea-ice feedback		
2xCO_2 / interactive ocean	Added effect from 2xCO_2		

Belowground Carbon Processes

Objectives:

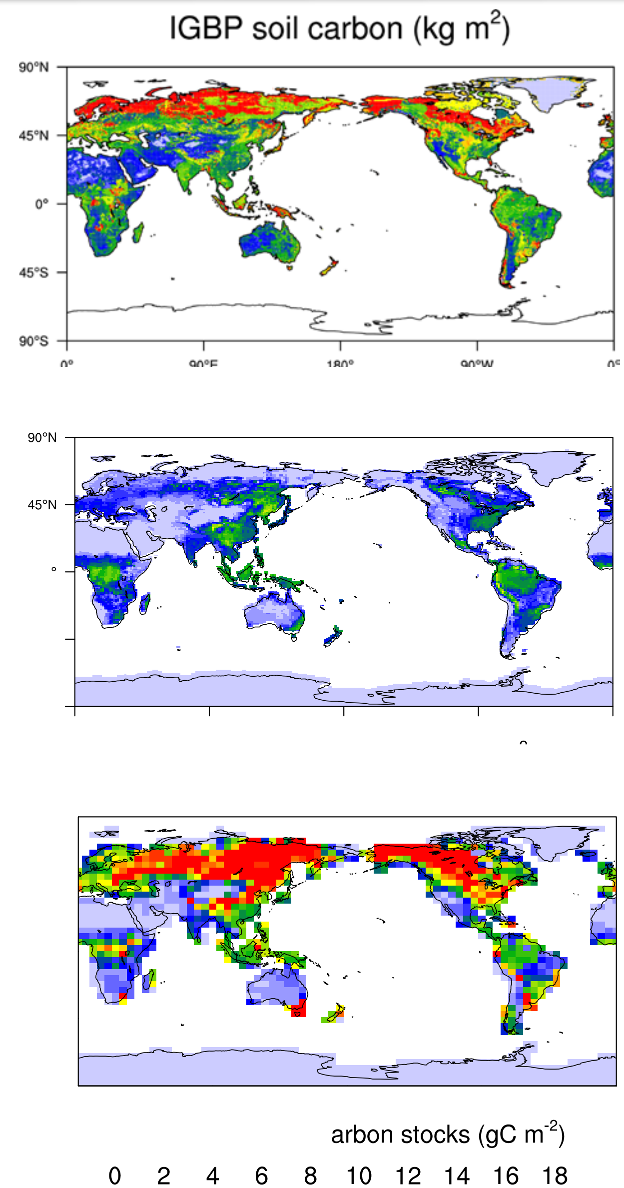
- Represent processes responsible for growth and loss of permafrost C, which is a large (>1000 Pg) and vulnerable fraction of the terrestrial C pool.

Implementation:

- Developed vertically-resolved belowground biogeochemistry, mixing.
- Improved SOM dynamics, growth of Permafrost C pools
- Improved N cycle at high latitudes leads to better productivity

Experiments and Next Steps:

- Equilibrium experiments, sensitivity to parameters and model structure
- Next Steps: Future scenarios; Coupling between soil and wetland biogeochemistry; coupled soil BGC and soil physics



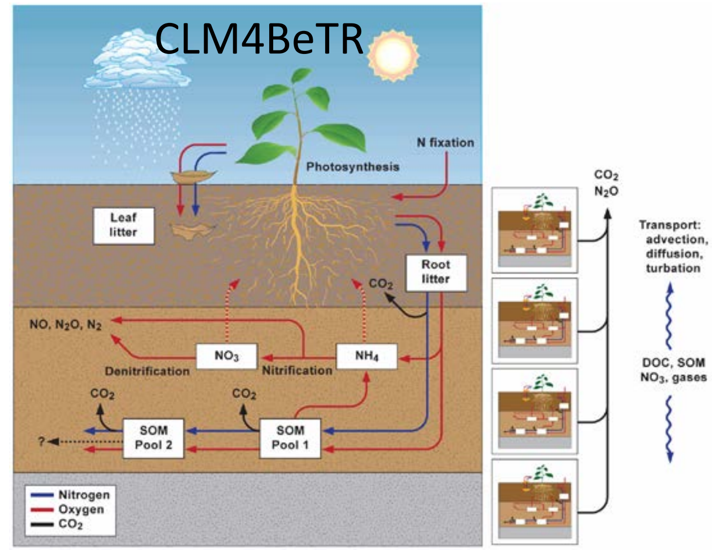
IMPACTS: Investigation of the Magnitudes and Probabilities of Abrupt Climate TransitionS

Reactive transport modeling-CLM4BeTR

Objectives:
- Uniform implementation of vertically-resolved underground biogeochemistry
- Multiphase description of C-Nutrient dynamics, gaseous, aqueous, sorbed

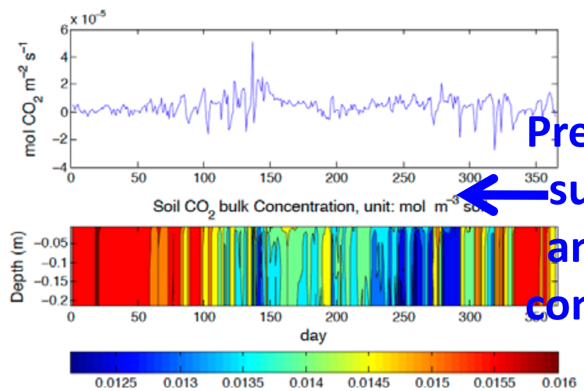
Implementation:
- Operator splitting approach
- Two-layer bi-directional modeling of atmosphere-surface exchange for different tracers, e.g. NH_3, N_2O, CH_4
- Evaluation against analytical results (successful) and measurement data

Experiments and :
- Tested single-point simulation of N_2O, CO_2 transport with vertically resolved C and N biogeochemistry
- Test the functionality of isotope fractionation and merge with CLM4Me



Vertical mixing & transport

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial t}\left(D\frac{\partial C}{\partial z}\right)-\frac{\partial}{\partial t}(uC)+R$$



Predicted CO_2 surface flux and soil-gas concentration

IMPACTS: Investigation of the Magnitudes and Probabilities of Abrupt Climate TransitionS

Processes governing the rapid onset of droughts

Drought-conducive mode of variability and initiation of future droughts

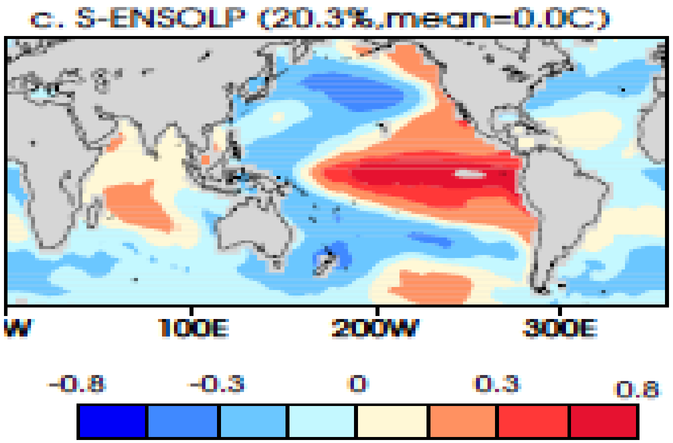
C Bonfils, B Santer, T Phillips, C Hannay, R Leung, M Wehner

Objectives:

- Assess whether the likelihood of ocean-induced drought initiation events will increase in the future

Results:

- We have identified a simple drought-conducive SST pattern
- We assessed whether the temporal statistics of this pattern will evolve in the future
- We plan to investigate whether the statistical SST/drought relationships are changing through time



Observed Drought-conducive pattern

Experiments to perform with CESM:

- A) 20th century run with 1975 forcing, climatological SSTs and sea-ice extent
- C) 21st century run with 2075 forcing, climatological SSTs and sea-ice extent
- B) and D) same as A and C, with the drought-conducive pattern superimposed

The Role of Surface Water – Groundwater Interactions on Long Term Droughts

Objectives:

- Study the role of surface water – groundwater interactions on long term droughts

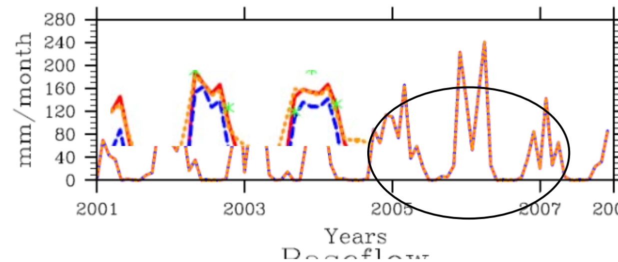
Implementation:

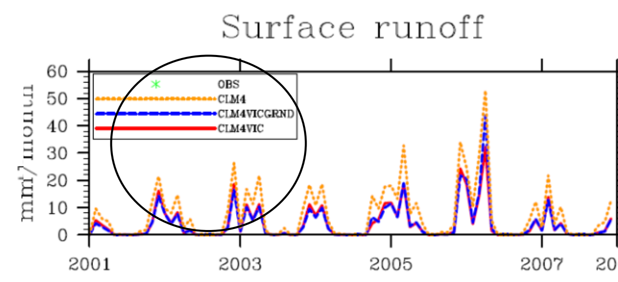
- Implemented the VIC runoff and groundwater parameterizations to CLM4
- CLM4 has been coupled to WRF using the CCSM flux coupler

Experiments and Results:

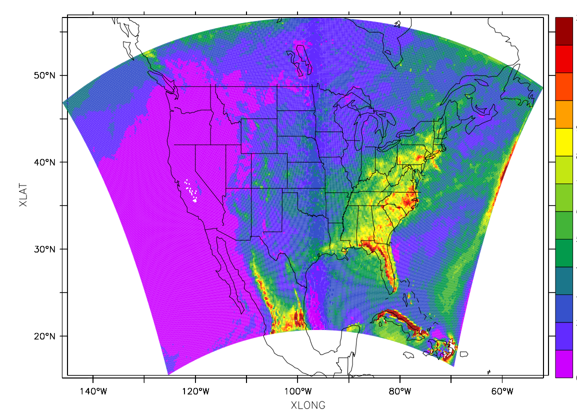
- CLM4VIC-ground has been applied to flux tower sites for comparison with CLM4 and CLM4VIC and showed improvements in simulating seasonal soil moisture
- WRF-CLM has been configured for the US using a new global 0.05° CLM input data
- WRF-CLM simulates realistic precipitation and surface temperature in North America
- WRF-CLM will be used to perform numerical experiments to study the role of surface water – groundwater interactions on long term droughts

Comparison of CLM4, CLM4VIC, and CLM4VIC-ground at Tonzi, CA





2003 JJA precipitation simulated by WRF-CLM



IMPACTS: Investigation of the Magnitudes and Probabilities of Abrupt Climate TransitionS

Simulations of Runoff in CLM: Model Parameterization and Evaluation

Objectives:

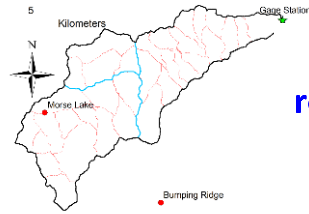
- Evaluate the CLM runoff simulations and explore methods for improvement

Implementation:

- The VIC runoff parameterizations have been added to CLM4 as an alternative option to the TOPMODEL approach for simulating surface and subsurface runoff

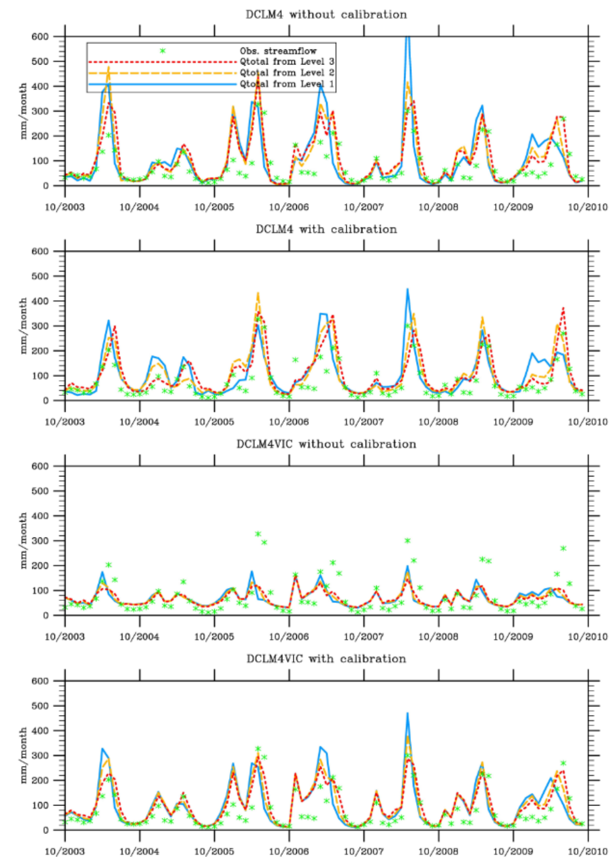
Experiments and Results:

- CLM4 and CLM4VIC were applied to a mountain watershed and 5 flux tower sites
- For the watershed, simulations were performed using subbasin as computational unit at three resolutions (1, 3, and 33 subbasins) with and w/o model calibration
- Results showed that CLM runoff simulations can be improved by: (1) increasing spatial resolution; (2) calibration of model parameters; and (3) using the VIC runoff parameterizations.



The American River represented by 1, 3, and 33 subbasins

Observed and CLM4 and CLM4VIC simulated runoff with and w/o calibration



Li, H., M. Huang, M. Wigmosta, Y. Ke, A. Coleman, L.R. Leung, A. Wang, and D.M. Ricciuto. 2011. "Evaluating Runoff Simulations From the Community Land Model 4.0 Using Observations From Flux Towers and a Mountain Watershed." J. Geophys. Res., accepted.

IMPACTS: Investigation of the Magnitudes and Probabilities of Abrupt Climate TransitionS

Impacts of Great Basin Dust on North American Summer Monsoon Precipitation

Objectives:

- Study the impacts of dust on North American summer monsoon precipitation

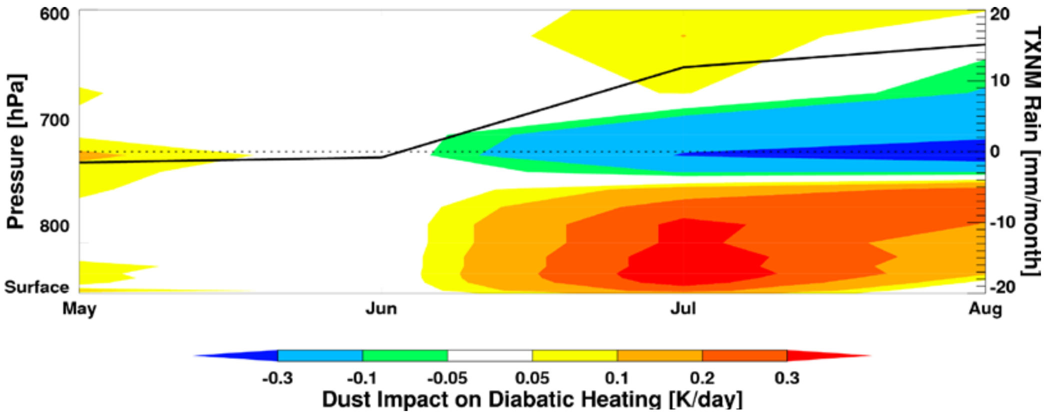
Implementation:

- WRF-Chem is used to conduct numerical experiments using the modal MADE/SORGAM scheme coupled with the GOCART dust emission scheme

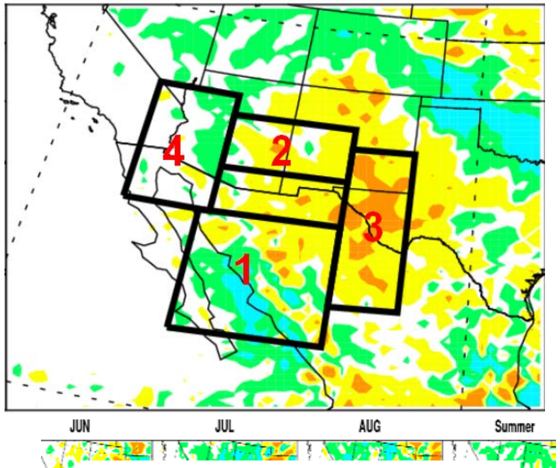
Experiments and Results:

- Simulations were performed for April – September of 1995 – 2009 at 36km resolution with and w/o dust
- The simulated dust concentration and AOD compare well with observations
- Dust from the Great Basin induces surface cooling of 1 W/m^2 and atmospheric heating of 0.4 W/m^2
- Dust heating of 0.3 K/day in the lower atmosphere strengthens the low-level meridional winds, leading to a 10-40% increase in NAM precipitation

Dust induced diabatic heating over the desert (contours) and precipitation changes over Texas-New Mexico (Region 3 shown below)



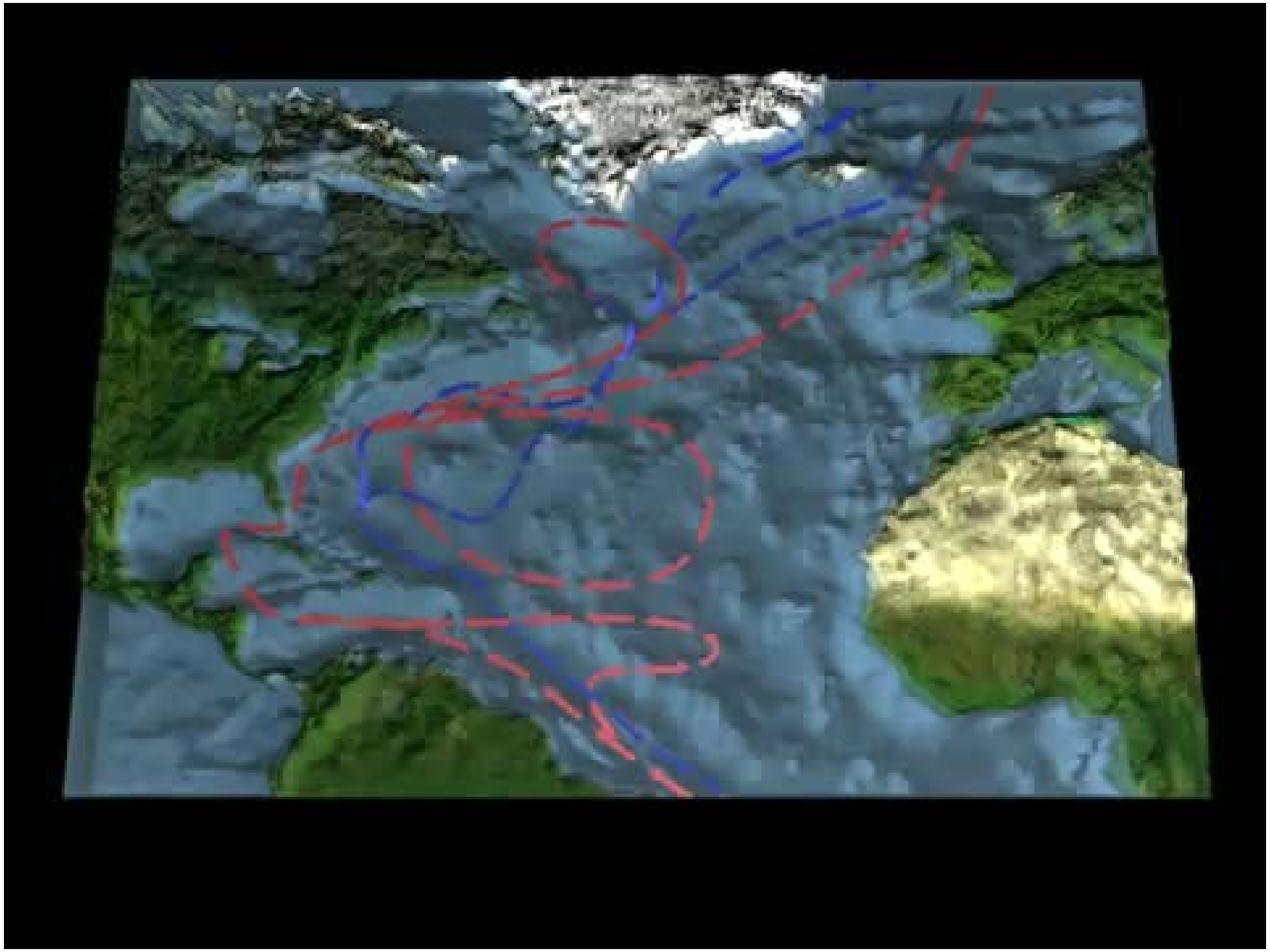
Summer precipitation change in the NAM region



Dust Impact on Rain (mm/day)

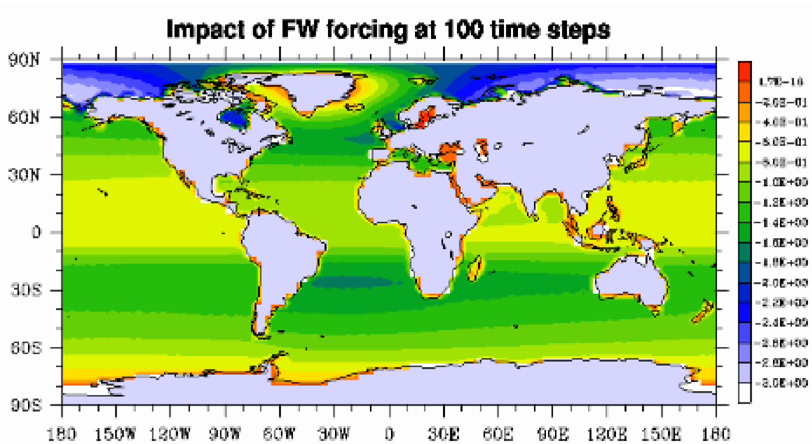
IMPACTS: Investigation of the Magnitudes and Probabilities of Abrupt Climate TransitionS

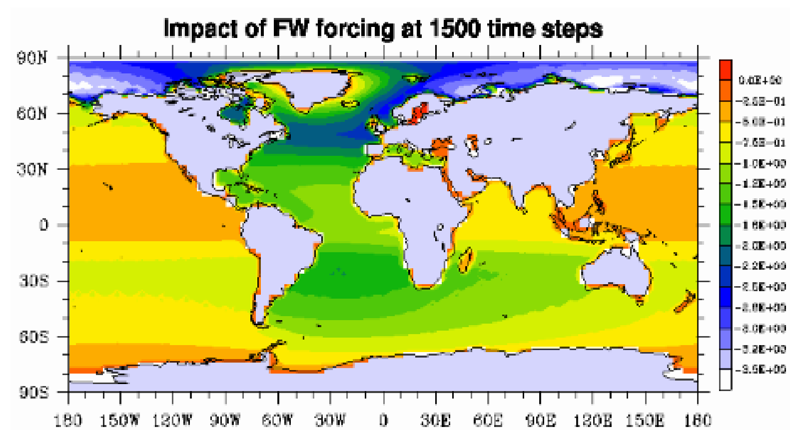
Tools for quantifying stability of the MOC

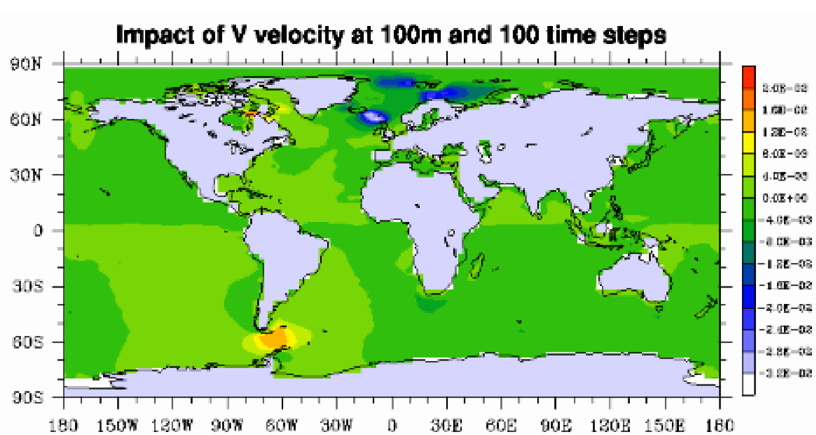


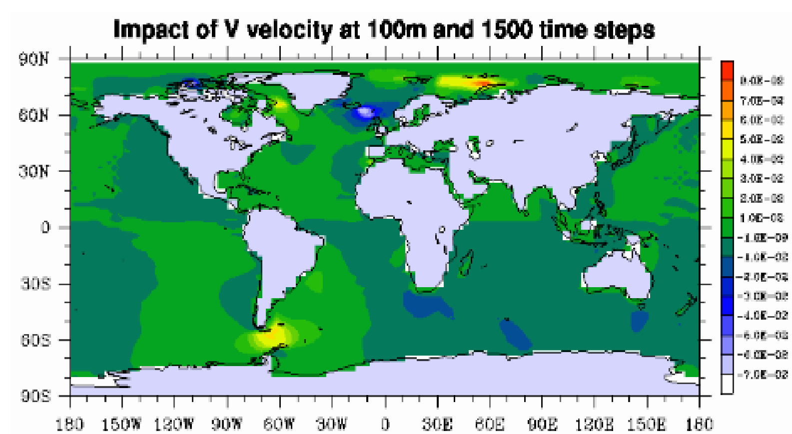
The Development of Tangent Linear and Adjoint versions of POP

- Test run: coarse grid problem (3 degree) with relatively short run of 2000 time steps for various combinations of independent and dependent variable sets for transient sensitivity computation
- Cost function is set with the MOC summed over the Atlantic ocean after 2000 time steps: with regard to the defined cost function, the following figures show the colormaps of transient sensitivities computed by the ADM code for each modeling variable at different time steps









Highlights of the IMPACTS in FY11

- **Development of ice-sheet physics to handle shifting land-ice peripheries.**
- **Introduction of a terrestrial methane cycle into CESM1, for release next year.**
- **Creation of a process-based and field-tested oceanic methane cycle for CESM1.**
- **Introduction of advanced (sub-)surface hydrology into CLM4.**
- **Completion of mathematical methods to characterize sensitivity of MOC.**

IMPACTS: Investigation of the Magnitudes and Probabilities of Abrupt Climate TransitionS