APPLICATION FOR FEDERAL ASSISTANCE
SF 424 (R&R)

1. * TYPE OF SUBMISSION	**2. DATE SUBMITTED**	**Applicant Identifier** N00014
❍ Pre-application ● Application ❍ Changed/Corrected Application	**3. DATE RECEIVED BY STATE**	**State Application Identifier**
	4. a. Federal Identifier	**b. Agency Routing Number** 322[Jeffries, Martin]

5. APPLICANT INFORMATION *** Organizational DUNS:**009095365

* Legal Name: University of Utah

Department: Division:

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* City: Salt Lake City County/Parish: Salt Lake * State: UT: Utah

Province: * Country: USA: UNITED STATES * ZIP / Postal Code: 84112-8930

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6. * EMPLOYER IDENTIFICATION NUMBER *(EIN) or (TIN)*: 876000525

7. * TYPE OF APPLICANT H: Public/State Controlled Institution of Higher Education

8. * TYPE OF APPLICATION: ● New ❍ Resubmission ❍ Renewal ❍ Continuation ❍ Revision

Other (Specify):

Small Business Organization Type ❍ Women Owned ❍ Socially and Economically Disadvantaged

If Revision, mark appropriate box(es).

❍ A. Increase Award ❍ B. Decrease Award ❍ C. Increase Duration ❍ D. Decrease Duration ❍ E. Other *(specify)*:

* Is this application being submitted to other agencies? ❍ Yes ● No
What other Agencies?

9. * NAME OF FEDERAL AGENCY: Office of Naval Research

10. CATALOG OF FEDERAL DOMESTIC ASSISTANCE NUMBER: 12.300
TITLE: Basic and Applied Scientific Research

11. * DESCRIPTIVE TITLE OF APPLICANT'S PROJECT:
Multiscale Models of Melting Arctic Sea Ice

12. PROPOSED PROJECT:
* Start Date 12/01/2012 * Ending Date 11/30/2015

13. CONGRESSIONAL DISTRICT OF THE APPLICANT:
UT-002

14. PROJECT DIRECTOR/PRINCIPAL INVESTIGATOR CONTACT INFORMATION

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SF 424 (R&R) APPLICATION FOR FEDERAL ASSISTANCE

15. ESTIMATED PROJECT FUNDING

a. * Total Federal Funds Requested	$481,616.00
b. Total Non-Federal Funds	$0.00
c. * Total Federal & Non-Federal Funds	$481,616.00
d. * Estimated Program Income	$0.00

16. * IS APPLICATION SUBJECT TO REVIEW BY STATE EXECUTIVE ORDER 12372 PROCESS?

a. YES ❍ THIS PREAPPLICATION/APPLICATION WAS MADE AVAILABLE TO THE STATE EXECUTIVE ORDER 12372 PROCESS FOR REVIEW ON:

DATE:

b. NO ● PROGRAM IS NOT COVERED BY E.O. 12372; OR

❍ PROGRAM HAS NOT BEEN SELECTED BY STATE FOR REVIEW

17. By signing this application, I certify (1) to the statements contained in the list of certifications* and (2) that the statements herein are true, complete and accurate to the best of my knowledge. I also provide the required assurances * and agree to comply with any resulting terms if I accept an award. I am aware that any false, fictitious, or fraudulent statements or claims may subject me to criminal, civil, or administrative penalties. (U.S. Code, Title 18, Section 1001)

● * I agree

** The list of certifications and assurances, or an Internet site where you may obtain this list, is contained in the announcement or agency specific instructions.*

18. SFLLL or other Explanatory Documentation. File Name: Mime Type:

19. Authorized Representative

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*** Signature of Authorized Representative** *** Date Signed**

20. Pre-application File Name: Mime Type:

RESEARCH & RELATED Other Project Information

1. * Are Human Subjects Involved? ❍ Yes ● No

1.a. If YES to Human Subjects

Is the Project Exempt from Federal regulations? ❍ Yes ❍ No

If yes, check appropriate exemption number

Exemption Number: __ 1 __ 2 __ 3 __ 4 __ 5 __ 6

If no, is the IRB review Pending? ❍ Yes ❍ No

IRB Approval Date:

Human Subject Assurance Number

2. * Are Vertebrate Animals Used? ❍ Yes ● No

2.a. If YES to Vertebrate Animals

Is the IACUC review Pending? ❍ Yes ❍ No

IACUC Approval Date:

Animal Welfare Assurance Number

3. * Is proprietary/privileged information included in the application? ❍ Yes ● No

4.a. * Does this project have an actual or potential impact on the environment? ❍ Yes ● No

4.b. If yes, please explain:

4.c. If this project has an actual or potential impact on the environment, has an exemption been authorized or an environmental assessment (EA) or environmental impact statement (EIS) been performed? ❍ Yes ❍ No

4.d. If yes, please explain:

5.a. * Is the research performance site designated, or eligible to be designated, as a historic place? ❍ Yes ● No

5.b. If yes, please explain:

6.a. * Does this project involve activities outside the U.S. or partnership with International Collaborators? ❍ Yes ● No

6.b. If yes, identify countries:

6.c. Optional Explanation:

7. * Project Summary/Abstract	Project_Summary1008034158.pdf	Mime Type: application/pdf
8. * Project Narrative	Technical_Propsal1008034164.pdf	Mime Type: application/pdf
9. Bibliography & References Cited		
10. Facilities & Other Resources		
11. Equipment		

PROJECT SUMMARY

Multiscale Models of Melting Arctic Sea Ice

During the Arctic melt season, the sea ice surface undergoes a remarkable transformation from vast expanses of snow covered ice to beautiful mosaics of ice and melt ponds. Small, disconnected ponds on the ice surface grow and coalesce to form much larger connected structures with complex boundaries. Melt pond area fraction ϕ can undergo a critical transition with a rapid rise from 0% to more than 70% in just a few days.

Sea ice albedo, a key parameter in climate modeling, is determined by the evolution of melt pond and ice floe configurations. Ice-albedo feedback has played a major role in the recent declines of the summer Arctic sea ice pack. However, understanding the evolution of melt ponds and sea ice albedo remains a significant challenge to improving climate models. In fact, not including the significant effects of melt ponds in the last generation of these models is a key factor in explaining why the observed losses outpaced the projections.

Viewed from high above, the sea ice surface can be thought of as a two phase composite of ice and melt water. The boundaries between the two phases evolve with increasing complexity and a rapid onset of large scale connectivity, or percolation of the melt phase. Pond fractal dimension transitions from about 1 to 2 around a critical length scale of 100 square meters in area. This type of behavior is similar to what is observed in phase transformations in statistical physics and geometrical transitions in composite materials.

We propose here to study the evolution of melt pond geometry on Arctic sea ice, and to develop multiscale models of pond structure which can provide fundamental new insights into the melting process and the evolution of sea ice albedo. We will explore how mathematical models arising in statistical mechanics, composite materials, and pattern formation can be used to efficiently characterize and quantify melt pond structure. Such systems often exhibit universal behavior described by critical exponents depending only on dimension and not on the details of the system. Developing such theories for melt ponds will provide novel ways of looking at the evolution of Arctic melting and ice albedo, as well as a rigorous framework for finding large scale properties from local information. Key components of our proposed research include:

- We will investigate the transition in fractal geometry of melt ponds, and develop mathematical models which capture this striking behavior. Related studies will focus on the melt pond percolation threshold and the onset of large scale connectedness.
- Models of statistical physics and composite materials will be used to explore universal properties of melt pond evolution. Theories of *homogenization* and *upscaling* provide a framework for the calculation of effective properties relevant to climate models.
- Mathematical findings and tools developed in this project will be exploited to improve the representation of melt ponds in high-resolution sea ice models.
- We will gather as much melt pond imagery as possible from a wide range of sources, and develop image analysis techniques to support the mathematical investigations, such as mapping complex melt ponds onto networks of nodes and edges.

TECHNICAL PROPOSAL

ONR BAA Announcement Number 12-001

ONR Arctic & Global Prediction Program
and
ONR Applied Computational Analysis Program

Multiscale Models of Melting Arctic Sea Ice

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Co−Principal Investigators: Donald K. Perovich[2]
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Bacim Alali[4]

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December 1, 2012 – November 30, 2015

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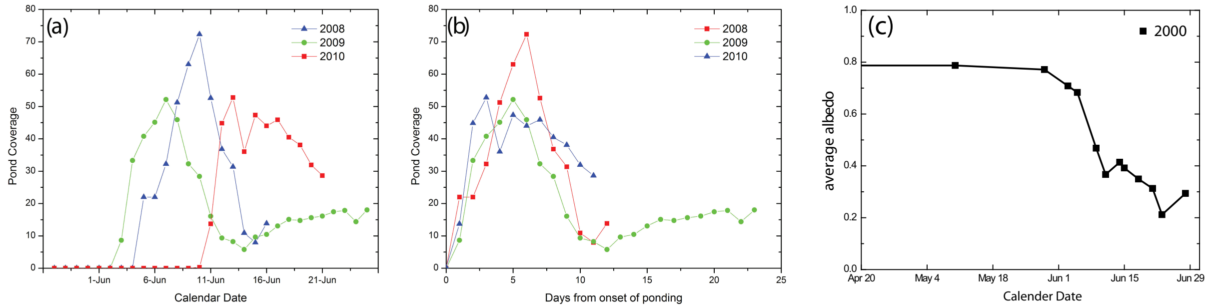

Figure 1: Arctic melt pond coverage vs. calendar date near Barrow, AK in (a) and melt pond coverage vs. days since onset of pond formation in (b), for the years 2008–2010 [51]. Average albedo vs. calender date in 2000 near Barrow is shown in (c). Each data set exhibits critical behavior at the onset of melt pond formation, similar to the behavior of order parameters characterizing phase transitions in statistical physics and composite materials.

1 Technical Approach

1.1 Introduction

During the melt season the Arctic sea ice cover becomes a complex, evolving composite of ice, melt ponds, and open water. Melting is strongly influenced by the morphological characteristics of the ice cover, such as the size and shape of melt ponds and ice floes. Albedo, light transmission, and melting are closely connected to melt pond characteristics, while floe perimeter is a primary controlling parameter for lateral melting. We propose to develop multiscale mathematical descriptions of the melting sea ice pack, focusing on the geometry and evolution of surface melt ponds. Models of phase transitions in statistical physics and composite materials will be used to investigate melt pond structure. This work will improve our ability to model the partitioning of solar radiation between reflection, absorption in the ice, surface melting, bottom melting, lateral melting, and heat storage in the upper ocean.

While snow and ice reflect most incident sunlight, melt ponds and ocean absorb most of it. The overall reflectance or albedo of sea ice is determined by the evolution of melt pond geometry [48, 57, 51] and ice floe configurations [64]. As melting increases, so does solar absorption, which leads to more melting, and so on. This *ice–albedo feedback* has played a significant role in the decline of the summer Arctic ice pack [50], which most climate models have underestimated [58, 7]. Sea ice albedo is a significant source of uncertainty in climate projections and a fundamental problem in climate modeling [20, 57, 47, 51].

From the first appearance of visible pools of water, often in early June, the area fraction ϕ of sea ice covered by melt ponds can increase rapidly to over 70% in just a few days [51, 56], as demonstrated in Figure 1 (a) and (b). Moreover, the accumulation of water at the surface dramatically lowers the albedo where the ponds form. A corresponding critical drop-off in average albedo is displayed in Figure 1 (c). The resulting increase in solar absorption in the ice and upper ocean accelerates melting [49], possibly triggering *ice-albedo feedback*. Similarly, an increase in open water fraction ψ lowers albedo, thus increasing solar absorption and subsequent melting. The spatial coverage and distribution of melt ponds on the surface

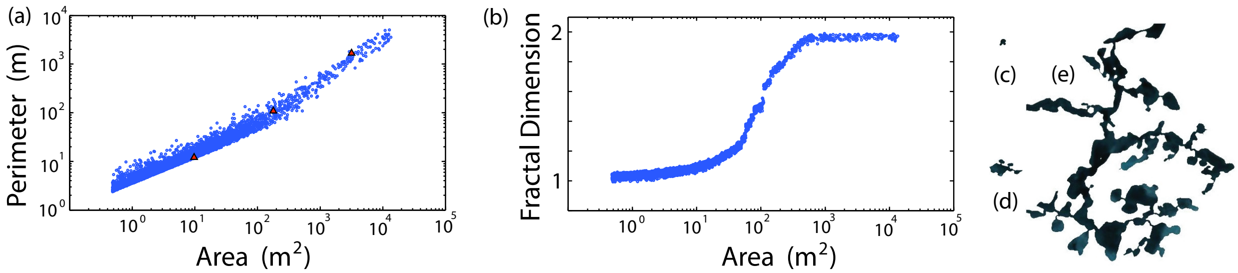

Figure 2: (a) Area – perimeter data for 5,269 Arctic melt ponds, plotted on logarithmic scales. The slope transitions from about 1 to 2 at a critical length scale of around 100 square meters. (b) Melt pond fractal dimension D as a function of area A, computed from the data in (a), showing the transition to complex ponds with increasing length scale. Ponds corresponding to the three red triangles in (a), from left to right, are shown in (c), (d), and (e), respectively. The transitional pond in (d) has horizontal scale of about 30 m.

of ice floes and the open water between the floes thus exerts primary control of ice pack albedo and the partitioning of solar energy in the ice-ocean system [16, 51].

While melt ponds form a key component of the Arctic marine environment, comprehensive observations or theories of their formation, coverage, and evolution remain relatively sparse. Available observations of melt ponds show that their areal coverage is highly variable, particularly for first year ice early in the melt season, with rates of change as high as 35% per day [56, 51]. Such variability, as well as the influence of many competing factors controlling melt pond and ice floe evolution, makes the incorporation of realistic treatments of albedo into climate models quite challenging [51]. Small and medium scale models of melt ponds which include some of these mechanisms have been developed [19, 59, 57], and melt pond parameterizations are being incorporated into global climate models [20, 38, 47].

The surface of an ice floe is viewed here as a two phase composite [45] of dark melt ponds and white snow or ice. The onset of ponding and the rapid increase in coverage beyond the initial threshold is similar to critical phenomena in statistical physics [13, 62] and composite materials [60]. Here we ask if the evolution of melt pond geometry exhibits universal characteristics which do not necessarily depend on the details of the driving mechanisms in numerical melt pond models. Fundamentally, the melting of Arctic sea ice is a phase transition phenomenon, where a solid turns to liquid, albeit on large regional scales and over a period of time which depends on environmental forcing and other factors. We thus look for features of melt pond evolution which are mathematically analogous to related phenomena in the theories of phase transitions and composite materials. As a first step in this direction, and a key finding which provides a principal route of investigation in the proposed work, we consider the evolution of complexity of Arctic melt ponds.

By analyzing area−perimeter data from hundreds of thousands of melt ponds, we have discovered an unexpected separation of scales, where the pond fractal dimension D exhibits a transition from 1 to 2 around a critical length scale of 100 square meters in area [36], as shown in Figure 2. Small ponds with simple boundaries coalesce or percolate to form larger connected regions, as shown in Figure 3 (a). Pond complexity increases rapidly through the transition region and reaches a maximum for ponds larger than 1000 m^2 whose boundaries

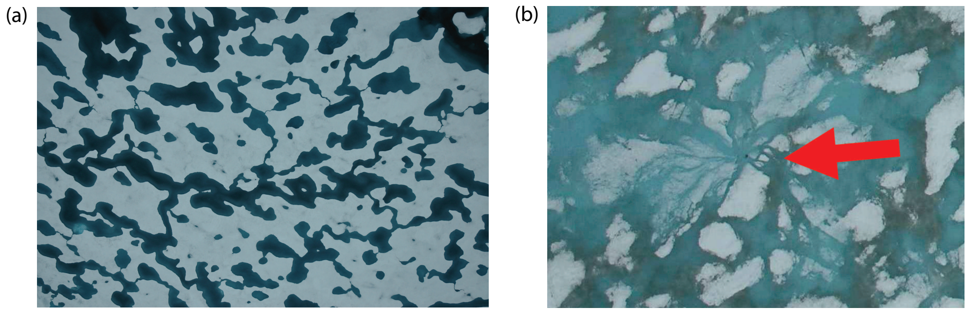

Figure 3: (a) The complex geometry of well developed Arctic melt ponds, illutrated in an aerial photo taken August 14, 2005 on the Healy-Oden Trans Arctic Expedition (HOTRAX), courtesy of Don Perovich. (b) A melt pond drains through a small seal hole (near the arrow tip). The length scale over which melt water drains through this hole is strongly influenced by the length scale of melt pond connectivity. Photo courtesy of Chris Polashenski.

resemble space filling curves [53] with $D \approx 2$. These configurations affect the complex radiation fields under melting sea ice, the heat balance of sea ice and the upper ocean [21], under-ice phytoplankton blooms [2], biological productivity, and biogeochemical processes.

Melt pond evolution also appears to exhibit a *percolation threshold*, where one phase in a composite becomes connected on macroscopic scales as some parameter exceeds a critical value [60, 13]. An important example of this phenomenon in the microphysics of sea ice, which is fundamental to the process of melt pond drainage, is the percolation transition exhibited by the brine phase in sea ice, known as the *rule of fives* [30, 31, 52]. When the brine volume fraction of columnar sea ice exceeds about 5%, the brine phase becomes macroscopically connected so that fluid pathways allow flow through the porous microstructure of the ice. Similarly, even casual inspection of aerial photos shows that the melt pond phase of sea ice undergoes a percolation transition where disconnected ponds evolve into much larger scale connected structures with complex boundaries. Connectivity of melt ponds promotes further melting and break-up of floes, as well as horizontal transport of meltwater and drainage through cracks, leads, and seal holes [56, 51], as illustrated in Figure 3 (b).

The rich behavior we observe for melt pond evolution is similar to phase transitions in statistical mechanics [13, 62, 14] and composite materials [60, 45]. Such systems often exhibit universal critical behavior, where order parameters like the effective conductivity of a composite or the magnetization of an Ising ferromagnet are described near their threshold by critical exponents depending only on dimension and not on the details of the system. Developing similar theories for melt ponds could provide fundamental new insights into the evolution of ice pack albedo and Arctic melting, as well as a rigorous framework for finding large scale, effective properties from local information, a fundamental issue in climate modeling. The application of modern theories of homogenization and statistical physics to melt pond and albedo evolution will lend insights into parameterizing sub-grid scale processes into sea ice and climate models. For example, the scale of connected fluid pathways on the surface influences melt pond drainage through cracks, seal holes, and the porous microstructure of sea ice [51]. Investigating critical behavior as a natural aspect of the polar marine environment will shed light on key questions such as the rapidity of the sea ice retreat and whether a so-called *tipping point* or critical transition has been passed in the decline [17]. It will also advance our ability to model the future trajectory of the Arctic sea ice pack.

1.2 Objectives and Goals

We propose to investigate the formation and evolution of Arctic melt ponds. Models and techniques of statistical physics and composite materials will be employed to provide new insights into melt pond structure, and to explore universal behavior characteristic of phase transition phenomena. We will also begin to investigate how such findings can impact the computation of ice pack albedo in sea ice numerical models.

1. Identify the critical melt pond area fraction ϕ_c, or percolation threshold, where the ponds become connected over large length scales. What is the critical exponent for the divergence of the correlation length? How does ϕ_c depend on local characteristics such as snow and ice topography, or whether the ice is first year or multiyear?
2. Investigate our finding that around a critical length scale, the fractal dimension of melt pond boundaries transitions from 1 (simple, Euclidean shapes) to about 2 (space filling curves) [36]. Explore the use of partial differential equations of pattern formation and phase change to model this striking phenomenon.
3. Use methods of homogenization and spectral measures to characterize melt pond and ice floe configurations, as well as critical transitions in their effective properties. This approach provides a rigorous framework for *upscaling* local morphological characteristics into larger scale models.
4. Develop stochastic lattice models of melt pond formation based on simple cellular automata and the Ising model for phase transitions in statistical mechanics.
5. Explore how our mathematical results can be exploited to improve the representation of melt ponds and albedo in global climate models and high-resolution sea ice models.
6. Develop methods of image analysis focused on addressing the questions about melt ponds raised above, such as tracking how features evolve in time, and mapping melt pond images to networks of nodes and edges. These techniques will likely be useful to other ONR investigators studying melt ponds.

1.3 Mathematical Models of Composites and Phase Transitions

Here we give a brief overview of some of the mathematical models and techniques that we will use in studying critical behavior of melting in the sea ice pack.

Percolation models. Consider the $d-$dimensional integer lattice $\mathbb{Z}^d$, and the square or cubic network of bonds joining nearest neighbor lattice sites. In the percolation model [8, 60, 33, 9], we assign to each bond a conductivity $\sigma_0 > 0$ with probability p, meaning it is open (black), and with probability $1-p$ we assign a 0, meaning it is closed. Two examples of lattice configurations are shown in Figure 4, with $p = 1/3$ in (a) and $p = 2/3$ in (b). Groups of connected open bonds are called *open clusters*. In this model there is a critical probability p_c, $0 < p_c < 1$, called the *percolation threshold*, at which the average cluster size

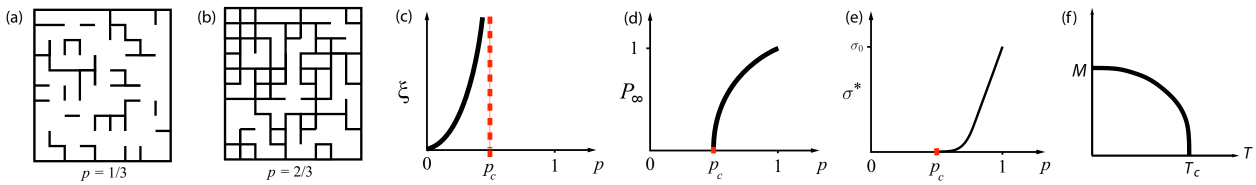

Figure 4: The two dimensional square lattice percolation model below its percolation threshold of $p_c = 1/2$ in (a) and above it in (b). (c) Divergence of the correlation length as p approaches p_c. The infinite cluster density of the percolation model is shown in (d), and the effective conductivity is shown in (e). (f) The magnetization of the Ising model.

diverges and an infinite cluster appears. For the two dimensional bond lattice $p_c = 1/2$. For $p < p_c$ the density of the infinite cluster $P_\infty(p)$ is 0, while for $p > p_c$, $P_\infty(p) > 0$ and near the threshold, $P_\infty(p) \sim (p - p_c)^\beta$ as $p \to p_c^+$, where β is a universal critical exponent, that is, it depends only on dimension and not on the details of the lattice. Let $x, y \in \mathbb{Z}^d$ and $\tau(x, y)$ be the probability that x and y belong to the same open cluster. Then for $p < p_c$, $\tau(x, y) \sim e^{-|x-y|/\xi(p)}$, and the correlation length $\xi(p) \sim (p_c - p)^{-\nu}$ diverges with a universal critical exponent ν as $p \to p_c^-$, as shown in Figure 4 (c).

The effective conductivity $\sigma^*(p)$ of the lattice, now viewed as a random resistor (or conductor) network, defined via Kirchoff's laws, vanishes for $p < p_c$ like $P_\infty(p)$ since there are no infinite pathways, as shown in Figure 4 (e). For $p > p_c$, $\sigma^*(p) > 0$, and near p_c, $\sigma^*(p) \sim \sigma_0(p - p_c)^t,\ p \to p_c^+$, where t is the conductivity critical exponent, with $1 \le t \le 2$ in $d = 2, 3$ [23, 24, 29], and numerical values $t \approx 1.3$ in $d = 2$ and $t \approx 2.0$ in $d = 3$ [60]. Consider a random pipe network with effective fluid permeability $\kappa^*(p)$ exhibiting similar behavior $\kappa^*(p) \sim \kappa_0(p - p_c)^e$, where e is the permeability critical exponent, with $e = t$ [12, 55, 29]. Both t and e are believed to be universal − they depend only on dimension and not the lattice. Continuum models can exhibit nonuniversal behavior with exponents different from the lattice case and $e \neq t$ [34, 18, 60, 54, 40].

Homogenization and spectral measures. *Homogenization* denotes a field of applied mathematics where the goal is to find a homogeneous medium which behaves macroscopically the same as a given inhomogeneous medium. The methods are focused on finding the effective properties of inhomogeneous media such as composites. This discussion provides a framework for an effective albedo of the ice pack, as well as the effective horizontal flow of melt water on the sea ice surface, where the inhomogeneities are melt ponds or topography. We will see that the *spectral measure* provides a powerful tool for upscaling geometrical information about a composite into calculations of effective properties.

We now briefly describe the *analytic continuation method* for studying the effective properties of composite materials [6, 43, 25, 28]. This method has been used to obtain rigorous bounds on effective transport coefficients of composite materials from partial knowledge of the microstrucure, such as the relative volume fractions of the phases. For simplicity we choose the electrical conductivity of a two phase composite, although the method applies to any classical transport coefficient. This framework has been extended to finding the effective diffusivity of a passive tracer advected by a fluid velocity field [3, 4].

We consider a two-phase random medium with $\sigma(x, \omega)$ the local conductivity, a spatially stationary random field in $x \in \mathbb{R}^d$ and $\omega \in \Omega$, where Ω is the set of realizations of the medium. Assume $\sigma(x) = \sigma_1\chi_1 + \sigma_2\chi_2$, where $\chi_j(x,\omega)$ is the characteristic function of medium $j = 1, 2$, equaling 1 for $\omega \in \Omega$ with medium j at x, and 0 otherwise. Let $E(x)$ and $J(x)$ be the stationary random electric and current fields, related by $J = \sigma E$, satisfying $\nabla \cdot J = 0$ and $\nabla \times E = 0$, where the average $\langle E(x)\rangle = e_k$, and e_k is a unit vector in the k^{th} direction. The effective conductivity tensor $\boldsymbol{\sigma}^*$ is defined as $\langle J\rangle = \boldsymbol{\sigma}^*\langle E\rangle$. We focus on one diagonal coefficient $\sigma^* = \sigma^*_{kk}$, with $\sigma^* = \langle \sigma E_k\rangle$, and since σ^* depends on $h = \sigma_1/\sigma_2$, we define $m(h) = \sigma^*/\sigma_2$, which is a Stieltjes function. It is analytic off $(-\infty, 0]$ in the h–plane, and maps the upper half plane to the upper half plane [5, 25].

The key step [25, 5, 43, 45] is to obtain an integral representation for σ^*. Consider $F(s) = 1 - m(h)$, $s = 1/(1-h)$, which is analytic off $[0,1]$ in the s–plane. Then [25]

$$F(s) = 1 - \frac{\sigma^*}{\sigma_2} = \int_0^1 \frac{d\mu(\lambda)}{s-\lambda}\,, \qquad s = \frac{1}{1-\sigma_1/\sigma_2}\,, \tag{1}$$

where μ is a positive measure on $[0,1]$. This formula arises from the resolvent representation of the electric field $E = (s + \Gamma\chi_1)^{-1}e_k$, where $\Gamma = \nabla(-\Delta)^{-1}\nabla\cdot$ and $\Delta = \nabla^2$ is the Laplacian, yielding $F(s) = \langle \chi_1[(s+\Gamma\chi_1)^{-1}e_k]\cdot e_k\rangle$. In the Hilbert space $L^2(\Omega, P)$ with weight χ_1 in the inner product, $\Gamma\chi_1$ is a bounded self adjoint operator. Formula (1) is the spectral representation of the resolvent, and μ is a spectral measure of $\Gamma\chi_1$, in the e_k state. Formula (1) separates the component parameters in s from the geometrical information in μ. (Extensions to multicomponent media involve several complex variables [26, 22, 46, 44, 15].) Information about the geometry enters through the moments $\mu_n = \int_0^1 z^n d\mu(z) = (-1)^n\langle \chi_1[(\Gamma\chi_1)^n e_k]\cdot e_k\rangle$. Then $\mu_0 = \phi$, where ϕ is the volume or area fraction of phase 1, such as the melt pond coverage, and $\mu_1 = \phi(1-\phi)/d$ if the material is statistically isotropic. In general, μ_n depends on the $(n+1)$–point correlation function of the medium.

Computing the spectral measure μ for a given composite microstructure first involves discretizing a two phase image of the composite into a square lattice filled with 1's and 0's corresponding to the two phases. Then the key operator $\Gamma\chi_1$, which depends on the geometry of the network via χ_1, becomes a self adjoint matrix. The spectral measure may be calculated directly from the eigenvalues $\{\lambda_i\}$ and eigenvectors $\{v_i\}$ of this matrix via

$$d\mu(\lambda) = \sum_{i=1}^{n} m_i \delta(\lambda - \lambda_i)d\lambda, \quad m_i = \langle e_0^T v_i v_i^T e_0\rangle, \tag{2}$$

where $\delta(\lambda)$ is the Dirac delta function and e_0 is a vector of ones. In [32] we computed the spectral measure for samples of healthy and osteoporotic bone to distinguish them via the connectivity of the trabecular architecture.

As the system size N increases, the eigenvalues become increasingly dense in the spectral interval [0,1]. The presence or absence of gaps in the spectrum near the endpoints of [0,1], and the details of how large a gap is or how large the spectral values m_i are, give important information pertaining to the connectivity and effective transport properties of the system.

Phase transitions and the Ising model of a ferromagnet. The Ising model of a ferromagnet in a magnetic field H and at temperature T is perhaps the most studied example of a phase transition in statistical mechanics [62, 13, 27]. We consider a finite box $\Lambda \subset \mathbb{Z}^d$

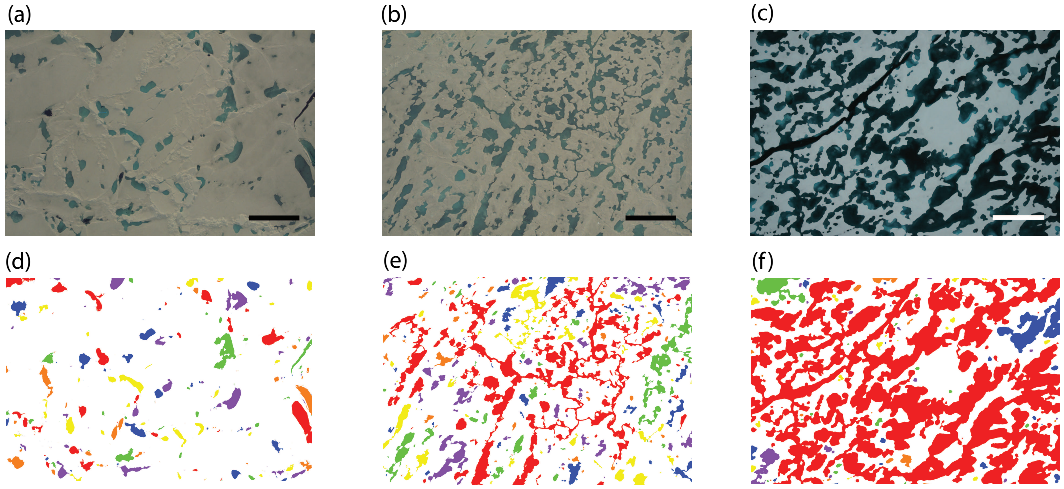

Figure 5: Evolution of melt pond connectivity. (a) Disconnected ponds, (b) transitional ponds, (c) fully connected melt ponds. The bottom row shows the color coded connected components for the corresponding image above: (d) no single color spans the image, (e) the red phase just spans the image, (f) the connected red phase dominates the image. The scale bars represent 200 m for (a) and (b), and 35 m for (c).

containing N sites. At each site there is a spin variable s_i which can take the values $+1$ or -1. We consider a Hamiltonian with ferromagnetic pair interaction $J \geq 0$ between nearest neighbor pairs $< i, j >$,

$$\mathcal{H}_\omega = -H \sum_i s_i \; - \; J \sum_{<i,j>} s_i s_j \; , \tag{3}$$

for any configuration $\omega \in \Omega = \{-1, 1\}^N$ of the spins. The average magnetization, which serves as the principal *order parameter* in the system, $M(T, H) = \lim_{N\to\infty} \frac{1}{N} \langle \sum_{i=1}^N s_i \rangle$, where $\langle \cdot \rangle$ in this context denotes averaging over $\omega \in \Omega$ with Gibbs weights, can be expressed in terms of the free energy (per unit site) f as $M(T, H) = -\frac{\partial f}{\partial H}$. The magnetic susceptibility $\chi(T, H)$, which is the analog of the effective conductivity in the models above, is given by $\chi(T, H) = \frac{\partial M}{\partial H} = -\frac{\partial^2 f}{\partial H^2} \geq 0$. When $H = 0$, $M(T) \sim (T_c - T)^\beta$ as $T \to {T_c}^-$, as shown in Figure 4 (f), and $\chi \sim (T - T_c)^{-\gamma}$ as $T \to {T_c}^+$. The universal exponent β here plays a similar role as β for the percolation model, but has a different numerical value. Below we will discuss how this framework can be used to model melt ponds.

1.4 Principal Scientific Investigations

1.4.1 Melt pond percolation

Melt pond connectivity, as shown in Figure 5, plays a fundamental role in the evolution of the melting Arctic sea ice pack. Such processes as horizontal melt water transport, illustrated in Figure 3 (b), facilitate drainage through macro-pores like seal holes, cracks, and leads. The break-up of ice floes as they melt is strongly influenced by the connectivity of the ponds. For example, as ponds deepen they weaken an ice floe, making it more susceptible to breakage and fracture. Connected ponds spanning an ice floe are more efficient at promoting fracture

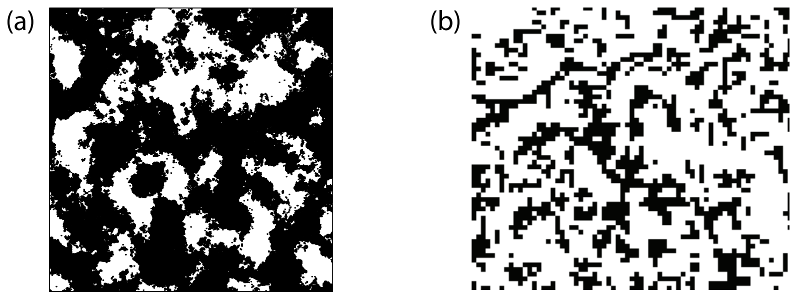

Figure 6: (a) Connected clusters in a continuum percolation model where a level set (water level) intersects a surface defined by a Gaussian random field with covariance determined by snow topography data [57]. The resulting configurations resemble melt ponds on first year sea ice. (b) A simple, stochastic lattice growth model yields fairly realistic "ponds," and also exhibits a transition in pond fractal dimension with length scale.

than a series of disconnected ponds. We therefore propose to examine the key issue of melt pond connectivity, as illustrated in Figure 5.

For melt ponds, we ask: what is the percolation threshold for melt pond evolution. More precisely, if ϕ is the area fraction of melt pond coverage on a large floe, what is the critical threshold ϕ_c for large scale connectivity? This can be addressed by using image analysis to study how the correlation length $\xi(\phi)$ grows as the ponds evolve. As outlined above, the percolation threshold can be characterized by where $\xi(\phi)$ "diverges," or in the case of large floes, where the scale of the correlation length spans the floe size. Does this threshold value depend on floe topography or the age of the floe? What is the variability of ϕ_c from floe to floe? In mathematical percolation theory, the threshold value depends on the details of the lattice model, such as square vs. triangular lattice. However, the critical exponent ν characterizing the divergence of ξ is universal, depending only on dimension. Does the value of ν for melt ponds match the universal lattice value of 4/3 in two dimensions?

We also expect that our investigations of melt pond connectivity will be aided by continuum percolation models based on the intersection of a level set with a random surface [39]. Here, the level set represents the melt water level and the random surface the ice or snow topography. A configuration for a Gaussian model is shown in Figure 6 (a). Questions of percolation thresholds and critical exponents have been studied in this context, and we expect that such studies will lend insights into the melt pond problem.

Since one aerial photo generally does not span a large floe, to address the above questions we must develop techniques for stitching together many images to create a mosaic. We are also interested in the time evolution of melt ponds and their geometry during the melt season, so being able to track the growth of individual ponds and their connectivity will drive some of the imaging work. Moreover, mapping melt ponds onto networks (graphs) of vertices and edges facilitates analysis of pond connectivity and the correlation length.

1.4.2 Transition in the fractal geometry of Arctic melt ponds

For simple objects like circles and polygons, the perimeter P scales like the square root of the area A, that is, $P \sim \sqrt{A}$. However, for complex planar regions with fractal curves as their boundaries,

$$P \sim \sqrt{A}^{\,D} \tag{4}$$

where the exponent D is the fractal dimension of the boundary curve. By analyzing area-perimeter data, Lovejoy [41] found that clouds have a fractal dimension of $D \approx 1.35$.

Viewing images of complex melt ponds, such as in Figures 3 and 5, suggests similar fractal behavior. However, after developing automated techniques for obtaining data on the area A and perimeter P for melt ponds from helicopter photos, and analyzing the data from thousands of melt ponds, we found something unexpected. In particular, we discovered a bend in the P *vs.* A data displayed on logarithmic scales around a critical length scale of about 100 square meters in terms of area, as shown in Figure 2 (a). We then devised an algorithm to statistically compute the derivative of this data set, yielding the graph for $D(A)$ in Figure 2 (b), the fractal dimension D as a function of melt pond length scale, as measured by the area A. These data showed that melt ponds exhibit a transition in fractal dimension from about 1 for A less than 10 m^2 to about 2 for A greater than 1000 m^2. We remark that $D = 2$ is the upper bound for the fractal exponent, since it corresponds to curves which fill two dimensional space, such as the famous Peano curve or Brownian motion.

A principal goal of the proposed research is to develop mathematical models of melt pond evolution. We will explore deterministic models involving partial differential equations (PDE) as well as stochastic models. In particular, we will look for models which help explain the transition in fractal dimension we observe in actual melt ponds, and the value of the critical length scale. In [36] we proposed an argument which relates the critical length scale to the onset of self-similarity, as illustrated in Figure 2. However, we seek a quantitative understanding of how this scale is set through appropriate mathematical models.

One natural approach is to explore the use of phase field equations, such as the Ginzburg–Landau model [10]. It was originally developed in the context of superconductivity, yet has been used in the study of many phase transition and pattern formation problems. The two main functions of interest are the order parameter $\psi = \psi(x, y, t)$ (not to be confused with open water fraction) and the temperature $u = u(x, y, t)$, for $(x, y) \in \mathcal{R}$ for some region $\mathcal{R} \subset \mathbb{R}^2$, and $t \geq 0$. In the case of melt ponds, we have two extreme states, ice and water. The frozen state is characterized by $\psi = -1$ and the melted state by $\psi = +1$. We use the following coupled equations for ψ and u,

$$u_t = K\Delta u - \frac{b}{2}\psi_t, \tag{5}$$

$$\alpha\xi^2\psi_t = \xi^2\Delta\psi + a^{-1}g(\psi) + 2(u - \theta), \tag{6}$$

where $g = c(\psi - \psi^3)$, θ is the melting temperature, K is the coefficient of thermal conductivity, the parameters a, b, c, α, and ξ are determined from the specific physics of the problem, and appropriate thermal boundary conditions are applied at the phase interface. We propose to explore how this system applies to the melt pond problem, by studying the evolution of the interface separating the melted and frozen states, and incorporating relevant physics, such as snow topography. Interestingly, using asymptotic methods, the classical Stefan and Hele-Shaw systems can be obtained from the Ginzburg–Landau model in the limit of a sharp interface [10], which we believe should be quite relevant for the melt pond problem.

We will also develop simple stochastic models on lattices to simulate the evolution of melt ponds. In Figure 6 (b) we show the results of one such very simple growth model. Here we

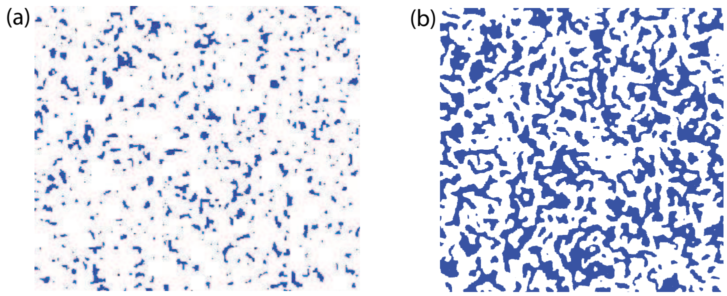

Figure 7: Islands of like spins in the Ising model of a ferromagnet. The configurations resemble melt ponds. (a) Early melt ponds. In this simulation the heat content $H > 0$ is small. (b) Well-developed melt ponds. In this simulation the heat content $H > 0$ is large.

specifically wanted to begin to understand why the fractal dimension undergoes a transition. We made the following simple observation, that adding a melted square connected only by a corner to an existing pond increases the perimeter more than a square connected along an edge. The probability of this occurring is significantly increased for pond sizes above some critical size, and in fact, we see a transition in the fractal dimension around that length scale, with data quite similar to Figure 2 (a). We plan to build on this initial success to construct more realistic models which develop a transition in fractal geometry on their own, now that we begin to understand one possible mechanism.

1.4.3 Ising model for melt pond formation

We consider an Ising model for melt ponds where the "spins" s_i are assigned either -1 for ice or $+1$ for melt water. We will explore various Hamiltonians that model the energy associated with melt pond configurations. The Ising model of statistical mechanics is a feasible model for melt pond evolution because it possesses the following two properties: 1. Disconnected small scale same-phase regions tend to cluster and favor the formation of larger regions when the system is not dominated by random fluctuations. 2. The system favors same-phase regions to grow or shrink their boundaries as opposed to, for example, shifting or being deformed.

The role of the applied magnetic field in Equation (3) can be played by the external forcing of the sea ice layer principally by net solar radiation and air temperature [1]. Then H can be thought of as external heating of the system. For $H > 0$, the system is driven toward more widespread melting. For $H < 0$, the system is driven toward less melting. The average magnetization $M(H)$ is then closely related to the sea ice albedo. Two realizations of the model configurations are shown in Figure 7, which bear striking resemblances to actual melt ponds. Moreover, the model yields an average albedo displaying the critical behavior shown in Figure 4 (f), which is similar to the albedo in Figure 1.

The model can be enhanced further by assuming an initial surface topography for the ice cover. For a given topography, represented by a height function h, we can define the interaction field $J = J_h(i, j)$ in such a way that the system favors water moving in the direction of steepest topographical descent. The surface topography used to initialize the model can ideally be obtained from measurements by our colleagues (C. Polashenski and D. Perovich), or calculated using topography models; see for example [57].

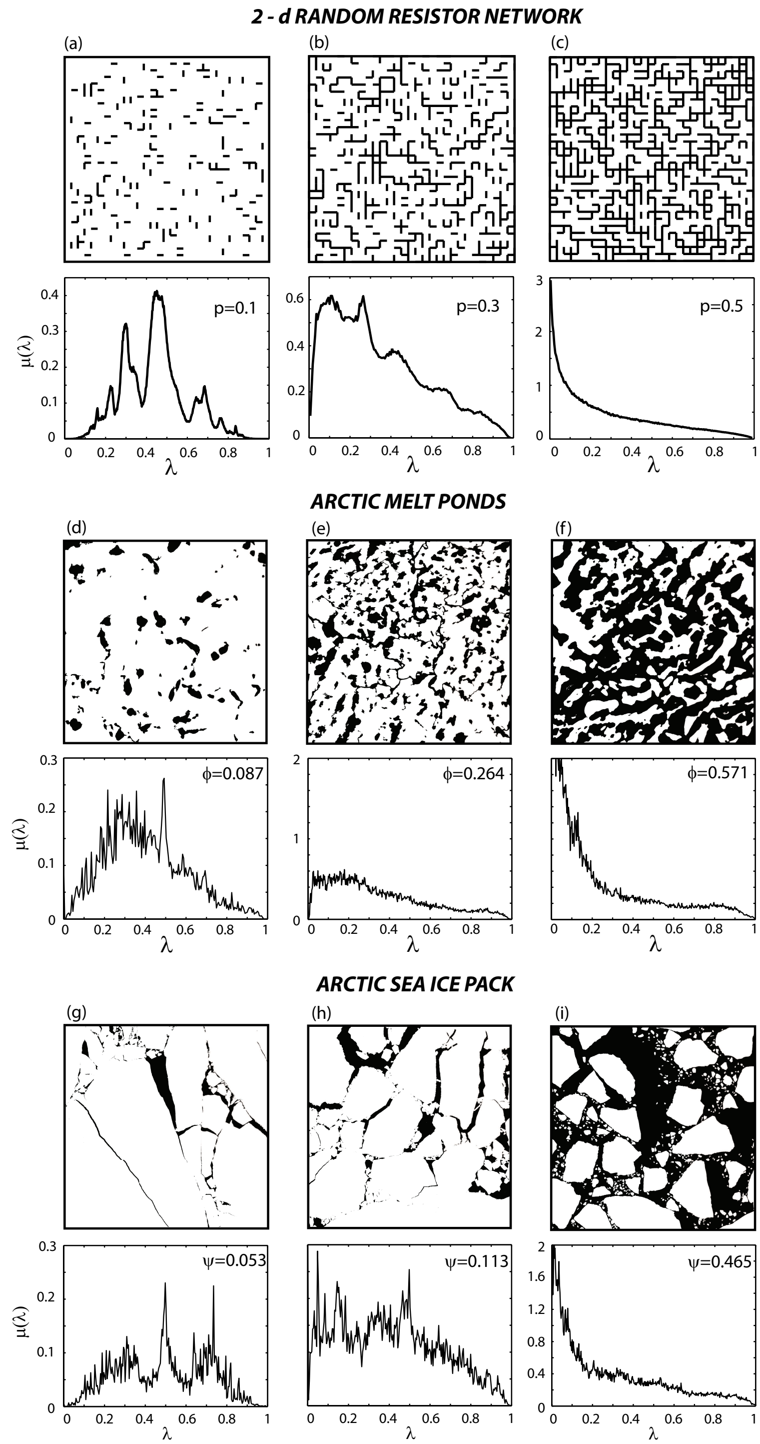

Figure 8: *Spectral analysis of sea ice structures.* Increasingly connected configurations of the percolation model (a)-(c), melt ponds (d)-(f), and leads in the ice pack (g)-(i), with corresponding spectral measures below. The area under each spectral function in (d)-(f) is the melt pond area fraction ϕ, and the open water fraction ψ in (g)-(i). For the network, the width of the gap in the spectrum near $\lambda = 1$ for $p = 0.1$ shrinks to 0 with increasing connectedness as the percolation threshold $p = 0.5$ is approached, with similar behavior for melt ponds and the ice pack.

1.4.4 Homogenization theory and spectral measures

As discussed above, homogenization theory [45, 63] provides a mathematical framework to analyze the effective transport and rheological properties of complex, heterogeneous systems. The analytic continuation method [25], in particular, is based on powerful integral representations for effective properties, and involves the *spectral measures* which depend on the composite geometry, such as the volume or area fractions of the phases, as well as the connectivity and percolation properties. The moments of the spectral measure are related to the correlation functions of the microstructure. We propose to use this framework to *upscale* the local geometry of the ice pack, such as melt pond and ice floe configurations, into calculations of their effective properties. In Figure 8 we show a series of spectral measures computed from discretizations of melt pond and ice pack images, which raises the following questions. Does the evolution of the melt pond spectral measures obey universal laws of critical behavior, such as the collapse of a spectral gap with the onset of large scale connectivity? Can critical behavior in the local geometry be related to critical behavior in effective rheological and transport properties? In view of Figure 3 (b), which illustrates the importance of horizontal flow of meltwater on the sea ice surface, we observe that the calculation of melt pond spectral measures immediately gives a rigorous formula for the effective behavior of such flows, such as the large scale, horizontal surface fluid permeability considered in the next section. Sinks representing seal holes and cracks, which are relevant to regional sea ice models and albedo evolution, can be incorporated into homogenized PDE models.

1.4.5 Calculating sea ice albedo in climate models

Modern global climate models (GCM's) account for melt pond albedo effects by explicitly calculating meltwater volume from sea ice or snow and then parameterizing the associated pond fractional coverage ϕ and depth h_p [47, 37]. The various parameterizations in use for ϕ and h_p are based on observed relationships [49], curves fit to output from high-resolution mass balance simulations [42], or the assumption that meltwater travels horizontally to cover the ice of lowest surface height [19, 20]. In higher-resolution frameworks with explicit sea ice topography, spatial patterns of ϕ and h_p are simulated by transporting meltwater horizontally according to Darcy's Law for flow through porous media [42].

We will investigate the potential for applying the mathematical models and techniques developed in this proposal to the simulation of melt ponds in modeling frameworks including GCM's. Recall that GCM's with physically based melt pond schemes calculate meltwater volume V_p, and then the albedo calculation involves specifying the associated pond fractional coverage ϕ. Pond depth h_p is often assumed constant on a given sea ice thickness class, so the governing equation

$$V_p = \phi h_p \tag{7}$$

is typically closed by assuming that ϕ is a known function of h_p [47, 37].

We expect that the critical transition in pond complexity discovered using pond perimeter and area [36] will project strongly into the GCM variable space (V_p, ϕ, h_p), and that this projection can be exploited to formulate a closure for (7) that obeys the observed universal scaling. For example, when meltwater volumes reach levels conducive to complex networking of ponds, it may be more natural to specify ϕ from V_p rather than from h_p. To enable

Region	Type	Year	Reference	Comment
Beaufort Sea	Aerial	1998	Perovich et al., 2002	Time series May–October
Trans-Arctic	Aerial	2005	Perovich et al., 2005	Spatial survey in August–September
Several years, several sites	Satellite	Several	Fetterer and Untersteiner, 2002	National Technical means
Chukchi, Beaufort Seas	Satellite	2011	Frey, personal communication	Images from Quickbird
Chukchi, Beaufort Seas	Satellite	2013, 2014	Results from Polashenski et al. proposal	Images from Quickbird
Arctic Ocean, north of Svalbard	Aerial	2012, 2013	Results from Granskog and Pedersen	Spatial survey in July-August

Table 1: Sources of images for melt pond analysis.

the required multivariate analyses, extraction of ϕ will be a straightforward addition to the perimeter-area analysis, and more sophisticated image processing will be used to make color-based estimates of h_p and hence V_p [36]. The required algorithms can build on the *color–gradient* technique developed in [36]. A validation and sensitivity analysis of the new specification of ϕ will be performed using the Los Alamos CICE model [38].

Finally, we will also explore developing a predictive modeling framework that captures the observed critical transition in melt pond complexity. We will begin with the high-resolution two-dimensional model introduced by Luthje and collaborators [42]. This framework's horizontal transport scheme is based on Darcy's Law for flow through porous media, and thus does not simulate more rapid horizontal movements of water across the surface of the ice in "outflow pathways" [51]. We will replace this scheme with a coupled framework that uses Darcy's Law for the porous subsurface flow and uses Navier Stokes equations for the surface flow [11]. Incorporating an explicit mechanism for surface outflow pathways will enable the model to develop more realistic networks of interconnected ponds and reproduce observed critical transitions in pond complexity [36]. The spectral calculations discussed above for the effective flow behavior based on melt pond geometry and connectivity will be employed here to make the computations more rigorous and efficient.

1.5 Image Analysis

We will first compile and then analyze a library of aerial and satellite images of sea ice during the melt season. Table 1 summarizes some of the sources for the image library. The spatial resolution of the images is approximately 1 m. In many cases a preliminary processing of these images has occurred that we will extend.

For the analysis in [36] we had access to image sets captured during two measurement campaigns: Healy Oden TRans Arctic EXpedition (HOTRAX, 2005) and Surface Heat Budget of the Arctic Ocean (SHEBA,1998). Helicopter photographic survey flights gave extensive high resolution imagery of the polar marine environment consisting of ice, melt ponds and open water. To obtain melt pond area–perimeter and connectivity data, it was

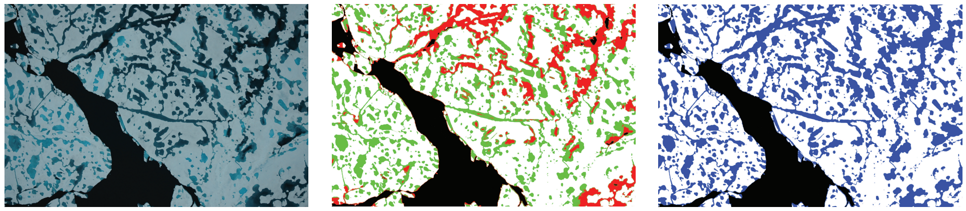

Figure 9: Image segmentation for August 14th (HOTRAX): (a) original image; (b) initial four color threshold with ice, shallow ponds, deep ponds and ocean/deep ponds colored as white, green, red and black, respectively; (c) segmented image with ice, ponds and ocean colored as white, blue and black, respectively.

Figure 10: A series of image tiles corresponding to a horizontal pass of the helicopter over the ice aligned into a strip using *ir-tweak*. The result is shown after 10× downsampling.

necessary to develop *segmentation algorithms* capable of distinguishing between ponds and open water. We developed a method based on computing the directional derivative in color space, where ponds have at least slight color gradients while open water generally does not. The segmenation algorithm is illustrated in Figure 9.

In our investigations of large scale connectedness and area–perimeter relations, individual ponds can be much larger than one image, thus it is critical to be able to *stitch* images together. Tasdizen *et al.* [61] have developed a suite of automatic and interactive software tools for mosaicking of microscopy image tiles. More specifically, *ir-tweak* is an interactive graphical user interface for image alignment. It allows users to drop and drag fiducial control points on either the moving or the stationary image. As the user moves the control points, the resulting warping of the moving image is shown in real time to the user allowing for a smooth interaction. The user utilizes information in overlapping areas of the moving and stationary images to bring them into alignment. Currently, *ir-tweak* does not support rigid rotation because it was designed to handle microscopy images which typically require deformable maps. In this project, we will add a rigid rotation capability into *ir-tweak* which is needed for better alignment of the ice images into strips.

Hogrebe *et al.* [35] have developed an automatic landmark based algorithm to align light microscopy sections of the retina with deformable transformations. In this project, we will modify the Hogrebe algorithm to track melt ponds in time. After segmentation of individual melt ponds, we will use their properties such as color, size, location and other shape properties to match them across time using bipartite matching. This matching will drive a deformable warping of the image at time $t+1$ to the image at time t. This calculated warp, iterated until convergence, allows refinement of the landmark matching.

As discussed above, a key tool which will facilitate the structural analysis of melt ponds is mapping them onto graphs, or networks of vertices and edges. In general, a melt pond consists of simpler round ponds, which correspond to vertices of a graph, connected through thin elongated channels, which correspond to its edges. For each melt pond, the thin elongated channels can be separated from the round convex parts by applying appropriate mathematical morphological operations. A graph which captures the essential geometrical and connectedness characteristics of a melt pond can be obtained using such methods. Viewing melt ponds as graphs allows for their classification as complex, simple, and transitional, as in Figure 2, and is essential to any studies of percolation in melt pond evolution.

1.6 Linkages to Other Programs

1. ONR Melt Pond Proposals. Following the suggestion of Dr. Jeffries, the Principal Investigators from the proposals Sunlight, sea ice, and the ice albedo feedback in a changing Arctic sea ice cover (Perovich and Light), Multiscale models of melting Arctic sea ice (Golden et al.), and Developing remote sensing capabilities for meter-scale sea ice properties (Polashenski et al.) have had several discussions about our projects and how best to integrate them and reduce costs. Describing melt ponds is a major focus in all three proposals. We believe that the proposals nicely complement each other and are synergistic. For example, the analysis of the high-resolution images proposed by Polashenski et al. could be implemented into the Golden et al. mathematical pond description. It could also be applied as input data for the Perovich and Light solar partitioning calculations. The results of these calculations would in turn provide context for the Polashenski work. Floe size distributions from Polashenski et al. could be used in the lateral melting computations of Perovich and Light, and in fractal analyses of Golden et al. Through these discussions, we identified several areas of collaboration where our efforts dovetail together. We also found a few places where there was some overlap. By eliminating the overlap, we were able to reduce our budgets.

Our project is more theoretically oriented, however, after developing mathematical descriptions of pond evolution, we will relate them to the physical processes that govern ponds, and to the other ONR melt pond projects. Melt pond formation and evolution is related to surface topography, melt rates, and ice permeability [51]. We will determine how changes in sea ice conditions, such as melt onset and ice permeability, relate to changes in pond fractal dimension. We will examine whether the variation in topography between first year and multiyear ice is manifested in the mathematical properties of ponds in these two ice types.

Ultimately, we will apply the mathematical description of melt ponds to examine the heat and mass balance of the ponds. The pond area affects the partitioning of incident solar radiation on the ice cover. The pond perimeter to area ratio influences the total amount of melting along the pond edges.

2. NSF Math Climate Research Network (MCRN). Golden is a Co-PI on a 5 year NSF DMS funded project to bring young mathematicians into climate research, through a network of 12 hub institutions, including the Math Department at the University of Utah. The MCRN grant is structured to facilitate interaction between core research programs, and the project proposed here would dovetail perfectly with the objectives of the MCRN. This linkage will broaden the expertise available to us in this project. For example the network would bring in additional expertise in dynamical systems, ice–albedo feedback, bifurcation theory, data assimilation, time series analysis, and climate modeling. It will also broaden the impact of our results, and speed the dissemination of the results of our work.

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3 Project Schedule and Milestones

Year 1: Collect melt pond images. Begin analysis of existing images using percolation theory and image processing techniques. Specifically address the issue of what determines the critical length scale where melt pond geometry changes from Euclidean to space filling behavior. Explore appropriate theories in statistical physics and composite materials to understand critical behavior of melt pond evolution. Begin development of image analysis techniques.

Year 2: Begin development of PDE models for melt pond evolution. Continue percolation and statistical mechanics investigations. Investigate how the mathematical models can aid in representing melt ponds in climate models. Begin publishing results on mathematical models and image analysis.

Year 3: Continue model development and tune the models with results from new images. Continue work on including our theoretical results in climate models. Continue data analysis, model development and synthesis with other investigators. Focus on producing group publications and disseminating results to the broader community.

Image software development: In years one and two, we will focus on developing the image processing software and testing it on the available data sets. By the end of the project, we plan to have a user-friendly software package for the analysis of melt pond and floe images. The software will be made available to other groups and we will pay particular attention to the packaging of the software including an easy to use graphical interface and help documentation.

4 Management Approach

University of Utah: The PI Golden will be responsible for the overall success of the project, for providing mathematical direction and undertaking investigations, for supervising the post-doc and students. The co-PI's Strong and Alali will be responsible for scientific computation and physical modeling of the systems of interest, and co-advising students. Tasdizen and Alali will be responsible for developing methods of image analysis.

ERDC–CRREL: Perovich and Polashenski will be responsible for obtaining melt pond imagery that satisfies the requirements of the principal modeling objectives. They will also be closely involved in relating the mathematical results to the geophysics of melt ponds, sea ice, and the upper ocean. Perovich will also contribute to formulating relationships between pond properties and melting on sides and bottoms of ponds.

Facilities and Equipment at the University of Utah

Department of Mathematics:

Computer
The Department provides outstanding computing facilities for use by faculty, students and staff. The fully internetworked workstation and microcomputer configuration includes almost 300 systems in a range of models from these architectures: Apple Macintosh, DEC Alpha, Intel IA-64, Itanium, Sun AMD64 Opteron, Intel IA-32 Pentium and AMD Athlon, Power PC GNU/Linux, Silicon Graphics, Sun Ray stations and SUN SPARC. These include at least one file server from each UNIX architecture.

Office
The Mathematics Department is housed in two buildings containing administrative, graduate student and private faculty offices. Also, there is a student tutoring center, computer labs and a mathematics library.

Equipment obtained by the PI for sea ice field research:

1. Agilent N9923A Field Fox Network Analyzer. Provides full two port transmission and reflection parameters (S21, S11, S12, S22) for frequencies from 2MHz to 4GHz. The network analyzer is water-resistant, rugged, and has built-in QuickCal technology that enables field calibration without a kit. The N9923A is the only handheld network analyzer compliant with Class 2 MIL PRF 28800F.

2. Agilent 85070E High-Temperature Dielectric Probe Kit. The dielectric probe provides complex permittivity measurements from 200MHz to 50GHz. The probe is hermetically sealed making it resistant to corrosive and abrasive chemicals. Additionally the probe can withstand a temperature range of -40C to +200C. The probe has a 3.5mm aperture, providing a larger sensing volume than other available probes.

3. Two AEMC 6470-B Earth Resistivity Meters. Capable of 3 and 4 point fall-of-potential measurement, 3-point earth coupoling measurement, automatic resistivity measurement using 4-point wenner and schlumberger method, and 2 and 4-wire DC resistance

measurement with automatic polarity reversal. Additionally the device performs automatic frequency scan from 40-513Hz for electrically noisy environments and can store up to 512 complete test results in internal memory.

4. Two BK Precision Model 886 Synthesized LCR / ESR Meter Measures complex-impedance providing magnitude and phase, inductance, capacitance, dc resistance, equivalent series resistance with a .2% basic accuracy. Additionally the meter provides information allowing calculation of meter error for each test measurement. The meter tests at 100Hz, 120Hz, 1kHz, 10kHz, 100kHz, and is capable of measuring at 1Vrms, 0.25Vrms, and 0.05Vrms.

5. Six Omega Model 866C thermistors, three WTW Cond 3110 salinometers, one Kovacs Mark II coring system, and a selection of drills and saws, custom made PVC packers for blocking horizontal flow in core holes during fluid permeability measurements, two custom made sea ice core platforms for conducting field experiments, and other items.

Department of Atmospheric Sciences:

Co-PI Strong's research group owns a 72-core Linux cluster built on Intel Nehalem processor technology configured with Infiniband Quad Data Rate linking and 3GB of RAM per core. This system is maintained and supported by the University of Utah Center for High Performance Computing (CHPC). PI Strong additionally has access to the 1000+ core meta-clusters maintained by CHPC, and owns an 8-core workstation suitable for developing and testing parallel code and performing expensive data analysis operations such as large matrix inversion.

The Department maintains a comprehensive meteorological archive on hard disks and tapes, including resources such as GOES satellite imagery. The Computation and Visualization Laboratory (CVL) is a state of the art 10-workstation facility for education and research in numerical weather prediction, atmospheric visualization, and dynamic meteorology.

SCI Institute Resources

The SCI institute has over 25,000 square feet of functional space allocated to its research and computing activities within the new John and Marva Warnock Engineering Building. Laboratory facilities for the researchers listed in this project include personal office spaces and access to a variety of common working areas.

Computing

The SCI computing facility, which has dedicated machine room space in the Warnock Engineering Building, includes

Shared-memory, multi-core computers

- 2 IBM 32 3.0 GHz Xeon core clusters with 192 GB of RAM running SUSE Enterprise 10 linux. Each of these systems can also be reconfigured into two separate 16 core systems with 96 GB of RAM.

- A 16-processor, 16 GByte shared memory SGI Altix-Linux system with Intel Itanium II 1.4 GHz processors.
- An 8-processor, 24 GByte shared memory SGI Altix-Linux system with Intel Itanium II 1.4 GHz processors.
- A variety of multi-core, linux desktop workstations.

Graphics and distributed-memory, multi-core computers

- The SCI Institute was recently named an NVIDIA Center of Excellence. As a result of this collaboration, the institute has installed a 128-node NVIDIA Tesla compute cluster. The GPU cluster is supported by a 512-core HP Nehalem-based CPU cluster and InfiniBand networking.
- Sun Cluster: 256 Dual-Quad Core Nodes (2048 total cores), 2.8 GHz Intel Xeon (Harpertown) processors, 16 Gbytes memory per node (2 Gbytes per processor core), Qlogic Infiniband DDR (InfiniPath QLE 7240) interconnect, Gigabit Ethernet interconnect.
- 3, 24 core, 2.5 GHz, AMD Opteron with NVIDIA Quadro FX 5600 graphics card) with a dual Gigabit Ethernet backbone and 96 GBytes RAM.
- An 8 core, 2.0 GHz, AMD Opteron, with NVIDIA Quadro 2FX graphics card) cluster with a dual Gigabit Ethernet backbone and 16 GBytes RAM.
- A 2-processor (3.0 GHz, Intel Pentium D, with NVIDIA Quadro FX graphics card) visualization head with a Gigabit Ethernet backbone and 2 GBytes RAM.
- A 2-processor (3.0 GHz, Intel Pentium D, with NVIDIA Quadro FX graphics card) Windows based visualization head with a Gigabit Ethernet backbone and 2 GBytes RAM.
- A 16 core, 3.0 GHz AMD Opteron with NVIDIA 8800GTX graphics card with a dual Gigabit Ethernet backbone and 64 GBytes RAM.
- A 16 core, 2.4 GHz AMD Opteron, with NVIDIA 7900GTX graphics card with a dual Gigabit Ethernet backbone and 64 GBytes RAM. The SCI Institute computing facility contains the following network, regression

Testing and storage systems

- A hierarchical SGI Infinitefile file system consisting of both FibreChannel and SATA disk and online tape storage and with an initial capacity of over 120 TBytes and significant expansion capacity.

- Six Sun quad-core AMD Opteron fileservers attached to a Hitachi AMS500 modular FC high-availability storage array with over five TBytes of high-end FibreChannel disk.
- Three LTO-2 tape libraries providing backup for SCI Institute researchers.
- A 250 slot LTO-3 StorageTek SL500 tape library.
- A fully redundant Foundry BigIron switching core that provides a Gigabit network backbone for all HPC computers, servers, and individual workstations connected via Foundry floor switches.
- Connections to the campus backbone via redundant 10 Gigabit Ethernet links—the first such attachments on campus.
- A variety of Intel and AMD based desktop workstations running Linux with the latest ATI or NVIDIA graphics cards.
- Numerous Windows 2000, Windows XP, and Vista workstations.
- Numerous Mac workstations running OSX.
- Regression cluster made of 8 workstations of various OS/hardware configurations used for nightly regression builds of CIBC software.
- Three conference rooms with teleconferencing/video conferencing capabilities.
- Multiple, high availability Linux servers providing core SCI IT services - website (www.sci.utah.edu), ftp, mail, and software distribution.
- 100 Megapixel powerwall composed of 24 Dell high-resolution monitors powered by six servers with high-end graphics cards.
- UPS power, including 100 minutes of battery backup for critical SCI servers.

David Evans Visualization Center (EVC)

The David Evans Visualization Center is an important collaboration and demonstration space within the SCI Institute and serves as a focal point for CIBC members to work collaboratively together, prepare multi-media components of presentations, and share work with visitors to the Center.

Equipment and functionality within the EVC include

- Three high-end, Mac based video editing bays with flatbed scanners, A/D video converters, Adobe CS Master Suite and Final Cut Pro.
- One midrange iMac flatbed scanning station.
- Two midrange Windows XP systems with Adobe CS Master Suite.

- One high-end Mac for running videos and 3D demos.
- One high-end PC for running videos and 3D demos.
- One Highlite 8000Dsx stereo 3D capable rear projection system with 1400x1050 native resolution.
- A 10 foot $\times$ 8 foot, high-resolution, rear projection system with stereo capability for collaborative group interaction and code development.

Office space

The SCI Institute houses its faculty and staff in individual offices and students have individual desk space equipped with a workstation in large, open common areas that facilitate student collaboration and communication. All workstations are connected to the SCI local area network via full-duplex Gigabit Ethernet.

The University of Utah is a member of the Internet2 advanced networking consortium. It is connected to the new Internet2 Network via Gigabit Ethernet (1 Gbit per second) and the National LambdaRail (NLR) via a dedicated link to the Front Range Gigapop. The University also has the ability to extend dedicated wavelengths into the campus from the Internet2 and NLR nodes collocated in a Level 3 Communications facility west of Salt Lake City.

5 Current and Pending Projects and Proposals

Kenneth M. Golden, Ph.D.

Current:

Title: EMSW21-VIGRE: Vertical Integration in Mathematics at the University of Utah
Summary: Provides leading-edge training and research opportunities in the mathematical sciences for students.
Source: National Science Foundation, DMS-0602219
Percent effort: 5%
Technical contact: Kenneth M. Golden
Administrative/business contact: Shauna Peterson; 1471 East Federal Way;
Tel: 801-585-0062; Fax: 801-581-3007; email: shauna.peterson@osp.utah.edu
Period of performance: 05/17/06 - 07/31/12
Total award (direct and indirect costs): $3,500,000
Person months devoted to project: 0
Overlap: None

Title: CMG COLLABORATIVE RESEARCH: Mathematics and Electromagnetics for Monitoring Transport Processes In Sea Ice
Summary: To develop methods of electromagnetically monitoring the internal state of sea ice, the thermal evolution of its microstructure, and the transport processes it controls.
Source: National Science Foundation, ARC-0934721
Percent effort: 20%
Technical contact: Kenneth M. Golden
Administrative/business contact: Shauna Peterson; 1471 East Federal Way;
Tel: 801-585-0062; Fax: 801-581-3007; email: shauna.peterson@osp.utah.edu
Period of performance: 10/01/09-09/30/13
Total award (direct and indirect costs): $541,271
Person months devoted to project: 0.75 summer months
Overlap: None

Title: Collaborative Research: Mathematics and Climate Change Research Network
Summary: The scientific objectives of the project are: 1) climate process modeling; 2) the processes of past and future climates; and 3) data analysis and the incorporation of data into Earth system and climate process models.
Source: National Science Foundation, DMS-0940249
Percent effort: 10%
Technical contact: Kenneth M. Golden
Administrative/business contact: Shauna Peterson; 1471 East Federal Way;
Tel: 801-585-0062; Fax: 801-581-3007; email: shauna.peterson@osp.utah.edu
Period of performance: 10/01/10-09/30/15
Total award (direct and indirect costs): $527,727 (There are 12 institutions involved in this

project, for a grand total of $5,000,000.)
Person months devoted to project: 0
Overlap: None

Title: Phase Transitions in Composite Media
Summary: To investigate the transitional behavior of electrorheological fluids and the existence of a critical electric field.
Source: National Science Foundation, DMS-1009704
Percent effort: 10%
Technical contact: Kenneth M. Golden
Administrative/business contact: Shauna Peterson; 1471 East Federal Way;
Tel: 801-585-0062; Fax: 801-581-3007; email: shauna.peterson@osp.utah.edu
Period of performance: 09/15/10-08/31/13
Total award (direct and indirect costs): $307,000
Person months devoted to project: 1 summer month
Overlap: None

Title: Spectral Theory of Advective Diffusion in the Ocean
Summary: We will develop a systematic spectral analysis of advection enhanced diffusion.
Source: Office of Naval Research, N000141210861
Percent effort: 10%
Technical contact: Kenneth M. Golden
Administrative/business contact: Shauna Peterson; 1471 East Federal Way;
Tel: 801-585-0062; Fax: 801-581-3007; email: shauna.peterson@osp.utah.edu
Period of performance: 07/01/12 – 06/30/13
Total award (direct and indirect costs): $50,000
Person months devoted to project: 0 month
Overlap: None

Pending:

Title: Geometry of the Antarctic Marginal Ice Zone
Summary: Determine controls on variability in the width of the Antarctic marginal ice zone, and investigate its evolution using mathematical models.
Source: National Science Foundation, Office of Polar Programs
Percent effort: 10%
Technical contact: Courtenay Strong
Administrative/business contact: Jesse Pugh, Officer, Office of Sponsored Projects; 1471 East Federal Way; Tel: 801-581-3008; Fax: 801-581-3007; email: Jesse.Pugh@osp.utah.edu
Period of performance: 01/01/13-12/31/15
Total award (direct and indirect costs): $498,544
Person months devoted to project: 1
Overlap: N/A

Title: Multiscale Models of Melting Arctic Sea Ice (this application)
Summary: We will investigate the formation and evolution of melt ponds on Arctic sea ice. This work will help to improve climate models by quantifying our understanding of ice pack albedo and key feedback mechanisms.
Source: Office of Naval Research
Percent effort: 15%
Technical contact: Kenneth M. Golden
Administrative/business contact: Shauna Peterson; 1471 East Federal Way;
Tel: 801-585-0062; Fax: 801-581-3007; email: shauna.peterson@osp.utah.edu
Period of performance: 12/1/12 – 11/30/15
Total award (direct and indirect costs): $481,616
Person months devoted to project: 1 summer month
Overlap: None

Courtenay Strong, Ph.D.

Current:

Title: Think Globally, Learn Locally
Summary: Graduate student fellows supported by this program serve as scientific role models and mentors to high school students.
Source: National Science Foundation, Division of Graduate Education
Percent effort: 5%
Technical contact: Courtenay Strong
Administrative/business contact: Jesse Pugh, Officer, Office of Sponsored Projects; 1471 East Federal Way Salt Lake City, Utah 84102-1821; Tel: 801-581-3008; Fax: 801-581-3007; email: Jesse.Pugh@osp.utah.edu
Period of performance: 05/01/09-04/30/14
Total award (direct and indirect costs): $2,143,634
Person months devoted to project: 0
Overlap: None

Title: Negative sea ice-circulation feedback along Arctic marginal ice zones
Summary: Innovative modeling frameworks (e.g., hybrid dynamical-statistical coupling) are used to investigate observed feedback process in Arctic marginal ice zone.
Source: National Science Foundation, Office of Polar Programs
Percent effort: 17%
Technical contact: Courtenay Strong
Administrative/business contact: Jesse Pugh, Officer, Office of Sponsored Projects; 1471 East Federal Way; Tel: 801-581-3008; Fax: 801-581-3007; email: Jesse.Pugh@osp.utah.edu
Period of performance: 08/15/10-07/31/13
Total award (direct and indirect costs): $242,991
Person months devoted to project: 2
Overlap: None

Title: Collaborative Research: CI-WATER, Cyberinfrastructure to Advance High Performance Water Resource Modeling
Summary: Acquire and develop software and hardware to support new large-scale, high-resolution computational models.
Source: National Science Foundation, EPSCoR Research Infrastructure Improvement Program, Track-2
Percent effort: 8%
Technical contact: Courtenay Strong
Administrative/business contact: Jesse Pugh, Officer, Office of Sponsored Projects; 1471 East Federal Way; Tel: 801-581-3008; Fax: 801-581-3007; email: Jesse.Pugh@osp.utah.edu
Period of performance: 09/01/11-08/31/14
Total award (direct and indirect costs): $3,435,873
Person months devoted to project: 1
Overlap: None

Title: iUTAH-innovative Urban Transitions and Aridregion Hydro-sustainability
Summary: Observe and model fundamental interactions and dynamic feedbacks among hydroclimate and the ecological and human aspects of urban and montane landscapes.
Source: National Science Foundation, EPSCoR Research Infrastructure Improvement Program, Track-1
Percent effort: 8%
Technical contact: Courtenay Strong
Administrative/business contact: Jesse Pugh, Officer, Office of Sponsored Projects; 1471 East Federal Way; Tel: 801-581-3008; Fax: 801-581-3007; email: Jesse.Pugh@osp.utah.edu
Period of performance: 08/01/12-07/31/17
Total award (direct and indirect costs): $4,000,000 renewable annually for up to five years
Person months devoted to project: 1
Overlap: None

Pending:

Title: Geometry of the Antarctic Marginal Ice Zone
Summary: Determine controls on variability in the width of the Antarctic marginal ice zone, and investigate its evolution using mathematical models.
Source: National Science Foundation, Office of Polar Programs
Percent effort: 17%
Technical contact: Courtenay Strong
Administrative/business contact: Jesse Pugh, Officer, Office of Sponsored Projects; 1471 East Federal Way; Tel: 801-581-3008; Fax: 801-581-3007; email: Jesse.Pugh@osp.utah.edu
Period of performance: 01/01/13-12/31/15
Total award (direct and indirect costs): $498,544
Person months devoted to project: 2
Overlap: N/A

Title: Multiscale Models of Melting Arctic Sea Ice (this application)
Summary: We will investigate the formation and evolution of melt ponds on Arctic sea ice. This work will help to improve climate models by quantifying our understanding of ice pack albedo and key feedback mechanisms.
Source: Office of Naval Research
Percent effort: 6%
Technical contact: Kenneth M. Golden
Administrative/business contact: Shauna Peterson; 1471 East Federal Way;
Tel: 801-585-0062; Fax: 801-581-3007; email: shauna.peterson@osp.utah.edu
Period of performance: 12/1/12 – 11/30/15
Total award (direct and indirect costs): $481,616
Person months devoted to project: 0.75 summer month
Overlap: None

Bacim Alali, Ph.D.

Pending:

Title: Multiscale Models of Melting Arctic Sea Ice (this application)
Summary: We will investigate the formation and evolution of melt ponds on Arctic sea ice. This work will help to improve climate models by quantifying our understanding of ice pack albedo and key feedback mechanisms.
Source: Office of Naval Research
Percent effort: 20%
Technical contact: Kenneth M. Golden
Administrative/business contact: Shauna Peterson; 1471 East Federal Way;
Tel: 801-585-0062; Fax: 801-581-3007; email: shauna.peterson@osp.utah.edu
Period of performance: 12/1/12 – 11/30/15
Total award (direct and indirect costs): $481,616
Person months devoted to project: 1 summer month
Overlap: None

Tolga Tasdizen, Ph.D.

Current:

Title: A Computational Framework for Mapping Long Range Genetic Circuits
Summary: This project addresses neurobiologic technologies and software tools needed for gene-specific 3D reconstructions of long range axon projections in the limbic system, at the axon level and on the scale of the primate brain using light microscopy.
Source: National Institutes of Health
Percent effort: 5%
Technical contact: Tolga Tasdizen

Administrative/business contact: Edward Black, Manager, Grants and Accounting, SCI; 72 S Central Campus Dr.; Tel: 801-587-7857; Fax: 801-585-6513; email: ed@sci.utah.edu
Period of performance: 09/30/09-08/31/11
Total award (direct and indirect costs): $996,734
Person months devoted to project: 0
Overlap: None

Title: MSPA-MCS: High-Dimensional, Nonparametric Density Estimation for the Analysis of Images and Shapes
Summary: This project addresses several computational challenges associated with estimating and representing probability densities in high-dimensional spaces and the application of this technology to several problems in image analysis.
Source: National Science Foundation
Percent effort: 5%
Technical contact: Tolga Tasdizen
Administrative/business contact: Edward Black, Manager, Grants and Accounting, SCI; 72 S Central Campus Dr.; Tel: 801-587-7857; Fax: 801-585-6513; email: ed@sci.utah.edu
Period of performance: 06/01/07-12/31/11
Total award (direct and indirect costs): $474,000
Person months devoted to project: .50 summer months
Overlap: None

Title: Scalable Large Analytic Segmentation Hybrid (SLASH)
Summary: This project addresses scalable large analytic segmentation hybrid.
Source: National Institutes of Health
Percent effort: 10%
Technical contact: Tolga Tasdizen
Administrative/business contact: Edward Black, Manager, Grants and Accounting, SCI; 72 S Central Campus Dr.; Tel: 801-587-7857; Fax: 801-585-6513; email: ed@sci.utah.edu
Period of performance: 06/01/11-05/31/16
Total award (direct and indirect costs): $635,903
Person months devoted to project: 1.2
Overlap: None

Title: Fluorender: An Imaging tool for visualization and analysis of confocal data
Summary: This project addresses visualization and analysis of confocal data specifically for Zebrafish developmental research .
Source: National Science Foundation
Percent effort: 10%
Technical contact: Tolga Tasdizen
Administrative/business contact: Edward Black, Manager, Grants and Accounting, SCI; 72 S Central Campus Dr.; Tel: 801-587-7857; Fax: 801-585-6513; email: ed@sci.utah.edu
Period of performance: 06/01/11-05/31/16
Total award (direct and indirect costs): $1,253,900

Person months devoted to project: 1.2
Overlap: None

Pending:

Title: CAREER: Deep sparse dictionary context models and their application to image parsing and neuron tracking for connectomics
Summary: This project addresses vnovel techniques for analysis of large scale electron microscopy data .
Source: National Science Foundation
Percent effort: 8%
Technical contact: Tolga Tasdizen
Administrative/business contact: Edward Black, Manager, Grants and Accounting, SCI; 72 S Central Campus Dr.; Tel: 801-587-7857; Fax: 801-585-6513; email: ed@sci.utah.edu
Period of performance: 01/01/12-12/31/16
Total award (direct and indirect costs): $409,406
Person months devoted to project: 1.0
Overlap: None

Title: Multiscale Models of Melting Arctic Sea Ice (this application)
Summary: We will investigate the formation and evolution of melt ponds on Arctic sea ice. This work will help to improve climate models by quantifying our understanding of ice pack albedo and key feedback mechanisms.
Source: Office of Naval Research
Percent effort: 10%
Technical contact: Kenneth M. Golden
Administrative/business contact: Shauna Peterson; 1471 East Federal Way;
Tel: 801-585-0062; Fax: 801-581-3007; email: shauna.peterson@osp.utah.edu
Period of performance: 12/1/12 – 11/30/15
Total award (direct and indirect costs): $481,616
Person months devoted to project: 0.75 summer month
Overlap: None

6 Qualifications

Kenneth Morgan Golden www.math.utah.edu/∼golden

Education

B.A.	1980	Dartmouth College, Mathematics and Physics
M.S.	1983	New York University, Mathematics
Ph.D.	1984	New York University, Mathematics

Employment

1984-87	NSF Mathematical Sciences Postdoctoral Fellow, Rutgers University
1987-91	Assistant Professor of Mathematics, Princeton University
1991-96	Associate Professor of Mathematics, University of Utah
1996-	Professor of Mathematics, University of Utah
2007-	Adjunct Professor of Bioengineering, University of Utah

Professional Summary

- Conducted field research on Antarctic sea ice in 1980, 1994, 1998, 1999, 2007, and 2010, with SIPEX II expedition scheduled for September - November 2012; field research on Arctic sea ice in 2000, 2001, 2002, 2003, 2004, 2007, and 2011, with scheduled field work in May 2012 and May 2013.
- Served as Modeling Coordinator for ONR Accelerated Research Initiative on Sea Ice Electromagnetics 1992-98, involving over 60 researchers at 20 institutions.
- Published 56 papers in mathematics, physics, geophysics, ocean sciences, electrical engineering, mechanical engineering, and biomechanics journals. Given over 300 invited lectures on 6 continents. Since 2008, invited to give over 70 plenary and keynote addresses, conference and university lectures.
- Member, Ed. Board of *SIAM J. on Appl. Math.* 1996-99; *Applic. Analysis* 2004–2008
- Chair, Committee for Math Awareness Month April 2009 on "Mathematics and Climate," Joint Policy Board for Mathematics (AMS, SIAM, ASA, MAA)
- Chair, American Mathematical Society Committee on Science Policy, 2012−2013; Member, 2010−2013; Member, AMS Committee on Education, 2012−2013
- Organized or co-organized 19 conferences and workshops on sea ice, polar climate, composite materials, and inverse problems. Examples include: Invited Minisymposium on *Polar Climate Modeling*, Joint Math Meetings (AMS, SIAM), Wash. D.C., 1/09; Invited Symposium on *Sea Ice in the Changing Climate*, AAAS Natl. Meeting, San Diego, 2/10; Invited Workshop on *Polar Climate*, IPAM, UCLA, 5/10; Ocean Ecologies in a Changing Climate, MBI, Ohio St., 7/11; Scientific Program Committee, 2012 Ocean Sciences Meeting, Salt Lake City, 2/12.
- Mentored 27 REU students, 2 high school students, 9 graduate students (4 current Ph.D. students), and 5 post-docs. Brought 8 undergrads (from 5 departments), 4 graduate students, and 2 postdocs on polar expeditions.

- Service to the U. of Utah Math Dept.: Director of Undergraduate Studies (2002-08), REU Program Coordinator (2003-07), Chair of the Undergraduate Curriculum Committee (2002-08), Executive Committee (1992-96, 2002-04), Engineering Math Coordinator (1996-98), many hiring committees and other positions.
- Since 1992, PI on 14 grants to U. of Utah from NSF (Division of Mathematical Sciences, Office of Polar Programs, and Arctic Natural Sciences) and ONR, totalling $3.7 M in funding. Co-PI or Senior Personnel on 2 NSF research and training grants, totalling $8.5 M in funding.
- Accounts of my research on sea ice and climate change, and related polar expeditions have been featured in newspapers, magazines, and web articles, and on radio and television. They include 4 TV appearances, several radio interviews, and over 30 articles, with profiles in *Science* (2009) and *Science News* (2000, 2010).

Honors and Awards

- 2012 Distinguished Scholarly & Creative Research Award, University of Utah, $10,000 prize; first math professor to receive the award since 1992.
- 2012 Myriad Faculty Award for Research Excellence, U. of Utah, College of Science, $20,000 prize.
- Selected as a Fellow of the Society for Industrial and Applied Mathematics (SIAM), March 2011, for "extraordinary interdisciplinary work on mathematics of sea ice."
- Presented my research on sea ice and climate change in the US Congress three times: for the American Mathematical Society in 2003 and 2007 and for SIAM in 2011.
- 2007 University Distinguished Teaching Award, University of Utah; first math professor to receive the highest teaching award since 1987, fourth since 1965.
- Excellence in Teaching Award, Princeton Engineering Council, Princeton, 1989
- Member, Electromagnetics Academy, 1996−; Member, Electrical Transport and Optical Properties of Inhomogeneous Media (ETOPIM) Association Committee, 2006−.

Related Publications

1. K. Golden and G. Papanicolaou, Bounds for effective parameters of heterogeneous media by analytic continuation, *Communications in Mathematical Physics*, 90, pp. 473–491, 1983.
2. K. Golden, S. Goldstein and J. L. Lebowitz, Nash estimates and the asymptotic behavior of diffusions, *Annals of Probability*, 16, pp. 1127–1146, 1988.
3. K. Golden, Convexity and exponent inequalities for conduction near percolation, *Physical Review Letters*, 65, pp. 2923–2926, 1990.
4. K. M. Golden, Statistical mechanics of conducting phase transitions, *Journal of Mathematical Physics*, 36, pp. 5627-5642, 1995.
5. K. M. Golden, Critical behavior of transport in lattice and continuum percolation models, *Physical Review Letters*, 78, pp. 3935-3938, 1997.

6. K. M. Golden, D. Borup, M. Cheney, E. Cherkaeva, M. S. Dawson, K. H. Ding, A. K. Fung, D. Isaacson, S. A. Johnson, A. K. Jordan, J. A. Kong, R. Kwok, S. V. Nghiem, R. G. Onstott, J. Sylvester, D. P. Winebrenner and I. H. H. Zabel, Inverse electromagnetic scattering models for sea ice, *IEEE Trans. on Geosci. and Remote Sensing*, 36(5), pp. 1675-1704, 1998.
7. K. M. Golden, S. F. Ackley and V. I. Lytle, The percolation phase transition in sea ice, *Science*, 282, pp. 2238-2241, 1998.
8. K. M. Golden, H. Eicken, A. L. Heaton, J. Miner, D. Pringle, and J. Zhu, Thermal evolution of permeability and microstructure in sea ice, *Geophysical Research Letters*, 34, L16501 (6 pages and issue cover), 2007.
9. K. M. Golden, Climate change and the mathematics of transport in sea ice, invited feature article for the *Notices of the American Mathematical Society*, Volume 56, Number 5, pages 562-584, (including issue cover), May 2009.
10. K. M. Golden, N. B. Murphy, and E. Cherkaev, Spectral analysis and connectivity of porous microstructures in bone, *Journal of Biomechanics*, Vol. 44, pp. 337-344, 2011.
11. L. B. Simeonova, D. C. Dobson, O. Eso, and K. M. Golden, Spatial bounds on the effective complex permittivity for time-harmonic waves in random media, *Multiscale Modeling and Simulation*, Vol. 9, No. 3, pp. 1113-1143, 2011.
12. C. Orum, E. Cherkaev and K. M. Golden, Recovery of inclusion separations in strongly heterogeneous composites from effective property measurements, *Proceedings of the Royal Society A: Mathematical, Physical & Engineering Sciences*, Vol. 468, No. 2139, pp. 784-809, 2012.
13. N. B. Murphy and K. M. Golden, The Ising model and critical behavior of transport in binary composite media, *Journal of Mathematical Physics*, 53, 063506, pp. 1-25, doi: 10.1063/1.4725964, 2012.
14. C. Hohenegger, B. Alali, K. R. Steffen, D. K. Perovich, and K. M. Golden, Transition in the fractal geometry of Arctic melt ponds, *The Cryosphere Discussions*, 6, 2161-2177, doi:10.5194/tcd-6-2161-2012; in submission to *The Cryosphere*, 2012.

Recent Selected Invited Lectures

2008 Conf. on Frontiers of Climate Science, Kavli Inst. for Theor. Phys., Santa Barbara
2008 Invited Guest Lecture at the Climate Change Summer School, MSRI, Berkeley, CA
2008 Keynote Address, Intl. Polar Year Forum, SACNAS Natl. Conf., Salt Lake City, UT
2009 The SIAM Invited Address at the Joint Math Meetings (AMS, MAA, SIAM), D.C.
2009 Houghton Lectures on *Sea Ice, Climate, and Multiscale Composites*, Department of Earth, Atmospheric and Planetary Sciences, MIT
2009 SIAM Conference on Dynamical Systems, Minisymposium on *Mathematical Challenges in Climate Change: Some Examples*, Snowbird, UT
2009 Mathematics of Climate Change, First Pacific Rim Math. Assoc. Congress, Sydney
2009 Kieval Lecture, Humboldt State University, Arcata, CA
2010 Random Matrix Theory and Appl., AMS Spring Western Sect. Meeting, Albuquerque

2010 Mini-Workshop on *Mathematics of Sea Ice in the Climate System* (two lectures), Institute of Pure and Applied Mathematics (IPAM), UCLA, Los Angeles

2010 Intl. Symp. on Sea Ice in the Phys. and Biogeochemical System, Tromso, Norway

2010 Plenary Science Lecture, Conference on Emerging Topics in Dynamical Systems and Partial Differential Equations, DSPDE's 10, Barcelona

2010 MSRI-NCAR Summer School on Mathematics of Climate Change, NCAR, Boulder

2010 Workshop on The Multiphase Physics of Sea Ice, Santa Fe

2011 Public Lecture, Conf. on Prob. Theory & Stat. Phys., NYU Abu Dhabi, UAE

2011 Simon Fraser University Seminar Series on Global Warming, a Scientific Perspective, Invited Lecture on *Evidence for Warming in the Arctic and Antarctic*, Burnaby

2011 Invited Plenary Address, Spring Eastern Sectional Meeting of the American Mathematical Society, College of the Holy Cross, Worcester, MA

2011 Ocean Ecologies and their Physical Habitats in a Changing Climate (two lectures), Mathematical Biosciences Institute (MBI), Ohio State University, Columbus

2011 7^{th} Intl. Congress on Industrial and Applied Math. (ICIAM 2011), Minisymposium on *Composites and Inversion: Asymptotic and Computational Methods*, Vancouver

2011 NSF-SIAM Workshop on Collaborations in Mathematical Geoscience, Washington DC

2011 AMS Fall Western Section Meeting, Minisymposium on *Electromagnetic Wave Propagation in Complex and Random Environments*, Salt Lake City

2011 Keynote Address, Ann. Conf. Amer. Math. Assoc. for Two-Year Colleges, Austin

2011 Neal Thorpe Memorial Lecture, 20^{th} Conference Undergraduate Research, Murdock Charitable Trust, Seattle

2012 Public Lecture, Pacific Institute for the Mathematical Sciences, Vancouver

2012 European Geosciences Union General Assembly 2012, Session on *Sea ice physical and biological processes and interactions with climate*, Vienna

2012 IUGG Conference on Mathematical Geophysics, Edinburgh

2012 9^{th} AIMS Conf. on Dynamical Systems, Diff. Eqs. and Applications, Session on *Mathematical Modeling of Upwelling Ocean Currents and Related Phenomena*, Orlando

2012 White Nights Workshop: Exotic Struct. and Homogenization, St. Petersburg, Russia

2012 Plenary Address, Ninth International Conference on Electrical Transport and Optical Properties of Inhomogeneous Media (ETOPIM9), Marseille

2012 Second Reunion Conference for the UCLA IPAM Climate Modeling Program, Lake Arrowhead, CA

2013 MAA-AMS-SIAM Gerald and Judith Porter Public Lecture, 2013 Joint Math Meetings, San Diego

2013 Session on *Recent Advances and New Challenges in Applied Analysis*, 2013 Joint Math Meetings, San Diego

2013 Inaugural Bernoulli Society Public Lecture, 36^{th} Conference on Stochastic Processes and their Applications, Boulder

Courtenay Strong http://www.inscc.utah.edu/~strong

Education

B.A.	1993	University of Texas at Austin, Journalism
B.S.	1999	Mississippi State University, Meteorology
M.S.	2003	University of Virginia, Environmental Sciences
Ph.D.	2005	University of Virginia, Environmental Sciences
Postdoc	2007-2009	University of California, Irvine, Climate dynamics

Employment

1994-2000	Broadcast Meteorologist, television network affiliates
2001-2002	Research and Teaching Assistant, University of Virginia
2003-2005	NSF Graduate Research Fellow, University of Virginia
2005-2006	Visiting Scientist / Instructor, University of Missouri
2007-2009	Postdoctoral Scholar, University of California, Irvine
2009-	Assistant Professor of Atmospheric Sciences, University of Utah

Professional Summary

- PI on NSF grant investigating the role of sea ice in atmosphere-cryosphere feedback $0.25 M; Co-PI or senior personnel on two NSF Experimental Program to Stimulate Competitive Research (EPSCoR) grants (Track-1 and Track-2) totaling approximately $7.5 M in awarded funding to date. Co-PI on NSF Think Globally, Learn Locally grant (Division of Graduate Education) $2.1 M.
- Lead author on 20 manuscripts in atmospheric, oceanic, and climate dynamics journals. Given 15 invited lectures and more than 20 contributed presentations in North America and Europe.
- Currently advising three graduate students (two Ph.D.) and one postdoctoral researcher. Member of advising committee for 15 additional students in three departments (Atmospheric Sciences, Biology, and Civil and Environmental Engineering)
- Developed and published the first method for objective and automated measure of marginal ice zone width using remote sensing data (method also provides marginal ice zone position and area)
- Expert reviewer for Southwest Technical Input to the 2013 National Climate Assessment. Proposal reviewer for Natural Sciences and Engineering Research Council (Canada) and National Science Foundation.
- Manuscript reviewer for 14 leading journals in my discipline: *Atmospheric Chemistry and Physics, Climate Dynamics, Climate Research, Geophysical Research Letters, International Journal of Climatology, Journal of the Atmospheric Sciences, Journal of Climate, Monthly Weather Review, Nature, Nature Climate Change, Nature Geoscience, Pure and Applied Geophysics, Quarterly Journal of the Royal Meteorological Society*
- Teach mathematically rigorous graduate course in climate dynamics. Developed advanced teaching materials for my co-taught graduate course in statistical methods, and introduced a new quantitative climate course for undergraduate majors and graduate students from outside atmospheric sciences.

Honors and Awards

- 2010 Invited speaker to NCAR Climate and Global Dynamics Division
- 2008 James R. Holton Junior Scientist Award, American Geophysical Union
- 2008 Invited postdoctoral participant, Leverhulme Climate Symposium, Cambridge University and The Royal Society of London
- 2003-05 National Science Foundation Graduate Research Fellowship
- 2002 American Meteorological Society First Prize for Student Oral Presentation: 25th Conference on Agricultural and Forest Meteorology, Norfolk, VA
- 2001-05 Consecutive Merit-based Departmental Dupont Fellowships
- 2001 Outstanding First Year Graduate Student in Atmospheric Science (University of Virginia)
- 1999 American Meteorological Society Seal of Approval for Broadcast Meteorology

Select Related Publications

1. J. Liptak and C. Strong, Propagating atmospheric patterns associated with sea ice motion through the Fram Strait, *Geophysical Research Letters*, submitted, 2012.
2. C. Strong, Atmospheric influence on Arctic marginal ice zone position and width in the Atlantic sector, February-April 1979-2010, *Climate Dynamics*, in press, doi:10.1007/s00382-012-1356-6, 2012.
3. C. Strong and S. C. Maberly, The influence of atmospheric wave dynamics on interannual variation in the surface temperature of lakes in the English Lake District. *Global Change Biology*, 17, pp. 2013–2022, 2011.
4. C. Strong and G. Magnusdottir, Dependence of NAO variability on coupling with sea ice, *Climate Dynamics*, 36, pp. 1681–1689, 2011.
5. C. Strong and G. Magnusdottir, The role of Rossby wave breaking in shaping the equilibrium atmospheric circulation response to North Atlantic boundary forcing, *Journal of Climate*, 23, pp. 1269–1276, 2010.
6. C. Strong and G. Magnusdottir, Modeled boreal winter sea ice variability and the North Atlantic Oscillation: a multi-century perspective, *Climate Dynamics*, 34, pp. 515–525, 2010.
7. C. Strong, G. Magnusdottir and H. Stern, Observed feedback between winter sea ice and the North Atlantic Oscillation, *Journal of Climate*, 22, pp. 6021-6032, 2009.
8. C. Strong, J. D. Fuentes, R. E. Davis, and J. W. Bottenheim, Thermodynamic attributes of Arctic boundary layer ozone depletion *Atmospheric Environment*, 36: pp. 2641–2652, 2002.

Bacim Alali www.math.utah.edu/∼alali

Education

B.S.	1998	Mathematics and Physics, Yarmouk University, Jordan
M.S.	2005	Mathematics, Louisiana State University
Ph.D.	2008	Mathematics, Louisiana State University

Employment

2011-	Ed Lorenz Postdoctoral Fellow in the Mathematics of Climate, U. of Utah
2008-2011	Wylie Assistant Professor, University of Utah
1998-2002	Research Mathematician, Estarta Solutions

Publications

1. C. Hohenegger, B. Alali, K. R. Steffen, D. K. Perovich, and K. M. Golden, Transition in the fractal geometry of Arctic melt ponds, *The Cryosphere Discussions*, 6, 2161-2177, doi:10.5194/tcd-6-2161-2012; in submission to *The Cryosphere*, 2012.

2. B. Alali and G. W. Milton, Corrections to the effective conductivity in composites in the presence of imperfect interfaces, in submission.

3. B. Alali and R. Lipton, New bounds on local strain fields inside random heterogeneous materials, *Mechanics of Materials*, Volume 53, pages 111-122, 2012.

4. B. Alali and R. Lipton, Multiscale dynamics of heterogeneous media in the peridynamic formulation. *Journal of Elasticity* (Online First), Dec. 8, 2010, pp. 1-33, DOI 10.1007/s10659-010-9291-4.

5. B. Alali and R. Lipton, Optimal lower bounds on local stress inside random media, *SIAM Journal on Applied Mathematics*, Volume 70, Issue 4, pages 1260-1282, 2009.

6. B. Alali and R. Lipton, Multiscale analysis of fiber-reinforced composites in the peridynamic formulation, *IMA Preprint Series 2241*, Institute for Mathematics and its Applications, University of Minnesota, 2009.

Academic Awards

2006-2008	Research assistantship supp. by The Boeing Company, LSU.
2004-2006	Research assistantship supp. by grants from AFOSR, NSF, and LSU.
2002-2006	Graduate School Enhancement Award, LSU.
1995-1998	Jordan's Ministry of Higher Ed. Math Fellowship, Yarmouk University.

Invited Talks and Recent Workshops

2012 Poster Presentation, 2012 Ocean Sciences Meeting, Salt Lake City.

2012 Large Scale Multimedia Search, Institute for Pure and Applied Mathematics (IPAM), Los Angeles.

2011 Poster Presentation, Mathematics and Climate Research Network Annual Meeting, Chapel Hill, North Carolina.

2011 Poster Presentation, New Kind of Science Summer School, Boston.

2011 Minisymposium Speaker, 2011 Joint Mathematics Meetings, American Mathematical Society (AMS), New Orleans.

2010 Modeling and Mathematics of Sea Ice, Institute for Pure and Applied Mathematics (IPAM), University of California, Los Angeles.

2009 Stochastic Multiscale Methods: Mathematical Analysis and Algorithms, University of Southern California, Los Angeles.

2009 Minisymposium Speaker, 10TH US National Congress On Computational Mechanics (USNCCM10), Columbus, Ohio.

2008 Minisymposium Speaker, SIAM Conference on Mathematical Aspects of Materials Science (MS08), Philadelphia.

2007 Minisymposium Speaker, SIAM Conference on Analysis of Partial Differential Equations (PD07), Mesa, Arizona.

2007 Contributed Poster, Workshop on Modeling, Analysis and Simulation of Multiscale Nonlinear Systems, Oregon State University, Corvallis, Oregon.

2007 DOE Summer School in Multiscale Mathematics and High Performance Computing, Oregon State University, Corvallis, Oregon.

2007 Contributed Poster, Workshop on Computational and Mathematical Aspects of Materials and Fluids (CAM2007), Department of Mathematics and Ames Laboratory, Iowa State University, Ames, Iowa.

Teaching Experience

Mathematics Department, University of Utah, 2008-present
Taught Calculus I, Calculus II, Business Algebra, ODE and Linear Algebra, and PDE's for Engineering Students.

Department of Mathematics, Louisiana State University, 2002-2005
Taught College Algebra and Calculus I.

Ph.D. Advisor: Robert P. Lipton, Louisiana State University.

Tolga Tasdizen www.sci.utah.edu/∼tolga

Education

B.S.	1995	Bogazici University, Istanbul, Electrical Engineering
M.S.	1997	Brown University, Engineering
Ph.D	2001	Brown University, Engineering

Employment

2001-04	Postdoctoral Research Scientist, Scientific Computing and Imaging Institute, University of Utah.
2004-08	Research Assistant Professor, School of Computing, University of Utah.
2006-	Adjunct Assistant Professor, Department of Neurology, Center for Alzheimer's Care, Imaging and Research, University of Utah.
2008-	Adjunct Assistant Professor, School of Computing, University of Utah.
2008-12	Assistant Professor, Electrical and Computer Engineering, U. of Utah.
20012-	Associate Professor, Electrical and Computer Engineering, U. of Utah.

Professional Summary

- PI on one grant from NIH (NIBIB National Institute of Biomedical Imaging and Bioengineering) $1.14 M in funding. Co-PI or Senior Personnel on 5 NIH (NINDS National Institute of Neurological Disorders and Stroke, NIBIB) and NSF, totalling $5 M in funding.
- Inventors on three patents on pattern recognition, image segmentation and characterization of datasets.
- Associate Editor, IEEE Signal Processing Letters and BMC Bioinformatics
- Review Editor, Frontiers in Computational Physiology and Medicine, 2011-present. Reviewer for prominent IEEE journals, Medical Image Computing and Computer-Assisted Intervention (MICCAI), Journal of Neuroscience Methods, Journal of Mathematical Imaging and Vision, Pattern Analysis and Applications, ACM Solid Modeling, SIAM Journal of Scientific Computing, VisSym, Eurographics, Eurographics Workshop on Visual Computing for Biology and Medicine, Journal of Electronic Imaging, The Visual Computer, SIGGRAPH Asia, Elsevier Methods.
- Panelist and reviewer for joint NSF/NIH Collaborative Research in Computational Neuroscience program, 2006, 2008, 2009 and 2010.
- Organizer MIAAB (Microscopic Image Analysis with Applications in Biology), 2008, 2009.
- IEEE Signal Processing Society, Bio imaging and Signal Processing (BISP) Technical Committee Associate Member, 2009-2012, Regular Member 2012-.
- Senior Member IEEE, IEEE Signal Processing Society and IEEE Computer Society.
- Advisor to eight students (five Ph.D.)
- Best paper award MICCAI 2010 MedIA special Issue
- Best Student Paper Award Honorable Mention, 15th IEEE Computer Society International Conf. on Pattern Recognition, 2000.

- Imaging and Computer in the Loop breakout session speaker, Opportunities in Biology at the Extreme Scale of Computing, Chicago, 2009.
- 6^{th} IEEE International Symposium on Biomedical Imaging (ISBI): From Nano to Macro; *Electron Microscopy* session chair, 2009.
- Program committee, International Symposium CompIMAGE 2010, CompIMAGE 2012.
- Program committee, IMAGAPP 2010
- Dean's letter for top instructors in the College of Engineering, Fall 2009, Spring 2010, Fall 2010

Related Publications

1. E. Jurrus and A. R. C. Paiva and S. Watanabe, J. R. Anderson, B. W. Jones, R. T. Whitaker, E. M. Jorgensen, R. E. Marc and T. Tasdizen, Detection of Neuron Membranes in Electron Microscopy Images using Auto-context, *Medical Image Analysis*, 2010.
2. T. Tasdizen, Principal Neighborhood Dictionaries for Non-local Means Image Denoising, *IEEE Trans. on Image Processing*, 2009.
3. A. R. C. Paiva, E. Jurrus and T. Tasdizen, Using Sequential Context for Image Analysis, *In* Int. Conf. on Pattern Recognition, 2010.
4. S. M. Seyedhosseini, A. R. C. Paiva and T. Tasdizen, Image Parsing with a Three-State Series Neural Network Classifier, *Int. Conf. on Pattern Recognition*, 2010.
5. S. Gerber, T. Tasdizen and R. T. Whitaker, Dimensionality Reduction and Principal Surfaces via Kernel Map Manifolds, *Int. Conf. on Computer Vision*, 2009.
6. E. Jurrus, T. Tasdizen, P. Koshevoy, P. T. Fletcher, M. Hardy, C. Chien, W. Denk, and R. Whitaker, Axon Tracking in Serial Block-Face Scanning Electron Microscopy, *Medical Image Analysis* 2009.
7. S. Gerber, T. Tasdizen, P. T. Fletcher, S. Joshi, R. Whitaker and the Alzheimers Disease Neuroimaging Initiative (ADNI), Manifold modeling for brain population analysis, *Medical Image Analysis*, 2010.
8. T. Tasdizen, R. T. Whitaker, P. Burchard and S. Osher, Geometric Surface Processing via Normal Maps, *ACM Transactions on Graphics*, 2003.
9. T. Tasdizen, R. T. Whitaker, P. Burchard and S. Osher, Geometric Surface Smoothing via Anisotropic Diffusion of Normals, *IEEE Visualization*, 2002.
10. T. Tasdizen, J.-P. Tarel and D. B. Cooper, Algebraic Curves that Work Better, *IEEE Computer Society Conf. on Computer Vision and Pattern Recognition*, 1999.

RESEARCH & RELATED BUDGET - SECTION A & B, BUDGET PERIOD 1

* ORGANIZATIONAL DUNS: 009095365

*** Budget Type:** ● Project ❍ Subaward/Consortium

Enter name of Organization: University of Utah

*** Start Date:** 12-01-2012 *** End Date:** 11-30-2013 **Budget Period: 1**

A. Senior/Key Person

Prefix	* First Name	Middle Name	* Last Name	Suffix	* Project Role	Base Salary ($)	Cal. Months	Acad. Months	Sum. Months	* Requested Salary ($)	* Fringe Benefits ($)	* Funds Requested ($)
1.	KENNETH	M	GOLDEN	PhD	PD/PI	164,274.00			1	15,000.00	5,550.00	20,550.00
2.	COURTENAY		STRONG	PhD	Co-PD/PI	74,582.00			0.75	6,083.00	2,251.00	8,334.00
3.	BACIM	Q	ALALI	PhD	Co-PD/PI	48,000.00	1			4,000.00	1,480.00	5,480.00
4.	TOLGA		TASDIZEN		Other Professional	80,000.00			1	8,000.00	2,960.00	10,960.00

Total Funds Requested for all Senior Key Persons in the attached file

Additional Senior Key Persons: File Name: Mime Type: **Total Senior/Key Person** **45,324.00**

B. Other Personnel

* Number of Personnel	* Project Role	Cal. Months	Acad. Months	Sum. Months	* Requested Salary ($)	* Fringe Benefits	* Funds Requested ($)
0	Post Doctoral Associates				0.00	0.00	0.00
2	Graduate Students		9	3	17,000.00	2,380.00	19,380.00
	Undergraduate Students						
	Secretarial/Clerical						
2	**Total Number Other Personnel**					**Total Other Personnel**	**19,380.00**
						Total Salary, Wages and Fringe Benefits (A+B)	**64,704.00**

RESEARCH & RELATED Budget {A-B} (Funds Requested)

RESEARCH & RELATED BUDGET - SECTION C, D, & E, BUDGET PERIOD 1

* ORGANIZATIONAL DUNS: 009095365

*** Budget Type:** ● Project ❍ Subaward/Consortium

Enter name of Organization: University of Utah

*** Start Date:** 12-01-2012 *** End Date:** 11-30-2013 **Budget Period: 1**

C. Equipment Description

List items and dollar amount for each item exceeding $5,000

Equipment Item	* Funds Requested ($)
Total funds requested for all equipment listed in the attached file	
Total Equipment	

Additional Equipment: File Name: Mime Type:

D. Travel	Funds Requested ($)
1. Domestic Travel Costs (Incl. Canada, Mexico, and U.S. Possessions)	3,000.00
2. Foreign Travel Costs	3,000.00
Total Travel Cost	**6,000.00**

E. Participant/Trainee Support Costs	Funds Requested ($)
1. Tuition/Fees/Health Insurance	
2. Stipends	
3. Travel	
4. Subsistence	
5. Other:	
Number of Participants/Trainees **Total Participant/Trainee Support Costs**	**0.00**

RESEARCH & RELATED Budget {C-E} (Funds Requested)

RESEARCH & RELATED BUDGET - SECTIONS F-K, BUDGET PERIOD 1

* ORGANIZATIONAL DUNS: 009095365

Budget Type: ● Project ❍ Subaward/Consortium

Enter name of Organization: University of Utah

Start Date: 12-01-2012 **End Date:** 11-30-2013 **Budget Period: 1**

F. Other Direct Costs	**Funds Requested ($)**
1. Materials and Supplies	4,000.00
2. Publication Costs	2,000.00
3. Consultant Services	
4. ADP/Computer Services	
5. Subawards/Consortium/Contractual Costs	
6. Equipment or Facility Rental/User Fees	
7. Alterations and Renovations	
8. Other (fax, mail, phone, etc)	1,000.00
Total Other Direct Costs	**7,000.00**

G. Direct Costs	**Funds Requested ($)**
Total Direct Costs (A thru F)	**77,704.00**

H. Indirect Costs

Indirect Cost Type	**Indirect Cost Rate (%)**	**Indirect Cost Base ($)**	*** Funds Requested ($)**
1. MTDC_Research	49.5	77,704.00	38,463.00
		Total Indirect Costs	**38,463.00**

Cognizant Federal Agency DHHS, Wallace Chan, 415-637-7820
(Agency Name, POC Name, and POC Phone Number)

I. Total Direct and Indirect Costs	**Funds Requested ($)**
Total Direct and Indirect Institutional Costs (G + H)	**116,167.00**

J. Fee	**Funds Requested ($)**

K. * Budget Justification File Name: Budget_Justification1008034159.pdf Mime Type: application/pdf
(Only attach one file.)

RESEARCH & RELATED Budget {F-K} (Funds Requested)

RESEARCH & RELATED BUDGET - SECTION A & B, BUDGET PERIOD 2

* ORGANIZATIONAL DUNS: 009095365

*** Budget Type:** ● Project ❍ Subaward/Consortium

Enter name of Organization: University of Utah

*** Start Date:** 12-01-2013 *** End Date:** 11-30-2014 **Budget Period: 2**

A. Senior/Key Person

Prefix	* First Name	Middle Name	* Last Name	Suffix	* Project Role	Base Salary ($)	Cal. Months	Acad. Months	Sum. Months	* Requested Salary ($)	* Fringe Benefits ($)	* Funds Requested ($)
1.	KENNETH	M	GOLDEN		PD/PI	164,274.00			1	15,000.00	5,550.00	20,550.00
2.	COURTENAY		STRONG		Co-PD/PI	74,582.00			0.75	6,083.00	2,251.00	8,334.00
3.	BACIM	Q	ALALI		Co-PD/PI	48,000.00	1			4,000.00	1,480.00	5,480.00
4.	TOLGA		TASDIZEN		Other Professional	80,000.00			1	8,000.00	2,960.00	10,960.00

Total Funds Requested for all Senior Key Persons in the attached file

Additional Senior Key Persons: File Name: Mime Type: **Total Senior/Key Person** **45,324.00**

B. Other Personnel

* Number of Personnel	* Project Role	Cal. Months	Acad. Months	Sum. Months	* Requested Salary ($)	* Fringe Benefits	* Funds Requested ($)
1	Post Doctoral Associates	12			31,000.00	11,470.00	42,470.00
2	Graduate Students		9	3	17,000.00	2,380.00	19,380.00
2	Undergraduate Students			3	5,000.00	700.00	5,700.00
0	Secretarial/Clerical				0.00	0.00	0.00
5	**Total Number Other Personnel**					**Total Other Personnel**	**67,550.00**
						Total Salary, Wages and Fringe Benefits (A+B)	**112,874.00**

RESEARCH & RELATED Budget {A-B} (Funds Requested)

RESEARCH & RELATED BUDGET - SECTION C, D, & E, BUDGET PERIOD 2

* ORGANIZATIONAL DUNS: 009095365

Budget Type: ● Project ❍ Subaward/Consortium

Enter name of Organization: University of Utah

Start Date: 12-01-2013 **End Date:** 11-30-2014 **Budget Period: 2**

C. Equipment Description

List items and dollar amount for each item exceeding $5,000

Equipment Item	*** Funds Requested ($)**
Total funds requested for all equipment listed in the attached file	
Total Equipment	

Additional Equipment: File Name: Mime Type:

D. Travel	**Funds Requested ($)**
1. Domestic Travel Costs (Incl. Canada, Mexico, and U.S. Possessions)	3,000.00
2. Foreign Travel Costs	3,000.00
Total Travel Cost	**6,000.00**

E. Participant/Trainee Support Costs	**Funds Requested ($)**
1. Tuition/Fees/Health Insurance	
2. Stipends	
3. Travel	
4. Subsistence	
5. Other:	
Number of Participants/Trainees **Total Participant/Trainee Support Costs**	**0.00**

RESEARCH & RELATED Budget {C-E} (Funds Requested)

RESEARCH & RELATED BUDGET - SECTIONS F-K, BUDGET PERIOD 2

* ORGANIZATIONAL DUNS: 009095365

*** Budget Type:** ● Project ❍ Subaward/Consortium

Enter name of Organization: University of Utah

*** Start Date:** 12-01-2013 *** End Date:** 11-30-2014 **Budget Period: 2**

F. Other Direct Costs	**Funds Requested ($)**
1. Materials and Supplies	3,000.00
2. Publication Costs	2,000.00
3. Consultant Services	
4. ADP/Computer Services	
5. Subawards/Consortium/Contractual Costs	
6. Equipment or Facility Rental/User Fees	
7. Alterations and Renovations	
8. Other (fax, mail, phone, etc)	1,000.00
Total Other Direct Costs	**6,000.00**

G. Direct Costs	**Funds Requested ($)**
Total Direct Costs (A thru F)	**124,874.00**

H. Indirect Costs

Indirect Cost Type	**Indirect Cost Rate (%)**	**Indirect Cost Base ($)**	*** Funds Requested ($)**
1. MTDC_Research	49	124,874.00	61,188.00
		Total Indirect Costs	**61,188.00**

Cognizant Federal Agency DHHS, Wallace Chan, 415-637-7820

(Agency Name, POC Name, and POC Phone Number)

I. Total Direct and Indirect Costs	**Funds Requested ($)**
Total Direct and Indirect Institutional Costs (G + H)	**186,062.00**

J. Fee	**Funds Requested ($)**

K. * Budget Justification File Name: Budget_Justification1008034159.pdf Mime Type: application/pdf

(Only attach one file.)

RESEARCH & RELATED Budget {F-K} (Funds Requested)

RESEARCH & RELATED BUDGET - SECTION A & B, BUDGET PERIOD 3

* ORGANIZATIONAL DUNS: 009095365

*** Budget Type:** ● Project ❍ Subaward/Consortium

Enter name of Organization: University of Utah

*** Start Date:** 12-01-2014 *** End Date:** 11-30-2015 **Budget Period: 3**

A. Senior/Key Person

Prefix	* First Name	Middle Name	* Last Name	Suffix	* Project Role	Base Salary ($)	Cal. Months	Acad. Months	Sum. Months	* Requested Salary ($)	* Fringe Benefits ($)	* Funds Requested ($)
1.	KENNETH	M	GOLDEN		PD/PI	164,274.00			1	15,000.00	5,550.00	20,550.00
2.	COURTENAY		STRONG		Co-PD/PI	74,582.00			0.75	6,083.00	2,251.00	8,334.00
3.	TOLGA		TASDIZEN		Other Professional	80,000.00			1	8,000.00	2,960.00	10,960.00

Total Funds Requested for all Senior Key Persons in the attached file

Additional Senior Key Persons: File Name: Mime Type: **Total Senior/Key Person** **39,844.00**

B. Other Personnel

* Number of Personnel	* Project Role	Cal. Months	Acad. Months	Sum. Months	* Requested Salary ($)	* Fringe Benefits	* Funds Requested ($)
1	Post Doctoral Associates	12			31,000.00	11,470.00	42,470.00
2	Graduate Students		9	3	17,000.00	2,380.00	19,380.00
2	Undergraduate Students			3	5,000.00	700.00	5,700.00
	Secretarial/Clerical						
5	**Total Number Other Personnel**					**Total Other Personnel**	**67,550.00**
						Total Salary, Wages and Fringe Benefits (A+B)	**107,394.00**

RESEARCH & RELATED Budget {A-B} (Funds Requested)

RESEARCH & RELATED BUDGET - SECTION C, D, & E, BUDGET PERIOD 3

* ORGANIZATIONAL DUNS: 009095365

*** Budget Type:** ● Project ❍ Subaward/Consortium

Enter name of Organization: University of Utah

*** Start Date:** 12-01-2014 *** End Date:** 11-30-2015 **Budget Period: 3**

C. Equipment Description

List items and dollar amount for each item exceeding $5,000

Equipment Item	*** Funds Requested ($)**
Total funds requested for all equipment listed in the attached file	
Total Equipment	

Additional Equipment: File Name: Mime Type:

D. Travel	**Funds Requested ($)**
1. Domestic Travel Costs (Incl. Canada, Mexico, and U.S. Possessions)	3,000.00
2. Foreign Travel Costs	3,000.00
Total Travel Cost	**6,000.00**

E. Participant/Trainee Support Costs	**Funds Requested ($)**
1. Tuition/Fees/Health Insurance	
2. Stipends	
3. Travel	
4. Subsistence	
5. Other:	
Number of Participants/Trainees **Total Participant/Trainee Support Costs**	**0.00**

RESEARCH & RELATED Budget {C-E} (Funds Requested)

RESEARCH & RELATED BUDGET - SECTIONS F-K, BUDGET PERIOD 3

* ORGANIZATIONAL DUNS: 009095365

*** Budget Type:** ● Project ❍ Subaward/Consortium

Enter name of Organization: University of Utah

*** Start Date:** 12-01-2014 *** End Date:** 11-30-2015 **Budget Period: 3**

F. Other Direct Costs	**Funds Requested ($)**
1. Materials and Supplies	3,000.00
2. Publication Costs	3,000.00
3. Consultant Services	
4. ADP/Computer Services	
5. Subawards/Consortium/Contractual Costs	
6. Equipment or Facility Rental/User Fees	
7. Alterations and Renovations	
8. Other (fax, mail, phone, etc)	1,000.00
Total Other Direct Costs	**7,000.00**

G. Direct Costs	**Funds Requested ($)**
Total Direct Costs (A thru F)	**120,394.00**

H. Indirect Costs

Indirect Cost Type	**Indirect Cost Rate (%)**	**Indirect Cost Base ($)**	*** Funds Requested ($)**
1. MTDC_Research	49	120,394.00	58,993.00
		Total Indirect Costs	**58,993.00**

Cognizant Federal Agency DHHS, Wallace Chan, 415-637-7820

(Agency Name, POC Name, and POC Phone Number)

I. Total Direct and Indirect Costs	**Funds Requested ($)**
Total Direct and Indirect Institutional Costs (G + H)	**179,387.00**

J. Fee	**Funds Requested ($)**

K. * Budget Justification File Name: Budget_Justification1008034159.pdf Mime Type: application/pdf

(Only attach one file.)

RESEARCH & RELATED Budget {F-K} (Funds Requested)

RESEARCH & RELATED BUDGET - Cumulative Budget

		Totals ($)
Section A, Senior/Key Person		**130,492.00**
Section B, Other Personnel		**154,480.00**
Total Number Other Personnel	12	
Total Salary, Wages and Fringe Benefits (A+B)		**284,972.00**
Section C, Equipment		
Section D, Travel		**18,000.00**
1. Domestic	9,000.00	
2. Foreign	9,000.00	
Section E, Participant/Trainee Support Costs		
1. Tuition/Fees/Health Insurance		
2. Stipends		
3. Travel		
4. Subsistence		
5. Other		
6. Number of Participants/Trainees		
Section F, Other Direct Costs		**20,000.00**
1. Materials and Supplies	10,000.00	
2. Publication Costs	7,000.00	
3. Consultant Services		
4. ADP/Computer Services		
5. Subawards/Consortium/Contractual Costs		
6. Equipment or Facility Rental/User Fees		
7. Alterations and Renovations		
8. Other 1	3,000.00	
9. Other 2		
10. Other 3		
Section G, Direct Costs (A thru F)		**322,972.00**
Section H, Indirect Costs		**158,644.00**
Section I, Total Direct and Indirect Costs (G + H)		**481,616.00**
Section J, Fee		

BUDGET JUSTIFICATION

Multiscale Models of Melting Arctic Sea Ice

The bulk of the funds being requested are to support the participants in the project. In particular, we are requesting between 3/4 and 1 month salary each for: the PI Golden, the Co-PI's Perovich, Strong and Alali, and Senior Personnel Tasdizen and Polashenski. We are requesting 2 years of 2/3 support for a postdoctoral associate to be based in the Math Department under the direction of Golden. The Math Department has generously agreed to contribute 1/3 of the $50,000 salary for the postdoc in years 2-3, in exchange for teaching one course each year in the Mathematics Department. We are also requesting partial support for graduate students, primarily to be used in the Math Department, with a small amount to partially support a student in the Scientific Computing and Imaging Institute (SCI) under Tasdizen for the development of the image analysis techniques. We are also requesting support for one undergraduate student each year.

Requests for travel funding are to support the participants in presenting our results at conferences, such as the Fall AGU Meeting, the Spring EGU Meeting, or the Ocean Sciences Meeting, and to facilitate travel between CRREL and Utah. For example, the cost for one person to attend the Fall AGU meeting is about $1500 and for EGU about $2000, and the cost for one person from CRREL to visit Utah for a week is about $1000. Requests for supplies are for software and related items to support the theoretical modeling efforts and the image analysis.