Final Report: Coupled simulations of Antarctic Ice-sheet/ocean interactions using POP and CISM

DOE Award: DE-SC0011982
PI: Xylar S. Asay-Davis
phone: +49-176-9730-7496
email: xylar.asay-davis@pik-potsdam.de

1 Project Summary

The project performed under this award, referred to from here on as CLARION (CoupLed simulations of Antarctic Ice-sheet/Ocean iNteractions), included important advances in two models of ice sheet and ocean interactions. Despite its short duration (one year), the project made significant progress on its three major foci. First, together with collaborator Daniel Martin at Lawrence Berkeley National Laboratory (LBNL), I developed the POPSICLES coupled ice sheet-ocean model to the point where it could perform a number of pan-Antarctic simulations under various forcing conditions. The results were presented at a number of major conferences and workshops worldwide, and are currently being incorporated into two manuscripts in preparation.

Second, in collaboration with the Ice and Ocean Team of the Accelerated Climate Modeling for Energy (ACME) project, I have implemented a scheme for computing melt fluxes under Antarctic ice shelves in Model for Prediction Across Scales Ocean (MPAS-O). During the CLARION project, I demonstrated that MPAS-O produced results in idealized test cases that are consistent with results from other ocean models. My work on the ACME project is continuing under a new DOE SciDAC award (DE-SC0013038: “Modeling coupled ice sheet-ocean interactions in the Model for Prediction Across Scales (MPAS) and in DOE Earth System Models”) referred to hereafter as MCINTOSH.

Third, as part of a large international collaboration involving more than 30 researchers, I have been the major developer of two idealized Model Intercomparison Projects (MIPs), one focused on ocean models with sub-ice-shelf cavities and one for coupled ice sheet-ocean models. I have also been involved in the design of a third, related MIP that focuses on standalone ice-sheet models. All three MIPs are being supported by an umbrella project, the Marine Ice Sheet-Ocean Model Intercomparison Project or MISOMIP, run by David Holland of New York University (NYU) and supported by the Climate and Cryosphere (CliC) project of the World Climate Research Programme (WCRP). MISOMIP activities are expected to provide improved understanding of the behavior of ice sheet and ocean models, and aim for an intercomparison of coupled, regional simulations of Wes Antarctica within the next three to four years. A publication of the experimental design for these three MIPs in currently under review.

With each part of CLARION project, I have cultivated strong collaborations with researchers from LBNL, Los Alamos National Laboratory (LANL), University of Bristol and New York University, as well as from other DOE labs (through ACME project) and other international institutions (through the MISOMIP activity).

2 POPSICLES development and simulation results

A primary focus of this project was to conduct pan-Antarctic simulations using the POPSICLES model. These simulations required further development of the model as well as improvements in topographic data sets based on observations to improve their consistency with ice-sheet and ocean model physics.

POPSICLES couples the Parallel Ocean Program version 2x (POP2x)[1] to the BISICLES ice-sheet model (Cornford et al., 2012). Development of POPSICLES began under the DOE Investigation of the Magnitudes and Probabilities of Abrupt Climate TransitionS (IMPACTS) project[2], with continued development under CLARION, as described in the next section. I have served as the primary developer with significant collaboration from Daniel Martin, a research scientist at LBNL funded through the DOE Predicting Ice Sheet and Climate Evolution at Extreme Scales (PISCEES) project[3], who was responsible for developing, configuring and initializing the ice-sheet component (BISICLES).

2.1 Model development

I made two significant enhancements to POP2x under CLARION. First, I modified the boundary-layer physics used to compute melt fluxes so that it converges with increasing vertical resolution. With the change, freshwater and heat fluxes become nearly independent of vertical resolution as long as the vertical resolution is sufficient to resolve the boundary-layer thickness, which is not the case for the commonly used scheme from Losch (2008). Second, I added support for a commonly used vertical mixing scheme, the K-Profile Parameterization (KPP; Large et al., 1994), in simulations with ice-shelf cavities.

2.2 Simulation results

Under previous funding (IMPACTS and PISCEES), Daniel Martin and I performed the first (to the best of our knowledge) coupled ice sheet-ocean simulations of the full pan-Antarctic region. These simulations had used the *LANL normal year*, a climatology based on the CORE-II normal year (Griffies et al., 2009) but modified by Mathew Maltrud at LANL to including a parameterizaiton of sea-ice thermodynamics. The parameterization required sea-surface temperature (SST) and salinity (SSS) data from high (1/10 degree ocean) resolution Community Climate System Model simulations (McClean et al., 2011). Results of a 30-year POPSICLES run are shown by the blue curve in Fig. 1. The antarctic melt flux begins near present-day values (presumably because the ocean has been initialized based on present-day observations) but decreased steadily as the upper several hundred meters of the ocean cooled.

Under CLARION, I began to investigate the cause of this bias. I performed several standalone ocean simulations with alternative vertical mixing schemes, but these showed a similar bias. With Martin, I performed a 27-year POPSICLES simulation, this time making use of the CORE-II interannual forcing (Griffies et al., 2009) and SST and SSS data from a coarser resolution Community Earth System Model (CESM) simulation, also with the CORE-II interannual forcing (IAF) but at coarser (one-degree ocean) resolution. In this simulation, the warm water in the deeper ocean made its way into surface layers, leading to warmer water under most ice shelves and a continual trend toward unrealistically large melt fluxes (see the green curve in Fig. 1).

A series of shorter standalone-ocean simulations revealed that vertical mixing schemes were not responsible for the differences upper-ocean heat content or melt fluxes. We believe that differences in the forcing data sets, and the lack of a dynamics sea-ice model are likely responsible for the biases in both multidecadal simulations.

[1] `http://oceans11.lanl.gov/svn/POP/branches/ice_shelf_partial_cells/`
[2] `http://esd.lbl.gov/research/projects/abrupt_climate_change/`
[3] `http://www.scidac.gov/PISCEES/`

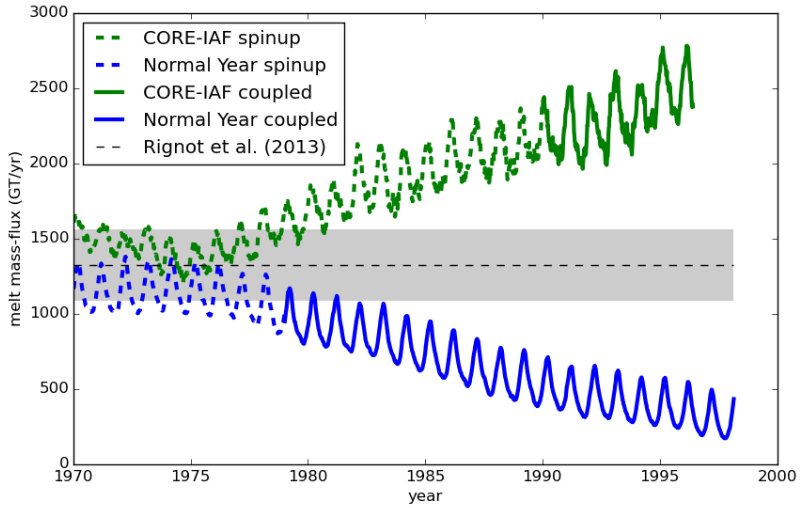

Figure 1: The average melt rate under all Antarctic ice shelves resulting from two different forcing data sets, the CORE-II interannual forcing (green) and the LANL normal year (blue). Ocean-only spinups are shown with dashed lines while coupled POPSICLES simulations are solid lines. The melt rate after the 20-year run is not within the error bars for present-day observations (gray box).

2.3 Improving topographic datasets

The coupled POPSICLES simulations included many locations where the grounded ice advanced and fill in parts of sub-ice-shelf cavities. Since this trend occurred in both simulations with increasing and decreasing melt fluxes, ocean melting was not responsible. We realized, instead, that the Bedmap2 topographic data set (Fretwell et al., 2013) that we used for the simulations had been interpolated in ways that were not consistent with model physics or subsequent observations. In particular, Martin and I discovered that Bedmap2:

- was missing observations of bathymetry under ice shelves (causing the ice to advance unrealistically as well as problems in ocean dynamics),
- had jumps in topography between grounded ice, floating ice, open ocean and bare bedrock (causing problems in ice dynamics across these jumps)
- had ice-shelf thickness, surface elevation and ice draft that were not consistent with exact flotation, as assumed by BISICLES and most other ice-sheet models
- required a correction for firn (compacted snow), which forms a low density layer at the top of the ice sheet not accounted for in most ice-sheet models, including BISICLES

I developed automated routines for correcting all these problems, resulting in a data set that we expect to be more appropriate for both POPSICLES and ACME simulations in the future.

2.4 Related presentations

- Asay-Davis, X. S. et al. Circum-Antarctic Simulations using the POPSICLES Ice Sheet - Ocean Model. WCRP Rising Coastal Seas on a Warming Earth workshop, Abu Dhabi, UAE, Oct. 27-29, 2014.

- Asay-Davis, X. S. et al. Present-day Circum-Antarctic Simulations using the POPSICLES Coupled Ice Sheet-Ocean Model. American Geophysical Union Fall Meeting, San Francisco, CA, US, Dec. 15-19, 2014.
- Martin, D. F., X. S. Asay-Davis et al. Response of the Antarctic ice sheet to ocean forcing using the POPSICLES coupled ice sheet-ocean model. American Geophysical Union Fall Meeting, San Francisco, CA, US, Dec. 15-19, 2014.
- Ng, E., D. F. Martin, X. S. Asay-Davis et al. High-resolution coupled ice sheet-ocean modeling using the POPSICLES model. American Geophysical Union Fall Meeting, San Francisco, CA, US, Dec. 15-19, 2014.
- Martin, D. F., X. S. Asay-Davis et al. Response of the Antarctic Ice Sheet to Ocean Forcing using the POPSICLES Coupled Ice sheet-ocean model. Land Ice Working Group, Boulder, CO, US, Feb. 2-3, 2015.
- Martin, D.F., X. S. Asay-Davis et al. A Tale of Two Forcings: Present-day Coupled Antarctic Ice-sheet/Southern Ocean Dynamics using the POPSICLES Model. European Geosciences Union General Assembly, Vienna, Austria, April 12-17, 2015.
- Asay-Davis, X. S. et al. Coupled ice sheet-ocean simulations with the POPSICLES model. **Invited presentation.** General Assembly of the International Union of Geodesy and Geophysics, Prague, Czech Republic, June 22-July 2, 2015.
- Martin, D. F., X. S. Asay-Davis et al. Response of the Antarctic ice sheet to a warming ocean using the POPSICLES coupled ice-sheet–ocean model. International Glaciological Society Symposium on Contemporary Ice-Sheet Dynamics, Cambridge, UK, Aug. 17- 21, 2015.

3 Design of three idealized ice-sheet and ocean MIPs

At the WCRP Rising Coastal Seas on a Warming Earth workshop in Abu Dhabi, UAE in Oct. 2014, I was invited to spearhead the design of two MIPs, one for standalone ocean models with ice-shelf cavities and one for coupled ice sheet-ocean models. The vision of the workshop participants was that these two MIPs would dovetail with an existing MIP under development for standalone ice-sheet models. The existing MIP, the third Marine Ice Sheet MIP (MISMIP+) was developed primarily by Stephen Cornford, a researcher at the University of Bristol who is one of the chief developers of BISICLES and already a collaborator of mine. Under CLARION and with Cornford's assistance, I developed the second Ice Shelf-Ocean MIP (ISOMIP+) and the first Marine Ice Sheet-Ocean MIP (MISOMIP1) as complementary projects that used a common topography and compatible design concept to those of MISMIP+. Based on preliminary ISOMIP+ and MISOMIP1 results, Cornford and I made modifications to the setup, in particular to the melt parameterization, in MISMIP+. We and 12 other coauthors submitted the experimental design to Geoscientific Model Development in Oct. 2015, where it is currently under review (see Sec. 6). A few dozen modeling teams from around the globe have agreed to participate in the three MIPs. Simulation results for MISMIP+ and ISOMIP+ will be requested by summer 2016, and an analysis paper summarizing he results is expected to be submitted in fall 2016. A clear timeline for MISOMIP1 participation has not yet been established because many participating models are still under development.

The ISOMIP+ experiments was designed to make a number of improvements on the first Ice Shelf-Ocean MIP (ISOMIP; Hunter, 2006) experiments. Whereas ISOMIP used highly idealized geometry, ISOMIP+ used relatively complex geometry from MISMIP+ BISICLES simulations. ISOMIP+ also used

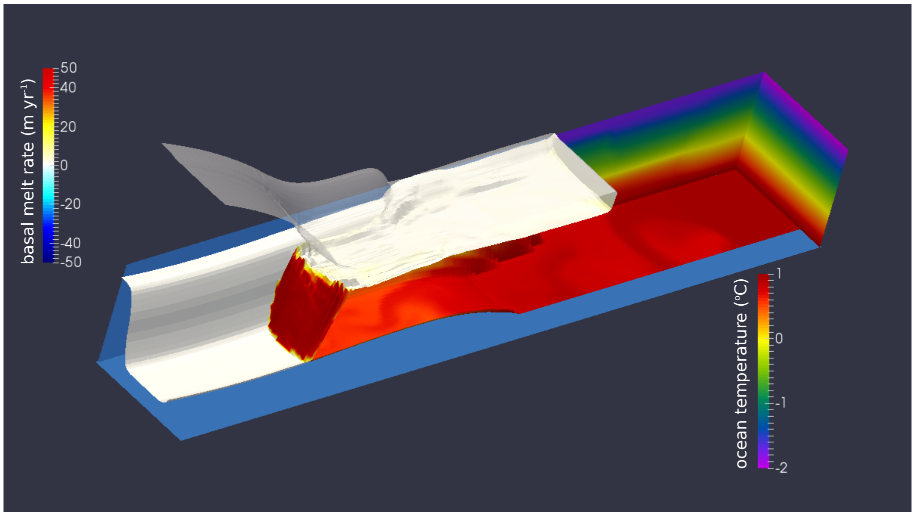

Figure 2: The ice topography 100 years into a POPSICLES simulation of a coupled MISOMIP experiment. The ice surface is the semi-transparent upper surface. The basal melt rate is plotted on the ice draft (middle surface) and the ocean temperature is plotted on the bedrock topography (bottom surface) and the side walls.

more sophisticated physical parameterizaitons than ISOMIP, including a velocity-dependent three-equation formulation of melt fluxes (e.g. Holland and Jenkins, 1999; Jenkins et al., 2010), eddy-permitting horizontal resolution, and realistic mixing parameters. ISOMIP+ should provide more appropriate test cases than ISOMIP, particularly for research focused on the Amundsen Sea region of West Antarctica, where the fastest ice-sheet retreat is currently observed.

The MISOMIP1 experiments were designed as a coupling of MISMIP+ and ISOMIP+. Building from previous work by Goldberg et al. (2012a,b), MISOMIP1 includes a narrow channel with strong ice-shelf buttressing and strong far-field restoring in the ocean. Innovations in MISOMIP1 include (1) stronger potential buttressing from steep side walls, (2) a region of open ocean that separates the ice-shelf cavity from the far-field forcing, and (3) more complex bedrock topography that could be used to study dynamical instabilities that are known to occor in unbuttressed ice sheets (Weertman, 1974).

As a proof of their feasibility, I performed POP2x simulations of all four ISOMIP+. With help form Daniel Martin, I also performed the first MISOMIP1 experiment. Martin is currently implementing the capabilities in BISICLES required to perform the second MISOMIP1 experiment, which will take place under the MCINTOSH project.

3.1 Related presentations

- Asay-Davis, X.S. et al. Design of the MISMIP+, ISOMIP+, and MISOMIP ice-sheet, ocean, and coupled ice sheet-ocean intercomparison projects. **Invited presentation.** European Geosciences Union General Assembly, Vienna, Austria, April 12-17, 2015.

- Asay-Davis, X. S. et al. Coupled ice sheet-ocean simulations with the POPSICLES model. **Invited presentation.** General Assembly of the International Union of Geodesy and Geophysics, Prague, Czech Republic, June 22-July 2, 2015.

- Asay-Davis, X.S. et al. Design and sample results from the ISOMIP+ (ocean-only) and MISOMIP1 (coupled ice sheet-ocean) model intercomparison projects. International Glaciological Society Symposium on Contemporary Ice-Sheet Dynamics, Cambridge, UK, Aug. 17-21, 2015.

3.2 Related Workshop

Together with Stephen Cornford, I organized the **ISMASS Workshop on the Marine Ice Sheet and Ice Shelf-Ocean Model Intercomparison Projects (MISMIP+, ISOMIP+, MISOMIP1)**, which took place in Cambridge, UK on Aug. 16, 2015. About 40 participants from around the world attended the workshop, which was co-sponsored and supported by the Scientific Committee on Antarctic Research (SCAR), the International Arctic Science Committee (IASC) and the CliC Project. The workshop allowed the the ice-sheet and ocean modeling communities to have further input into the design of the three MIPs before the design was submitted for publication.

4 ACME development and results

4.1 Model development

Under CLARION, I implemented land ice-ocean melt fluxes and the associated sub-ice-shelf boundary layer in MPAS-O. Fluxes of heat, salt and mass across the land ice-ocean interface are computed based on a parameterizaiton of the heat and salt fluxes across the boundary layer. The boundary-layer fluxes include two key parameters, the nondimensional transfer coefficients for heat and salt, following implementations from either Jenkins et al. (2010) or Holland and Jenkins (1999).

Because of the flexible vertical coordinate in MPAS-O (Petersen et al., 2014), the ocean layers can become much thinner than the turbulent boundary layer as they are compressed by the weight of the overlying ice. The boundary-layer parameterization handles thin layers by averaging the ocean temperature and salinity over a fixed vertical distance (a parameter to be calibrated) and distributes the resulting melt fluxes over approximately the same vertical distance. During the MCINTOSH project, more sophisticated and physically self-consistent mixing parameterizations for the sub-ice-shelf boundary layer will be investigated. In collaboration with ACME, boundary-layer parameters will also be tuned based on observed melt rates and using the few observations that are currently available of sub-ice-shelf melt plumes.

In collaboration with Jeremy Fyke at LANL, some components of the melt parameterization have been duplicated in the ACME coupler. This allows for melt fluxes to be computed in MPAS-O in standalone ocean runs with sub-ice-shelf cavities but in the coupler during coupled ACME runs.

MPAS-O and ACME development under CLARION has involved close collaboration with several researchers from the Climate Ocean and Sea Ice Modeling team at LANL. In particular, a two-week visit to LANL in Sept. 2015 allowed for a number of fruitful discussions with Steven Price, Bill Lipscomb, Mark Petersen, Jeremy Fyke, Doug Jacobson and Todd Ringler. The visit allowed us to more easily brainstorm solutions to some roadblocks we faced in implementing land ice-ocean coupling (e.g. handling moving model boundaries) and helped me to become better acquainted with the ACME workflow. Prior and subsequent semiweekly ACME Ice-Ocean team meetings have also been helpful in coordinating and troubleshooting remotely.

4.2 Simulation results

To gain confidence in the implementation of the sub-ice-shelf melt parameterizaiton, we performed two experiments from ISOMIP using standalone MPAS-O. The resulting horizontal (barotropic) and meridional (overturning) streamfunctions as well as temperature distributions and melt rates were within the range of behavior seen in other models.

I also set up two ISOMIP+ experiments in MPAS-O. Under CLARION, preliminary results indicated that MPAS-O was experiencing large amounts of spurious kinetic energy and sometimes even numerical instabilities in locations with particularly thin grid cells (cm or less) near grounding lines (where the ice sheet transitions from grounded on bedrock to floating on the ocean). These issues are currently being addressed under the MCINTOSH project.

5 PhD mentoring

I served as a co-mentor and thesis committee member for Gunter Leguy, a PhD student at the New Mexico Institute of Mining and Technology in Socorro, NM, US. Leguy's PhD project explored numerical modeling of ice-sheet dynamics near grounding lines. Leguy received his PhD in July 2015, and his work is expected to produce a total of three publications, two of which are based on work partly supported by CLARION (additional details in the next section). My mentorship of Leguy included weekly Skype calls lasting between one and two hours during which we discussed his progress and next steps for his work. I also provided assistance in designing numerical algorithms, programming, using computing resources and extensive critique and revision of his manuscripts.

6 Publications supported by CLARION

One paper based on CLARION work is currently under review:

- Asay-Davis, X. S., Cornford, et al. (2015). Experimental design for three interrelated Marine Ice-Sheet and Ocean Model Intercomparison Projects. Geoscientific Model Development. Under review. `http://www.geosci-model-dev-discuss.net/8/9859/2015/`

Two further publications are in preparation based on work supported by CLARION, with submission expected in early 2016:

- Asay-Davis, X. S., D. F. Martin, W. D. Collins, S. L. Cornford, D. M. Holland, W. H. Lipscomb, M. W. Maltrud, E. G. Ng, & S. F. Price. The POPSICLES v. 0.5 coupled ocean-ice sheet model. Geoscientific Model Development. In preparation.
- Leguy, G. R., X. S. Asay-Davis & W. H. Lipscomb. Parameter sensitivity of grounding-line errors in a one-dimensional ice sheet model. The Cryosphere. In preparation.

Model development and simulation results were performed under CLARION that are expected to contribute to three additional publications that we expect to submit later in 2016:

- A paper describing pan-Antarctic coupled simulations with POPSICLES under different forcing scenarios. Authors include : X. S. Asay-Davis and D. F. Martin.
- A paper analyzing the ISOMIP+ simulation results from all participants. Primary author: X. S. Asay-Davis.
- A paper introducing ice sheet-ocean interactions in the ACME model using idealized, coupled simulations. Authors include: X. S. Asay-Davis, M. R. Petersen, J. G. Fyke, T. D. Ringler and S. F. Price.
- A paper describing three-dimensional, idealized simulations with CISM v. 2.0 using various stress approximations. Authors: G. R. Leguy, X. S. Asay-Davis and W. H. Lipscomb.

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