My current research interests broadly lie in problems in computational geophysics, particularly in climate modeling, as well as problems in uncertainty quantification and data assimilation. Below are a few of my current projects discussed in a bit of detail.

## Oceanic transport in a snowball Earth model scenario

The goal for this modeling study is to investigate the role of oceanic heat transport in the event that the Earth is completely covered in ice, a so called "Snowball Earth" state. These events are speculated to have occurred in our planet's distant past, and is interesting in climate dynamics because a completely ice covered Earth has a very high albedo, and the question arises of how the Earth could ever get out of such a state. The ocean is an important mechanism for redistributing heat on the planet, and we aim to study it's role in a low complexity global climate model. In collaboration with my advisor, Dr. Juan Restrepo, and Dr. Doug Kurtze of St. Joseph's University, we have developed a simple conceptual energy balance model for global climate dynamics. A notable contribution of this work is the formulation of a comprehensive and consistent thermodynamic model for the interaction of the ocean, the radiative balances, and the ice model.

For the ocean component of the model, the key feature we want to capture is the circulation, so we model the ocean as existing in 4 bins or boxes to separate warm and cool water, and these boxes represent the ocean in one hemisphere (Northern or Southern) that are zonally averaged across longitude. They consist of a thin surface box for the equatorial region with warm water, a thin surface box for the polar region with cooler water, and two deep ocean boxes water with fluxes between the boxes by a circulation driven by density differences. Each box has a temperature and salinity that evolves in time, coupled with the other model components.

The ice component of the model follows [GP03], where ice is allowed to form and melt, as well as advect towards the equator. Ice sits on top of our ocean boxes, and interacts with the ocean through temperature and melting equations. There is also a surface temperature component of the model, that is also coupled to both the ocean and ice components, and is largely driven by a radiative balance between incoming solar radiation, and outgoing long wave radiation. The incoming solar radiation is modeled using a parameterization from [ML12] that is dependent on latitude, as well as parameters related to the Earth's orbit around the sun, which produce cycles in the intensity of the sun's radiation that reaches the Earth. We assume the Earth is a traditional black body, and model the outgoing long wave radiation by the Stefan-Boltzmann law, weakened by an emissivity parameter to account for greenhouse effects in the atmosphere. The ice-albedo effect is also accounted for by having different albedos for the portion of the model covered in ice and ocean.

We initialize the model with no ice, and let the ice cover form and evolve through the energetic dynamics - that is, the resulting ice margin is strictly determined by the dynamics of our model. Given reasonable parameter values, we can recreate current conditions of

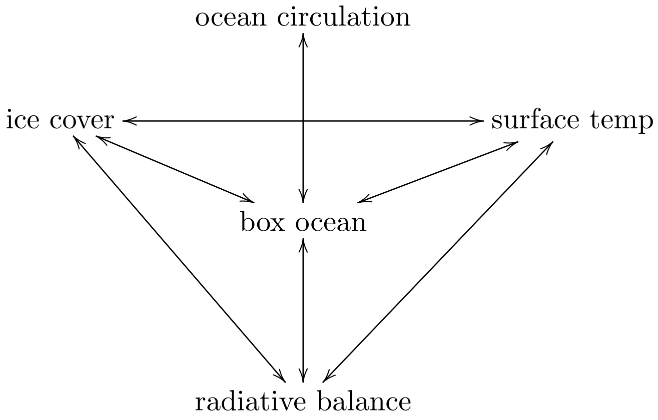

Figure 1: Schematic of energy balance climate model components and coupling.

partial ice cover, and running the model without the ice component recreates an ocean circulation of roughly 20 Sv (Sv = $10^6$ $m^3/s$), in agreement with [GT95]. Our model predicts that the oceanic circulation reduces the thickness of the ice cover and significantly slows down the ice's velocity. The model also predicts that the presence of ice actually weakens the ocean's circulation, eventually shutting circulation down entirely as the ice serves as an insulating layer. Our continued work is in paleoclimate setting taking into account a slightly weaker, younger sun, and determining if reasonable parameter values produce a "Snowball" earth scenario, and whether the heat transported through the ocean's circulation is enough to escape such a scenario.

## A dynamic / thermodynamic iceberg implementation in CICE

On the other end of the climate modeling spectrum, I have been in collaboration with Dr. Elizabeth Hunke of the Climate, Ocean, and Sea Ice Modeling group at Los Alamos National Laboratories on developing an iceberg parameterization in the sea ice model CICE. Using the iceberg momentum equation from [LH01], icebergs move dynamically in response to atmosphere, ocean, Coriolis, pressure gradient, and sea ice forcing terms. Novel in our approach is we allow icebergs to dynamically interact with the surrounding sea ice. Depending on the relative direction of motion between the icebergs and sea ice, icebergs act as either physical obstacles to the sea ice or as an additional forcing term in the sea ice momentum equation. Icebergs are also modeled thermodynamically through empirical melting terms that account for different melting mechanisms: basal turbulence, lateral convection, and wave erosion. Freshwater from melted icebergs and the associated latent heat flux is calculated, however we are not currently running with a coupled ocean model, so additional feedbacks from these quantities are not present. We focus on icebergs in the Antarctic, which constitute an estimated 90 % of the world's global iceberg mass flux.

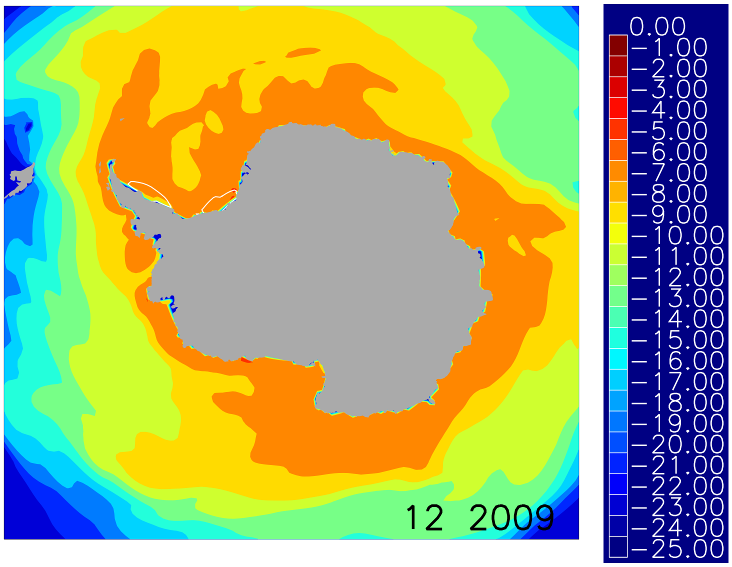

Figure 2: Freshwater flux from icebergs (kg/m$^2$/s log scale) at end of 20 year run.

Unique to our modeling approach, we have developed two different frameworks for icebergs: as Lagrangian particles, and as an Eulerian fluid field. In the Lagrangian framework, iceberg locations are tracked and moved through a grid cell, and forcing terms are interpolated from the grid cell corners by weights according to position within the cell. This method is too computationally demanding to be of use for a realistic number of icebergs, which would be in the tens to hundreds of thousands, but is of use in modeling specific giant iceberg events. In [HC11], we discuss the results of experiments in this framework (without the thermodynamic component), using a benchmark of a giant iceberg calved in 1990 that was about the size of Rhode Island in the Weddell sea. We obtain model trajectories in broad agreement with the observed trajectory, and find localized regions of increased sea ice volume as a result of the dynamic interaction. Sea ice typically moves much faster than icebergs, and we see sea ice mechanically deforming and piling upon itself, known as ridging, behind icebergs. This process then provides open water in front of the iceberg, prompting production of level sea ice. These regions of increased sea ice volume are then stretched with the flow as the sea ice pack moves beyond the icebergs. Since there is little perennial sea ice in the Antarctic, the retreating sea ice largely eliminates the increased sea ice volume from year to year.

In the Eulerian framework, icebergs take up a fractional portion of grid cells, where precise location is not tracked but rather total iceberg volume in a cell, and the field is advected using a method called incremental remapping ([LH04]). Icebergs are divided into ten size categories that loosely follow an observed log normal distribution, and are initially calved from all coastal Antarctic grid cells uniformly. Each size category has representative iceberg dimensions that are used for modeling the dynamics and thermodynamics, and iceberg volumes are redistributed across these categories after melting occurs. From a standard model run of 2000 Gt/yr calved uniformly across the Antarctic continent and across 4 calving events per year, we obtain a spatial distribution of icebergs and meltwater largely consistent with other modeling results ([MA10], [JDF$^{+}$09]), and we find up to 10% more Antarctic sea ice produced compared with a run with no icebergs through the dynamic interaction. Detailed results and analysis of our iceberg parameterization are to appear in [CH].

## Non-parametric method for determining a tendency of a non-stationary signal

In collaboration with Drs. Juan Restrepo, Shankar Ventkataramani, and Hermann Flaschka of the University of Arizona, I have been investigating a signal processing technique first proposed by [FO07] called the Intrinsic Time-Scale Decomposition (ITD). The method decomposes a given signal in a lossless way by an ad-hoc iterative process. A 'baseline' is extracted from the original signal by forming a function that lies between all local extrema, and subtracting this from the signal yields the 'rotation'. The process is then repeated on the baseline signal, extracting higher frequency information through the rotations, until a monotonic signal remains. The result is a lossless (though not orthogonal) series of baselines and rotations, decreasing in complexity through the iterations. This method does not assume any statistical structure of the signal, but rather decomposes the signal using only the data itself. This is particularly useful in analyzing non-stationary signals or signals with multi-scale features, where most a priori basis structures (such as a Fourier decomposition) or test in a statistical framework (such as linear regression or testing if the signal belongs to a particular distribution) necessarily assume stationarity. Furthermore, lack of data may also yield testing against particular statistical distribution unfeasible. This is particularly true in climate signals, whose analysis is made difficult by both non-stationarity and lack of data.

We aim to make use of the ITD to propose methodology for producing a trend or tendency of a data set that does not make use of any parametric or statistical framework, and is defined in precise mathematical terms. We have begun to apply this methodology to a suite of examples both synthetic, as well as to real data, primarily climate signals, allowing us to provide a reduced representation of the input signal. This tendency offers reduced complexity of the original signal, while still maintaining the basic structure. A desired tendency would have the property that subtracting it from the original signal would yield a unimodal distribution of values with smaller variance than the original signal. We compare our method to similar methods and studies, such as the Empirical Mode Decomposition (EMD).

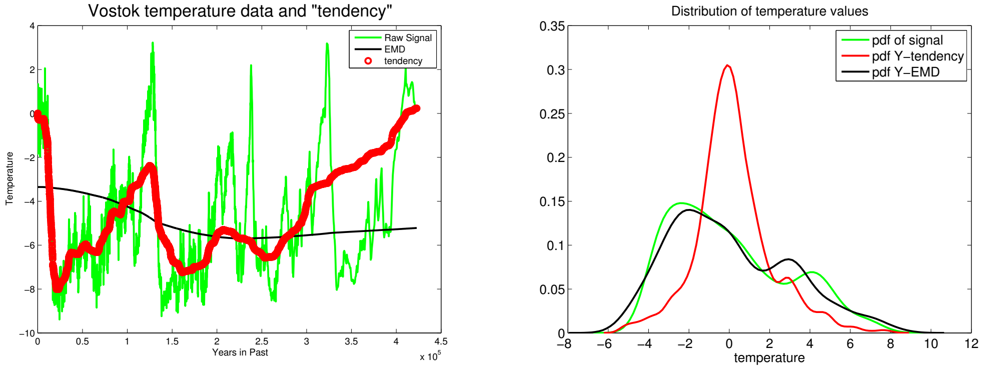

Figure 3: (Right) An example of a ”tendency” extracted from Vostok temperature data. The tendency has filtered out much of the noise in the original signal, while maintaining overall structure. (Left) Removing the tendency from the original signal yields a distribution of temperature values that is unimodal, and of smaller variance than the original signal.

## Other research interests

I have been a member of the Uncertainty Quantification group at the University of Arizona since 2008, and was as a Graduate Research fellow at the Statistics and Applied Mathematical Sciences Institute (SAMSI) during the Spring 2012 semester as part of their year long theme on Uncertainty Quantification. As a result I have been exposed to and interested in a number of topics in the area, including sampling and filtering methods, as well as data assimilation. Earlier in my graduate career I was involved in research in methods for modeling flow in random porous media. I was particularly interested in cases of strong heterogeneity in the media, following the approach of [Neu06] where the media is treated as a realization of a ”truncated” fractional Brownian motion. I have also worked with an approach put forth by [LZ07], using Karhunen-Loeve, polynomial chaos expansions and probabilistic collocation to solve the flow equation in Monte-Carlo type framework. These are research areas in which I am still interested and wish to pursue in the future.

## Planned research

### Energy balance climate model

Our conceptual climate model is a model in development, and we aim to further explore the model's lesser constrained parameters, as well as looking at improving some of the process parameterizations. In particular, a couple key components we wish to further explore are:

- As our line of research was to determine the role of heat transport through the ocean's circulation in global climate setting, we began our ocean component development with a traditional thermohaline circulation (THC) model over one hemisphere. Our next installment of the model will involve a full ocean component with a meridional overturning circulation (MOC) component as the next level of complexity.
- Currently in our energy balance model, we are only representing atmospheric effects through an emissivity multiplicative constant in the Stefan-Boltzmann law for our outgoing long wave radiation parameter, and do not have a precipitation minus evaporation term. Our justification for this is that our focus is on the role of oceanic transport, but to make the model more robust we are looking to explicitly include parameterizations for other atmospheric effects.

### Iceberg GCM model

Our most pressing goal with the iceberg parameterization is to couple the model with the full Community Earth Systems Model (CESM), of which the Los Alamos sea ice, ocean, and land ice models are components. This will allow us to send freshwater and latent heat fluxes from the icebergs to the ocean model, as well as receive calving fluxes from the land ice model. We will then be able to study thermodynamic feedbacks from the icebergs, as the freshwater flux will cool and freshen the ocean. In addition, we would like to move to a more physics based approach for modeling the iceberg thermodynamics, rather than using empirical equations, which largely were developed from studying smaller Arctic icebergs, and the first step for this will be to use the existing sea ice thermodynamics module in CICE.

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