Project Description

1. Overview

The **goal** of the proposed research is to **test a new 3-step paradigm** for self-stimulating, explosive ice-shelf disintegration that has emerged in the wake of studies of the 2008 and 2009 disintegration events of the Wilkins Ice Shelf [Scambos *et al.,* 2009; Braun *et al.,* 2009]. This 3-step paradigm is described in the *Project Summary* (above), in *Section 2* (below), and in Figure 1 (below). The primary focus of the research will be on steps 2 and 3 of the 3-step paradigm: the transition from an ice-shelf/ocean system possessing a large amount of gravitational potential energy to various forms of kinetic energy in a chaotic jumble of ice fragments (referred to as *ice mélange*, word usage: designating a material). The kinetic energy includes large-amplitude ocean waves that stimulate further iceberg calving and fragmentation in a self-reinforcing chain reaction.

The **motivation** for understanding steps 2 and 3 of the paradigm (trigger and explosive phases) is embodied in the following 4 questions (among other, subsidiary questions):

- Does better understanding of steps 2 and 3, which are responsible for the "explosiveness" of ice-shelf disintegration, inform our knowledge of the **environmental/climate enabling conditions** that start ice-shelf collapse in the first place (step 1)?
- What properties **differentiate ice shelves** that are **vulnerable** to catastrophic, explosive collapse from ice shelves that are not, regardless of environmental conditions?
- What **limits ice-shelf collapse** in cases such as the 29 February 2008 event of the Wilkins Ice Shelf, *e.g.,* where the apparent self-sustained collapse mechanism halts prior to consuming the entire ice shelf?
- Are ice-mélange processes **universal**, *e.g.,* are Antarctic ice-shelf disintegration processes similar to iceberg calving in Greenland fjords, and do ice-shelf disintegration processes mimic non-glaciological systems (*e.g.,* avalanching sand piles) where transitions occur between order and disorder?

Theoretical, Numerical and Observational Activities.

Theoretical research activity (led by physicist, co-PI Wendy Zhang) will facilitate the application of key universal ideas in physics (*e.g.,* arising from condensed matter physics such as 'depinning transitions' in charge-density wave conductors, see Sethna *et al.,* 2001, and 'jamming transitions' in loose particle materials and foams, Zhang *et al.,* 2009). By relating ice-shelf collapse to broadly based ideas of how disordered systems exhibit transitions, insight into how to best model and predict the phenomena of ice-shelf collapse will be gained.

Numerical research activity (led by glaciologist/physical oceanographer, lead-PI Doug MacAyeal) will develop and apply new (to glaciology) numerical methods for simulating processes in the *'mosh pit'* (word usage: designating a place) described in Figure 1. Advanced techniques will include *smoothed particle hydrodynamics* (SPH) recently used in simulation of tsunamigenic subaerial landslides [Schwaiger, 2008a; Schwaiger and Higman, 2007; Schwaiger, 2008b; Dalrymple and Herault, 2008], impulsive waves [Ataie-Ashtiani and

Shobeyri, 2008; Dalrymple and Rogers, 2006], internal waves and ocean-column mixing [Tartakovsky and Meakin, 2005], and dike intrusions [Fujita, 2008].

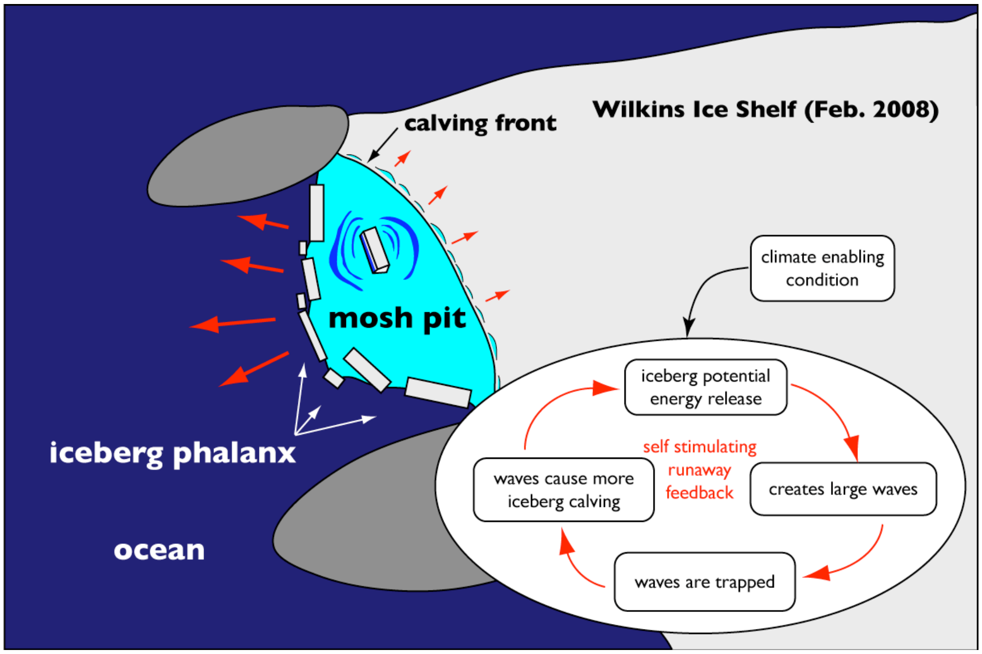


Figure 1 *– Conceptual, 3-step paradigm of ice-shelf collapse at work on the Wilkins Ice Shelf (schematic map of collapse with inset in lower right showing runaway feedback mechanism of step 3 of the paradigm). In* ***step 1****, the climate and glaciological systems interact to slowly, over time, enable ice-shelf vulnerability by increasing free surface water and surface and basal crevasses. In* ***step 2****, a leading 'phalanx' of uncapsized tabular icebergs [Scambos et al., 2009] is released from the ice shelf to form a pocket between the ice shelf and icebergs called a 'mosh pit' (a term used here to designate a place, and which is borrowed from nomenclature designating a place at a rock-and-roll music concert). In the mosh pit, surface-gravity waves excited by iceberg capsize are trapped and reflected back on the calving front of the ice shelf so that, in* ***step 3****, a runaway feedback is developed between iceberg capsize/break-up, ocean wave excitation, wave-flexure-induced calving and further iceberg capsize.*

Observation research activity (led by seismologist/tsunami expert, co-PI Emile Okal) will employ new observational methodologies for enquiry into the fast-phases of ice-shelf disintegration. These methodologies will allow us to analyze observations of ice-shelf disintegration at large distances (*e.g.,* using seismic and hydroacoustic signals in the Pacific, *e.g.,* Okal, 2007a, Okal *et al.,* 2007b) and to forecast impending ice-shelf collapse from precursor signals derived from routine observations (*e.g.,* from seismic arrays located on vulnerable ice shelves, *e.g.,* MacAyeal *et al.,* 2009, and Cathles *et al.,* 2009).

2. State of Current Knowledge: Ice-Shelf Collapse and the 3-Step Process

Since Mercer's [1978] pioneering work proposing ice-shelf retreat as the precursor to general West Antarctic Ice Sheet involvement in a rapid sea-level response to climate change, the Antarctic Peninsula has witnessed 10 glaciologically distinct ice-shelf retreat events representing a total loss of about 27,000 km^2 (*i.e.,* as summarized by Vaughan *et al.,* 2009).

The most spectacular and worrisome of these events were embodied by the spectacular explosive break-ups of the Larsen A, Larsen B and Wilkins ice shelves. Of particular note is the speed-up and thinning of glaciers previously feeding the Larsen B in response to its disintegration [Scambos *et al.,* 2004; Shuman *et al.,* 2008]. This consequence of Larsen B's break-up confirms Mercer's idea that when ice shelves are removed, inland ice that is buttressed by the ice shelves can flow faster into the ocean.

Observations, primarily by satellite, of the abrupt collapse of Larsen B Ice Shelf in 2002, and of the several abrupt collapse episodes of the Wilkins Ice Shelf through 2008 and 2009 have narrowed working theories of the collapse mechanism (*e.g.,* Scambos *et al.,* 2000; MacAyeal *et al.,* 2003) to the following 3-step process paradigm suggested by Scambos *et al.* [2009].

Step 1, Environmental Enabling Condition. According to Scambos *et al.* [2009], the key environmental enabling condition leading to the collapse of an ice shelf is the development of a water-saturated firn layer, either by direct surface melting in response to lengthening summer melt seasons or by infiltration of seawater (brine) from the ice front or through basal crevasses. A subsidiary environmental enabling involves the development of near-ice-front fractures (crevasses) in both the base and surface. According to initial model results reported by Scambos *et al.* [2009] local bending moments introduced at the ice front by hydrostatic pressure in the ocean can give rise to fractures (see their Figs. 7 and 8) which, when subject to wet conditions, are likely to calve icebergs that are unstable and likely to capsize, *i.e.,* they are narrower than they are thick.

Step 2, Trigger Mechanism. Once the environmental enabling conditions have been met, and the ice shelf has evolved into a state that is vulnerable to collapse, the initial trigger (step 2) that sets off the abrupt episode (step 3) is the initial calving of a long sequence of ice-front parallel tabular icebergs (either calved *en echelon*, or calved as a single iceberg that subsequently breaks into several). The presence of this 'leading phalanx' (a term first used by T. Scambos, personal communication) of tabular ice-front parallel icebergs creates a 'mosh pit' (Fig. 1) where ocean wave energy is trapped by reflective boundaries that surround the zone of explosive ice-shelf fragmentation.

The leading phalanx of tabular icebergs witnessed at the outer, seaward edge of the expanding blue-colored ice-mélange 'collapse bubble' of the Wilkins Ice Shelf event of 29 February 2008, is shown in the right 2 panels of Figure 2. In the case of the 2002 collapse of Larsen B, the leading phalanx was less distinct than those of the February 2008 event of Wilkins Ice Shelf (Fig. 2). There were, however, several calving events of large, uncapsizable icebergs that preceded the more violent stage of the Larsen B Ice Shelf collapse.

Step 3, Energy Release and Fragmentation. Once the collapse of an ice shelf has been triggered, a relatively fast (hours to days) period of evolution unfolds in which the primary activity is the release of gravitational potential energy stored in the original configuration of the ice shelf. The typical 'death assemblage', or *taphonomy* (borrowing a term from paleontology), of a collapsed ice shelf shows an arrangement of ice-shelf fragments (mélange) that densely covers an area of the ocean surface that is greater than the original area of the collapsed ice shelf. This implies a redistribution of ice volume from deep in the water column over a limited area to the surface layer extending over a larger area. This releases gravitational potential energy because it allows dense seawater to move downward and buoyant ice to move upward. A crude estimate for the February 2008 event of the Wilkins Ice Shelf is summarized in Figure

3, giving a total of about 2.4×10^{15} J of energy liberated by the event. For comparison, this energy is comparable to that of the large Pacific Ocean tsunami of 1946 triggered by an earthquake and subsequent submarine landslide (an avalanche of seabed material) in the Aleutian Islands [Okal, 2003; Okal *et al.,* 2003; Okal and Hebert, 2007; Fryer *et al.,* 2004]. This 1946 tsunami rose to 42 m on Unimak island near its source, caused >150 deaths in Hawaii and was cited as the cause of damage to a British Antarctic base in Graham Land [Fuchs, 1982].

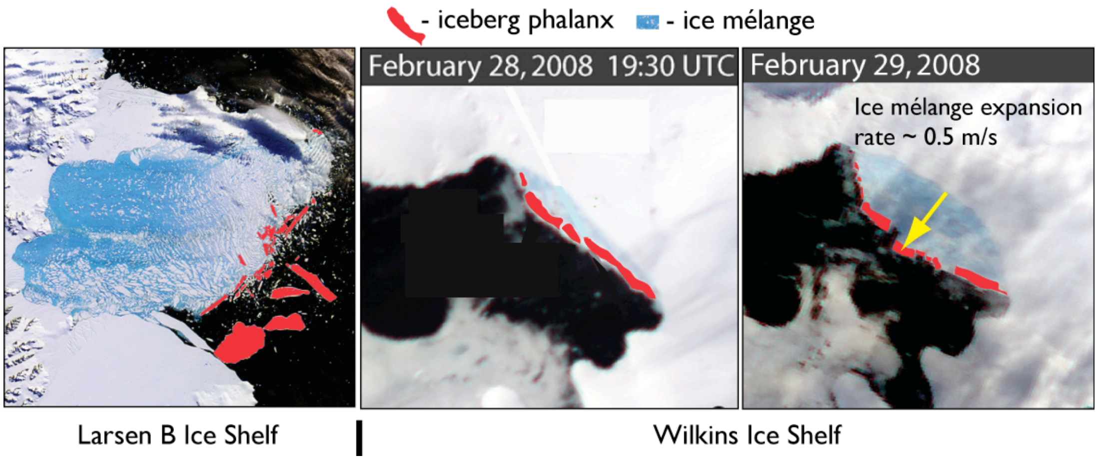


Figure 2 *– Triggering phase (Step 2) of ice-shelf break-up involves the initial calving of a 'leading phalanx' of tabular icebergs (denoted by red color in above images) [Scambos et al., 2009; the term 'leading phalanx' coined by T. Scambos, personal communication, 2008].*

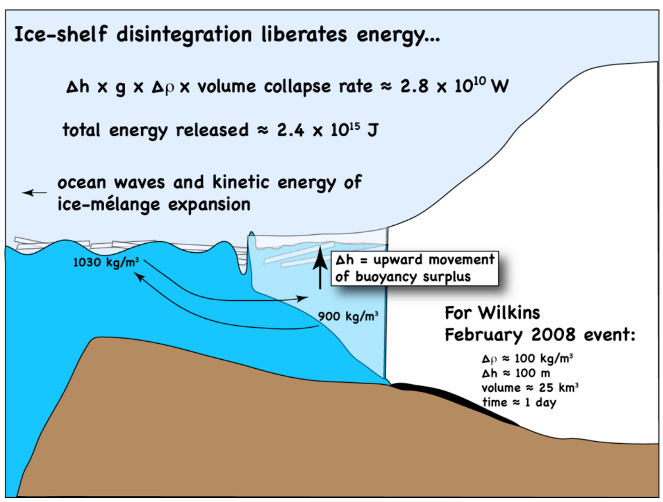


Figure 3 *– Energy release phase of the collapse of the Wilkins Ice Shelf in February 2008. The gravitational potential energy released by this process is partitioned into three forms: energy carried by ocean waves (that are destructive to icebergs and the remaining ice shelf), kinetic energy of the macroscopic expansion rate of the blue mélange across the ocean surface, and kinetic energy of micro- and meso-scale movements of the ice and water.*

The energy release of a collapsing ice shelf is so fast that most forms of motion driven by this release are extremely destructive to the icebergs and the remaining ice shelf. Viscous dissipation is not immediately capable of handling the estimated 3×10^{10} W energy release rate during the collapse (Fig. 3). Energy is instead converted into (1) the kinetic energy of ice-mélange expansion (as shown in Fig. 2 by the right panel) and (2) energy of surface gravity waves trapped within the mosh pit. There are other energy conversions, but these two are special because they explain key observations: the rapid expansion of the blue ice mélange bubble behind the leading iceberg phalanx and the extreme degree of fragmentation with non-glaciological style fracture geometries and erratic fragment arrangements indicative of the destructive effects of large waves (Fig. 4).

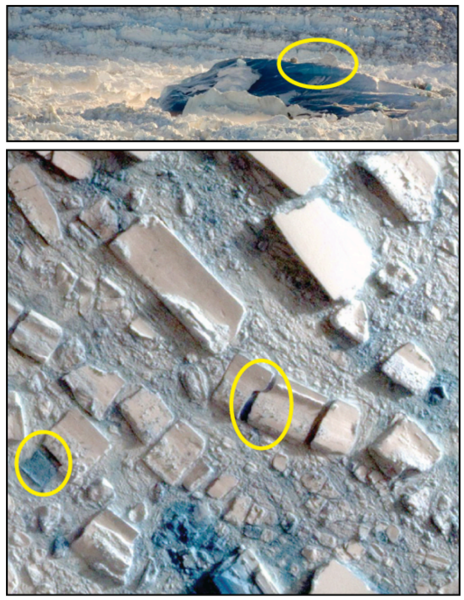


***Figure 4** – Taphonomy, or post-collapse 'death assemblage', of Wilkins Ice Shelf (bottom panel, from NSIDC website) and ice-mélange near the calving face of a Greenland outlet glacier (top panel, courtesy Jason Amundson). Circled features denote arrangements indicative of violent wave/iceberg interaction.*

2.1 Initial Models of Ice-Shelf Collapse Dynamics

Three previous efforts have been made to model the destructive stage of ice-shelf collapse. Scambos *et al.* [2009] present a numerical analysis of bending stresses at the seaward front of a collapsing ice shelf, and show that the presence of free surface water can lead to calving of icebergs that are unstable with respect to capsize (are more narrow than initially thick).

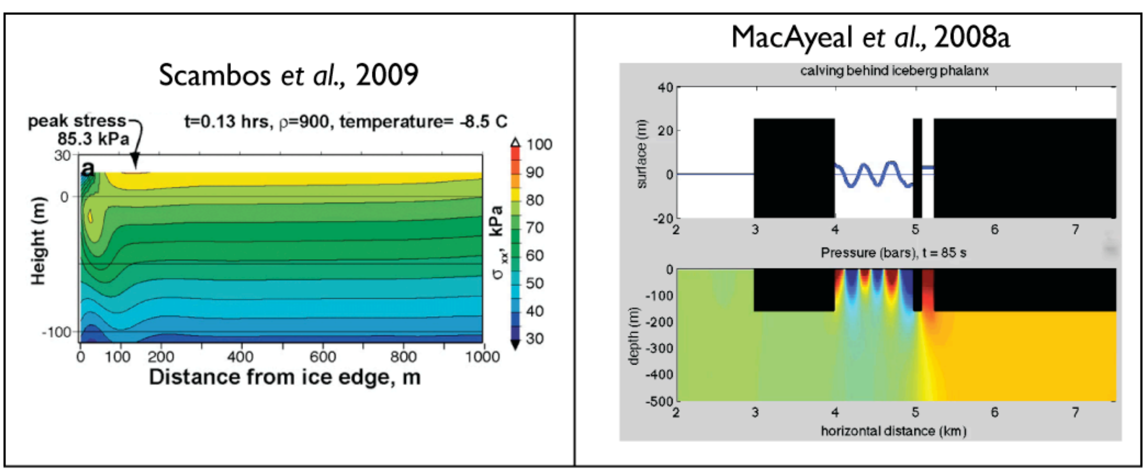


***Figure 5** – Initial numerical models of mosh-pit dynamics. The left panel from Scambos et al. [2009] shows simulations of iceberg-calving relevant stress intensity at an ice front due to static effect of bending moments at the ice/seawater boundary. The right panel from MacAyeal et al. [2008a] shows the vertical decay of wave pressure perturbation (colors, ranging from -100 to 100 kPa for 10 m waves).*

MacAyeal *et al.* [2008a], present numerical model analysis of the hydrodynamic interaction between capsizing icebergs and the ocean's free surface gravity waves. This work, although conducted with model assumptions that were far from the parameter range where model tools are most appropriate (*i.e.,* ignoring nonlinearity and non-hydrostatic pressures), demonstrated the effectiveness of the leading tabular iceberg phalanx as a ***wave trap*** that gives rise to the mosh pit. The third effort, by Sergienko *et al.* [2008], examines the degree to which ice-shelf (and eventually iceberg) flexure is involved in ocean-wave transmission and reflection during ice-shelf collapse events. A summary of two of the three model efforts is provided in Figure 5.

3. Proposed Research

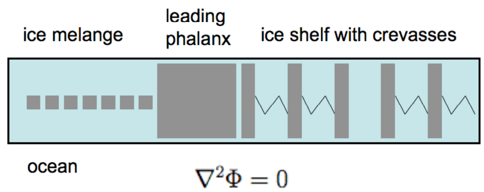
Our research efforts will focus primarily on steps 2 and 3 of explosive ice-shelf disintegration described above: the chain-reaction behaviors associated with 'mosh pit' dynamics. Work will advance on three fronts: **theoretical analysis**, **computational method development** and application and **observational exploration of new data sources** in seismology, photogrammetry and hydroacoustics.

3.1 Theoretical Analysis:

Here we propose to develop and analyze a hierarchy of simple models describing the ice-shelf disintegration process. The goal is to examine idealized situations that yield insights on the key inputs responsible for the qualitative features of explosive disintegration. Such 'toy' models serve three important purposes: **(1)** they test general ideas about wave propagation and fragmentation processes, such as **'band gap'** formation [Sigalas and Economou, 1992] and **'depinning transitions'** [Fisher, 1998; Sethna *et al.,* 2001] which have developed in other physical contexts (described below). **(2)** These qualitative results complement the development of full numerical simulations (Section 3.2) that seek to provide a *quantitative* account of the disintegration process. **(3)** The models may also predict trends that can be directly assessed by data from image analysis, seismic signals or lab experiments (Section 3.3).

Figure 6 illustrates one such idealized model (among the many that will be considered) for how the capsizing of a leading phalanx of icebergs can trigger the disintegration of an entire ice shelf. We divide the problem into two halves: (1) bulk flow in the ocean underneath the ice cover, idealized as inviscid and irrotational (described by a divergence-free velocity potential), and (2) surface motion of the mélange and the ice shelf. In the simplest version of the model, the mélange is idealized as identical blocks with mass m, and the ice shelf is idealized as vertical slabs with a larger mass M, connected by linear springs to the neighboring slabs. Rifts which cut through the ice shelf are modeled as spring-free gaps.

For simplicity we have depicted the masses as being of equal size in figure 6. It is straightforward to adapt this model to analyze the more relevant situation where the sizes of ice bodies vary in accordance with some size probability distribution, information we can obtain from high-resolution satellite image analysis (Section 3.3). Another promising direction is to examine the dynamical response when the material property of the mélange, evidently a complex viscoelastic fluid, is approximated in a more realistic manner. A reasonable starting point for the low-order model is that the viscous response within the mélange is dominated by flow through the small gaps between the loose pieces of ice, thus resembling the response of disordered, wet foam. The elastic response is dominated by the rigid blocks, and thus resembles a 2D suspension of polydispersed particles (colloidal, having a range of sizes). Both assumptions can be checked against results from lab experiments.



$$\nabla^2\Phi = 0$$

$$|\nabla\Phi| \to 0 \text{ as } \sqrt{x^2+y^2} \to \infty$$

$$\mathbf{n}\cdot\nabla\Phi = U_n \text{ at } h(x,t)$$

***Figure 6** – Idealized model of a collapsing ice shelf.*

Coupling bulk flow to surface deflection: We impose a kinematic condition requiring that the normal velocity in the water match the normal velocity of the blocks, *i.e.,* that there is no flow through the ice layer. We also impose a normal stress balance, in which each mass element in the mélange and in the shelf, experiences a pressure force due to the bulk flow. The slabs also experience spring forces associated with the relative displacements of the adjacent slabs. For simplicity, we assume that the ice shelf is bound to shore on the right-hand side, and thus require that the very last vertical slab be fixed. In contrast, the mélange expands freely into the ocean.

Modeling rift formation, calving and onset of capsize: An ice shelf will break apart, or form a rift that penetrates the entire depth of the shelf, when subjected to a large stress, or a large strain. We model this effect by simply removing the connecting spring whenever, and wherever, a surface deflection separates two adjacent vertical slabs by a distance $\Delta s > \Delta s_c$. A vertical slab that loses both of its springs is simply held upright by geometric pinning. If it is now exposed to the mélange, instead of being in the middle of the ice shelf, it will capsize, transforming into several blocks of mass m. The capsize also releases gravitational potential energy into the ocean and to the 'surface tension' resisting deformation of the ice mélange covered free surface.

Modeling capsize via pressure impulse theory: Since capsize of an iceberg produces an acceleration which is large in magnitude and short in duration, we can approximate it, at least in an idealized case, as an impulsive change. This approach is commonly used in models of liquid drop impact, as well as collision of projectiles [Batchelor, 1977, sec. 6.10]. The idea is that the sudden acceleration endures so briefly that the boundaries, here corresponding to the positions of the mélange and the ice shelf, do not move significantly. Instead, the most pronounced effect of the acceleration is to create large, non-hydrostatic pressure gradients within the ocean. The large pressure gradients, in turn, create an abrupt change in the bulk flow velocity profile within the ocean. Given this new bulk flow velocity, we can then calculate the surface deformation via the normal stress balance. Finally, with the new surface deflection, we can update the bulk flow in accordance with the kinematic boundary condition.

Despite the oversimplifications of the above treatments, such low-order models can account for several important effects not addressed by the first-generation models (*e.g.,* MacAyeal *et al.,* 2008a; Scambos *et al.,* 2009; Sergienko *et al.,* 2008). Two examples are: **(1) Large-amplitude disturbances.** By using a boundary integral formulation to solve for the inviscid and irrotational bulk flow, large amplitude deformations of the surface and of the velocity can be accommodated. In other words, this formulation provides a correct treatment of both the Bernoulli pressure term and the kinematic condition, regardless of the motion amplitude. One of the PIs (Wendy Zhang) has successfully modeled the final stage of the extremely nonlinear collapse of an air cavity in water using this approach [Schmidt *et al.,* 2009]. **(2) Viscous damping.** By modeling the ice surface as solid masses in the mélange portion and as slab-shaped mass-and-spring systems in the shelf region, we are able to incorporate viscous effects, both in the fluid between the mass elements and also in the fluid within the water below the mass elements, as damping coefficients. This is a phenomenological approach. Our hope is that these damping coefficients can be made more exact by more realistic and appropriate model of the small-scale processes.

The low-order models also provide the first proof-of-principle tests for several general ideas about how energy can be trapped by propagating waves. We expect results from these tests will guide our thinking in the design of numerical simulations and lab experiments. Some possible organizing ideas are:

(1) 'Band gap' emergence. Suppose that the crevasses of a given depth are spaced a regular distance L apart, then it is possible for the disturbance produced by capsize of one slab to experience successive scatterings that accumulate. This results in a non-propagating, or standing, wave of a particular frequency. This phenomenon, known in the condensed-matter physics literature as a 'band gap' [Ashcroft and Mermin, 1976], arises naturally when a plane wave propagates through a periodic array of obstacles. The ice-shelf problem is an interesting variation on the classic problem because the propagation occurs both through a bulk flow (via the ocean) and through a surface layer. If the surface mode dominates then an analog of the band gap phenomenon may be possible and act to concentrate the gravitational potential energy released by capsizing ice slabs. If the spatial structure is random, then the wave excited by the initial capsize may undergo many partial reflections and transmissions due to the large density of scattering events at the ice-covered surface. All these waves will have different phases and interfere with each other. Studies of wave propagation in semiconductors, in acoustics and in fluids have shown that, when the spatial disorder is strong, the waves do not propagate, but instead attenuate exponentially over a length-scale that is characteristic of the disorder.

(2) Large-scale disintegration as a 'depinning transition'. (The term 'depinning transition' is commonly used in physics to describe transition phenomena such as avalanches and earthquakes in complex or disordered systems, and stems from theoretical work on charge-density wave (CDW) conductors in the 1980's, see Sethna *et al.,* 2001.) One of the most remarkable, and spectacular, features of the explosive ice-shelf disintegration process is that a relatively small-scale event, the failure of a leading phalanx, can lead to the destruction of a large area of ice shelf in a short amount of time. Our 'toy' model offers an extremely simple version of this amplification process. Suppose the leading-phalanx fails and creates a bulk disturbance flow, which deflects the surface. As a result, several of the springs are broken, creating regions of the surface which now move more readily in response to the bulk flow. If the disturbance is weak, the system oscillates and eventually, due to viscous effects, dies down.

If the disturbance is sufficiently strong, however, the first capsize will yield a second capsize, causing a vertical slab at the edge of the shelf to fail, thus setting up a second flow which further weakens the shelf. This process amplifies itself (a domino effect) and rapidly destroys the entire shelf. When a random distribution of slab sizes, or spring constants, is present, such a transition resembles other depinning transitions, which have been used to study the formation of avalanches, earthquakes, as well as the motion of vortices in superconductors [Fisher, 1988; Sethna *et al.,* 2001].

3.2 Computational Fluid Dynamics: Development of Glaciologically Novel Numerical Techniques for 'Mosh-Pit' Dynamics

Two new techniques to be explored and adapted to the ice-shelf collapse problem are: **1.** smooth particle hydrodynamics (SPH) and **2.** unstructured finite-element mesh techniques. Sergienko, Naaim and Schwaiger (see letters of support) will guide the methodologies used, educate the research participants (notably PI MacAyeal, the postdoctoral scholar and one or more of the graduate students and undergraduate interns). Computer support will be provided by Arctic Region Supercomputing Center (ARSC) at the University of Alaska (requested independently of this proposal). Figure 7 shows examples of hydrodynamic wave phenomena simulated by smoothed particle hydrodynamics (SPH) and other mesh-free methods that resemble applications envisioned in the proposed research [Tartakovsky and Meakin, 2005; Dalrymple and Rogers, 2006; Schwaiger and Higman, 2007; Ataie-Ashtiani and Shobeyri, 2008; Dalrymple and Herault, 2008]. Specific modeling experiments to be conducted in the proposed research will focus on the following areas:

Large-amplitude wave-making by icebergs and ice shelves. Waves on the ice-mélange surface in the vicinity of capsizing icebergs; spray and jets produced by iceberg fragment collapse and in-fall, upwelling of submerged iceberg fragments with water drain-off from emerged surfaces.

True, two-way coupling between water and ice, and among ice fragments, in large-amplitude iceberg fragment and ice-mélange movements, inclusion of nonlinear Bernoulli terms (velocity-squared terms) applied to free-surfaces that have complex large-amplitude deviation from the mean sea surface, large Froude-number effects (*e.g.,* when iceberg bobbing frequencies are greater than the frequency of free-surface gravity waves that have a wavelength equal to the horizontal dimensions of the iceberg), and ice-on-ice collisions and jamming.

Kinetic-energy cascade processes within a resonant chamber (or 'mosh pit') from large-scale ice-fragment motions to small scale and turbulent water motion.

Sudden ocean-stratification mixing events driven by iceberg capsize will be examined as a subsidiary thermodynamic feedback effect that may subsequently influence ice mélange behavior following the end of ice-shelf collapse.

Iceberg fracture and disintegration processes. Elastic stresses in icebergs during capsize, and in ice shelf regions that are exposed to 'mosh pit' sourced ocean waves, will be calculated to estimate likely fracture and disintegration scenarios.

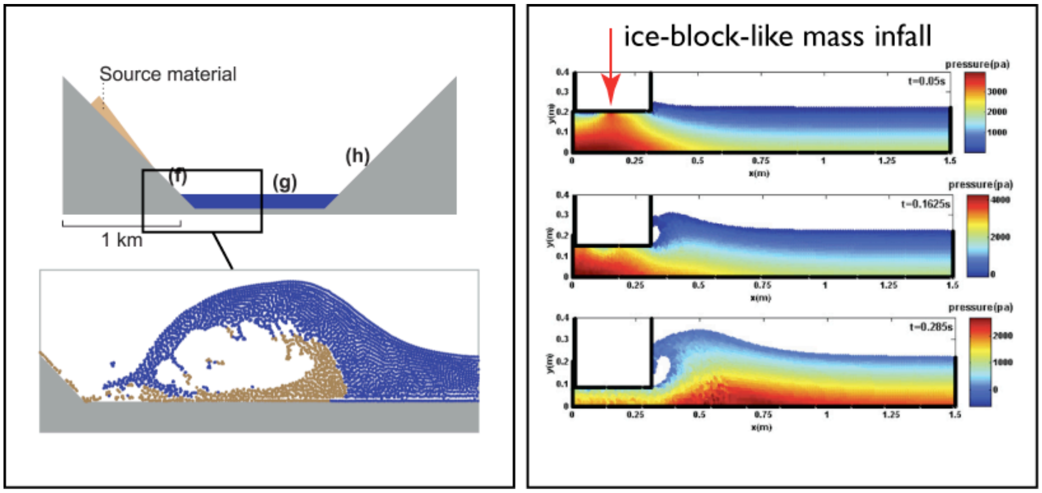


***Figure** 7 – Examples of SPH modeling techniques at work simulating the generation of water waves by mass in-fall. Left panel, simulation of tsunamigenic rockslide by Schwaiger and Higman [2007]. Right panel, vertical impact of mass (similar to ice block) from Ataie-Ashtiani and Shobeyri [2008].*

Numerical method development efforts will be directed toward the establishment of a number of specific model performance criteria and the performance of a number of specific simulation experiments. These include (only a few are listed):

Computational energy-spread "Green's" functions. A key goal in the study of ice-shelf collapse is the determination of how gravitational energy is transmitted from sources to sinks. To further progress toward this goal, we shall perform a class of experiments where a single ice-mélange element (*i.e.,* a single iceberg fragment) is given an initial energy perturbation. This energy will be provided in a form relevant to the collapse process (*e.g.,* a potential form, if the ice fragment is initially located below the water surface, or a kinetic form, if the ice fragment is given an initial translational kinetic energy). The subsequent radiation/scattering of this energy within the surrounding ice mélange will be computed numerically to determine the ice-mélange energy cascade. In effect, a computational Green's function will be created to characterize the inter-particle behaviors of ice mélange.

Single-ice-fragment dynamics. Numerical methods will be developed for and used to simulate large-scale ice-shelf fragment movements associated with calving. In particular, iceberg capsize will be simulated using unstructured methods or adaptive mesh technology. Two key aspects of the capsize process that must be accounted for are (i) the strength of the ice fragment relative to stresses induced by hydrostatic forces, (ii) ice-fragment break-up, and (iii) large-amplitude hydrodynamic effects, including high Froude-number effects, cavitation, spray production and perched water-reservoir drainage [*e.g.,* Ataie-Ashtiani and Shobeyri, 2008]. Examples of analytical treatments which will guide initial model application and testing come from literature addressing wave-making from ships, *e.g.,* Froude [1861; 1874], Ursell [1948; 1949; 1953], Clarisse *et al.* [1995].

Wave-propagation dynamics in multi-phase, obstacle filled media. Attention will be paid to the problem of glacial tsunamigenesis [*e.g.,* Schwaiger and Higman, 2007]. Characterization of large-scale source mechanisms, *e.g.,* ice pieces falling into the water, or capsizing, through the use of numerical simulation will be a goal of the research so as to better characterize some of the wave/ice-mélange interactions that exist within the collapsing ice-shelf mosh pit. An example of analytical treatments useful for testing and model development purposes include Marchenko [1997].

Ice-front flexure and fracture processes. To examine the triggering phenomena and the process which maintains explosive ice-shelf collapse, we shall perform numerical simulation of full 3-D ice-shelf elastic and viscoelastic deformation in response to various forms of ice-front excitation [Sergienko *et al.,* 2008; Scambos *et al.,* 2009]. The purposes of these simulations will be to examine both the initiation mechanism and the termination process that limits ice-shelf collapse.

Ocean-stratification effects. Mixing of a stratified ocean from iceberg capsize will be examined using models that capture the effects of buoyancy. Abrupt mixing events associated with iceberg capsize may help to explain thermodynamic aspects of the ice-mélange behavior following the termination of collapse, such as a delay in freeze-up of the mélange into an integrated cover prior to its dispersion by winds and ocean currents.

Normal Mode effects. Significant insight into the generation and propagation of gravity waves in a fluid layer may be gained from the concept of applying normal-mode theory to tsunamis, an idea originally proposed by Ward [1980], and later applied extensively by co-PI Okal [*e.g.,* Okal, 1982; 1988; 1990; 2003]. The advantage of this technique is that it can cover both internal waves and gravity waves of any frequency, and easily quantifies their excitation by dynamic sources located in or below the fluid column, and seamlessly allows for any stratification of the structure (including a multi-layer fluid, a floating ice shelf, a sedimentary coastal structure, and even the upwards continuation of the wave into the atmosphere, *e.g.,* in the framework of Harkrider *et al.,* 1974).

3.3 Observation: Analysis of Ice Mélange Imagery, Time-Lapse Photography, Seismic and Hydroacoustic Signals

A considerable, but disparate, body of observation remains untapped in the study of ice-shelf disintegration. Effort will be undertaken in the proposed project to perform the following observational steps needed to support both the theoretical and computational parts of the research. A list of the observational activity is provided below:

High-resolution satellite imagery, notably the Formosat-2 imagery reported by Scambos *et al.* [2009] will be used to develop size and geometry statistics for ice-mélange resulting from the explosive break-up of the Wilkins Ice Shelf. Oblique photographs and time-lapse image sequences provided by shore cameras deployed around ice-mélange-filled fjords in Greenland will also be examined to provide statistics associated with the calving and iceberg break-up mechanisms at play at the seaward margins of Greenland outlet glaciers.

Time-lapse photography. A plethora of automatic camera records of iceberg calving, capsize and ice-mélange processes has been collected from Greenland fjords that contain the termini of ice-sheet outlet glaciers [Amundson *et al.,* 2008; Amundson *et al.,* submitted]. We will extract quantitative information about iceberg capsize and ice-mélange movements to be used in constraining models of such phenomena (*e.g.,* how long does it take for an iceberg to capsize, and what angle is it when it fragments?).

Seismometer records from Greenland [*e.g.,* Amundson *et al.,* 2008], Antarctica, and Pacific Islands (*e.g.,* Rarotonga, Fig. 8) will be examined for seismic and hydro-acoustic signals emanating from ice-mélange processes. Historical data capturing the February 2008 break up of the Wilkins Ice Shelf will be sought from the 'Polenet' Seismic Array deployed in Antarctica at the time [R. Aster, personal communication]. Data will be obtained either from the investigators of the various Antarctic and Greenland projects or from the data management center (DMC) supported by the IRIS seismological consortium of the U.S.

Far-field records obtained on seismometers and hydrophones will be interpreted to obtain quantitative constraints on the relevant sources, based on our experience both in the hydroacoustic frequency range and the domain of gravity waves, from swell frequencies (0.1 Hz) to short-period tsunamis (approx. 0.01 Hz) [*e.g.,* Talandier *et al.,* 2006; Okal, 2007a; Okal *et al.,* 2007b]. An example of such signals is illustrated in Figure 8, where *T*-phase events observed on Rarotonga, and island in the South Pacific, may be linked to the 29 February 2008 break-up of the Wilkins Ice Shelf.

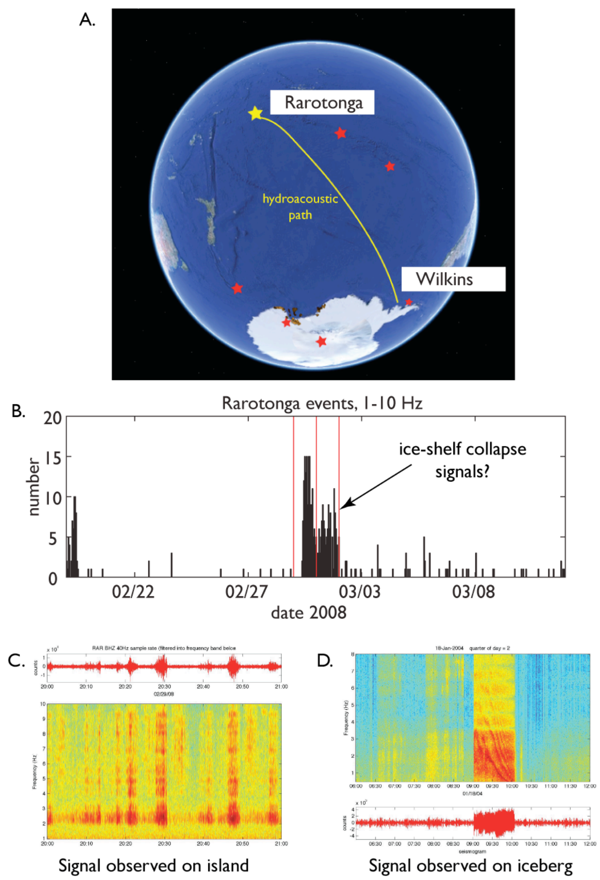


Figure 8 – A. *Hydroacoustic path of possible signal propagation from Wilkins Ice Shelf to Rarotonga (yellow star), a Pacific Island seismometer station. Red stars indicate other seismic stations at island sites and in Antarctica that may provide data that contain signals of ice-shelf collapse.* ***B.*** *Number histogram of observed short-burst (> 2 min. duration) signal energy in the 1 – 10 Hz frequency band, a band in which hydroacoustic signals from icebergs recorded as T-phase have been observed in past examples. The relatively large number of signals observed on 29 February and 1 March may be indicative of hydroacoustic radiation*

from the collapse of the Wilkins Ice Shelf during that time period. ***C.*** *Example of seismic signals of possible ice-shelf origin in the signal observed at Rarotonga, South Pacific (data from IRIS DMC).* ***D.*** *Example of seismic signals observed on an Antarctic Iceberg [MacAyeal et al., 2009].*

4. Broader Impacts

Advancement of Discovery and Understanding lies in the fact that discovery in the area of ice-shelf disintegration will enhance the ability to predict future sea level changes that directly bear on social and economic infrastructures around the world. Current community ice-sheet model experiments (*e.g.,* the US community's SeaRISE effort) designed to forecast sea level contributions from Antarctica for the next IPCC assessment involve various forms of "ice-shelf removal" as key forcing scenarios [R. Bindschadler, "SeaRISE" unpublished document draft, 2009]. The research conducted here will directly bear on the validity of these forcing scenarios.

Training and Learning Across Disciplinary Boundaries will be enhanced by involving PIs and participants who can cross-fertilize each other's primary disciplines with ideas and techniques from others: **Wendy Zhang** (co-PI), a physicist with expertise in theoretical fluid dynamics and condensed matter physics, will team with **Doug MacAyeal** (lead PI) who has expertise in 'traditional' ice-shelf and iceberg observation and modeling, and **Emile Okal** (PI from Northwestern U.) who has extensive experience in tsunami research. Additional non-PI team members will include: **Jason Amundson** (Postdoctoral Scholar) with expertise in ice-mélange dynamics, seismology and time-lapse photography of iceberg calving, **Olga Sergienko** (Princeton University/GFDL) with expertise in flexural-gravity wave modeling of ice shelves and icebergs, **Mohamed Naaim** (Cemagref, St. Martin d'Heres, France) and **Hans Schweiger** (USGS Cascade Volcano Observatory, currently at Sandia National Lab) both with extensive experience in advanced methods in computational fluid mechanics (including SPH).

Mentoring. A postdoctoral scholar and two graduate students (one for the Department of Physics and one for the Department of Geophysical Sciences) will be mentored during the project. Dr. Jason Amundson will be the postdoctoral scholar (**see a 1-page mentoring plan**, a supporting letter of interest from Jason and his short bio **in the supplemental documents**).

Diversity. The project will participate in both the Research Experience for Undergraduates (REU) program in the Physics Department and the Summer Research Early Identification Program (SR-EIP) of the Leadership Alliance, of which the University of Chicago is a member. The PIs will set up a Research Experience Program Site at the University of Chicago to host a summer collegiate scholar to perform research tasks that match the ability and timeframe of the intern's commitment to the project (*e.g.,* satellite image analysis using Formosat-2 data published by Scambos *et al.,* 2009, to determine ice-mélange fragment size and geometry). These programs offer 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. Funds are not needed for the summer intern's stipend or travel, as they are provided by the SR-EIP; but funds are needed for work-related costs such as a computer workstation. Funds are asked, however, for a University of Chicago undergraduate intern to partner with the summer intern from SR-EIP.

Integration of Research and Education. The PIs, postdoctoral scholar, graduate students and unfunded participants will develop a graduate-level seminar/tutorial to introduce advanced computational methods to glaciology, such as use of smoothed particle hydrodynamics to iceberg capsize and fragmentation. Course development will include creation of lecture materials, notes, computation lab experiments and performance assessment tools to be used in future teaching activities both at the University of Chicago and elsewhere (*e.g.,* ice-sheet modeling summer schools, such as proposed for summer of 2009 in Portland, Oregon, C. Hulbe, personal communication). The PI (MacAyeal) has a long-standing involvement in creating ice-sheet model learning materials (*e.g.,* the unpublished, 429-page *"Lessons in Ice-Sheet Modeling"* manuscript written by MacAyeal for the EISMINT ice-sheet model intercomparison project of the mid 1990's), and will use the experience of the proposed project to produce new materials relevant for teaching methods to students of Antarctica's ice sheet. Travel and a month of accommodation are requested for unfunded participants during year 1 of the proposed project as a means of facilitating the start of this teaching effort. General public literacy will be enhanced by participation (by one PI per year) in a *'Café Scientifique'* program organized by University of Chicago researchers to foster connection with the general public in the Chicago area.

Stewardship. MacAyeal will be a co-chief editor of the Annals of Glaciology associated with the *International Symposium on Snow, Ice and Humanity in a Changing Climate*, to be held in Sapporo, Japan in 2010. MacAyeal also serves on the PASSCAL standing committee of IRIS. Okal serves on the National Academy of Science (NAS) *Committee on Tsunami Warning and Preparedness* of the Ocean Board Studies of the NRC. Zhang serves as the Physics Department advisor for the Luce fellowship for women in science (Physics) 2007 – present.

5. Results from Prior NSF Support

A. (combined) D. R. MacAyeal and E. A. Okal: NSF OPP 0229546 ***Collaborative Research of Earth's largest Icebergs,*** 07/01/2003 to 06/30/2008, $483,865 (DRM); $299,672 (EAO). (PIs: MacAyeal and Okal).

This collaborative project (involving U. Chicago and Northwestern U.) 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 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 PIs 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. **Public Outreach:** The PIs were interviewed by NPR's *All Things Considered*, and one PI 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 PIs and graduate students have given public lectures in the Chicago area. The PIs also conducted radio and television interviews abroad, notably France and Canada. The Northwestern U. PI, Okal, served on the National Academy of Science (NAS) *Committee on Tsunami Warning and Preparedness* of the Ocean Board Studies of the NRC. **Publications:** see reference list for Brunt *et al.,* 2006; Cathles *et al.,* 2009; Leonard *et al.,* 2006; MacAyeal *et al.,* 2009; MacAyeal *et al.,* 2008b; MacAyeal *et al.,* 2008c; Okal and MacAyeal, 2006; MacAyeal *et al.,* 2006; Sergienko and MacAyeal, 2005. **Data Archive and Availability:** 100% of the actual data is archived and freely available at the IRIS DMC and at NSIDC.

B. Zhang. NSF CBET-0730629 ***"Fundamentals of viscous entrainment, cell encapsulation and light-driven jetting"*** (PI W. W. Zhang) 2007-2010 $145,000.

This project aims to understand the onset of entrainment when one viscous flow draws another one inwards and also to predict the stable thin tendril created after the onset of entrainment. **Findings: Nature of the viscous entrainment transition.** Zhang developed a novel boundary integral simulation of interface deformation near onset of entrainment. Results from the simulation together with scaling and analysis of experimental data conclusively showed that the transition is discontinuous and analogous to a saddle-node bifurcation. Previously a variety of conflicting scenarios were proposed. Zhang also identified the relevant stress balanced and showed that a similar argument is relevant for entrainment of a viscous miscible liquid, such as occurs in mantle convection. **Light-induced jetting.** In collaboration with a nonlinear optics group (Delville, Bordeaux), Zhang showed that the interaction of scattering with viscous flow produces an expected mode of light-induced transport. She also analyzed the stable bridge structure formed by radiation pressure. **Contribution to Learning and Stewardship:** These works have resulted in 3 PhDs, 1 awarded to a woman, and 3 completed postdoctoral fellowships (1 woman). One postdoctoral scholar is currently an assistant professor at U. California at Merced, another will be joining M.I.T. in 2010. **Public Outreach:** Zhang's group has participated in MRSEC outreach programs on presenting science in museums (Science Museum, Aurora IL) and the Physics department's annual open house lecture "Physics with a Bang". The research by Zhang has been reported in the *New York Times*, the *Chicago Tribune* as well as on the radio and television. The work on splash formation ranked No. 8 in the annual list of the Top Physics Stories by the American Institute of Physics. **Publications:** see publication list for Schmidt *et al.,* 2009; Keim *et al.,* 2006; Xu *et al.,* 2005; Blanchette *et al.,* 2009; Delville *et al.,* 2009; Berkenbusch *et al.,* 2008; Schroll *et al.,* 2008; Schmidt and Zhang, 2008; Schroll *et al.,* 2007.