

## Project Description

### 1. Overview

Free surface water plays a well-known and direct role in the most abrupt, explosive forms of ice shelf collapse [e.g., as reviewed by Vaughan *et al.*, 2008, and Scambos *et al.*, 2008]. Observations suggest that ice-shelf rifting processes enabled by surface meltwater played a role in initiating abrupt disintegration of Larsen B in 2002 [e.g., Scambos *et al.*, 2003; Sergienko and MacAyeal, 2005; van den Broke, 2005]. This has led to the widely held view that an increase in the intensity of surface melting, and the retention of the meltwater thus produced in large reservoirs on the surface, such as in ponds and water-filled crevasses, are necessary precursors to ice-shelf collapse. The Austral winter collapse of part of the Wilkins Ice Shelf in 2008 was also attributed in part to free water at, or near, the ice-shelf surface, as brine infiltration leading to water-saturated firn was identified as a key precursor to the collapse event [Scambos *et al.*, 2009].

**Goal:** Given the relative dearth of observational study in the Antarctic environment (but with notable exceptions underway along the Antarctic Peninsula, e.g., the NSF-funded project entitled *IPY: Stability of Larsen C Ice Shelf in a Warming Climate*), we propose a **numerical modeling** study to investigate the processes by which free surface water, in its various forms (e.g., contained in pools or in saturated firn), initiates and interacts with surface features such as ponds, rivers, crevasses, cracks, fractures and dolines. Our goal is to discover how these important water-related surface features evolve in ways that influence **ice-shelf stability**.

**Motivation:** Ultimately, our model development and simulation experiments will help to **establish:**

- (1) **environmental thresholds that enable ice-shelf collapse, and**
- (2) **ice-shelf-surface morphologies that predispose ice shelves to collapse.**

Our simulations will additionally yield a comprehensive prediction of ice-shelf stability over the 100-year time scale of interest to the IPCC.

### 2. Proposed Research: A Numerical Model Study

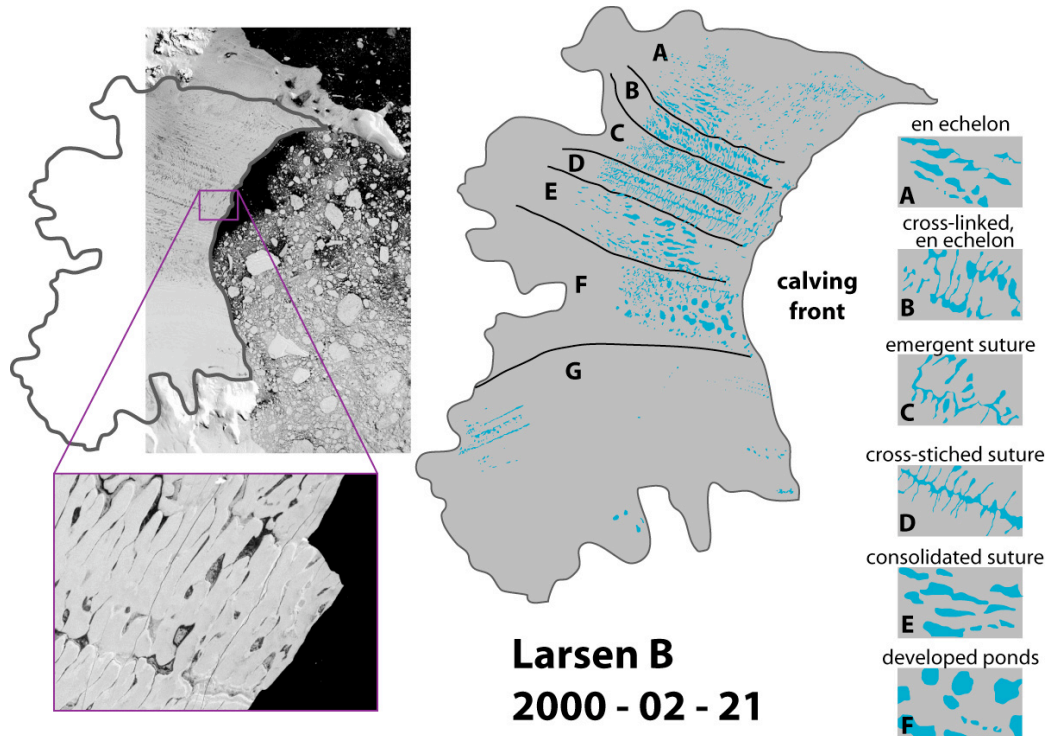
The research activity will be directed to the formulation of 6 types of interrelated numerical models and their application to ice-shelf specific problems. These **6 numerical model areas** are described as follows:

**Model Area 1. Energy balance models of wet surface firn and meltwater features.** Use of a “time-on-above-freezing-temperature” (positive degree day) method as a primary predictor of ice-shelf surface water production is inadequate (e.g., Sergienko, 2005; Sergienko and MacAyeal, 2005; Sergienko *et al.*, 2007) because the positive degree day method tends to work in situations where surface radiative parameters are unlikely to change appreciably, such as in well-established ablation zones of Greenland. Given the fact that Antarctica’s ice shelves must convert from being predominantly dry to being wet-surfaced as part of the disintegration process, it is vital to establish energy-balance approaches to dealing with wet snow and ice surface features. As exemplified in preliminary model formulations described below in *Section 4*, our approach will be to adapt existing approaches to modeling surface energy balance through the full evolution of an ice-shelf surface from dry conditions

to wet conditions. Distinguishing features of the energy-balance approach to be developed include treatments of: spectral dependencies of surface albedo and absorption, treatment of direct solar beam and diffuse full sky radiation, geometric focusing (*e.g.*, of crevasse features, MacClune *et al.*, 2003; Pfeffer and Bretherton, 1987), surface water body (pond) radiative transfer with internal phase change boundaries (*e.g.*, superimposed ice and lake ice), and multiyear evolution effects.

**Model Area 2. Firn-water flow.** As demonstrated by the winter-season collapse of the Wilkins Ice Shelf in 2008 [Scambos *et al.*, 2009], free surface water located in saturated firn below the firn/atmosphere interface is important as a source of crevasse-supporting water in ice-shelf instability. To adequately treat subsurface water, a ‘groundwater’ type model will be adapted for use (*e.g.*, coupled to the above energy balance model describing firn water sources) in predicting the evolution of free water within permeable firn.

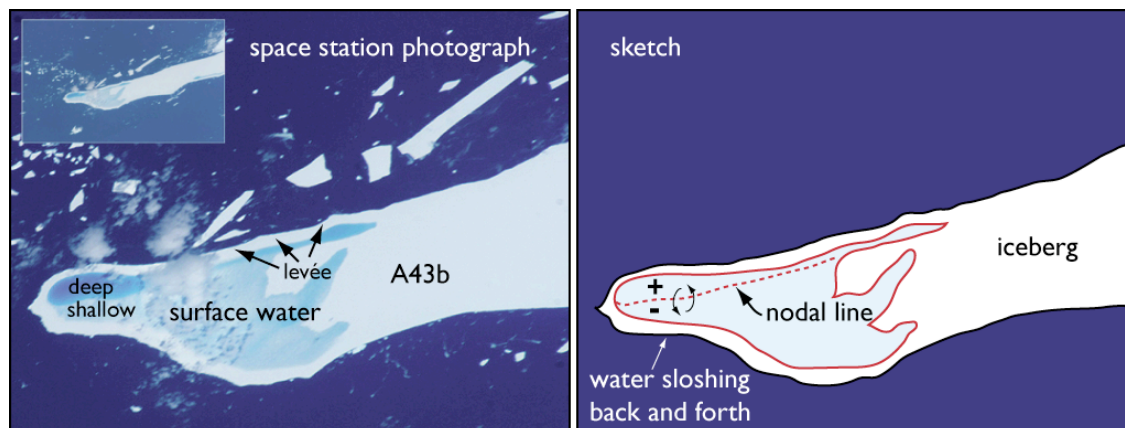
**Model Area 3. Surface water flow and surface erosion.** As described in Figure 1, surface-water features exhibit complex geometries indicative of processes that control both the erosion (by phase change) of the ice shelf surface and movement of water from one feature to another. Except for the description of water movement and surface pond evolution in the presence of Moulin drainage (*e.g.*, Das *et al.*, 2008), relatively little attention has been devoted to understanding the interrelationship of surface meltwater features on ice shelves. Our approach will make use of the burgeoning field of drainage network geomorphology being developed by Abrams *et al.* [2009] to understand the morphological features summarized in Figure 1. What especially attracts us to the approach by Abrams *et al.* [2009] is that it predicts channel growth on the kilometer scale from only a few geometric and flow-related parameters. As an initial approach to understanding runoff and seepage incision on an ice-sheet or ice-shelf surface, the methodology articulated by Abrams *et al.* [2009], that relies on simple scaling laws for flow and erosion, and on simple parameters of the evolving geometry, appears most promising.



**Figure 1** – (left panels) Images of the former Larsen B Ice Shelf from February 21, 2000 taken from Landsat 7. The panels at the right depict a digitization of meltpond plan-forms on the image. Seven regions are identified in the cartoon in panels A-F. These regions offer distinct melt-pond geometries that correspond nearly identically to the distinct glacier-source provenance (i.e., which outlet glacier ice came from) described by Glasser and Scambos (2008). Similarity in the results of two separate selection methods (ours and that of Glasser and Scambos, 2008) suggests a possible connection between provenance of ice and surface-meltwater morphology.

**Model Area 4. Ice-shelf surface-mass loading and flexure.** As described by Sergienko [2005] and by Scambos *et al.* [2005], surface meltwater cannot evolve on an ice shelf without producing movable mass loads that must be accommodated by ice-shelf flexure and hydrostatic balance. In the most extreme example, surface meltwater ponding on a floating iceberg produces a self-levéed reservoir, where the upward bulge of the iceberg's edges create a dam that surrounds a giant interior water pond, as shown in Figure 2. (As defended by Scambos *et al.*, 2005, explosively disintegrating tabular icebergs that originate from Antarctic ice shelves are excellent natural experiments that give insight into ice-shelf instability.) The development of surface-water features such as ponds and drainage networks on the surfaces of various ice shelves in Antarctica will also produce flexure that subsequently feeds back on water depths and drainage patterns. At the very least, determination of whether self-levéeing is possible on Antarctic ice shelves is an important step toward understanding the fate of surface meltwater in Antarctica, *i.e.*, will it run off the ice front or stay behind due to a levee? In a more speculative mode of thinking, the apparent 'surface water seiche' modes visible on tabular icebergs (Fig. 2) suggest that water movements induced or excited by sea swell, which is a well-established mechanical forcing

of ice shelves [e.g., Cathles *et al.*, 2009], might amplify the effects of sea swell and cause crevasse formation that contributes to explosive fragmentation.



**Figure 2** – Space station images (left panel) of iceberg A43b in the South Atlantic just prior to its catastrophic, explosive break-up (22 Jan., 2004; Scambos *et al.*, 2005) displaying surface-water ponds that are prevented from draining off the edges of the icebergs by water-load-induced flexural bulges (*levées*). The contrast in depth between the upper and lower halves of the extreme left most extension of the pond (deep being darker blue) suggests that a nodal line for a cross-iceberg flowing surface-water seiche extends down the left-to-right longitudinal axis of the pond, as depicted schematically in the right panel. Contrast in the color of the pond implies that there are contrasts in solar radiation absorption that could drive convection. Seiche motions on icebergs and ice shelves may introduce flexure stresses important in producing sub-meltwater-pond crevasses that ultimately destabilize the iceberg or ice shelf.

**Model Area 5. Convection in surface ponds and crevasses.** Thermally-driven convection within surface water bodies driven by surface cooling (assuming fresh water, where maximum density is reached when the water temperature is 4°C), solar absorption, and cooling at the basal ice contact is another key process that determines the local evolution of free water on the surface of ice shelves. Our treatment of these processes will focus on the most idealized cases that can be envisioned, so as to produce results that can readily be compared to observations as a way of evaluating the overall importance of this class of processes. Initial approaches are described below in Section 5.3.

**Model Area 6. Thermohaline convection in basal crevasses.** As with convection in surface-water features, convection in basal crevasses driven by phase changes along the crevasse walls and heat in the underlying water column will be examined as a corollary to the model processes described in the previous paragraph. While not a central goal of the proposed research, the effort will at least characterize the relative importance of both convection regimes (one in surface features, the other in basal crevasses) as a guide for future research.

## 2.1 Relationship with other research projects

The work proposed here will complement existing projects in 2 distinct ways. First, it will independently explore methodologies that are needed by larger-scale climate models that are used by the broader community to predict climate, e.g., as for the next assessment of the IPCC. The modeling exercises envisioned here will inspire ice-shelf surface **parameterizations** for

various **large-scale climate-modeling** efforts. Second, the proposed work will enhance the value of several projects that are currently funded to install instruments, collect remote sensing data, and monitor the stability of ice shelves along the Antarctic Peninsula (AP) [*IPY: Stability of Larsen C Ice Shelf in a Warming Climate (USA)* and associated international projects reported on NSF's website]. While these projects have modeling components, we contend that support of multiple approaches to modeling adds value.

## 2.2 Specific scientific questions:

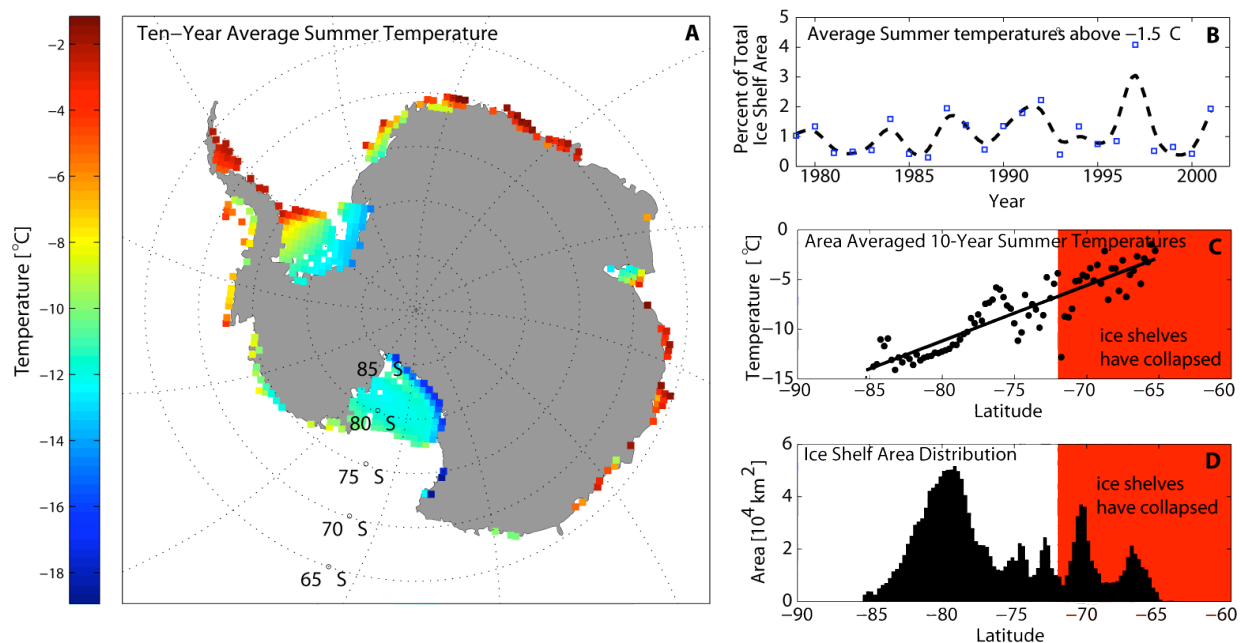
1. Under what conditions do surface meltwater lakes form as perennial features each summer? Is the  $-1.5^{\circ}\text{C}$  mean summer temperature a robust indicator of meltpond formation?
2. Under what climate conditions (if any) can surface meltwater ponds grow to be large and deep enough to avoid freezing solid during the winter? Will surface lakes on the Antarctic ice shelves suffer the same sensitivity to conditions that promote an "ice-free Arctic Ocean" scenario, *i.e.*, where lakes on the ice sheet will persist year round?
3. How do the size, shape and aerial extent of lakes vary as a function of surface morphology of the ice shelf (*i.e.*, surface roughness and surface slope of the ice shelf)? What controls the geometric differences observed prior to the Larsen B collapse?
4. How do the size, depth and shape of lakes affect the probability of intersecting with an englacial drainage feature?
5. How does the geometry of pre-existing, but inactive, englacial fractures promote or inhibit englacial drainage? How likely is it that englacial conduits reactivate?
6. How do tidal elevation gradients affect supra shelf water transport? Do surface water features align along maximum tidal gradients?
7. What bending stress is applied to an ice shelf by surface meltwater features? Is this stress sufficient to cause crack formation between ponds?
8. Does basal melting on the underside of an ice shelf act to inhibit basal crevasse formation, or is there enhanced melting at the crevasse tip?
9. Why was there an abrupt transition from ponding to no-ponding on the Larsen Ice Shelf, as apposed to the gradual decrease in size and density of ponds observed in Greenland?
10. How long does it take for onset of ponding, and how does the delay in ponding vary with melt rates? Do ice lenses form, and once formed, can they subsequently melt, releasing the stored surface water into the firn?

## 3. Background

We argue here that a simple statement of summer temperature is insufficient as a predictor of ice-shelf vulnerability to instability and collapse. Additional information, particularly the form that the water takes on the surface of ice shelves, and the thermodynamic/dynamic processes that influence this form, is argued here to also be a determinant of ice-shelf instability.

### 3.1 Empirical surface-temperature thresholds.

The environmental ‘setting’ and other data for Antarctic Ice Shelves shown in Figure 3 suggests that the relationship between surface temperature and vulnerability to ice shelf collapse is complex. Previous study [e.g., Scambos *et al.*, 2003] suggests that when the mean surface air temperature in January rises above  $-1.5^{\circ}\text{C}$ , surface ponds begin to form, and the ice shelf on which they form becomes vulnerable to collapse. Temperature records and satellite images provide a history of the Larsen B ice shelf over the last 30 years which supports this idea, and further suggests that a mean annual temperature of greater than  $-9^{\circ}\text{C}$  may constitute another way of quantifying the environmental threshold for stability [Scambos *et al.*, 2003; Morris and Vaughan, 2003; Skvarca and De Angelis, 2003]. Figure 1 shows a Landsat image of Larsen B two years prior to its collapse, when an automated weather station just north of Larsen B had a mean summer temperature of  $0^{\circ}\text{C}$  [Scambos *et al.*, 2003]. The inset magnifies a region near the edge, showing in detail the melt ponds and rivulets. The  $-1.5^{\circ}\text{C}$  threshold suggested by Scambos *et al.* [2003] seems reasonable, as the temperature in the firn below the ice surface can rise above the surface atmospheric value due to heating associated with solar energy penetrating below the firn/air boundary. However, it is not clear whether the  $-1.5^{\circ}\text{C}$  threshold value is robust (e.g., applicable to other ice shelves at other times), nor is it clear what length of time mean summer temperatures must remain above the  $-1.5^{\circ}\text{C}$  for ice-shelf instability to ensue.



**Figure 3** – Summary of Antarctic ice-shelf environment and vulnerability to collapse. (A) Average summer surface temperature over Antarctic ice shelves modeled using the polar MM5 model (Monaghan *et al.*, 2006). Data is shown using a Wiechel equal-area projection. (B) Percent of total Antarctic ice shelf area which has a model-derived summer (D J F) average surface temperature above  $-1.5^{\circ}\text{C}$  as a function of year since 1979 (blue boxes). A smooth spline fitting the data is shown to illustrate both variability and trend. (C) Modeled summer surface temperature on ice shelves as a function of latitude follows a roughly linear relationship. The most southerly latitude where at least one ice shelf has collapsed is designated by left edge of the red ‘caution’ region. The left edge of this red band coincides

with a mean summer temperature of  $-6.7^{\circ}\text{C}$ . (D) Histogram of ice-shelf area as a function of latitude. The red region indicates latitudes where at least one ice shelf has already collapsed.

### 3.2 Complex morphology of standing meltwater on ice-shelf surfaces.

As an initial, preliminary research step, we digitized melt ponds and other surface-water features visible in the Landsat image shown in Figure 1, and determined that 7 categories of meltwater features (characterized by sketches on the right-hand side of Fig. 1) could be tentatively identified as morphologically distinct. Between each region, there appears to be an abrupt transition where the morphology changes. The categorization criteria of surface water morphology shown in Figure 1 is distinct from that described in Glasser and Scambos [2008, see Fig. 2], but the two categorizations (ours and that published) involve nearly identical regions. Glasser and Scambos [2008] used criteria based on the source glacier feeding the region of the shelf and flowline features traced from the outlet glaciers to the calving front. Although the 2 surface-morphology categorization techniques are different, both agree that ice-shelf ‘outlet glacier provenance’ appears to play an important role in determining the morphology of water features on the surface of the ice shelf.

Perhaps one of the more interesting features presented in Figure 1 is the spatially abrupt transition from large melt ponds to no melt ponds (regions F to G). An immediate question is whether this transition coincides with the  $-1.5^{\circ}\text{C}$  isotherm. It is more likely that a difference in some other ice-shelf property (such as associated with provenance, Glasser and Scambos, 2008) accounts for the shift of meltpond geometry.

Automatic weather station (AWS) data only provides a partial answer to the above question. The mean summer temperature recorded at an AWS on Larsen C Ice Shelf shows a mean summer temperature of  $-3^{\circ}\text{C}$  [determined using the AMRC AWS data archive] and an AWS to the north is warmer, thus the  $-1.5^{\circ}\text{C}$  mean summer temperature isotherm must lie somewhere in the vicinity of the transition in question. Understanding the summer temperature constraints that coexist with conditions that promote meltwater ponding will be a major focus of the proposed work.

### 3.3 Greenland ice-sheet analogues for Antarctic surface-meltwater features.

In contrast to the extreme example of the former Larsen B, most of Antarctica does not experience appreciable surface melting. Surface melting in Antarctica is largely confined to the low-altitude coastal zone, mainly on floating ice shelves, and in most years amounts to an aerial extent of only  $\sim 17\%$  of Antarctica [Liu *et al.*, 2006]. This is in contrast to Greenland where, in 2005 over 90% of its surface area experiences surface melt for at least a brief time interval [Tedesco, 2007]. However, the absolute melting area is 1.6 times greater in Antarctica than in Greenland, simply because the Antarctic Ice Sheet is much larger.

Much attention has been, and currently is, focused on surface meltwater ponding and transport in Greenland [*e.g.*, Bougamont *et al.*, 2005; Lüthje *et al.*, 2006a; Das *et al.*, 2008, Catania *et al.*, 2008]. Much attention has been paid to the effects of melting on ice shelves (Fig. 2) in Antarctica [*e.g.*, Scambos *et al.*, 2003], but little attention has been paid to the onset and evolution of ponds and other surface and subsurface water features in Antarctica. Mean January 2008 temperatures recorded at the Larsen C automatic weather station (AWS) were just below  $-1.5^{\circ}\text{C}$  [AMRC AWS (raw unprocessed data)]. Substantial surface melting has been observed with backscatter radiometers, showing a long (50 day) melt season, but significant

melt ponds have yet to form [Shuman *et al.*, 2006]. If warming continues in the area, we might expect melt ponds to begin to form more abundantly.

Some features of ice shelves are not as easily observed as mean summer or mean annual surface temperature. Surface firn, for example, stores melt water and allows for subsurface water transport, and this may have been an important factor in the break-up of the Wilkins Ice Shelf during the austral winter months of 2008 [Scambos *et al.*, 2009]. Waterlogged firn was identified as the source of free water in the Wilkins break-up, and this makes sense from the standpoint that firn temperatures, particularly deep below the surface, can remain temperate even in the face of cold atmospheric temperature [Sergienko *et al.*, 2007]. The relevance to ice-shelf stability of **wet firn processes**, particularly those associated with permeable flow and brine saturation (from seawater sources), presents a major new challenge to studies of ice-shelf stability.

### 3.4 Basal melting.

While much of the proposed research will focus on surface meltwater features and processes, basal melting has also been identified as an important process in ice shelf collapse [Shepherd *et al.*, 2003; Fricker *et al.*, 2008; Thoma *et al.*, 2008]. Ice-shelf-wide basal melting rates are known for many ice shelves [*e.g.*, Rignot and Jacobs, 2002], however, small-scale variation in basal melting are largely unknown. Of particular concern is the problem of determining how melting within the confines of basal crevasses [Peters *et al.*, 2007] may influence their propagation and closure and thus provide a control on ice-shelf stability.

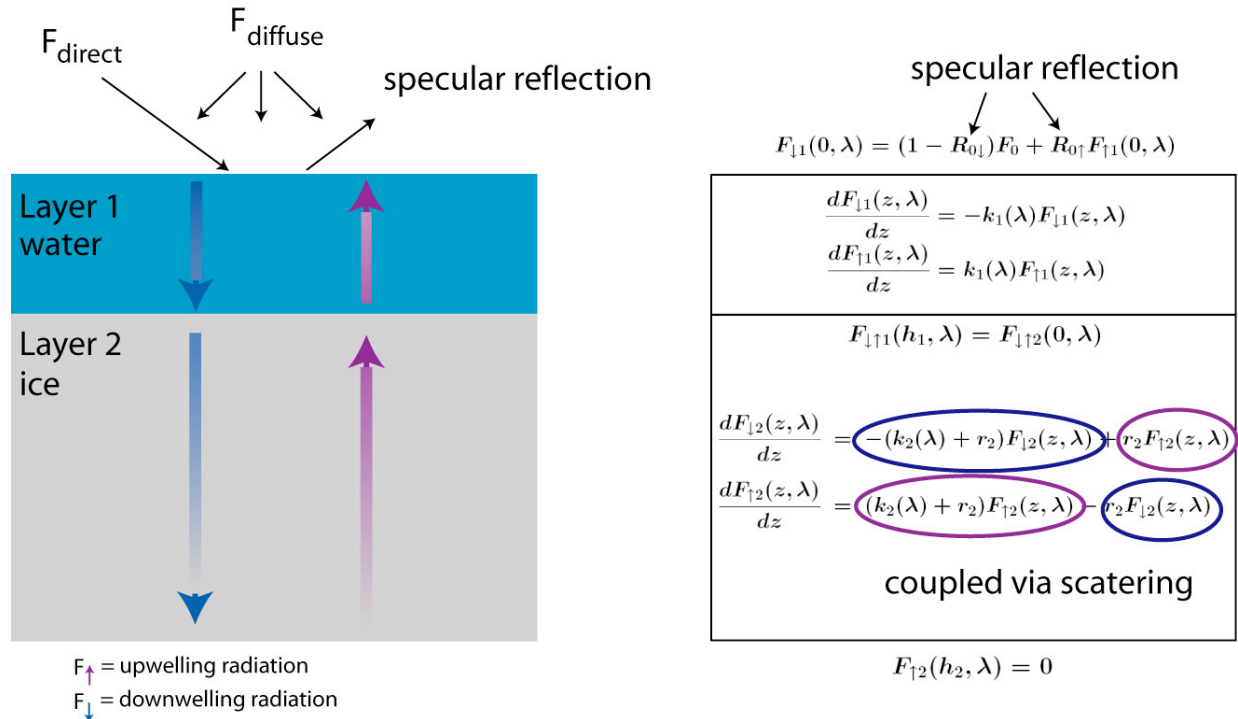
## 4. Initial Results and Proof-of-Concept

Below are descriptions of initial efforts in model development. All of these results constitute work done by the graduate student, Mac Cathles, in preparation for the examinations leading to PhD candidacy at the University of Chicago.

### 4.1 Surface Energy Balance

A surface energy balance (SEB) model will serve as the basis of our modeling efforts [Cathles *et al.*, 2008]. This will enable our investigation to explore a wide range of climate scenarios while explicitly accounting for energy transmission from the environment into the ice shelf system (including surface-water features). Most of our efforts will go into further developing a radiative-transfer model used to describe the absorption of incoming solar energy in surface water features of complex geometry and variable depth, and to couple this absorption to the near-surface thermodynamics of both the ice and the water feature. The energy fluxes between the surface and the atmosphere have been well studied [*e.g.*, Mölg and Hardy, 2004], and we plan to adapt proven methods to our needs. In formulating the turbulent heat fluxes at various fluid/fluid and solid/fluid interfaces, we will assume that the typical vertical velocity scale is proportional to the horizontal wind at the surface. We will account for buoyancy effects by applying the Monin-Obukhov similarity theory [Garratt, 1992], and will solve for sensible and latent heat fluxes separately. A key goal of our proposed treatment is to establish bounds on the probable range of behavior by fully exploring the parameter space; thus the surface-energy fluxes will be varied over a wide range of plausible values. By far the dominant flux in the SEB is the incoming shortwave radiation from the sun.

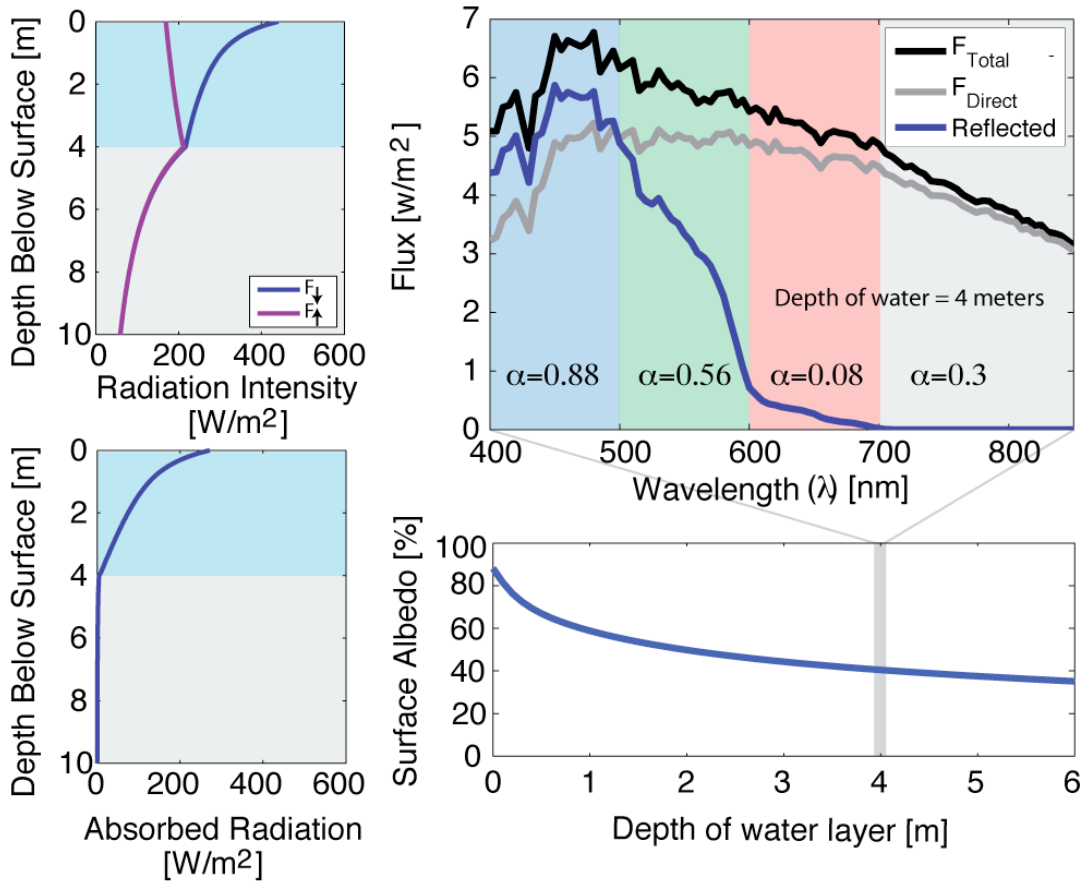
Figure 4 shows the two streams (downwelling and upwelling) of radiation that are tracked in the above-described model. The model is spectrally dependent using the latest compilation of optical properties of ice [Warren and Brandt, 2008]. The model is driven using the formulation of atmospheric radiative transfer developed by John Frederick at the University of Chicago [Frederick and Erlick, 1995; Frederick and Lubin, 1988]. This formulation specifies both the direct and diffuse downward radiation from sun, clouds and clear sky in 5 nm bands for wavelengths within 400 – 850 nm.



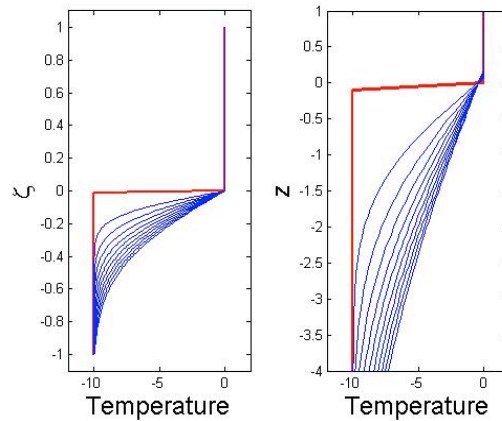
**Figure 4** - Conceptual diagram of a radiative transfer in a surface melt pond (left panel) and governing equations in each layer (right panel) from Cathles et al. [2008]. Equations in the right panel represent two-direction radiative stream conservation equations that relate the vertical derivative of stream intensity (denoted by variables  $F$  with appropriate subscripts) to various absorption and scattering processes. Parameters appearing in the right panel are:  $k$ , the absorption coefficient,  $r$ , the scattering coefficient,  $\lambda$ , the wavelength, and  $R_0$ , the specular scattering coefficient. The flux of diffuse and direct radiation is given as input, e.g., from time-of-day, time-of-year and cloudiness parameterizations. The downwelling and upwelling streams of radiation are tracked separately, and are coupled to the ice portion of the domain via scattering; for instance, downwelling radiation in the ice is scattered in both directions, the light scattered backwards is added to the upwelling stream.

The results shown in Figure 5 highlight the need to explicitly treat the spectral dependence [Warren and Brandt, 2008] of the optical properties, finding that the inclusion of spectral properties decreases the amount of energy absorbed by up to a factor of 2. We also find that cloud cover decreases the energy absorbed, but proportionally decreases less when the sun is at low angle. The spectrum of the reflected light shows clearly that the longer wavelengths are more highly attenuated, as opposed to the shorter wavelengths which are largely backscattered.

For this proposal, the treatment of surface energy balance will be extended to 3-layer systems, where there is lake ice on the surface of the meltwater layer. We also plan to explore the inclusion of depth-varying soot or dust, which upon melting, forms an absorptive layer at the water – ice interface.



**Figure 5** – Initial results from the radiative transfer model appearing in Fig. 4. For the example shown here, the model domain consists of 4 m of water sitting on top of 6 m of ice (for development purposes, a flux free ‘false bottom’ to the ice layer was implemented). The plots on the left show: (top) the two streams of radiation, and (bottom) the absorbed radiation. The top plot on the right shows the input radiation from the sun  $F_{Total}$ , the direct flux  $F_{Direct}$  consisting of the direct solar beam (not including light received as scattered from the sky) and the reflected flux in blue. The plot on the bottom right shows the variation in integrated albedo over the full spectrum as a function of pond depth.



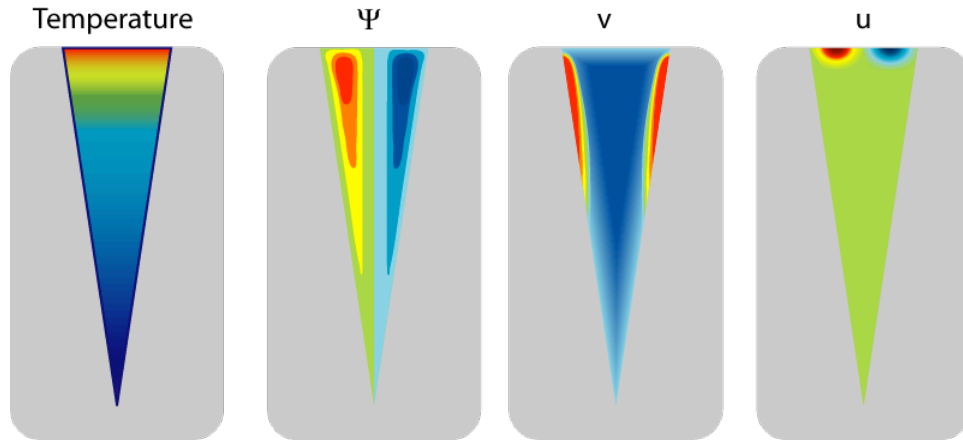
**Figure 6** – Phase boundary evolution in moving ( $\xi$ , left panel) and fixed ( $Z$ , right panel) reference frames. Initial conditions are in red, and time steps are in blue showing every 7 days, for a total run time of 70 days. This illustrates the amount of freezing that would occur over a winter on the bottom of a pond. The total amount frozen in 70 days is  $\sim 20$  cm.

## 4.2 Lake Evolution by Freezing

Geometric evolution of surface meltwater features will be modeled by tracking melting and freezing fronts that move according to the Stefan condition [Worster, 2000]. Heat is distributed within the ice according to a diffusive law, and will be treated with a finite-element approximation, as we expect complex geometries. Figure 6 shows an initial 1-dimensional model which explicitly tracks the position of the ice boundary by switching to a moving coordinate system in which the boundary is fixed. This method works well in 1D, but is not extendable to 2 dimensions. We will test this model against an enthalpy method model in 1D first, and then extend the enthalpy approximation to 2D. The enthalpy method essentially allows for partial freezing of an element that is at the boundary between two phases of water.

## 4.3 Water Convection and Viscous Heating

In our initial 1D model for ice melting or freezing shown in Figure 6 we set the liquid to a fixed temperature, moving heat within the ice. In reality, the water is a fluid with thermally varying density that can support thermal convection. Convection will distribute heat depending on the buoyancy of the liquid. Since there is a density inversion for fresh water below  $4^{\circ}\text{C}$ , warmer water in a near freezing pond will sink, transporting its heat to the bottom where it can cause melting. In our initial modeling efforts we have coupled the viscous, buoyant vorticity equation (expressed in terms of a stream function) to a heat advection/diffusion equation. Figure 7 depicts the resulting circulations within a fixed, V-shaped crevasse geometry. The illustrations show a simple heating term that decays exponentially with depth. We will use the full radiative transfer code described in section 4.1 to provide the heating distribution for future model development.



**Figure 7** – Illustration describing expected results from solution to the convection of water in a crevasse driven by absorption of incoming solar energy. This model will be improved and adapted to convection processes in fresh-water surface ponds and crevasses and in salt-water bottom crevasses. Temperature (left panel) due to solar absorption (relative temperature indicated by color), stream function  $\psi$  (next panel to right), vertical velocity  $v$  (second panel from right), and horizontal velocity  $u$  (right panel). Convective circulations are oriented along the upper sides of the crevasse, with upward motion (denoted by red colors in the plot of  $v$ ) along the crevasse walls and downward motion in the center, where warm water sinks as a result of the density maximum at  $4^{\circ}\text{C}$ .

## 5. Model Experimentation Tactics and Strategies – Work Plan

The previous discussion has highlighted the 6 principal areas of model development we believe will contribute to understanding how surface meltwater features might evolve and influence the evolution of the ice shelf and its contribution to sea level rise. Here, we describe several of the model-development and experimentation exercises we intend to carry out.

We intend to organize our work in 4 stages of model development/experimentation.

**Stage 1 – Model verification and quality control.** The first stage of model experimentation is that which translates physical process descriptions into numerical model codes such as those developed by researchers (*e.g.*, by Prof. John Frederick, see Frederick and Erlick, 1995, and Frederick and Lubin, 1988) at the University of Chicago. Experimentation at this stage will be mostly focused on establishing that the models are free of conceptual and coding errors, and that they run efficiently and make good use of computer resources.

**Stage 2 – Parameter exploration and range of model behavior.** The second stage of model experimentation (that blends seamlessly with the first) involves examining the range of model output behavior that results from reasonable control-parameter regimes. A common criticism of energy balance modeling approaches in glaciology is that many of the parameters and forcing fields are largely unknown or poorly constrained by observation. We do not dispute this; however, we do posit that progress in understanding ice-shelf evolution in response to climate change demands continued effort in this arena. Judicious use of inverse methods, *e.g.*, control methods developed in the context of ice-stream flow simulations in the presence of unknown basal parameters, may help to define parameter ranges that are otherwise difficult to observe. Perhaps more importantly, however, is the need to define the full range of accessible states that are reachable by reasonable ranges of parameters. Sensitivity tests will be conducted to map-

out the parameter spaces and tie aspects of surface meltwater lake behavior to specific ranges of controlling variables.

**Stage 3 – Prediction experiments under simplified, idealized climate forcing scenarios.** As part of the culmination of model-development and experimentation, efforts will be made to fully outline and predict likely consequences to surface conditions on the Antarctic ice shelves in response to simple, idealized scenarios of climate change. These experiments will yield results that are useful to scientific and public policy advisory panels that are tasked with estimating Antarctica's contribution to future sea-level rise.

**Stage 4 – Coupled prediction experiments.** In the final stages of our project we shall seek partners from other groups and institutions that do large-scale ice-sheet climate forecast modeling. Our models will be configured as both Fortran and Matlab™ subroutines, for use as estimator elements in an asymmetric up-scaling/down-scaling (in both space and time) scheme needed for prognostic simulations of the Antarctica's ice shelves. Ultimately, our models will be set up on-line as a resource for other glaciologists and climatologists to refer to and use.

## 6. Broader Impacts

**Discovery and Learning.** We shall build upon the extensive and richly informative work on surface meltwater/ice-sheet interaction processes currently available in the literature in the following ways:

- The subject of Antarctic surface melting will be a primary topic of science and public policy advisory panels charged with the responsibility of assessing future sea-level rise (and other effects of ice sheet melting). A key paradigm in the success of these panels, most notably exemplified by the recent IPCC report, is the realization of consensus opinion. Our proposed involvement in Antarctic ice-shelf surface melting research will add depth and diversity to the consensus.
- We plan to investigate/model some processes for the first time (*i.e.*, ice-shelf surface-meltwater feature incision effects driven by radiative balance and hydrodynamic seiche effects), and to propose alternative models of other processes (*i.e.*, surface energy balance of a wet ice shelf).
- Our effort is focused on micro- and meso-scale processes (centimeter to kilometer scale) whereas the majority of previous modeling efforts have been geared toward macroscopic (tens to hundreds of kilometer scale) processes that affect the large-scale mass balance of the Antarctic Ice Sheet. Improved understanding of the sub-grid scale processes may allow a parameterized version of the processes to be incorporated into numerical ice sheet models designed to address the evolution of the ice sheet as a whole. A **website** reporting our results and providing **suggested parameterizations** for large scale models will be constructed as a community dissemination activity.

**Training and Mentoring.** The proposed project will also provide support for the PI to mentor a graduate student (L. Mac. Cathles). Mac Cathles is a promising young scientist that has participated in 5 field campaigns in both Greenland (with Dr. Mary Albert) and Antarctica (with Dr. Ted Scambos, and with the PI), and has published several first-authored papers in major journals on problems relating to ice-sheet surface temperature and iceberg calving (his short bio is included as a supplemental document). Cathles's professional development will

continue with plans for him to: (1) complete a dissertation on the subject of the research described in this proposal, (2) become familiar with scientific discourse via his attendance at meetings, conferences and symposia, and (3) learn to teach and interact with the public via participation in our outreach activities (see below). The PI will meet regularly with Mac Cathles to discuss progress toward goals.

***Broad dissemination to enhance public understanding.*** Project resources will be used to produce a series of lessons, lectures and demonstrations to be offered to Chicago's high-school science teachers as part of a summer enrichment program organized by Prof. Noboru Nakamura (of our Department) and other colleagues in the Division of Physical Sciences at the University of Chicago. Mac Cathles, the graduate student involved in this proposal was a workshop helper during the 2008 event, and plans to participate more formally in future years by developing demonstrations that illustrate aspects of the cryosphere which influence every-day life, as well as interesting demonstrations that capture the intrinsic curiosity of young people and teachers. We shall also approach the Science and Technology Mentoring and Outreach Program of the University of Chicago to see if our demonstration materials can be used in one of their 6 outreach and mentoring activity channels (*e.g.*, Science Teacher for a Day).

Chicago is a diverse Metropolitan city, with a multitude of opportunities for dissemination of scientific ideas through both the community in the immediate vicinity of the university (Hyde Park) and the city at large. The PI and graduate student will at a minimum give 1 public lecture in the greater Chicago area each year. An examples of the types of lecture is "*Café Scientifique*"; a gathering of up to 50 people (generally aimed at non-academics) at a local public house for a lecture, followed by questions and informal discussion for the rest of the evening. The PI and graduate student will also become involved with *Science Chicago's Find A Scientist* online database. This community resource links scientists interested in enlivening and enlightening science learning with local classroom teachers.

***Fostering diversity.*** The University of Chicago participates in the Summer Research Early Identification Program (SR-EIP) of the Leadership Alliance, which is a program to help address the diversity in the nation's scientific workforce. The program offers many advantages for small research teams to participate in the encouragement of undergraduate students from underrepresented and underserved groups to become involved in scientific activities and careers. The PI will set up a Research Experience Program Site at the University of Chicago to host a summer collegiate scholar to perform satellite image analysis of Antarctic ice-shelf surface lakes (*e.g.*, both on presently existing ice shelves and on ice shelves that have disintegrated recently, but for which satellite images exist). The SR-EIP vets the collegiate scholars who apply and provides stipends and travel funds for collegiate scholars to attend program sites. We shall ask for funds to support the workstation and data storage needs of the summer intern we hope to attract from the SR-EIP program. The summer intern will be co-mentored by the PI and by the graduate student. Funds are not needed for the summer intern's stipend or travel, as they are provided by SR-EIP

## **7. Results from Prior NSF Support**

**MacAyeal.** NSF OPP 0229546 "*Collaborative Research of Earth's largest Icebergs*", 07/01/2003 to 06/30/2008, \$483,865.

This project was designed to investigate (a) the drift, evolution and ultimate break-up and melting of iceberg B15, and (b) the origin of iceberg tremor (a seismic signal picked up on various islands in the South Pacific).

**Findings: Glacial tsunamigenesis and iceberg calving.** Seismometers deployed over a 3-year period on icebergs in the Ross Sea and on the Ross Ice Shelf, Antarctica, reveal that impulsive sources of ocean surface-waves are frequent (*e.g.*, about 200 events per year in the Ross Sea) in the ice-shelf and iceberg covered environment of coastal Antarctica. The 368 events recorded by our field deployment suggest that these impulsive events are generated by glaciological mechanisms, such as (a) small-scale calving and edge wasting of icebergs and ice shelf ice fronts, (b) edge-on-edge closing and opening associated with iceberg collisions, and (c) possibly the impulsive opening of void space associated with ice-shelf rifting and basal crevasse formation. The observations described here provide a background of glaciogenic ocean-wave phenomena relevant to the Ross Sea and suggest that these phenomena may in the future be exploited (using more purposefully designed observation schemes) to understand iceberg calving and ice-shelf disintegration processes.

**Contributions to Learning, Mentoring and Stewardship:** Three PhD and two MS degrees were awarded as a result of research performed on this project. Of these, two PhD and one MS degrees were awarded to women. The PI also contributed to the mentoring of a postdoctoral scholar, Dr. Jeremy Bassis, who has successfully completed his tenure as a postdoctoral scholar and has moved on to accept a faculty position at the University of Michigan. The PI served on a scientific editorial board for *Annals of Glaciology* (Manali, India symposium on snow and avalanches) and currently serves on the PASSCAL (NSF-supported seismometer equipment consortium) standing committee.

**Public Outreach:** The PI was interviewed by NPR's *All Things Considered*, and was featured in Werner Herzog's film *Encounters at the End of the World* made when Herzog was an artist in residence at McMurdo Station. In addition, the PI and his graduate students have given public lectures in the Chicago area. The graduate student, Mac Cathles was an assistant organizer for the NSF-sponsored teaching workshop for secondary school teachers in subjects pertaining to fluid dynamics, weather and climate (a project directed by Prof. Noboru Nakamura, U. of Chicago) during summer of 2008.

**Data Archive and Availability:** 100% of the actual data is archived and freely available at the IRIS DMC and at NSIDC.

**Publications:** (see reference list for full citations) Brunt *et al.* [2006], Cathles *et al.* [2009], MacAyeal *et al.* [2006, 2008a, 2008b, 2009], Scambos *et al.* [2005], Sergienko *et al.* [2005, 2007], Okal and MacAyeal [2006].