COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./DUE DATE PD 16-1266 11/15/19	☐ Special Exception to Deadline Date Policy	FOR NSF USE ONLY NSF PROPOSAL NUMBER
FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.) DMS - APPLIED MATHEMATICS, (continued)		

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NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE University of Utah	ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE University of Utah 75 S 2000 E Salt Lake City,UT.841128930
AWARDEE ORGANIZATION CODE (IF KNOWN) 0036756000	
NAME OF PRIMARY PLACE OF PERF UNIV OF UTAH	ADDRESS OF PRIMARY PLACE OF PERF, INCLUDING 9 DIGIT ZIP CODE UNIV OF UTAH 155 S 1400 E RM 233 SALT LAKE CITY ,UT ,841120090 ,US.

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TITLE OF PROPOSED PROJECT **Collaborative Research: Ultra-Realistic Modeling and Simulation of Arctic Sea Ice**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 569,053	36 months	07/01/20	

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- ☐ HISTORIC PLACES
- ☐ VERTEBRATE ANIMALS IACUC App. Date ______
  PHS Animal Welfare Assurance Number ______
- ☒ TYPE OF PROPOSAL Research
- ☐ HUMAN SUBJECTS Human Subjects Assurance Number ______
  Exemption Subsection ______ or IRB App. Date ______
- ☐ FUNDING OF INT'L BRANCH CAMPUS OF U.S IHE ☐ FUNDING OF FOREIGN ORG
- ☒ INTERNATIONAL ACTIVITIES: COUNTRY/COUNTRIES INVOLVED
  AS
- ☒ COLLABORATIVE STATUS
  A collaborative proposal from multiple organizations (PAPPG II.D.3.b)

PI/PD DEPARTMENT Department of Mathematics	PI/PD POSTAL ADDRESS 155 S 1400 E RM 233 Salt Lake City,UT 84112 United States
PI/PD FAX NUMBER 801-581-4148	

NAMES (TYPED)	High Degree	Yr of Degree	Telephone Number	Email Address
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CO-PI/PD Elena A Cherkaev	PhD	1988	801-581-7315	elena@math.utah.edu
CO-PI/PD				
CO-PI/PD				
CO-PI/PD				

COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./DUE DATE **PD 16-1266** **11/15/19**	☐ Special Exception to Deadline Date Policy	**FOR NSF USE ONLY** **NSF PROPOSAL NUMBER**
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NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE **University of California-Los Angeles**	ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE **University of California-Los Angeles** **10889 Wilshire Boulevard** **Los Angeles,CA.900951406**
AWARDEE ORGANIZATION CODE (IF KNOWN) **0013151000**	
NAME OF PRIMARY PLACE OF PERF **University of California-Los Angeles**	ADDRESS OF PRIMARY PLACE OF PERF, INCLUDING 9 DIGIT ZIP CODE **University of California-Los Angeles** **520 Portola Plaza, MS 7619-E** **Los Angeles ,CA ,900951555 ,US.**

IS AWARDEE ORGANIZATION (Check All That Apply) ☐ SMALL BUSINESS ☐ MINORITY BUSINESS ☐ FOR-PROFIT ORGANIZATION ☐ WOMAN-OWNED BUSINESS ☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **Collaborative Research: Ultra-Realistic Modeling and Simulation of Arctic Sea Ice**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ **320,001**	**36** months	**07/01/20**	

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- ☐ PROPRIETARY & PRIVILEGED INFORMATION
- ☐ HISTORIC PLACES
- ☐ VERTEBRATE ANIMALS IACUC App. Date ______ PHS Animal Welfare Assurance Number ______
- ☒ TYPE OF PROPOSAL **Research**
- ☐ HUMAN SUBJECTS Human Subjects Assurance Number ______ Exemption Subsection ______ or IRB App. Date ______
- ☐ FUNDING OF INT'L BRANCH CAMPUS OF U.S IHE ☐ FUNDING OF FOREIGN ORG
- ☐ INTERNATIONAL ACTIVITIES: COUNTRY/COUNTRIES INVOLVED ______
- ☒ COLLABORATIVE STATUS **A collaborative proposal from multiple organizations (PAPPG II.D.3.b)**

PI/PD DEPARTMENT **Mathematics**	PI/PD POSTAL ADDRESS **Department of Mathmatics** **6363 Math Sciences Building** **LOS ANGELES,CA 900951406** **United States**
PI/PD FAX NUMBER **310-206-6673**	

NAMES (TYPED)	High Degree	Yr of Degree	Telephone Number	Email Address
PI/PD NAME **Joseph M Teran**	**DPhil**	**2006**	**310-206-0048**	**jteran@math.ucla.edu**
CO-PI/PD				
CO-PI/PD				
CO-PI/PD				
CO-PI/PD				

TPI: 8010094

COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

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611730890		

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE	ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE
Oregon State University	Oregon State University 1500 SW Jefferson Way Corvallis,OR.973318507
AWARDEE ORGANIZATION CODE (IF KNOWN): 0032102000	
NAME OF PRIMARY PLACE OF PERF	ADDRESS OF PRIMARY PLACE OF PERF, INCLUDING 9 DIGIT ZIP CODE
Oregon State University	Oregon State University 104 CEOAS Admin Building Corvallis ,OR ,973315503 ,US.

IS AWARDEE ORGANIZATION (Check All That Apply) ☐ SMALL BUSINESS ☐ MINORITY BUSINESS ☐ FOR-PROFIT ORGANIZATION ☐ WOMAN-OWNED BUSINESS ☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **Collaborative Research: Ultra-Realistic Modeling and Simulation of Arctic Sea Ice**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 209,622	36 months	07/01/20	

THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

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- ☐ DISCLOSURE OF LOBBYING ACTIVITIES
- ☐ PROPRIETARY & PRIVILEGED INFORMATION
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- ☐ VERTEBRATE ANIMALS IACUC App. Date ________
- PHS Animal Welfare Assurance Number ________
- ☒ TYPE OF PROPOSAL Research
- ☐ HUMAN SUBJECTS Human Subjects Assurance Number ________
- Exemption Subsection ________ or IRB App. Date ________
- ☐ FUNDING OF INT'L BRANCH CAMPUS OF U.S IHE ☐ FUNDING OF FOREIGN ORG
- ☐ INTERNATIONAL ACTIVITIES: COUNTRY/COUNTRIES INVOLVED
- ☒ COLLABORATIVE STATUS
  A collaborative proposal from multiple organizations (PAPPG II.D.3.b)

PI/PD DEPARTMENT	PI/PD POSTAL ADDRESS
CEOAS	Oregon State University 104 CEOAS Administration Building Corvallis,OR 977315503 United States
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CO-PI/PD				
CO-PI/PD				
CO-PI/PD				

TPI: 8011343

PROJECT SUMMARY

Overview:

A central issue in advancing the science of the changing Arctic marine environment, and climate modeling more broadly, is to improve our ability to model, simulate, and visualize the dynamic and thermodynamic behavior of sea ice. The multiscale nature of sea ice as a porous polycrystalline composite of pure ice with brine and air inclusions presents formidable challenges, as does the sea ice cover itself, which has a multiscale composite structure of snow-covered ice floes, with sizes ranging over many orders of magnitude, in an oceanic host. Much of sea ice modeling has been geared toward parameterization in large scale, coarse grained climate models. Here we focus on developing the mathematics and computations needed for ultra–realistic modeling and simulation of key intermediate scale processes, such as the formation of ridges and leads, the evolution of melt ponds, and the interaction of sea ice with ocean surface waves. A recently developed framework offers the potential to transform sea ice simulation and visualization, with its capability of accurately handling rheologies ranging from fluid to solid. Based on the Material Point Method (MPM), it has been applied to simulating the beautiful yet varied dynamics of snow, yielding a new level of insight and predictability into the complex mechanics of avalanches and wet sand. What particularly distinguishes this approach, beyond rigid adherence to the physics, is the significant advance in visual realism, as evidenced by the MPM-produced snow scenes in the animated Disney film Frozen.

Here we propose to build an MPM framework for sea ice to bring this new level of realism, resolution, and physical accuracy to modeling important processes in the Arctic sea ice cover. We focus on building blocks of sea ice dynamics, such as floe collision and break-up, and the response of sea ice to waves and other forcings. As phase change and thermo-mechanical processes fall within MPM capabilities, we will consider the freezing and melting of sea ice, such as pancake formation in a wave field and the evolution of surface ponding and floe break-up. We will develop an MPM framework and related mathematics designed to efficiently treat the wide range of material parameters, rheologies, fracture, phase transitions and topological changes arising in complex sea ice scenes. Our framework will capture the essential physics and produce ultra-realistic visual representations of processes controlling ice pack morphology and properties.

Intellectual Merit:

Our approach will drive major advances in mathematical and computational modeling of sea ice and other complex multiscale materials with a broad range of rheological and phase change characteristics (e.g., land ice, biomaterials, concrete, tectonic plates). It will provide researchers in sea ice dynamics and thermodynamics with a powerful new class of modeling techniques with unprecedented realism and fidelity to the physics, with the capability to produce stunning visual renderings. Extensive algorithm and software development will be essential to building a realistic MPM framework for sea ice. However, there are other critical components which must be addressed, such as determining the constitutive equations describing the rheological behavior of sea ice over a range of length and time scales, by incorporating the results of field studies into the numerical simulations. We will bring to bear advanced methods of mathematical homogenization to determining the effective rheological properties of sea ice and their dependence on the characteristics of the brine and polycrystalline microstructures, which are key inputs in the proposed sea ice MPM. Moreover, our project features close connections to major field campaigns on Arctic sea ice, with access to extensive data on the scenarios we are simulating. MPM is particularly well suited to the efficient assimilation of these data into the models to achieve desired realism and accuracy.

Broader Impacts:

The investigators are active in outreach involving young people at many levels. We expect that the very high level of visual realism that we will achieve in our simulations will attract students, and the broader public, to the story of sea ice and its role in our changing climate. Participants in the project will be immersed in a highly interdisciplinary melding of cutting edge computational physics and mathematics of homogenization for multiscale composites, as well as the science of Arctic sea ice and the broader marine environment.

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Appendix Items:

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TABLE OF CONTENTS

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Appendix Items:

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

1 Results of Prior NSF Support

Golden and Cherkaev

NSF Grant DMS-1413454, $320,000, 08/01/2014 - 07/31/2018, *Homogenization for Sea Ice*.
PI: K. M. Golden, co-PIs: E. Cherkaev and C. Strong (Atmospheric Sciences)

Intellectual Merit. We address fundamental questions in sea ice homogenization, where we are interested in rigorous representations and calculations of effective or homogenized sea ice behavior on larger scales (macroscale) from some knowledge of behavior or structure on smaller scales (microscale). We are also interested in the inverse problem of estimating parameters controlling smaller scale processes from larger scale observations. Our results fall roughly into four types of sea ice homogenization problems, with 16 publications supported by this award (fully or partially) listed below. A theme which runs through a number of these works, across problem type, focuses on developing rigorous Stieltjes integral representations for the homogenized parameter in the problem. For example, for electromagnetic wave propagation and the effective complex permittivity of sea ice treated as a composite of pure ice with brine inclusions, the Stieltjes integral involves a *spectral measure* which depends on the composite microgeometry, and a complex variable involving the ratio of the complex permittivities of the ice and brine. With only partial information such as brine volume fraction or statistical isotropy, the representation yields rigorous bounds, in this case regions in the complex plane where the homogenized parameter must lie. From an image of the microstructure, we have developed methods of computing the spectral measure [90, 89], which yield much more detail about the effective behavior. One of the main thrusts of the project was to develop this type of powerful representation, bounding theory, and computational framework for other problems in sea ice physics.

1. *Fluid and electromagnetic transport in sea ice.* We developed a Stieltjes integral representation and bounds for the effective complex permittivity of polycrystalline composites given crystal orientation statistics, where sea ice crystals are themselves composites of pure ice with brine inclusions [48]. Our inverse bounds lay the groundwork for using remote sensing techniques to distinguish between ice types, such as granular vs. columnar. When sea ice forms in conditions with a well-defined current direction, then the c-axes of the crystals tend to align with the current. We have used our polycrystalline integral representation to develop a theory of bounds for sea ice with anisotropy in the horizontal plane [84]. Algae living in the brine phase in sea ice secrete extracellular polymeric substances (EPS), which modify inclusion geometry and aid survival in the extreme environment. We constructed a network model of the fluid permeability of EPS-laden sea ice, which reproduces observed behavior [117].

2. *Advection diffusion models.* Diffusion in a flow field is encountered throughout the geosciences and sea ice physics in particular. Examples include thermal transport through sea ice in the presence of brine convection and ice floe dynamics in winds and ocean currents. We have developed a comprehensive theory of Stieltjes integral representations for the effective diffusivity in the homogenized advection diffusion equation, for time independent velocity fields in [92] and time dependent fields in [91]. We constructed a mathematical framework for analyzing and computing the spectral measure, and have connected geometrical properties of the advective field to spectral characteristics. We have applied this theory to obtain the first set of rigorous bounds on the effective thermal conductivity of sea ice for model convective flow fields, which capture field measurements [71]. It has been observed that GPS position data from an ice floe could display, through its mean squared displacement and Hurst exponent, diffusive, sub-diffusive and super-diffusive behavior depending on advective and ice pack conditions. We have built a floe-scale numerical model that replicates and explains this fascinating behavior [34]. On the scale of the Arctic basin, we have used idealizations of the sea ice concentration field, such as assuming it solves Laplace's equation, to analyze the width of the marginal ice zone [120]. By adding a stochastic term, we have developed objective methods for filling in the famous "pole-hole," or gap in satellite data around the North Pole [121].

3. *Melt ponds on Arctic sea ice.* As Arctic sea ice melts in late spring, distinctive ponds form on its surface. Their geometrical patterns largely determine the solar reflectance and transmittance of the sea ice cover,

which are key parameters in climate modeling and upper ocean ecology. In prior work, we discovered that as the ponds grow and coalesce, their fractal dimension transitions from 1 to about 2 in a critical regime centered around 100 square meters in area. In [10] we modeled the pond boundaries using the level sets of a random surface that represent the snow topography, which enables us to study the fractal transition in terms of the surface characteristics. In [81] we adapted the Ising model, created about 100 years ago to explain ferromagnetic materials, to understand melt pond geometry. With only one measured parameter input, the model captures the essential mechanism of pond pattern formation, with predictions that agree very closely with observed scaling of pond sizes and fractal transition. In [96] we present results from the NSF 2014 SUBICE Arctic expedition, and solve a fundamental conundrum. If sea ice is so porous in late spring, which is what we measured, how does it support melted snow on its surface to begin pond formation?
4. *Waves in sea ice.* As the Arctic Ocean has opened up, wave-ice interactions have received increased attention. Continuum models of wave propagation through sea ice depend on a complex viscoelasticity which characterizes the mechanical response of the sea ice layer. We derived a Stieltjes integral for this homogenized parameter, where the spectral measure depends on the geometry of the ice floe configurations. We obtain the first rigorous bounds on it in the long wavelength regime, given the sea ice concentration [107].

In [44] Golden reviews a number of the areas in sea ice modeling mentioned above.

Broader Impacts. *Scientific.* First, a number of the results described above, while motivated by the physics of sea ice, have much broader applicability. Our theory of bounds on the complex permittivity of polycrystalline sea ice applies just as well to glacial ice, rocks, and other polycrystalline composites. Our Stieltjes representations and bounds for the advection enhanced diffusivity apply in general to systems whose effective behavior is described by the homogenized advection diffusion equation, which arise for example in engineering, geoscience, and biophysics. Our work is advancing how sea ice is represented in climate models, and helping to improve our ability to predict the behavior of polar sea ice and its role in the rapidly changing Arctic and the climate system more broadly.
Human Resources. Golden has used examples from this project as material in Math Week for the Summer ACCESS Program for 30 – 35 undergraduate women each year entering the University of Utah in Science, Math and Engineering, with the theme of *Mathematics of Climate and Energy*, that he has been running for the past two years. During spring of the freshman year the ACCESS students work with a professor, and several ACCESS students have worked with Golden on projects related to this grant. Golden also led an American Mathematical Society Mathematics Research Community, June 2015 in Snowbird, UT on *Differential Equations, Probability, and Sea Ice*, to immerse 39 graduate students and postdoctoral researchers in problems of mathematics of sea ice. At the University of Utah, participants in our grant projects included 1 postdoctoral researcher, 3 Ph.D. students, 6 undergraduates, and 2 high school students.
Public Awareness and Media Coverage. During the grant period, our work and interviews with Golden were featured in several outreach videos, including: 2014 NSF Science Nation Video: Mathematician Combines Love for Numbers and Passion for Sea Ice to Forecast Melting, 2015 NSF Discoveries Video: On Golden's Melt Pond - Math on Ice, 2015 Video Synopsis of the First National Math Festival, 2017 SIAM Video: Math Behind Sea Ice and our Changing Planet. Other interviews with Golden about sea ice and climate included 2015 NSF *Science360* Radio show and a 2015 Weather Channel interview on Al Roker's morning show. Web magazine articles during this period included a 2016 profile in *Physics Today* and coverage in 2015 *Yahoo News* and 2017 *Smithsonian Magazine*. In [122] we were invited to write a popular article in *SIAM News* for the broader applied math community on our work in filling the polar data gap.

Hutchings

NSF Grant OPP-1722729, $407,452, 10/01/17 - 09/30/2021, *Collaborative Research: Thermodynamic and Dynamic Drivers of the Arctic Sea-Ice Mass Budget at MOSAiC*.
PIs: M. Shupe, T. Stanton, D. Perovich and J. Hutchings.
Intellectual Merit. The Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC),

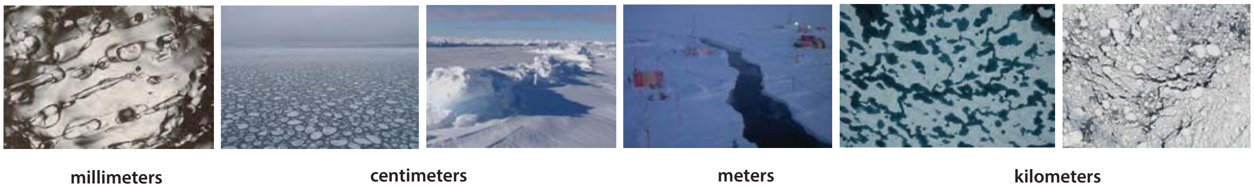

Figure 1: Multiscale structure of sea ice. From left to right: millimeter scale brine inclusions [134]; centimeter scale pancake ice forming in a wave field (Golden); pressure ridge in sea ice (Golden); lead in Arctic sea ice (Perovich); Arctic melt ponds (Perovich); large scale view of the Arctic ice pack (NASA).

a year long sea ice drift station deployed October 2019, includes an autonomous network monitoring ocean-ice-atmosphere fluxes and the evolution of pack ice dynamics. Hutchings leads the ice dynamics field team: tracking ice pack dynamic and thermodynamic evolution, and the pack's mechanical response to this. During MOSAiC planning she has published with international collaborators [73, 74].

Broader Impacts. We developed lessons for 4/5th graders, middle school and high school math students, and tested them in Oregon after-school science clubs. Students forecast sea ice drift with persistence models. Partnering with the Sea Ice Dynamics Forecasting Experiment (SIDFEx), students see that persistence is a reasonable forecast compared to current state of the art models, which necessitates research into improving models. In this proposal we are asking for support to further develop the math lesson packages that meets Next Generation Learning Standards, to be disseminated widely to high school teachers.

Teran

NSF Grant CCF-142279, $261,014.00, 1/01/14 - 12/31/2017, *RI: Small: Collaborative Research: An accelerated numerical solver framework for simulation of solid-fluid dynamics*.

PIs: E. Sifakis, J. Teran, P. Kavehpour

Intellectual Merit. This collaborative effort (UCLA and U. Wisconsin) was focused on the development of parallel computing for complex fluids and other related materials. The focus of the effort was on structured-grid-based discretizations, particularly those related to the Material Point Method (MPM). The effort resulted in a number of publications, including the following that were MPM related [63], [65], [100], [39], [40]. In this effort, MPM emerged as a powerful option for simulating a wide range of materials exhibiting non-linear and complex rheologies due to its ease in tracking material deformation history, natural resolution of self-collision and fracture. Furthermore, performance on parallel architectures was naturally achieved due to the structured nature of the gridded nature of the hybrid representation of material.

Broader Impacts. Graduate students Gergeley Klar, Michael Royston, Chenfanfu Jiang and Daniel Ram were trained in various aspects of numerical methods for PDEs, particularly those related to MPM. All received their PhD during the effort. The publications produced in the effort have impacted many subsequent works in the computer graphics and computational physics literature.

2 Introduction

Among the greatest scientific challenges of the 21$^{\text{st}}$ century are to observe, understand, model and predict the pronounced changes in Earth's polar regions. The emerging dynamics of the changing Arctic marine environment are complex and highly variable, yet increasingly important to consider and study as human activities in the region expand. In the Arctic Ocean, the sea ice cover has bearing on almost any studies of the polar marine system. The Arctic ice pack is a critical component of Earth's climate system, reflecting sunlight and coupling the ocean and atmosphere thermally and mechanically. Much of the previous mathematical and computational modeling work on sea ice has treated this complex medium at very fine scales as a composite material, or on much larger scales when simulating, for example, sea ice dynamics and thermodynamics over regions of the Arctic basin. Incorporation and parameterization of these large scale sea ice model components into global climate models is then critical to making long term projections of the changing climate system. However, current large scale numerical models with grid sizes on the order of tens of kilometers are generally unable to accurately simulate or resolve much finer scale processes in the formation, ridging, fracture, deformation, melting, and break-up of sea ice. This inhibits our ability to accurately predict the dynamics of the ice cover on scales of meters and kilometers in space and hours and days in time. These intermediate scale model studies of basic sea ice behavior and interactions can form the building blocks for fundamental advances in larger scale predictive models of sea ice dynamics and thermodynamics. Such studies can also be pivotal for short term sea ice predictions for scientific, civilian, commercial, and military operations in the Arctic.

Here we propose to build what we believe will become the most advanced, most visually realistic and physically accurate computational framework to simulate and visualize key processes in the dynamics and thermodynamics of Arctic sea ice. The idea is to initially focus on creating extremely high resolution, ultra-realistic simulations and visual renderings of the basic building blocks of sea ice dynamics, such as the formation of ridges and leads on the floe scale, the interaction of sea ice with waves, ponding, and sea ice break-up. We expect this work to advance our understanding and capability of predicting the mechanics and rheology of sea ice on *intermediate* length and time scales. Here we focus on sea ice scenes that a person on a ship may observe. This type of research at these scales has generally not been undertaken in prior canonical modeling of sea ice physical phenomena, or in improving how sea ice is represented and incorporated in general circulation models.

We address this intermediate range of scales by building a new MPM-based computational framework that we believe can revolutionize the mathematical modeling and visualization of sea ice processes. We will develop this framework with the objective of providing simulations and visual renderings of model dynamic scenarios that reach an unprecedented level of realism, resolution, and adherence to the physics. Reaching this new level of realism and accuracy will be facilitated by the assimilation of extensive field data. We anticipate mathematical results in data assimilation and machine learning to meet the challenges of achieving fidelity of the model to actual sea ice behavior. Moreover, we will employ advanced techniques of homogenization theory to compute, estimate, and bound the effective rheological behavior of sea ice on the smaller scales needed as input into the MPM framework, and in laying the foundation for larger scale rheological models of sea ice from our intermediate scale studies.

To achieve these objectives, our project will be built upon an interdisciplinary melding of computational physics, theoretical modeling of dynamic and thermodynamic processes in the physics of sea ice, mathematics of homogenization for composites, and close connection with extensive field data from ongoing field experiments, like MOSAiC. In particular, our team includes Joseph Teran of UCLA, the principal creator and developer of probably the most advanced, realistic computational framework for simulating the dynamics of snow. This fascinating material is a key part of the sea ice system, and like sea ice exhibits a wide range of rheological behaviors from fluid to solid. Teran's recent development of an extremely flexible, hybrid Eulerian/Lagrangian particle-based Material Point Method (MPM), has been used to revolutionize snow modeling. We believe this approach has the potential to transform how we model sea ice.

The particles in Teran's MPM are small pieces of a continuum model of the material under study. For sea ice – which displays complex composite structure over a wide range of length scales – these small pieces are composites themselves. As a material sea ice is composed of a pure ice host with a porous microstructure of brine and air inclusions on the submillimeter scale, a polycrystalline microstructure on the centimeter scale, and larger brine channels on the meter scale. The volume fraction, geometry and connectivity of the brine phase in sea ice is highly temperature dependent, which strongly influences effective rheological characteristics. As the effective properties of these "particles" are key inputs into the MPM, Cherkaev brings her expertise in the effective rheological properties of composites in general and porous media in particular, as well as in geophysical inverse problems. Golden brings expertise in homogenization and mathematical modeling of the brine phase and polycrystalline microstructure, as well as extensive hands-on field experience with sea ice. Pedro Ponte Castañeda of UPenn has expressed strong interest in this project and its close connection to his research on homogenizing the rheological properties of polycrystalline sea ice, and is happy to collaborate and contribute his valuable expertise.

To achieve the new levels of realism and physical accuracy that we propose, it is critical for the success of this project to be able to incorporate data from observations of the processes and scenarios under study into the computational framework. Thus we have initiated a collaboration, as a key component of the project, with Jennifer Hutchings of Oregon State University, an expert in both modeling and measuring sea ice dynamical processes, and co-director of two Arctic sea ice dynamics field campaigns over the next two years, ONR Sea Ice Dynamics Experiment (SIDEx) and the dynamics component of MOSAiC. Extensive field measurements constraining the mechanical and rheological properties of sea ice will be made. Golden's colleague Donald Perovich of Dartmouth College, who is sea ice team co-coordinator on MOSAiC, has indicated his strong interest in this project, and will act as a data liason for us. Perovich is an expert in melt ponds, and will be particularly helpful in that part of our project. We will have timely access to these critical measurements, and the data will be used to help us calibrate the models, determine the best parameters, and develop MPM-based data assimilation techniques in order to achieve the ultra-realism we seek.

3 Intellectual Merit

Our approach will expand the boundaries of applied mathematics further into polar science, and drive significant advances in mathematical and computational modeling of sea ice and other multiscale materials with complex phase change and rheological characteristics. In this project we will exploit the robustness and flexibility of the MPM approach and the range of fluid and solid rheologies that it can handle to bring unprecedented simulation and visualization capabilities to basic sea ice processes. We will develop a modeling and computational framework that efficiently and deftly treats the wide range of material parameters, rheological behaviors, fracture and phase changes arising in complex sea ice scenarios. We will create realistic simulations of key sea ice processes, on scales that have generally not been looked at in any depth. Our initial focus will be to develop an efficient, user–controllable sea ice constitutive model integrated with a hybrid Eulerian/Lagrangian MPM to simulate ridge formation, fracture and lead development, the influence of waves, and the evolution of ponding and break-up. Toward these objectives, we will:
(i) Design novel thermo-mechanical constitutive models for multi-species interactions with sea ice, snow and water mixtures that are accurate at macro- and micro-scales, and account for phase changes. (ii) Explore appropriate representations for sea ice brine and polycrystalline microstructures for use in MPM; explore the accuracy of associated rheological models for different scenarios and scale regimes. (iii) Develop novel MPM algorithms for discretizing and coupling water, snow and ice phases, as well as their fracture, failure, cohesion and related interactions. (iv) Employ homogenization methods to obtain constitutive equations for sea ice rheology on scales of centimeters to meters as input into MPM; determine effective rheology of sea ice as a polycrystalline porous composite, with focus on temperature dependence. (v) Create GPU and HPC implementations of MPM discretizations that allow for simulations with 100 million to 10 billion particles, and extremely high visual resolution. (vi) Incorporate extensive observational data from the major field experiments MOSAiC and SIDEx, and other data sets into the MPM computational framework.

4 Broader Impacts

We believe our project has the potential to significantly impact (i) our capability to predict the mechanical, rheological and phase change behavior of sea ice over a range of length and time scales, as well as for other multiscale media, (ii) the science of the Arctic Ocean and the climate system, (iii) the engineering of structures which interact with sea ice, such as icebreaking ships, and (iv) modeling the ecology of the upper ocean using our realistic melt pond models, and even modeling the world and ecology of a brine inclusion.

We will engage Citizen Scientists on tourist cruises in ice covered waters. Ice Watch and Hutchings have worked with tour operators providing a research experience since 2015 [36]. We will continue working with these groups to provide photos and videos of specific ice features of interest. We will build an archive of sea ice scenes categorized according to the physical state of the ice pack and thermo-mechanical processes controlling the floe size, ice concentration, thickness and deformation features in the images. Some of this imagery could be used to validate our models.

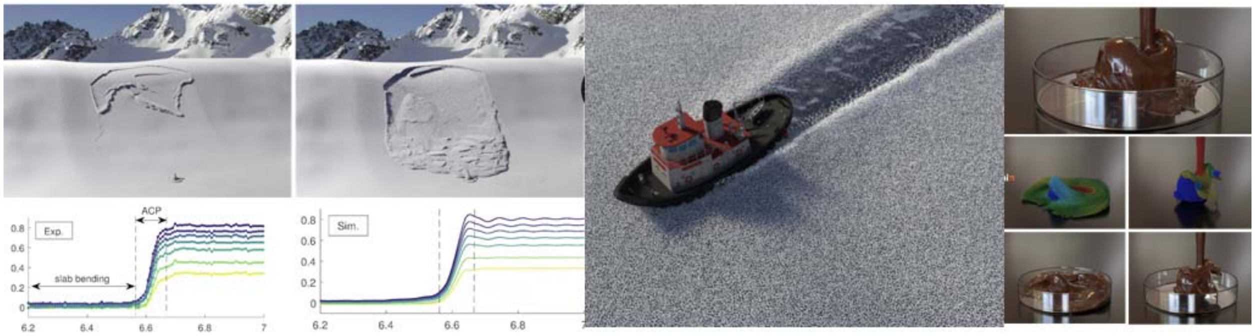

Figure 2: MPM simulation of snow, ice and phase change. Left: Teran *et al.* (2018) developed a novel constitutive model for remotely triggered avalanches. Left top: Slope scale simulation of avalanche with 30 million particles. Left bottom: Plot shows that the model reproduces experimental field data with a comparison of snow slab bending and failure. Middle: Initial MPM simulation with one hundred thousand particles of an ice breaker interacting with ice/snow on top of water. Right: Teran and colleagues (2014) demonstrate successful simulation of phase change with a thermo-mechanical MPM approach and simulated molten chocolate.

With education Ph.D. candidate Megan Brunner, we will develop a high school Algebra II lesson package aligned with Next Generation Math Standards in Learning. The lessons bring support of polar activities, near-real time data and modeling into the classroom where students build trigonometry, pre-calculus and statistical skills in developing a persistence forecast of buoy drift, determining the skill of the forecast and comparing against state-of-the-art forecasts. Lessons will be disseminated on the internet, advertised through magazines teachers read and at National Council for Teachers of Mathematics Regional Conferences.

The proposed project will open a new chapter in sea ice modeling, with the potential to provide a major leap forward in addressing central challenges in modeling on scales relevant to societal needs. This project will offer the postdoctoral, graduate, undergraduate and high school investigators unique and unusual learning experiences at the exciting interface of cutting edge applied mathematics, transformative computational methods, mechanics of composite materials, and Arctic field science. With the direct connection of the proposed work to the Academy Award winning movie *Frozen*, and our focus here on visual realism, we anticipate that the future success of this project could become a focal point of outreach to students and the public regarding federally funded research and its impact on matters of public, as well as academic interest.

5 Background

5.1 Numerical Modeling of Sea Ice Rheology and Dynamical Processes

Sea ice moves under the influence of ocean currents and winds. On time scales shorter than days the largest terms in the force balance are wind stress τ_a, ocean drag τ_o, inertia and the divergence of the ice stress $\boldsymbol{\sigma}$. We can ignore body forces due to gravitational acceleration down the sea surface and the Coriolis force on the intermediate scale. Typically ice is considered to be a thin plate, and the forces and stresses are depth integrated, resulting in an equation for the momentum balance,

$$m\frac{D\mathbf{v}}{Dt} = \tau_o + \tau_a + \nabla \cdot \boldsymbol{\sigma}, \tag{1}$$

where m is ice mass, $\mathbf{v}$ is ice velocity and t is time. The cauchy stress tensor is $\boldsymbol{\sigma}$. The stresses at the upper and lower ice surfaces, τ_a and τ_o, are estimated with boundary layer parameterizations and weather/ocean model winds and currents. These models describe how the mass of sea ice is distributed with a thickness distribution function, and a transport equation tracks changes in area of ice of a given thickness through melt, growth and mechanical redistribution via ridging or opening of leads. Our proposal to produce visually realistic simulations of ice dynamics requires that we simulate these processes with a 3-D representation of ice in the ocean, where τ_o and τ_a are applied to the upper and lower boundaries of the simulation and are zero inside the material. The internal ice stress is given by the second-order Cauchy stress tensor, with 3 normal stress components and 6 shear stress components. The ice mass must obey a continuity equation

$$\frac{Dm}{Dt} - m\nabla \cdot \mathbf{v} = F, \tag{2}$$

Figure 3: Material Point Methods – thermodynamically driven viscoelastoplastic solids for baking. MPM naturally accommodates materials with complex thermodynamically varying material properties, as was recently demonstrated by Teran et al. [33] for simulation of baking and cooking.

where F is a thermodynamically governed rate of ice melt or growth, which tracks the changing density of ice as its structure evolves and changes phase.

In modeling the kinematics and stress state of sea ice and snow one needs to relate the deformation, or strain rate $\dot{\boldsymbol{\epsilon}} = \frac{1}{2}(\nabla \mathbf{v} + \nabla \mathbf{v}^T)$, to the stresses in the ice or snow pack. This relationship can be viscous, elastic and/or plastic and is modeled with constitutive relationships expressed as a rheological model, that aggregates behaviour over defined scales, or through expressions describing particle interaction.

Typically, modeling the intermediate scale has been performed to support civil engineering projects. Various approaches have been effective, recently using hybrid finite element and discrete methods [76, 62]. Previous efforts have focused on idealized simulations with the discrete element method (e.g. [57, 56, 137, 88]) and engineering problems tackled with Particle-In-Cell (PIC) methods (e.g. [38, 2, 110]). These methods either assume a continuum that requires a rheological model relating stress to strain that is homogenized to the model resolution or they are discrete methods that assume viscous, elastic and/or plastic behavior when particles of ice interact. Discrete methods are computationally expensive and require reinitialization for simulations longer than several days, however they are effective at modeling granular and plastic behavior and can be used as a research tool to identify appropriate constitutive relations for continuum models (e.g. [112]). Continuum approaches are computationally cheaper and should be employed where homogenization of the stress-strain relation is appropriate. The PIC models took advantage of the homogenized nature of the viscous-plastic rheology [52, 53] (which arguably is not appropriate at the scale of ice-structure interaction) to increase efficiency of numerical solution of sea ice momentum balance while allowing precise representation of discrete features in the ice pack such as the ice edge.

Previous modeling efforts have been limited by uncertainty in rheological relationships for the intermediate scale and a lack of validation data for these models. In this proposal we introduce a novel approach addressing this. Advances in computer technology now support modeling at scales previously not achieved for sea ice except in limited DEM experiments [132]. We will use the Material Point Method (MPM), with such high resolution and large numbers of small scale particles that for the scenarios we initially investigate we have much more certainty and methods of analysis of the relevant homogenized rheology for polycrystalline sea ice with porous microstructure. MPM has been applied on much larger scales for sea ice [124] and is an improvement on the older PIC methods. MPM enables unique strategies for modeling compared to previous Lagrangian or semi-Lagrangian methods, such as mixed phase/media modeling and efficient 3-D simulation. We believe MPM will initially be appropriate for meter to km scales as the homogenization methods we will employ will be valid for ice structure at these scales.

To date, models have treated water, ice, snow and air as separated from each other, handling their interaction as fluxes between these constituents controlled by parameterized processes that do not resolve spatio-temporal variability at intermediate scales. Three dimensional MPM simulations will allow us to resolve these interactions directly in mass and momentum transfer between constituents. Developing such models will provide test beds for designing larger scale models, in particular providing avenues for testing candidate constitutive models for meter to sub-km scales.

5.2 Material Point Methods

The Material Point Method [123] was designed as a generalization of Particle-In-Cell (PIC) [49] and Fluid Implicit Particle (FLIP) [11] to history dependent materials such as elastoplastic granular solids. Particle-In-Cell techniques of this type are characterized by their hybrid usage of unstructured particles and structured regular grids. The hybrid nature allows for efficient resolution of topology change, e.g. for fracture and failure as well as automatic resolution of self contact and multi-material interactions. These aspects of PIC, combined with the algorithmic insights of the history dependent MPM developers [123] make these techniques ideally suited to computational problems related to a wide range of materials and time scales. Teran *et al.* have proven that MPM is capable of simulating snow and ice for both primarily visual applications like Walt Disney's "Frozen" [118] as well as engineering applications like avalanche modeling in *Nature Communications* [41]. Given the abundance of multi-material interactions between water, sea ice and snow during ocean wave propagation in the marginal ice zone as well as the fracture/failure and multi-material contact incurred during formation of ridges and leads, we believe MPM-based techniques can provide a revolutionary improvement in simulation technology for these materials, particularly in visual and spatial resolution accuracy. Furthermore, melt pond evolution and other thermo-mechanical behaviors can be easily incorporated into MPM, as was done by Teran *et al.* [119, 33] (see Figure 3).

Despite the natural advantages of MPM approaches for simulating snow and related materials, novel algorithmic improvements are needed to model problems in sea ice dynamics. In particular, while the unstructured particle nature of the approach allows for automatic resolution of topology change with fracture/failure, it is difficult to isolate individual cracks. Ironically, since the method automatically resolves these phenomena, it cannot detect exactly where they are. We will develop algorithmic modifications to MPM that allow for explicit tracking and modeling of cracks. A natural way to do this is by augmenting MPM with a Lagrangian mesh, as was done in [63]. This removes MPM's natural treatment of topology change by computing spatial derivatives with the help of the Lagrangian mesh, albeit while enslaved in an updated Lagrangian manner to grid based degrees of freedom during the momentum update stage. However, fracture and failure can the be introduced in a controlled manner via damage and plasticity in the Lagrangian mesh. Another challenge is resolving wide ranges of stiffness in the encountered materials. Implicit time stepping is particularly challenging with elastoplasticity since the linearization of the systems of equations arising in implicit time stepping are not symmetric (by virtue of the plasticity). Resolving these aspects in a manner that is both accurate and that scales well with HPC will be a challenging aspect of the work.

5.3 Homogenization for Rheological Properties of Composite Structures

Mechanical behavior and effective properties of heterogeneous materials depend on their constituents as well as on the microstructure. There has been extensive work in the past on estimating and bounding the effective properties of composites. The classical variational Hashin-Shtrikman-Walpole bounds [50, 51] derived in the 1960s were significantly improved with a powerful translation method [79, 80] for finding optimal bounds on the elastic energy stored in a composite, which generate bounds for the effective stiffness C^* and compliance S^* of the composite:

$$W_\epsilon(\boldsymbol{\epsilon}_0) = \boldsymbol{\epsilon}_0 : C^* : \boldsymbol{\epsilon}_0 = \min_{\boldsymbol{\epsilon}:<\boldsymbol{\epsilon}>=\boldsymbol{\epsilon}_0} < \boldsymbol{\epsilon}_0 : C : \boldsymbol{\epsilon}_0 >, \quad \text{and} \quad \boldsymbol{\epsilon} = (\nabla \mathbf{u} + \nabla \mathbf{u}^T)/2, \tag{3}$$

$$W_\sigma(\boldsymbol{\sigma}_0) = \boldsymbol{\sigma}_0 : S^* : \boldsymbol{\sigma}_0 = \min_{\boldsymbol{\sigma}:<\boldsymbol{\sigma}>=\boldsymbol{\sigma}_0} < \boldsymbol{\sigma}_0 : S : \boldsymbol{\sigma}_0 >, \quad \text{and} \quad \boldsymbol{\sigma} = \boldsymbol{\sigma}^T, \quad \nabla \cdot \boldsymbol{\sigma} = 0. \tag{4}$$

Here $\mathbf{u}$ is the displacement and $\boldsymbol{\epsilon}^0$ ($\boldsymbol{\sigma}^0$) is a constant strain (stress) tensor. The fourth order tensors $C(\mathbf{x})$ and $S(\mathbf{x})$ are the spatially varying stiffness and compliance tensors which depend on the properties of the phases and microgeometry of the composite determined by the characteristic function $\chi = \chi(\mathbf{x})$ that takes the value 1 if $\mathbf{x} \in \Omega_1$ and zero if $\mathbf{x} \in \Omega_2$, where Ω_1, Ω_2 are the regions occupied by the phases.

Various methods for calculating the effective properties from known microstructural information have been developed using the variational approach and asymptotic homogenization theory [108, 66, 87]. An alternative approach to deriving rigorous bounds on the effective complex permittivity ε^* of composites is the analytic continuation method, where the effective parameter is treated as an analytic function of the ratio of the component parameters [85, 5, 64, 42]. These bounds assume that the complex permittivities ε_1 and ε_2 of each component are known and that there is some partial information available about the microstructure. The method is based on a Stieltjes integral representation for the function $F(s)$ which is analytic (or complex differentiable) in the complex $s-$plane except on $[0, 1]$,

$$F(s) = 1 - \frac{\varepsilon^*}{\varepsilon_2} = \int_0^1 \frac{d\mu(z)}{s - z}\,, \qquad s = \frac{1}{1 - \varepsilon_1/\varepsilon_2}\,, \tag{5}$$

involving a positive measure μ which is the spectral measure of a self-adjoint operator $\Gamma\chi$, with $\Gamma = \nabla(-\Delta)^{-1}(\nabla\cdot)$, and Δ the Laplacian operator. The analytic continuation method was extended to viscoelastic shear modulus in [7, 23, 94, 22] with Γ changed to the corresponding operator for elasticity.

6 Formulation

6.1 Sea Ice Rheology

In modeling the motion of deforming solid materials, a rheological model is required to relate strain in the material to its internal stress field. This stress is described by a Cauchy stress tensor $\boldsymbol{\sigma}$, and this is estimated as a function of strain or strain-rate and material properties such as Young's modulus, viscosity and the yield stress at which plastic failure occurs. These constitutive relationships are often found empirically in laboratory experiments, and such an approach is successful for simulating sub-meter scale processes. On larger scales it is not possible to measure stress and strain over the same scales such that an empirical rheological model can be developed. Hence past efforts have relied on co-opting models from different scales (e.g. [55]) or making *ad-hoc* assumptions regarding the isotropic or anisotropic nature of sea ice, compressive strength of ice being approximated by its thickness [53], or ice having no tensile strength and obeying an isotropic yield relationship. Some of these assumptions are still open to debate or are suggested to be flawed [28], and it is not well defined what a suitable constitutive relation should be for intermediate or larger scales. The most commonly used rheological model for sea ice is the viscous-plastic (VP) model [53]. However a variety of models have been developed to handle proposed anisotropy in the sea ice yield stress [131, 136, 113] or to simulate brittle fracture (e.g. the elastic-brittle model [101]) which is more realistic compared to the ductile yielding implied [128, 52] by the VP model.

For continuum models we require that the stress field is described by an average stress at the model resolution. For other materials, homogenization approaches have been successful in identifying such relationships, however it is important that the material strain is not discontinuous within elements. This suggests these methods are appropriate when the resolution is orders of magnitude smaller than the size of ice floes, which varies from kilometers in the consolidated winter ice pack to centimeters in the marginal ice zone. In such a rheology the mean stress across an element is related to material properties and the strain $\boldsymbol{\epsilon}$. For plastic materials the yield stress is described as a curve or surface in principle stress space, which for large scale 2-D sea ice simulations might be assigned as either the cone described by Mohr-Coulomb theory [130, 55], a tear-drop shape based on (potentially flawed [102]) energetic considerations in ridging of ice [104], an ellipse for analytic and computational efficiency [53], or sine lens shaped based on homogenization over randomly orientated cracks [133]. This variety, and uncertainty in which models to apply, highlights unknowns in sea ice mechanical properties at large scales that are difficult to resolve with observations and current knowledge. At sub-meter scales we can identify material properties in the laboratory, in the field, or using homogenization, and these properties can be reasonably scaled up to tens of meters (e.g. [31]). We can take advantage of recent advances in computation to resolve the small scales for which we have knowledge to simulate the intermediate scale.

At the intermediate scales the vertical and horizontal dimensions of pack ice become similar and 3-D models are more appropriate than the thin plate approximation for the stress field used to justify 2-D models at larger scales. Observational evidence [114] suggests a Mohr-Coulomb relationship, with a cap representing the ice strength to normal stress, is suitable at sub-meter scales. This behaviour can be scaled to tens of meters [3, 32] and has been used to model ice-structure interaction [109, 62]. Hence we will take this as a starting point for our simulations, recognizing a caveat that under some confining stresses ice failure might occur in other modes not indicative of Coulombic faulting [106] or that brash (non-consolidated small ice pieces) might collectively be better represented by a Von-Mises yield criteria [111].

We assume sea ice can be treated as a continuum at scales an order of magnitude smaller than floe dimensions and that it is a quasi-brittle material, following [4], with elastic behaviour prior to yield. Cracking can be represented through weakening of the ice on yielding, and freezing accounted for by temperature and time dependent strengthening. Slip-stick behavior is observed in fractured ice that indicates frictional processes are rate and temperature dependent on times scales of seconds, suggesting healing at low strain rates and weakening at higher strain rates [77]. Values for Young's modulus and the compressive, tensile and flexural strength of sea ice are found to be temperature and ice structure dependent [127]. The temperature and time dependence have not been considered directly in simulations of ice interaction before, we will use this observed information (reviewed in [127], friction angle informed by [61]) to inform parameter choice to realistically simulate deformation with synoptic to seasonal variability in material properties. Along any plane in stress space the shear stress τ can be related to normal stress σ_N as $\tau = \sigma_N \, tan(\phi) + c$, where ϕ and c are the material properties friction angle and cohesion, respectively. At yield the material can deform, and the rate of deformation is described by a flow rule that relates yield stress to strain rate. Typically this flow law is taken to be associative where strain is normal to the yield curve. We will consider a non-associative flow law that allows for dilation in shear by setting strain normal to a cone defined by a dilation angle $\delta \neq \phi$. Within the yield curve we expect the behavior is linear elastic $\boldsymbol{\sigma} = C\boldsymbol{\epsilon}$, where C is a stiffness tensor. This assumption will be tested by the SIDEx team who we expect will provide insight into the nature of C.

6.2 Material Point Method

Continuum model: The thermo-mechanical governing equations arise from conservation of mass, momentum, as well as heat transfer,

$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{v} \tag{6}$$

$$\rho \frac{D\mathbf{v}}{Dt} = \nabla \cdot \boldsymbol{\sigma} + \mathbf{f}^b + \mathbf{f}^s \tag{7}$$

$$\rho \frac{Du}{Dt} = -\nabla \cdot \mathbf{q}, \; \mathbf{q} = \kappa \nabla T, \; c = \frac{\partial u}{\partial T}. \tag{8}$$

Here $\mathbf{f}^b$ is the material body force (e.g. gravity), $\mathbf{f}^s$ is stress applied along the material boundaries (e.g. wind and ocean drag), ρ is the mass density, $\mathbf{v}$ is the velocity, $\boldsymbol{\sigma}$ is the Cauchy stress, u is the stored heat enery per unit mass, T is the temperature, $\mathbf{q}$ is the heat flux, κ is the heat conductivity and c is the heat capacity per unit mass. The stress can often be expressed in terms of the potential energy density and its variation with flow map Jacobian. We will base this variation on a large-strain plastic decomposition of the motion in terms of elastic and plastic (permanent) parts. This mechanism is standard and consistent with the chemistry of plastic deformation. Mathematically we use the decomposition to satisfy a yield condition on the stress. We will design novel thermo-elastoplastic models capable of reproducing experimental observations of the formation of ridges and leads, ocean wave propagation in marginal ice zones, melt pond evolution and more. As noted by Hibler [54] and Feltham [37], sea ice constitutive modeling is an open and challenging area of research involving various aspects of engineering and physical and mathematical rigor. The constitutive model we use will be guided by literature (section 6.1) and new observational data. Teran *et al.* [41] have designed an elastoplastic formulation for snow and anticrack propagation in weak layers exhibited by remotely triggered avalanches (see Figure 2). This appeared in *Nature Comm.* and was recently highlighted in *Wired* Magazine. We will build on these efforts, adding viscous behaviour, to develop the proposed model.

To resolve sea ice as a mixture of air, water, snow and ice, we will also incorporate aspects of multi-species porous media. This requires some modifications to the governing equations where mixture theory is used to incorporate volume and mass fractions of the different species and to resolve the momentum, mass and energy exchanges. MPM is well suited for these types of problems, as Teran *et al.* have shown [126].

MPM discretization: In MPM, the discrete state consists of a collection of particles that partition the domain based on initial volumes, with discrete time sampled positions, masses, and linear, affine and polynomial velocities used for novel particle/grid transfers developed in [63, 39]. Each particle additionally stores the elastic portion of the deformation gradient and local yield surface properties. An MPM time step from time typically consists of three steps: (1) mass and momentum are transferred from particles to grid using weights defined by Eulerian grid interpolating functions that describe the degree of interaction between particles and grid nodes, (2) the grid momentum is then updated in a variational way from the potential energy in the system, and finally (3) the motion of the grid under the updated momentum is interpolated to the particles. In step (2), the deformation gradient is stored per particle and is updated using an updated Lagrangian view. With this assumption the deformation gradient is computed as the product of the time deformation gradient and the deformation of the grid over the time step which is naturally computed as the derivative of grid interpolating functions.

6.3 Homogenization of Multiscale Composites

Sea ice is a multiscale multiphase highly anisotropic composite material with complex structure on many length scales. Its rheological response depends on a variety of different factors [60, 32, 37], it varies with scale, the state of the microstructure as well as history of previous deformations and damage events. It also depends on the time of the season. For instance, the winter ice pack could be modeled as a solid plate with a random distribution of cracks, but in summer, the network of leads results in viscoplastic behavior.

Homogenization theory provides results that can be applied to sea ice at small scales. Sea ice is a polycrystalline composite material of pure ice with brine and air inclusions. The effective properties of such polycrystalline composites (or bounds for them) can be calculated using variational methods [50, 51, 108, 46, 18, 15, 86, 16] or Stieltjes integral representations [85, 64, 42, 43, 23]. Nonlinear homogenization methods have been developed [97, 99, 72] that use linear comparison media or estimate the effective behavior using low-order statistics of the microstructure [29]. These results should be incorporated into the mesoscale models that account for the relevant physics, geometries and thermodynamics as well as the modes of damage [54, 55, 14, 78]. For instance, in columnar ice, with highly anisotropic elongated grains which easily glide along basal planes [1, 35], this microstructure strongly influences the macroscopic response and the rheological properties of sea ice, as well as the direction and propagation of cracks.

7 Proposed Research

Sea ice and snow exhibit a broad range of rheological behaviors depending on length and time scale, temperature, forcing structure, and other factors. These complex media can maintain their shape elastically, but can also fracture, fail or even flow like a granular or fluid medium with sufficient loading. We will create a flexible, particle-based computational framework that can accurately simulate key sea ice processes and interactions, that is highly faithful to the physics, and can provide extremely realistic visual renderings. This framework will be able to encompass a range of relevant rheological behaviors, from fluid to solid, with temperature determining phase changes. We will develop a new thermo-mechanical model capable of producing simulations that accurately recreate – physically and visually – observed phenomena. We will develop novel Material Point Methods with unprecedented spatial and visual resolution to discretize our model. The MPM is a Particle-In-Cell technique designed for history dependent materials. It is very efficient for simulating elastoplastic and related rheologies, and it naturally resolves large deformation, plastic straining, fracture, failure, cracking and coupling with varied materials.

7.1 Dynamical Scenarios

We propose to investigate, in detail, several typical processes and scenarios in the dynamics and thermodynamics of Arctic sea ice. As we develop our MPM framework, these are the examples that we keep in mind

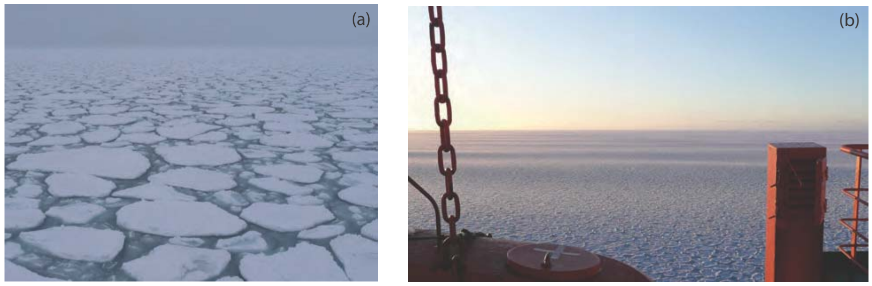

Figure 4: (a) Sea ice broken into floes in the marginal ice zone (Golden). The larger floes are 2 to 3 meters across, and are separated by frazil ice. (b) A field of pancake ice interacting with ocean swells in the marginal ice zone (Golden). The larger floes in the foreground are approximately 1 meter across.

to simulate and visualize with extreme accuracy and realism. The structures and scenarios we consider will serve as building blocks for larger scale models and simulations.

As a material, sea ice is a polycrystalline composite of pure ice with brine and air inclusions, with effective rheological properties depending on spatiotemporal scales. As winds or currents force sea ice convergence, pressure ridges form, and with divergence and shearing, leads open up. Here we propose to initially focus in on smaller intermediate spatiotemporal scales and consider the interaction of two or three floes on the scale of 10 m – 100 m each. With forces driving the floes together we will study in depth the process of floe collision, material failure, and pressure ridge formation. Likewise, with floes subjected to divergent or shearing forces, we will study the process of floe cracking, material failure, and lead formation.

A wave field can break up sea ice floes, or create large fields of "pancakes" that can accrete into large floes, as shown in Fig. 4. The interaction of ocean waves with sea ice in various forms is of great interest, and the mix of species (water, sea ice, snow, frazil, pancakes) and types of dynamics in these scenes is particularly well suited to the MPM framework we will develop. Subjecting a large unbroken floe to an incident ocean wave, where the floe may have uniform structure from quiescent congelation growth, or formed from "gluing" together smaller floes, will yield fascinating pattern and size distributions of broken pieces. By considering suspensions of frazil crystals in a wave field we will simulate the process of pancake formation, which is increasingly prevalent in the Arctic with increasing waves and areas of open ocean.

Typically, sea ice has a layer of snow on top which is important mechanically, thermally, and electromagnetically. The snow may be saturated with brine or sea water, like wet sand, and melting snow forms the iconic blue ponds on top of summer Arctic sea ice as in Figure 1. While numerical simulations of melt pond evolution used in large scale climate models keep track of melt water volume, they do not typically produce digital versions of melt ponds on Arctic sea ice that are physically and visually accurate representations of real ponds. With the thermo-mechanical MPM framework we propose, we will be able to simulate processes such as the evolution of melt ponds, the formation of snow-ice – the freezing of snow on the ice surface saturated with brine or sea water, and the break-up of rotted, highly porous sea ice saturated with melt water and sea water. We remark that by changing the range of scales and zeroing in on the brine microstructure over a sample of a few centimeters, we should be able to simulate – and visualize – the detailed thermal evolution of the brine microstructure and its geometrical and fluid transport characteristics [45].

7.2 Material Point Method for Sea Ice

While MPM has been used with great effect to simulate snow and other granular materials and mixtures, much work remains to develop a technique capable of achieving the realism desired for the proposed effort. The primary obstacles are (1) development of techniques capable of scaling up to hundreds of millions and even billions of particles, (2) development of novel rheological models, including homogenization considerations that are capable of simulating mixtures of air, water, ice and snow over a wide range of scales, including thermo-mechanical effects, (3) fitting parameters of these models to Arctic sea ice data generated from MOSAiC, SIDEx, and other sources.

Figure 5: MPM simulation: manycore. We simulate a cubic meter block of snow falling onto the ground with MPM. The simulation was run on an Intel Xeon E5-2690 V2 system with 20 threads and 128GB of RAM. Our techniques scale well up to 20 threads which allows us to simulate the block with a total of 610,000 particles. Our simulation was done with less than one particle per cubic centimeter.

Teran has developed many parallel computing techniques for MPM simulations. Indeed every paper written in the Teran Lab related to MPM uses either manycore or GPU level parallelism. Parallelism where kernels scale in tens of cores is necessary for running simulations at high resolution, with many hundreds of thousands up to a few tens of millions of particles. However, manycore and GPU approaches do not have sufficient cores or memory to run simulations at the scale desired in the proposed effort. For example, consider the simple one meter cubed block of snow simulated in Figure 5. 610,000 particles are used to represent the block, this is less than one particle per cubic centimeter. The bulk behavior on the scale of meters is resolved, however we would like to achieve resolution down to the sub-millimeter scale for simple scenarios such as this. Furthermore, at the centimeter scale, we would like to simulate many tens or hundreds of cubic meters of material. In order to provide this performance capablitiy, we will need to use HPC involving multiple machines. We will generalize prior approaches developed in the Teran Lab to this hardware setting and leverage resources at the UCLA IDRE and U. of Utah SCI computing centers.

While Teran and collaborators have developed techniques that include thermo-mechanical and multi-species effects, they have not done so with the level of complexity required in the proposed effort. Furthermore, inclusion of homogenization effects and non-continuum related aspects will require novel treatment. The Teran lab will use much of their existing computing infrastructure to provide this functionality, however many novel algorithmic and modeling advances will be required. The Teran Lab's existing computing experience and computing infrastructure will provide a strong starting point for these developments.

In order to develop models and simulation techniques capable of reproducing ice floes, ridging, cracking and related phenomena, our models will have to have many tens or even hundreds of rheological parameters. While the flexibility engendered by a wide range of parameters is necessary, it comes at the cost of complicating the process of fitting the model to data. We will have access to a wide range of kinematic and physical data from the MOSAiC and SIDEx projects and it will be critically important that we can choose our parameters so that we can reproduce the observed data. We will address this with traditional approaches such as casting the parameter estimation as an optimization problem as well as using more modern promising ideas such as machine learning enhanced fitting.

7.3 Visualization of Dynamical Processes

We will develop ultra-realistic visualizations of sea ice, snow and water simulations. Teran has many years of experience producing visualization of MPM simulation data that are nearly photo-real. Indeed Teran's MPM simulations have been used in a number of Walt Disney motion pictures, including Frozen, Moana, and Zootopia. We will use the same techniques in the proposed effort that were used to render scenes for the motion picture industry. To achieve maximal realism in rendering, we will use the latest advances from the computer graphics literature related to ray tracing, including global illumination, photon maps, depth of field, ambient occlusion, glossy reflections, soft shadows and bloom. We will use the Mental Ray ray tracer to achieve this. Teran's students are experts at using these techniques and software. The images in Figures 2 and 5 were rendered by Teran's group using these approaches.

MPM is a particle method, and this can pose some challenges for rendering. Typically, there are three options for rendering this type of data: (1) render the raw simulation particles as tiny spheres, (2) splat the particles to a regular grid to define a density function and render based on a light ray's occlusion with this field, (3) wrap a surface (implicit or explicit) around the particles and render the surface. Option (1) is appropriate for dry snow and sand, but looks too particulate for cohesive, wetter snow. (2) was used in Figures 2 and 5. (3) is more appropriate for water. Part of our efforts will be in developing new options that increase the achievable visual realism. Teran's group has recently made great progress in this for ductile materials, which may lead to rendering techniques for brittle ice, snow and water in close proximity.

7.4 Homogenization for Multiscale Building Blocks in the Material Point Method

As a multiphase anisotropic composite with complex structure on many length scales, sea ice has different effective properties on different scales and different discretization levels. We propose to develop a multiscale iterative homogenization approach for calculating the properties of the ice "blocks" needed in MPM simulations, over a range of resolutions, or block sizes.

The effective properties on smaller scales will be obtained by analytical and computational homogenization methods [125, 12, 18, 95, 75, 94], yielding effective parameters depending on the microgeometry: volume fraction, shape and orientation of brine inclusions, distribution of the polycrystalline c-axes, and account for viscoelastic properties [19, 23] and a nonlinear dilatational response [98, 116, 29].

To help simulate floe collisions, fractures, ridge and lead formation, and to inform our MPM development, we propose to develop a numerical multiscale approach based on upscaling the behavior of the inhomogeneous sea ice composite accumulating microdamage on different scales. This damage accumulation can be incorporated into the MPM calculations through the internal variables evolving in time; such evolution can be modeled using a system of differential equations that is solved at each time iteration step [30, 13, 103, 139, 82, 22]. The coefficients of the ODE system are determined by the parameters of the spectral measure in the Stieltjes representation of the effective properties [22]. This spectral measure μ contains all information about the structure of the composite [42, 20]. We propose to investigate the evolution of μ due to the evolution of the structure of the ice, due to fracture, creep and viscoplasticity, as well as healing of ice (e.g. refreezing leads). This will provide a link between the evolutionary processes that release or dissipate energy and the internal variables used in the upscaled simulation with the MPM method.

The model for damage accumulation and criteria for the propagation of damage and cracks will be developed based on the previous work for damage accumulation and propagation in nonlinear lattice structures [17, 115]. To facilitate the numerical modeling of the dynamics of ice floes, we will build a model of large scale crack propagation using a stochastic description of inhomogeneous ice structure that might be influenced by the thickness, cracks, leads, and ridges. If we view large floes as inhomogeneous structures "glued" together from smaller floes whose size distribution statistics we have [105, 129, 58, 59] then the locations of potential cracks in the large floe can be modeled as a weakened random 'pre-crack' network. Under compressive loadings [135], the ice floes experience frictional sliding and ridging which results in viscoelastic or viscoplastic deformation. We will develop criteria for the opening of leads and the dynamics of ice breakage due to various impacts based on partial damage accumulation. Using accurate forcing MPM simulation data and incorporating a fracture model, we will determine the conditions for ridge initiation, formation, and evolution. This will also lead to a model of ridges and rafting resulting from a fracture due to buckling of a thin compressed plate.

7.5 Field Data on Dynamic Sea Ice Processes

High quality data is critical to the success of this project. MOSAiC will be a major real-time source of this data (https://www.mosaic-expedition.org/). MOSAiC is a large, international, interdisciplinary program with a central scientific question of "What are the causes and consequences of an evolving and diminished Arctic sea ice cover." The centerpiece of MOSAiC is a yearlong drift experiment in the Central Arctic from

Sept. 2019 to Sept. 2020.

MOSAiC will provide an extraordinary data set covering a range of spatial scales over an entire annual cycle. The sea ice observations will encompass spatial scales from computer tomography of sea ice microstructure to satellite observations. MOSAiC will focus on three spatial scales; the Central Observatory (mm to km), the Distributed Network (km to tens of km), and the large scale (tens of km to thousands of km). Measurements will be made over an entire annual cycle. Sea ice measurements of particular value to our project (on various scales) include:

- 3-D maps of ice microstructure (sub-mm)
- Snow stratigraphy (millimeter)
- Surface topography maps (kilometers)
- Ridges: number, shape, spacing (tens of km)
- Floes: size and shape (tens of km)
- High resolution ice deformation (tens of km)
- Electromagnetic signatures (kilometers)
- Sea ice porosity (millimeter)
- Snow depth surveys (kilometers)
- Ice thickness surveys (thousands of km)
- Leads: number, shape, spacing (tens of km)
- Ponds: number, size, geometry (10s of km)
- Internal ice stress (kilometers)
- Partitioning of solar radiation (kilometers)

The SIDEx field campaign will track ice pack stress and strain fields on scales from sub-meter to the interaction of floes in the consolidated ice pack. As in MOSAiC, the ice drift, thickness, snow cover, snow stratigraphy and topography will be monitored. We will also be obtaining high resolution video and images of various sea ice scenes of interest.

7.6 Assimilation of Data from Field Experiments

The physical model for sea ice will vary with many rheological parameters related to various modes of stress generation. In order to develop a model with sufficient ability to reproduce the many desired modes of deformation, failure and cohesion, it will be necessary to have many tens of parameters. While this will make the models flexible in terms of the phenomena they can recreate, it also makes fitting the parameters to observed data much more difficult.

We will have many types of data available to us, and it is vitally important that we can determine the appropriate rheological parameters to reproduce them. This can be done in many ways, but in most cases it is very useful to differentiate the simulated configurations of the material with respect to rheological parameters. Teran and collaborators [27] recently generated a technique for estimating elasticity related paramaters for Kirchhoff-Love thin shell models utilizing an orthotropic hyperelastic assumption. The orthotropic model was designed to be flexible enough to capture modes of stress and strain exhibited by woven fabrics like denim, and silk. From a set of simple laboratory measurements, Teran and colleagues developed a method for determining tens of parameters needed to match observed stress-strain curves from data. This was done by penalizing the least squares deviation in the simulated result from the observed data.

Different smoothing (quadratic) and non-smoothing (total variation) penalization functionals were studied in [6] in applications to an inverse geophysical problem of fitting the parameters of the subsurface to the data measured on the surface of the earth. Reconstruction of spatially varying rheological parameters which requires fitting many hundreds of parameters to observed data can use model order reduction techniques [67, 68] originally developed by Cherkaev and collaborators [69, 70] for magnetotelluric imaging problem.

To provide a more accurate estimate for the rheological parameters, we will use the inverse bounds approach [24] developed by Cherkaev and Golden for evaluation of microstructural parameters of composites. This method takes measurements of the effective properties of composite materials and produces rigorous bounds for the geometric parameters and other properties of the composite [20, 21, 26]. This inverse homogenization approach is based on the reconstruction of the spectral measure in the Stieltjes integral representation for the effective properties of the composite material [20, 22, 25, 138]. The method has been used with complex permittivity data to recover brine porosity in sea ice [24, 93] and connectivity in human bone [8, 47]. Moreover, this approach was extended to polycrystalline materials and tested on sea ice data [48, 83]. An extension of this approach to elasticity was developed and applied to viscoelastic shear modulus measurements for the reconstruction of bone properties and geometric parameters [7, 9, 23].

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[119] A. Stomakhin, C. Schroeder, C. Jiang, L. Chai, J. Teran, and A. Selle. Augmented MPM for phase-change and varied materials. *ACM Trans Graph*, 33(4):138:1–138:11, 2014.

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[121] C. Strong and K. M. Golden. Filling the polar data gap in sea ice concentration fields using partial differential equations. *Remote Sensing*, 8:442 – 451, 2016.

[122] C. Strong and K. M. Golden. Filling the sea ice data gap with harmonic functions. *SIAM News*, 50, 2017.

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

Professional Preparation

Dartmouth College	Mathematics and Physics	B.A.	1980
New York University	Mathematics	M.S.	1983
New York University	Mathematics	Ph.D.	1984
Rutgers University	NSF Mathematical Sciences Postdoctoral Fellow		1984–1987

Appointments

2017–	Distinguished Professor of Mathematics, University of Utah
2007–	Adjunct Professor of Biomedical Engineering, University of Utah
1996–2017	Professor of Mathematics, University of Utah
1991–1996	Associate Professor of Mathematics, University of Utah
1987–1991	Assistant Professor of Mathematics, Princeton University

Publications Most Closely Related

1. Y. Ma, I. Sudakov, C. Strong, and K. M. Golden, Ising model for melt ponds on Arctic sea ice, *New Journal of Physics* 21, 063029, 9 pp., 2019.
2. N. B. Murphy, E. Cherkaev, J. Zhu, J. Xin, and K. M. Golden, Spectral analysis and computation for homogenization of advection diffusion processes in steady flows, *Journal of Mathematical Physics*, in press, 36 pp., 2019.
3. B. Bowen, C. Strong, and K. M. Golden, Modeling the fractal geometry of Arctic melt ponds using the level sets of random surfaces, invited, *Journal of Fractal Geometry* 5, 121-142, 2018.
4. C. Polashenski, K. M. Golden, D. K. Perovich, E. Skyllingstad, A. Arnsten, C. Stwertka, and N. Wright, Percolation blockage: A process that enables melt pond formation on first year Arctic sea ice, *Journal of Geophysical Research* (*Oceans*) 122, 28 pp., 2017.
5. K. M. Golden, H. Eicken, A. L. Heaton, J. Miner, D. Pringle, and J. Zhu, Thermal evolution of permeability and microstructure in sea ice, *Geophys. Res. Lett.* 34, L16501, cover, 2007.

Other Significant Publications

1. K. M. Meiners, K. M. Golden, P. Heil, J. L. Lieser, R. Massom, B. Meyer, G. D. Williams, SIPEX-2: A study of sea-ice physical, biogeochemical and ecosystem processes off East Antarctica during spring 2012, *Deep Sea Res. II: Top. Studies Oceanography* 131, 1-6, 2016.
2. C. Strong and K. M. Golden, Filling the polar data gap in sea ice concentration fields using partial differential equations, invited, *Remote Sensing* 8(6), 442-451, 2016.
3. K. M. Golden, Mathematics of sea ice, invited, *The Princeton Companion to Applied Mathematics*, N. J. Higham (Ed.), M. R. Dennis, P. Glendinning, P. A. Martin, F. Santosa, and J. Tanner (Assoc. Eds.), Princeton University Press, 694-705, 2015.
4. A. Gully, J. Lin, E. Cherkaev, K. M. Golden, Bounds on the complex permittivity of polycrystalline composites by analytic continuation, *Proc. Roy. Soc. A* 471, 17 pp., cover, 2015.
5. K. M. Golden, S. F. Ackley and V. I. Lytle, The percolation phase transition in sea ice, *Science* 282, 2238-2241, 1998.

Synergistic Activities

- **Polar expeditions.** I have traveled to the polar regions eighteen times to study sea ice and its role in the climate system – seven to Antarctica and eleven to the Arctic. I have been involved in observations and measurements of the growth and melting of sea ice, its polycrystalline and brine microstructures, as well as dynamic and thermodynamic processes. I've conducted experiments on the fluid and electromagnetic transport properties of sea ice, microwave backscatter experiments, and helped develop electromagnetic tomographic methods for recovering sea ice properties. I have brought a number of undergraduates, graduate students, and postdoctoral fellows on these expeditions to assist in the field work.

- **Media coverage.** My mathematical sea ice research and expeditions have been featured in over 55 newspaper, magazine, and web articles, including profiles in *Science*, *Science News*, *Scientific American*, and *Physics Today*. I have been interviewed about 20 times on radio, television, and the web, and featured in videos produced by NSF, SIAM, and NBC News.

- **Scientific and general audience lectures.** Given over 400 invited lectures on 6 continents, including three presentations in the U.S. Congress, many plenary and keynote addresses, as well as lectures for the general public, student groups, and business leaders. My recent public lectures have included the following: 2019 Community Talk, Workshop on *Mathematical Models For Pattern Formation*, Carnegie Mellon University; 2018 Dartmouth's 250th Anniversary; 2018 Friends of Math Lecture, Kansas State University; 2017 ICERM Public Lecture, Brown University; 2015 First National Math Festival, Smithsonian Institution, Washington D.C.; 2014 *Math Encounter* at the National Museum of Mathematics in NYC; 2013 MAA-AMS-SIAM Gerald and Judith Porter Public Lecture at the Joint Math Meetings in San Diego; 2013 Inaugural Bernoulli Society Public Lecture at the 36th Conference on Stochastic Processes and their Applications in Boulder.

- **Outreach and organizational service.** Coordinator, Mathematics Week of ACCESS Summer Program for First Year Undergraduate Women entering the University of Utah in Science, Math and Engineering 2018, 2019; Chair, American Mathematical Society Committee on Science Policy, 2012−2013; Chair, Committee for Math Awareness Month 2009, *Mathematics and Climate*, Joint Policy Board for Mathematics (AMS, SIAM, ASA, MAA); Director of Undergraduate Studies, U. of Utah Math Dept. 2002 − 08; Research Experiences for Undergraduates (REU) Program Coordinator, U. of Utah Math Dept. 2003 − 07; Modeling Coordinator (overseeing theoretical research) for Office of Naval Research Accelerated Research Initiative on Sea Ice Electromagnetics, 1992-98. Organized or co-organized 30 conferences, workshops, and minisymposia on sea ice, composite materials, inverse problems, and climate change.

- **Recognition of broader impact and knowledge transfer.**

  2014 Fellow of the Explorers Club (Members have included Armstrong, Peary, Goodall.)

  2014 United States Coast Guard Arctic Service Medal

  2013 Inaugural Fellow of the American Mathematical Society (AMS)

  2012 Myriad Award for Research Excellence, U. of Utah, for fostering undergraduate research.

  2011 Fellow of the Society for Industrial and Applied Mathematics (SIAM), for "extraordinary interdisciplinary work on the mathematics of sea ice."

  2009 Houghton Lecturer, Department of Earth, Atmospheric and Planetary Sciences, MIT

  2007 University Distinguished Teaching Award, University of Utah

  1996 Fellow of the Electromagnetics Academy

Elena Cherkaev www.math.utah.edu/∼elena

Professional Preparation

St. Petersburg State University	Russia	Applied Mathematics	B.S/M.S.	1978
St. Petersburg State University	Russia	Applied Mathematics	Ph.D.	1988
Academy of Sciences of U.S.S.R.	Russia	Applied Mathematics	Postdoc	1988 – 1991

Appointments

2007 - present: Adjunct Professor, Department of Bioengineering, University of Utah
2004 - present: Professor, Department of Mathematics, University of Utah
2003 - 2004: Research Professor, Department of Mathematics, University of Utah
1996 - 2003: Research Associate Professor, Department of Mathematics, University of Utah
1998 - 2003: Adjunct Associate Professor, Department of Geophysics, University of Utah
1993 - 1998: Adjunct Assistant Professor, Department of Geophysics, University of Utah
1992 - 1993: Associate Scientist, Earth Science Lab, University of Utah Research Institute
1991 - 1992: Adjunct Instructor, Courant Institute of Mathematical Sciences, New York University

Publications Most Closely Related

1. N.B. Murphy, E. Cherkaev, J. Zhu, J. Xin, K.M. Golden, Spectral analysis and computation for homogenization of advection diffusion processes in steady flows, *Journal of Mathematical Physics*, in press, 36 pp., 2019.
2. E. Cherkaev, Internal friction and the Stieltjes analytic representation of the effective properties of two-dimensional viscoelastic composites, *Arch. Appl. Mech.*, 2019, 89, 3, 591-607.
3. M-J. Ou, E. Cherkaev, On the integral representation formula for a two-component elastic composite, *Mathematical Methods in the Applied Sciences*, 2006, 29, 6, 655-664.
4. N.B. Murphy, E. Cherkaev, C. Hohenegger, K.M. Golden, Spectral measure computations for composite media, *Communications Mathematical Sciences*, 2015, 13, 4, 827-864.
5. E. Cherkaev, Inverse homogenization for evaluation of effective properties of a mixture, *Inverse Problems*, 2001, 17, 1203-1218.

Other Significant Publications

1. N. Wellander, S. Guenneau, E. Cherkaev, Two-scale cut-and-projection convergence; homogenization of quasiperiodic structures, *Mathematical Methods in the Applied Sciences*, 2018, 41(3), 1101-1106.
2. N.B. Murphy, E. Cherkaev, J. Zhu, J. Xin, K.M. Golden, Spectral analysis and computation of effective diffusivities in space-time periodic incompressible flows, *Annals of Mathematical Sciences and Applications*, 2017, 2(1), 3-66.
3. N.B. Murphy, E. Cherkaev, K.M. Golden, Anderson transition for classical transport in composite materials, *Phys. Rev. Lett.*, 2017, 118, 036401.
4. M. Kordy, P. Wannamaker, V. Maris, E. Cherkaev, G. Hill, 3-D magnetotelluric inversion including topography using deformed hexahedral edge finite elements and direct solvers parallelized on SMP computers - Part I: forward problem and parameter Jacobians, Part II: direct data-space inverse solution, *Geophysical J. International*, 2016, 204(1), 74-93, 94-110.
5. M. Kordy, E. Cherkaev, P. Wannamaker, Null space correction and adaptive model order reduction in multi-frequency Maxwell's problem, *Advances in Computational Mathematics*, 2017, 43(1), 171-193.

Synergistic Activities

- **Organizational service:** SIAM AG on Mathematical Aspects of Materials Science, Secretary, 2017-18; Executive / Scientific Advisory Committee Member: ETOPIM Society (Electrical Transport and Optical Properties of Inhomogeneous Media); Herglotz-Nevanlinna functions and their applications to dispersive systems and composite materials, 2020; Member of Organizing Committees: ETOPIM, 2018; Workshop Bone tissue: Multiscale simulation, 2010; Inverse Problems, Homogenization and Related Topics in Analysis, 2007; Co-organizer of special sessions and minisymposia: on Linking Scales in Earth's Sea Ice System SIAM Conf. on Mathematics of Planet Earth, 2018; Herglotz-Nevanlinna Function Theory and its Applications, ETOPIM, 2018; on Inverse Problems, Homogenization, Optimal design, AMS 2011; on Computational Methods in Large-scale & Multiscale Inverse Problems at the Internat. Congress Industrial Applied Mathematics (ICIAM) meetings. Co-organizer and Lecturer at VIGRE Mini-courses in the Dept. Mathematics, University of Utah: Waves in Inhomogeneous Media; Nonconvex Variational Problems and Applications.

- **Selected talks (from more than 200) given as Plenary/Keynote/Invited Speaker.** Invited Lecturer at the European Doctoral School on Metamaterials Marseille, France, 2017. Herglotz-Nevanlinna Theory Applied to Passive, Causal and Active Systems, Banff, Canada, 2019; Workshop Herglotz-Nevanlinna Functions and Applications, Institute Mittag-Leffler, Sweden, 2017; Workshop Computational Inverse Problems for Partial Differential Equations, the Mathematisches Forschungsinstitut Oberwolfach, Germany, 2017.

  Plenary Speaker: Workshop on Physics and Mechanics of Random Structures, Oleron, France, 2018; Multiscale Problems in Materials and Biology, The Fields Institute for Research in Math. Sciences, 2018; ETOPIM, Krakow, Poland, 2018, Israel, 2015; Marseille, 2012; Workshop on Interdisciplinary Mathematics, Penn State, 2015; Mathematics of Metamaterials, 2016; Diff. Equations and Dynamical Systems, 2012.

  Keynote and Invited speaker: Symposium Bridging scales: homogenization and related topics in solid mechanics and crystal plasticity, 2017; Workshop Dynamic Phenomena in Media with Microstructure, 2018; Composites, Metamaterials, and Inverse Problems, South Korea, 2016. ICIAM meetings, 2019, 2015, 2011, 2007, 2003, 1999; SIAM MS Math. Aspects of Materials Science, 2018, 2016, 2013, 2010, 2004, 2000, 1997; SIAM MPE, 2018; SIAM PDE 2015; SIAM Annual meetings 2018, 2014; AMS meetings: Maine, 2016; Louisville, 2013; Salt Lake City, 2011; 2006; Miami, FL, 2006; Eugene, OR, 2005; Continuum Models and Discrete Systems, 2014; Workshop Exotic Structures and Homogenization, 2012; Applied Inverse Problems, 2011; ASME, 2015, 2013, 2011; European Solid Mechanics Conference, 2018; MCIAM Workshop on Inverse Problems, MSU, 2010; Intern. Conf. Advances in Continuum Mechanics and Thermodynamics, Germany, 2010; Intern. Symposium Electromagnetic Theory Germany, 2010; Meetings on Comp. Mechanics: SES, IUTAM, WCSMO, USNCTAM.

- **Outreach, Mentoring, Advising.** Director of Graduate Studies, U. of Utah, Math Dept.. I mentored 5 Ph.D. students, 5 postdocs, 15 M.S. students, more than 20 undergraduate (REU, honors, and underrepresented) students. Among them, 15 are female students.

- **Broader impact service.** Curriculum developer for applied math track masters program and masters in science and technology program. Track Director, Professional Master of Science and Technology Program, Computational and Data Science Track, U. of Utah; Guest editor: Mechanics of Materials, Special Issue, 2009; AWM sponsor of UU Student AWM Chapter 2004-2011; UU College of Science Women & Minorities Task Force Committee member, 2008; ACCESS Panel Women in Mathematics, U. of Utah, 2009.

Joseph Teran

PROFESSIONAL PREPARATION

UC Davis	Davis, California	Mathematics	B.S., 2000.
Stanford University	Stanford, California	Scientific Computing	Ph.D., 2005.
New York University	New York, New York	Applied Mathematics	2005-2007.

APPOINTMENTS

Professor, Department of Mathematics, UCLA, 2013-present.

Associate Professor, Department of Mathematics, UCLA, 2010-2013.

Assistant Professor, Department of Mathematics, UCLA, 2007-2010.

PRODUCTS/PUBLICATIONS

- Q. Guo, X. Han, C. Fu, T. Gast, R. Tamstorf, J. Teran, *A Material Point Method for Thin Shells with Frictional Contact*, ACM Transactions on Graphics (SIGGRAPH 2018), 37(4), pp. 147:1-147:15, 2018.
- M. Royston, A. Pradhana, B. Lee, Y. Chow, W. Yin, J. Teran, S. Osher, *Parallel Redistancing using the Hopf-Lax Formula*, Journal of Computational Physics, 365(1), pp. 7-17, 2018.
- C. Fu, Q. Guo, T. Gast, C. Jiang, J. Teran, *A Polynomial Particle-In-Cell Method*, ACM Transactions on Graphics (SIGGRAPH Asia 2017), 36(6), pp. 222:1-222:12, 2017.
- D. Clyde, J. Teran, R. Tamstorf, *Modeling and Data-Driven Parameter Estimation for Woven Fabrics*, ACM SIGGRAPH/Eurographics Symposium on Computer Animation (SCA), pp. 1-11, 2017.
- C. Jiang, T. Gast, J. Teran, *Anisotropic Elastoplasticity for Cloth, Knit and Hair Frictional Contact*, ACM Transactions on Graphics (SIGGRAPH 2017), 36(4), pp. 152:1-152:14, 2017.
- A. Pradhana, T. Gast, G. Klar, C. Fu, J. Teran, C. Jiang, K. Museth, *Multi-species Simulation of Porous Sand and Water Mixtures*, ACM Transactions on Graphics (SIGGRAPH 2017), 36(4), pp. 105:1-105:12, 2017.
- C. Jiang, C. Schroeder, J. Teran, *An Angular Momentum Conserving Affine-Particle-In-Cell Method*, Journal of Computational Physics, 338(1), pp. 137-164, 2017.
- G. Klar, T. Gast, A. Pradhana, C. Fu, C. Schroeder, C. Jiang, J. Teran, *Drucker-Prager Elastoplasticity for Sand Animation*, ACM Transactions on Graphics (SIGGRAPH 2016), 35(4), pp. 103:1-103:12, 2016.
- T. Gast, C. Schroeder, A. Stomakhin, C. Jiang, J. Teran *Optimization Integrator for Large Time Steps*, IEEE Transactions on Visualization and Computer Graphics, 21(10) pp. 1103-1115, 2015.

- D. Ram, T. Gast, C. Jiang, C. Schroeder, A. Stomakhin, J. Teran, P. Kavehpour *A Material Point Method for Viscoelastic Fluids, Foams and Sponges*, ACM SIGGRAPH/Eurographics Symposium on Computer Animation (SCA), pp. 157-163, 2015.

SYNERGISTIC ACTIVITIES

1. Organizer for 2017 ACM SIGGRAPH/Eurographics Symposium on Computer Animation
2. Papers committee member, 2018 ACM SIGGRAPH Asia
3. Papers committee member, 2010, 2014 ACM SIGGRAPH
4. Member human resources committee, MSRI
5. Reviewer for Journal of Computational Physics, International Journal of Numerical Methods in Engineering, SIAM.

Jennifer Katy Hutchigns https://ceoas.oregonstate.edu/profile/hutchings

Professional Preparation

University College London	Physics	B.Sc.	1996
University College London	Remote Sensing	Ph.D.	2001
University of Alaska Fairbanks	Sea Ice Modeling	Post Doc.	2001–2005

Appointments

2019–	Associate Professor, Oregon State University
2013–2019	Assistant Professor, Oregon State University
2008–2013	Research Assistant Professor, University of Alaska Fairbanks
2005–2008	Research Associate, University of Alaska Fairbanks
2001–2005	Postdoctoral Researcher, University of Alaska Fairbanks
2000-2001	Research Scientist, The Met Office (UK)

Publications Most Closely Related

1. Lewis, B. J., Hutchings, J. K. Leads and Associated Sea Ice Drift in the Beaufort Sea in Winter. *Journal of Geophysical Research (Oceans)*, 124(5), 3411-3427, 2019.
2. Kohout, A. L., Williams, M. J. M., Toyota, T., Lieser, J., Hutchings, J. In situ observations of wave-induced sea ice breakup. *Deep Sea Research Part II: Topical Studies in Oceanography*, 131: 22-27, 2016.
3. Hutchings, J. K., D. K. Perovich. Preconditioning of the 2007 sea ice melt in the eastern Beaufort Sea. *Anns. Glaciol.* 10.3189/2015AoG69A006, 2015
4. Hutchings, J.K., Heil P., Steer A., Hibler W.D., Subsynoptic scale spatial variability of sea ice deformation in the western Weddell Sea during early summer. *Journal of Geophysical Research (Oceans)*, 117(C1), 2012.
5. Hutchings, JK, Roberts A, Geiger C, Richter-Menge J., Spatial and temporal characterisation of sea ice deformation. *Annals of Glaciology*, 52(57), 360-368, 2011.

Other Significant Publications

1. Farmer, L., A. Cowen, J.K. Hutchings, D. K. Perovich. Citizen scientists train a thousand eyes on the pole, *EOS*, 97, doi:10.1029/2016EO054989, 2016.
2. Vivier, F., Hutchings, J. K., Kawaguchi, Y., Kikuchi, T., Morison, J. H., Loureno, A., Noguchi, T. Sea ice melt onset associated with lead opening during the spring/summer transition near the North Pole. *Journal of Geophysical Research (Oceans)*, 121(4), 2499-2522, 2016.
3. Hutchings, J.K., Rigor I.G., Role of ice dynamics in anomalous ice conditions in the Beaufort Sea during 2006 and 2007. *Journal of Geophysical Research (Oceans).* 117, 2012.
4. Hutchings, J. K. , P. Heil, W. D. Hibler III, On modelling linear kinematic feature in sea ice. *Monthly Weather Review*, (12):3481-3497, 2005.
5. Hutchings, J. K. , H. Jasak, S. W. Laxon, A Strength Implicit Correction Scheme for the Viscous-Plastic Sea Ice Model. *Ocean Modelling*, (7): 111-133, 2004.

Synergistic Activities

- **Polar expeditions.** Hutchings has participated in polar sea ice field work (8 summer cruises, 1 winter cruise, 2 ice camps) since 1999. In spring 2007 she was the chief scientist of the Applied Physics Laboratory Ice Station (APLIS), an ice camp in the Beaufort Sea. She is on the U.S. leadership team, leads the sea ice dynamics group and is coordinating ship bridge observation for the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) field campaign. She is a co-lead on the ONR funded Sea Ice Dynamics Experiment (SIDEx) field project.

- **Citizen Science.** Jennifer developed Ice Watch, a program to standardize and archive Arctic ship based sea ice observations, and initiated a citizen science program for sea ice observations. She now shares leadership with Penny Wagner, at the Meteorological Office in Norway (MetNo). The Ice Watch program is currently being transferred from the University of Alaska Fairbanks to MetNo. https://sites.google.com/a/alaska.edu/ice-watch/

- **Education.** She maintains an active involvement in scientific education through attending teacher workshops, K-12 lesson development following national curriculum standards, visits to local schools to discuss polar science with elementary school children, and presentation for specialized audiences such as local engineering chapters. She has been an undergraduate research advisor for 10 students between 2005 and present, has been primary advisor for 2 graduate students and post-doctoral mentor for 3.

- **Conference Sessions and Workshops.** She led a community workshop, Sea Ice Mass Budget of the Arctic, in 2005. The discussions at this workshop have been incorporated into the Study of Environmental Arctic Change (SEARCH), International Polar Year and Arctic Observing Network planning. Organized 6 conference sessions at the American Geophysical Union Fall Meeting or International Glaciological Society Conferences.

- **Editing.** She was associate editor for Journal of Geophysical Research (2009-2014) and for Frontiers in Earth Science: Cryospheric Sciences (2015-2018), has been guest editor for Annuals of Glaciology (2010) and Polar Science (2013); and is now an editor for The Cryosphere (2016-present).

SUMMARY PROPOSAL BUDGET

YEAR 1

ORGANIZATION: **University of Utah**				FOR NSF USE ONLY: PROPOSAL NO.	DURATION (months): Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: **Kenneth M Golden**				AWARD NO.		
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months: CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)	
1. **Kenneth M Golden - Distinguished Professor**	0.00	0.00	1.00	21,147		
2. **Elena A Cherkaev - Professor**	0.00	0.00	1.00	13,648		
3.						
4.						
5.						
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0		
7. (2) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	2.00	34,795		
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. (0) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	0		
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0		
3. (1) GRADUATE STUDENTS				20,000		
4. (0) UNDERGRADUATE STUDENTS				0		
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0		
6. (0) OTHER				0		
TOTAL SALARIES AND WAGES (A + B)				54,795		
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				13,830		
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				68,625		
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)						
TOTAL EQUIPMENT				0		
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				5,000		
2. INTERNATIONAL				5,000		
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 8,000 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 6,214						
TOTAL NUMBER OF PARTICIPANTS (4) TOTAL PARTICIPANT COSTS				14,214		
G. OTHER DIRECT COSTS						
1. MATERIALS AND SUPPLIES				3,000		
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				1,500		
3. CONSULTANT SERVICES				0		
4. COMPUTER SERVICES				0		
5. SUBAWARDS				0		
6. OTHER				0		
TOTAL OTHER DIRECT COSTS				4,500		
H. TOTAL DIRECT COSTS (A THROUGH G)				97,339		
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **MTDC (Rate: 52.5000, Base: 83125)**						
TOTAL INDIRECT COSTS (F&A)				43,641		
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				140,980		
K. FEE				0		
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				140,980		
M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $					
PI/PD NAME: **Kenneth M Golden**				FOR NSF USE ONLY: INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*				Date Checked	Date Of Rate Sheet	Initials - ORG

 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

TPI: 8009618

SUMMARY PROPOSAL BUDGET

YEAR 2

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months)	
	Proposed	Granted
AWARD NO.		

ORGANIZATION
University of Utah

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Kenneth M Golden

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Kenneth M Golden - Distinguished Professor	0.00	0.00	1.25	27,227	
2. Elena A Cherkaev - Professor	0.00	0.00	1.00	14,057	
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (2) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	2.25	41,284	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (1) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	26,000	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (1) GRADUATE STUDENTS				20,000	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				87,284	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				25,917	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				113,201	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				5,000	
2. INTERNATIONAL				6,000	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 8,000 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 6,214					
TOTAL NUMBER OF PARTICIPANTS (4) TOTAL PARTICIPANT COSTS				14,214	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				3,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				3,000	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				0	
TOTAL OTHER DIRECT COSTS				6,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				144,415	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) MTDC (Rate: 52.5000, Base: 130201)					
TOTAL INDIRECT COSTS (F&A)				68,356	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				212,771	
K. FEE				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				212,771	

M. COST SHARING PROPOSED LEVEL $ 0 AGREED LEVEL IF DIFFERENT $

PI/PD NAME
Kenneth M Golden

ORG. REP. NAME*

FOR NSF USE ONLY		
INDIRECT COST RATE VERIFICATION		
Date Checked	Date Of Rate Sheet	Initials - ORG

 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

SUMMARY PROPOSAL BUDGET YEAR 3

ORGANIZATION: **University of Utah**				FOR NSF USE ONLY	
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: **Kenneth M Golden**				PROPOSAL NO. / AWARD NO.	DURATION (months): Proposed / Granted

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Kenneth M Golden - Distinguished Professor**	0.00	0.00	1.25	**28,044**	
2. **Elena A Cherkaev - Professor**	0.00	0.00	1.00	**14,479**	
3.					
4.					
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	**0**	
7. (**2**) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	2.25	**42,523**	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**1**) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	**26,000**	
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	**0**	
3. (**1**) GRADUATE STUDENTS				**20,000**	
4. (**0**) UNDERGRADUATE STUDENTS				**0**	
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				**0**	
6. (**0**) OTHER				**0**	
TOTAL SALARIES AND WAGES (A + B)				**88,523**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				**26,338**	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				**114,861**	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				**0**	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				**5,000**	
2. INTERNATIONAL				**6,000**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **8,000** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **6,214**					
TOTAL NUMBER OF PARTICIPANTS (**4**) TOTAL PARTICIPANT COSTS				**14,214**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**3,000**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**3,000**	
3. CONSULTANT SERVICES				**0**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**0**	
TOTAL OTHER DIRECT COSTS				**6,000**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**146,075**	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **MTDC (Rate: 52.5000, Base: 131861)**					
TOTAL INDIRECT COSTS (F&A)				**69,227**	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**215,302**	
K. FEE				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				**215,302**	
M. COST SHARING PROPOSED LEVEL $ **0**	AGREED LEVEL IF DIFFERENT $				

PI/PD NAME: **Kenneth M Golden**	FOR NSF USE ONLY		
	INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

TPI: 8009618

SUMMARY PROPOSAL BUDGET

Cumulative

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months)	
	Proposed	Granted
AWARD NO.		

ORGANIZATION
University of Utah

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Kenneth M Golden

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Kenneth M Golden - Distinguished Professor	0.00	0.00	3.50	76,418	
2. Elena A Cherkaev - Professor	0.00	0.00	3.00	42,184	
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (2) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	6.50	118,602	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (2) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	52,000	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (3) GRADUATE STUDENTS				60,000	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				230,602	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				66,085	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				296,687	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				15,000	
2. INTERNATIONAL				17,000	
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS $ 24,000					
2. TRAVEL 0					
3. SUBSISTENCE 0					
4. OTHER 18,642					
TOTAL NUMBER OF PARTICIPANTS (12) TOTAL PARTICIPANT COSTS				42,642	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				9,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				7,500	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				0	
TOTAL OTHER DIRECT COSTS				16,500	
H. TOTAL DIRECT COSTS (A THROUGH G)				387,829	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS (F&A)				181,224	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				569,053	
K. FEE				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				569,053	

M. COST SHARING PROPOSED LEVEL $ 0 AGREED LEVEL IF DIFFERENT $

PI/PD NAME
Kenneth M Golden

ORG. REP. NAME*

FOR NSF USE ONLY		
INDIRECT COST RATE VERIFICATION		
Date Checked	Date Of Rate Sheet	Initials - ORG

C *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

TPI: 8009618

Budget Justification

SENIOR/KEY PERSONNEL:
The bulk of the funds being requested are to support the participants in the project. In particular, we are requesting 1 month salary for the PI Golden in Year 1, and 1.25 months salary in years 2 and 3, and 1 month each year for the Co-PI Cherkaev. Salaries are expected to increase at the rate of 3% per year.

OTHER PERSONNEL:
We are requesting partial support (half annual salary) in years 2 and 3 for a postdoctoral researcher to be based in the Math Department under the direction of Golden. We are also requesting $20,000 each academic year to support 1 graduate students as a research assistant.

FRINGE BENEFITS:
Faculty benefits are calculated at 34% of salary, postdoctoral researchers at 38%, and graduate students at 10%.

TRAVEL:
Requests for travel funding are first, to support travel by the participants – senior investigators, postdocs, graduate and undergraduate students – to collaborate at our partner institutions. Our travel funding requests are also to support the participants in presenting our results at conferences, such as the SIAM Annual Meeting, the SIAM Conference on Mathematical and Computational Issues in the Geosciences, the Joint Math Meetings, the Australasian Conferences on Wave Science, the Fall AGU Meeting, or the Spring EGU Meeting. For example, the cost for one person to attend the SIAM Annual Meeting is about $2000 and for EGU about $2500.

PARTICIPANT SUPPORT:
We are requesting academic year tuition support each year for 1 graduate student in the Math Department, and funding to help support two undergraduate investigators each semester.

OTHER DIRECT COSTS:
Requests for supplies are for software and related items to support modeling and computing efforts.

INDIRECT COSTS:
Utah's federally negotiated rate is 52.5%.

SUMMARY PROPOSAL BUDGET

YEAR 1

ORGANIZATION: **University of California-Los Angeles**	FOR NSF USE ONLY — PROPOSAL NO. / DURATION (months): Proposed / Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: **Joseph Teran**	AWARD NO.

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Joseph M Teran - Co-PI	0.00	0.00	1.00	20,333	
2.					
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	1.00	20,333	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (0) GRADUATE STUDENTS				0	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (1) OTHER				24,388	
TOTAL SALARIES AND WAGES (A + B)				44,721	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				8,874	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				53,595	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) Workstation $ 32,287					
TOTAL EQUIPMENT				32,287	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				2,368	
2. INTERNATIONAL				0	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				264	
TOTAL OTHER DIRECT COSTS				264	
H. TOTAL DIRECT COSTS (A THROUGH G)				88,514	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) MTDC (Rate: 56.0000, Base: 56225)					
TOTAL INDIRECT COSTS (F&A)				31,486	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				120,000	
K. FEE				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				120,000	

M. COST SHARING PROPOSED LEVEL $ 0 AGREED LEVEL IF DIFFERENT $

PI/PD NAME: **Joseph Teran**	FOR NSF USE ONLY — INDIRECT COST RATE VERIFICATION
ORG. REP. NAME*	Date Checked / Date Of Rate Sheet / Initials - ORG

1 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

TPI: 8010094

SUMMARY PROPOSAL BUDGET

YEAR 2

ORGANIZATION **University of California-Los Angeles**		FOR NSF USE ONLY			
		PROPOSAL NO.	DURATION (months)		
			Proposed	Granted	
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Joseph Teran**		AWARD NO.			

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Joseph M Teran - Co-PI**	0.00	0.00	1.00	**20,740**	
2.					
3.					
4.					
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	**0**	
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	1.00	**20,740**	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**0**) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	**0**	
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	**0**	
3. (**0**) GRADUATE STUDENTS				**0**	
4. (**0**) UNDERGRADUATE STUDENTS				**0**	
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				**0**	
6. (**1**) OTHER				**30,447**	
TOTAL SALARIES AND WAGES (A + B)				**51,187**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				**10,851**	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				**62,038**	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				**0**	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				**1,801**	
2. INTERNATIONAL				**0**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **0** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **0**					
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS				**0**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**0**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**0**	
3. CONSULTANT SERVICES				**0**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**264**	
TOTAL OTHER DIRECT COSTS				**264**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**64,103**	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **MTDC (Rate: 56.0000, Base: 64102)**					
TOTAL INDIRECT COSTS (F&A)				**35,897**	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**100,000**	
K. FEE				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				**100,000**	

M. COST SHARING PROPOSED LEVEL $ **0** AGREED LEVEL IF DIFFERENT $

	FOR NSF USE ONLY		
PI/PD NAME **Joseph Teran**	INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

TPI: 8010094

SUMMARY PROPOSAL BUDGET

YEAR 3

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months)	
	Proposed	Granted
AWARD NO.		

ORGANIZATION
University of California-Los Angeles

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Joseph Teran

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Joseph M Teran - Co-PI**	0.00	0.00	1.00	21,155	
2.					
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	1.00	21,155	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (0) GRADUATE STUDENTS				0	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (1) OTHER				31,360	
TOTAL SALARIES AND WAGES (A + B)				52,515	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				11,166	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				63,681	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				158	
2. INTERNATIONAL				0	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				264	
TOTAL OTHER DIRECT COSTS				264	
H. TOTAL DIRECT COSTS (A THROUGH G)				64,103	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **MTDC (Rate: 56.0000, Base: 64103)**					
TOTAL INDIRECT COSTS (F&A)				35,898	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				100,001	
K. FEE				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				100,001	

M. COST SHARING PROPOSED LEVEL $ 0 | AGREED LEVEL IF DIFFERENT $

PI/PD NAME
Joseph Teran

ORG. REP. NAME*

FOR NSF USE ONLY		
INDIRECT COST RATE VERIFICATION		
Date Checked	Date Of Rate Sheet	Initials - ORG

 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

TPI: 8010094

SUMMARY PROPOSAL BUDGET

Cumulative

ORGANIZATION: University of California-Los Angeles				FOR NSF USE ONLY	
				PROPOSAL NO.	DURATION (months) Proposed / Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: Joseph Teran				AWARD NO.	

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Joseph M Teran - Co-PI	0.00	0.00	3.00	62,228	
2.					
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	3.00	62,228	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (0) GRADUATE STUDENTS				0	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (3) OTHER				86,195	
TOTAL SALARIES AND WAGES (A + B)				148,423	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				30,891	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				179,314	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) $ 32,287					
TOTAL EQUIPMENT				32,287	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				4,327	
2. INTERNATIONAL				0	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				792	
TOTAL OTHER DIRECT COSTS				792	
H. TOTAL DIRECT COSTS (A THROUGH G)				216,720	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS (F&A)				103,281	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				320,001	
K. FEE				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				320,001	
M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $				

PI/PD NAME: Joseph Teran	FOR NSF USE ONLY		
	INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

C *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

TPI: 8010094

UCLA Budget Justification

Three years of project funding are requested. Project years follow the UCLA Fiscal Year, July 1st – June 30th.

Senior Personnel
We request 1.0 months of summer salary support each year for the Co-PI, Joseph Teran. We anticipate a 3% cost of living increase effective 10/1/2020. We use the Co-PI's current 10/1/19 annual 9-month salary of $183,000 as the basis. The PI will develop novel algorithms designed to simulate sea ice and water mixtures that scale efficiently on parallel computing infrastructure. The PI will supervise an Assistant Adjunct Professor in this development effort.

Other Personnel
Assistant Adjunct Professor – We request support for one Assistant Adjunct Professor at 33% in the first year and 40% in the remaining years for 12 calendar months each year. Effective 10/1/2020, inflation of 3.0% has been added to the 10/1/2019 annual rate of $73,900 per year. The Assistant Adjunct Professor will help develop and run algorithms that scale efficiently on parallel computing infrastructure and in producing final simulation results needed for publication and demonstration of techniques.

Fringe Benefits
Composite fringe benefit rates are applied based on employee category. The benefit rate is assessed at 4.9% for faculty summer and 32.3% for the assistant adjunct professor.
Please refer to link: https://www.finance.ucla.edu/composite-benefit-rate-assessment

Equipment
We request funding a workstation for a total of $32,287 which includes Los Angeles County sales tax for 9.5%. This machine will be used for algorithm development using GPU and manycore level parallelism. It will also be used to test single node performance of aspects of MPI distributed implementations.

Travel
To support travel costs, we request $2,369 in Year 1, $1801 in Year 2, and $158 in Year 3. Figures are based on estimated costs which can be subject to change.

Domestic – The PIs will meet regularly to collaborate and share results. These meetings will rotate between UCLA, Oregon St. and Utah St.

Other Direct Costs
Technology Infrastructure Fee – We request a total of $791 to cover the campus mandated Technology Infrastructure Fee (TIF) of $43.96/month per full-time employee for each employee supported by this proposed grant. Faculty-Summer payments are not assessed TIF; however, Assistant Adjunct Professors are assessed TIF for all months they are employed.

Facilities and Administrative Cost Rates
We request a total of $126,654 in indirect costs. Facilities and administrative cost rates are applied to a Modified Total Direct Cost (MTDC) base of 56.0% (excluding graduate student fee

remission, equipment, participant support). Our rates were approved by U.S.D.H.H.S. (the responsible Federal audit agency) on October 12, 2018.
Please refer to link: http://ora.research.ucla.edu/OCGA/Documents/Standard-Instit%20Info/F-A-rate-agreement-2018.pdf

SUMMARY PROPOSAL BUDGET

YEAR 1

ORGANIZATION: **Oregon State University**				FOR NSF USE ONLY		
				PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: **Jennifer Hutchings**				AWARD NO.		
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)	
1. **Jennifer K Hutchings**	1.00	0.00	0.00	10,002		
2.						
3.						
4.						
5.						
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0		
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	1.00	0.00	0.00	10,002		
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. (0) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	0		
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0		
3. (1) GRADUATE STUDENTS				10,182		
4. (0) UNDERGRADUATE STUDENTS				0		
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0		
6. (0) OTHER				0		
TOTAL SALARIES AND WAGES (A + B)				20,184		
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				5,904		
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				26,088		
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)						
TOTAL EQUIPMENT				0		
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				7,400		
2. INTERNATIONAL				0		
F. PARTICIPANT SUPPORT COSTS						
1. STIPENDS $ 6,900						
2. TRAVEL 2,050						
3. SUBSISTENCE 1,104						
4. OTHER 0						
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				10,054		
G. OTHER DIRECT COSTS						
1. MATERIALS AND SUPPLIES				3,400		
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				2,500		
3. CONSULTANT SERVICES				0		
4. COMPUTER SERVICES				1,200		
5. SUBAWARDS				0		
6. OTHER				0		
TOTAL OTHER DIRECT COSTS				7,100		
H. TOTAL DIRECT COSTS (A THROUGH G)				50,642		
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Facilities and Administration (Rate: 48.5000, Base: 40588)**						
TOTAL INDIRECT COSTS (F&A)				19,685		
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				70,327		
K. FEE				0		
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				70,327		
M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $					
PI/PD NAME: **Jennifer Hutchings**				FOR NSF USE ONLY: INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*				Date Checked	Date Of Rate Sheet	Initials - ORG

 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

TPI: 8011343

SUMMARY PROPOSAL BUDGET

YEAR 2

ORGANIZATION: **Oregon State University**				FOR NSF USE ONLY — PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: **Jennifer Hutchings**				AWARD NO.		
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)	
1. **Jennifer K Hutchings**	1.00	0.00	0.00	**10,302**		
2.						
3.						
4.						
5.						
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	**0**		
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)	1.00	0.00	0.00	**10,302**		
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. (**0**) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	**0**		
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	**0**		
3. (**0**) GRADUATE STUDENTS				**10,488**		
4. (**0**) UNDERGRADUATE STUDENTS				**0**		
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				**0**		
6. (**0**) OTHER				**0**		
TOTAL SALARIES AND WAGES (A + B)				**20,790**		
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				**6,142**		
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				**26,932**		
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)						
TOTAL EQUIPMENT				**0**		
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				**7,548**		
2. INTERNATIONAL				**0**		
F. PARTICIPANT SUPPORT COSTS						
1. STIPENDS $ **7,107**						
2. TRAVEL **2,091**						
3. SUBSISTENCE **1,104**						
4. OTHER **0**						
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS				**10,302**		
G. OTHER DIRECT COSTS						
1. MATERIALS AND SUPPLIES				**1,000**		
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**2,500**		
3. CONSULTANT SERVICES				**0**		
4. COMPUTER SERVICES				**1,200**		
5. SUBAWARDS				**0**		
6. OTHER				**0**		
TOTAL OTHER DIRECT COSTS				**4,700**		
H. TOTAL DIRECT COSTS (A THROUGH G)				**49,482**		
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Facilities and Administration (Rate: 48.5000, Base: 39180)**						
TOTAL INDIRECT COSTS (F&A)				**19,002**		
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**68,484**		
K. FEE				**0**		
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				**68,484**		
M. COST SHARING PROPOSED LEVEL $ **0**	AGREED LEVEL IF DIFFERENT $					
PI/PD NAME: **Jennifer Hutchings**				FOR NSF USE ONLY — INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*				Date Checked	Date Of Rate Sheet	Initials - ORG

 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

TPI: 8011343

SUMMARY PROPOSAL BUDGET

YEAR 3

ORGANIZATION: **Oregon State University**	FOR NSF USE ONLY — PROPOSAL NO.	DURATION (months) Proposed	Granted		
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: **Jennifer Hutchings**	AWARD NO.				

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Jennifer K Hutchings - Assoc. Prof.	2.00	0.00	0.00	21,223	
2.					
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	2.00	0.00	0.00	21,223	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (0) GRADUATE STUDENTS				0	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				21,223	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				9,763	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				30,986	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				4,890	
2. INTERNATIONAL				0	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 7,320 2. TRAVEL 2,132 3. SUBSISTENCE 1,104 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				10,556	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				1,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				2,500	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				1,200	
5. SUBAWARDS				0	
6. OTHER				0	
TOTAL OTHER DIRECT COSTS				4,700	
H. TOTAL DIRECT COSTS (A THROUGH G)				51,132	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) Facilities and Administration (Rate: 48.5000, Base: 40576)					
TOTAL INDIRECT COSTS (F&A)				19,679	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				70,811	
K. FEE				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				70,811	
M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $				

PI/PD NAME: **Jennifer Hutchings**	FOR NSF USE ONLY — INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

TPI: 8011343

SUMMARY PROPOSAL BUDGET

Cumulative

ORGANIZATION: **Oregon State University**				FOR NSF USE ONLY	
				PROPOSAL NO.	DURATION (months) Proposed / Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: **Jennifer Hutchings**				AWARD NO.	

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Jennifer K Hutchings	4.00	0.00	0.00	41,527	
2.					
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	4.00	0.00	0.00	41,527	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (1) GRADUATE STUDENTS				20,670	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				62,197	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				21,809	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				84,006	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				19,838	
2. INTERNATIONAL				0	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 21,327 2. TRAVEL 6,273 3. SUBSISTENCE 3,312 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				30,912	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				5,400	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				7,500	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				3,600	
5. SUBAWARDS				0	
6. OTHER				0	
TOTAL OTHER DIRECT COSTS				16,500	
H. TOTAL DIRECT COSTS (A THROUGH G)				151,256	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS (F&A)				58,366	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				209,622	
K. FEE				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				209,622	
M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $				

PI/PD NAME: **Jennifer Hutchings**	FOR NSF USE ONLY		
	INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

C ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

TPI: 8011343

Budget Justification: Oregon State

Salary support is requested for Hutchings, 1 month per year in years 1 and 2, 2 months in year 3. She will collaborate closely with the Utah and California teams, provide data from her observational programs to coordinate with the model development, and work on collaborative analysis and papers. We request 3 months summer salary for a Ph.D. student in the School of Education, Megan Brunner, in years 1 and 2. Megan will work on curriculum development for the educational component of the project, dissemination of the lessons and will author publications in mathematics education journals.

Fringe Benefits are requested at Oregon State University recommended rates and will be charged to the grant as actual.

Travel support is requested in each year to ensure Hutchings can attend 2 project meetings or conferences (coordinated with team meetings) each year. One conference per year, in years 1 and 2, is requested for Brunner, attending the American Mathematical Society annual meeting or national teachers conferences. Each trip is estimated at $2000, including $600 airfare, 4 nights accommodation ($180/night) and 5 day per diem ($66/day), $200 ground transportation and $150 miscellaneous charges such as mileage, parking and luggage fees. Conference registration and abstract fees are estimated at $700 per conference (two in years 1 and 2 and 1 in year 3). There is a 2% increase per year to reflect inflation.

Participant Support is requested for one undergraduate to join the Oregon State University College of Earth Ocean and Atmospheric Sciences Research Experience for Undergraduates program in each year. This program seeks students from minority serving or non-graduate degree awarding institutions and we will advertise for students interested in expanding their mathematical talents to the geosciences. We request stipend ($6900 with a 3% cost of living increase in each year), travel to Oregon to join the program (estimated at $550 based on past average cost) and subsistence ($1104 for university accommodation) be covered. We also request travel for each student to present at a national conference, which is estimated at $1500 per trip. Travel estimates have a 2% increase per year to reflect inflation

Other Direct Costs. In the first year of the project we request $2400 to purchase hard drives totaling 20TB for processing remote sensed imagery and model data. Materials and supplies are requested for incidental costs of portable data storage, poster printing, software licenses and computer repair required to perform project work. We estimate these costs at $1000 per year. Publication costs are based on the cost of publishing open access in journals such as the Journal of Geophysical Research or The Cryosphere, at $2500/paper. We budget for a scientific paper in each of years 2 and 3. In year one we expect to publish in an education journal such as Mathematics Educator, also estimated to be $2500/paper. Computer services costs are estimated to be $1200 per year.

Indirect cost: Oregon State University's federally negotiated indirect cost rate is 48.5% of modified total direct costs (MTDC).

Current and Pending Support

(See PAPPG Section II.C.2.h for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Kenneth Golden

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Multiscale Homogenization for Sea Ice

Source of Support: Office of Naval Research

Total Award Amount: $ 583,573 Total Award Period Covered: 07/01/18 - 06/30/21

Location of Project: University of Utah

Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 1.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Random Matrix Theory for Homogenization of Composites

Source of Support: National Science Foundation

Total Award Amount: $ 353,794 Total Award Period Covered: 08/15/17 - 07/31/20

Location of Project: University of Utah

Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 1.00

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Collaborative Research: Ultra-Realistic Modeling and Simulation of Arctic Sea Ice (this proposal)

Source of Support: National Science Foundation

Total Award Amount: $ 0 Total Award Period Covered: 07/01/20 - 06/30/23

Location of Project: University of Utah

Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 1.00

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

(See PAPPG Section II.C.2.h for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Elena Cherkaev

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Random Matrix Theory for Homogenization of Composites

Source of Support: National Science Foundation
Total Award Amount: $ 353,794 Total Award Period Covered: 08/15/17 - 07/31/20
Location of Project: University of Utah
Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 1.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Multiscale Homogenization for Sea Ice

Source of Support: Office of Naval Research
Total Award Amount: $ 583,573 Total Award Period Covered: 07/01/18 - 06/30/21
Location of Project: University of Utah
Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 1.00

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Collaborative Research: Ultra-Realistic Modeling and Simulation of Arctic Sea Ice (this proposal)

Source of Support: National Science Foundation
Total Award Amount: $ 0 Total Award Period Covered: 07/01/20 - 06/30/23
Location of Project: University of Utah
Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 1.00

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

JOSEPH TERAN

CURRENT SUPPORT

W81XWH-15-1-0147 (Teran, J., Benharash, P.) 07/01/2015 – 06/30/2020 1 summer month
Source: DOD-Army Medical Research Acquisition $3,501,032
Location: UCLA
"Virtual Tissue Modeling for Realtime Surgical and Interventional Procedure Simulation"

27IR-0056 (Teran, J., Santhanam, A.) 04/01/2018 – 03/31/2021 1 summer month
Source: UC Tobacco-Related Disease Research Program $919,571
Location: UCLA
"Improving Diagnostic and Therapeutic Imaging Tools for Better Management of Chronic Obstructive Pulmonary Disease"

1R56HL139767-01A1 (Teran, J., Santhanam, A.) 09/15/18 – 08/31/20 1 summer month
Source: NIH-NHLBI $369,388
Location: UCLA
"Flow Structure Interaction Model for COPD"

4000168298 (Teran, J.) 02/01/19-01/31/21 1 summer month
Source: Oak Ridge National Laboratory $196,259
Location: UCLA
"A High Performance Computing Model of Powder-Scale Melting and Solidification Simulations in Additive Manufacturing of Metals via the Material Point Method (MPM)"

Gift Fund (Teran, J.) 08/31/18 – no expiration 0 months
Source: Adobe Systems, Inc. $28,050
Location: UCLA
"Adobe Research Software Donation Program"

PENDING SUPPORT

NSF LEAP (Teran, J.; Wang, B.; Soga, K.) 05/01/20 - 04/30/24 1 summer month
Source: NSF $471,803
Location: UCLA
"High Performance Computing and High-Resolution Video Modeling: Transforming Communications about Natural Hazards (HIPER-VM)"

NSF Applied Mathematics (Teran, J.; Golden, K.) 07/01/20-06/30/23 1 summer month
Location: UCLA $385,108
"Collaborative Research: Ultra-Realistic Modeling and Simulation of Arctic Sea Ice"

Current and Pending Support Form

Has the current proposal been submitted to any other funding source? No								
Current Support	**Supporting Agency**	**19**	**20**	**21**	**22**	**23**	**Start/End Dates**	**Award Amounts**
		PI time (months/calendar						
CR: Thermodynamic and dynamic drivers of the Arctic sea-ice mass budget at MOSAiC	NSF	1.0	4.0	3.0			10/01/17 09/30/21	$407,452
Scale invariance of sea ice deformation: identifying how boundary conditions define the spatial ranges of these relationships	NSF	1.0	1.0				06/01/18 05/31/21	$469,735
Observational study to constrain rheological models for sea ice	NASA	2.0	2.0				10/01/18 9/30/21	$319,311
ROMS ice model in Alaska region	NOAA		0.5				10/01/19 9/31/20	$100,000
A Plan for an Integrated Sea Ice Dyanmics Experiment (SIDEx)	ONR	2.0	1.0	4.0	2.0	2.0	11/01/18 10/30/23	$515,312
Pending Support								
Collaborative Research: Ultra-Realistic Modeling and Simulation of Arctic Sea Ice (this proposal)	NSF			1.0	1.0	2.0	07/01/20 06/31/23	$209,623

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, GNU/Linux (Dell & IBM), Solaris (Oracle/SUN), and Sun Ray thin client stations. These include at least one file server from each UNIX architecture. We also have offsite file storage mirrors with daily snapshots capable of several years of storage.

Office

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

U. of Utah Scientific Computing and Imaging (SCI) Institute Facilities

Some of our data analysis and computational modeling and simulation will be performed at the SCI Institute. The SCI research group was founded in 1994 by Drs. Chris Johnson and Rob MacLeod along with five graduate students. In 1996, they became the Center for Scientific Computing and Imaging and in 2000, the SCI Institute. The SCI Institute is now one of eight permanent research institutes at the University of Utah and home to 200 faculty, students, and staff. The 17 tenure-track faculty are drawn from the School of Computing and the Departments of Biomedical Eng., Math, and Electrical and Computer Eng.

The SCI Institute has established itself as an internationally recognized leader in visualization, scientific computing, and image analysis applied to a broad range of application domains, including biomedicine, defense, and energy. The overarching research objective is to conduct application-driven research by creating new scientific computing techniques, tools, and systems. SCI Institute researchers also apply many of these computational techniques within their own particular scientific and engineering subspecialties.

The SCI Institute either directs or has been associated with several national research centers: the NIH Center for Integrative Biomedical Computing (CIBC), the DoE Scalable Data Management, Analysis, and Visualization (SDAV), the Center for Extreme Data Management, Analysis, and Visualization, the NIH National Alliance for Medical Image Computing (NA-MIC), the DOD Alliance for Computationally-guided Design of Energy Efficient Electronic Materials, and a NVIDIA Center of Excellence.

A particular hallmark of SCI Institute is the development and ongoing maintenance of innovative and robust software packages including the SCIRun scientific problem-solving environment, Seg3D, ImageVis3D, Shapeworks, BioMesh, Cleaver, Pfeifer, and *map3d* which are available to the scientific community under open-source licensing and supported by web pages, documentation, and user groups.

The SCI institute has over 25,000 square feet of functional space within the John and Marva Warnock Engineering Building. The data analysis, computational modeling, and simulation studies will be performed at the SCI Institute using the expansive computational resources available. The SCI Institute computing facility, includes shared memory multi-processor computers, clusters, and dedicated graphics systems. Among the abundance of resources, are the following:

1. Nvidia DGX-1 with 8X Tesla V100, Dual 20-Core Intel Xeon E5-2698 v4 2.2 GHz Processors, and 128 GB RAM.

2. 264 core, 2.8TB shared memory SGI UV 1000 system with Intel X7542 2.67GHz Processors.

3. 64 node CPU cluster. Each node has 8 cores, 24GB of RAM, with a 4x DDR Infiniband backbone with dual 10G network connections to SCI core switches.

4. 32 node GP-GPU cluster. Each node has 16 cores, 64GB of RAM with Intel E5-2660 2.20GHz processors. Each node has 2x Nvidia k20 GPUs with 2 full speed FDR Infiniband connections. System has a total of 128 56Gb/s Infiniband connections.

5. 10 blade HPE Apollo 6000 cluster system with 10 Xeon-7210 CPUs with 480GB of total RAM.

6. 64 core, 512GB shared memory HP DL980 G7 with Intel Xeon X7560 2.27GHz processors.

7. 12 core Intel Xeon E5-2640 2.50GHz with 32GB of RAM and 3x K20c GPUs.

FACILITIES AND EQUIPMENT AVAILABLE

COMPUTING RESOURCES

Investigators at UCLA Mathematics have access to significant computing resources. All offices are equipped with modern Intel-based desktop computers running Linux, Windows or MacOS. A broad variety of applications and scientific software are available to all, including Matlab, Maple, and Mathematica. Many development and visualization tools are also available. The department data center features a large number of general-purpose servers, three levels of tiered-storage, and dedicated backup systems.

In support of both the desktop and data center, the department maintains a modern switched 100 MB/sec networking infrastructure, redundant fast routing, a locally managed firewall, and intrusion detection software. In conjunction with the Physical Sciences Network (PSnet), a 10 GB/sec uplink to the Internet has been proposed. Wireless networking is available to all department members and authorized visitors.

The department maintains an evolving High Performance Computing environment. Both a 96-CPU and an 18-CPU Beowulf cluster are available to all department members for parallel and batch computing. In addition, Mathematics users enjoy access to UCLA's Hoffman Cluster and Grid environments.

Several computer labs are available to students, providing 101 seats. Monochrome and color printing and copying are available. A contemporary video conferencing system is also available, and a dedicated premium video conferencing facility is in the building. Technical support for all systems is provided by an experienced and reliable team of system administrators.

OFFICE SPACE

The Principal Investigator has been provided office space in the Mathematical Sciences Building. Office space will be provided for postdocs, graduate students, and visitors as needed.

FACILITIES AND EQUIPMENT: JENNIFER KATY HUTCHINGS

Center for Earth, Ocean and Atmospheric Science (CEOAS), Oregon State University.

Computing

The CEOAS Environmental Computing Center contains modern, high-throughput computing- class infrastructure in order to facilitate, deliver and meet the challenges of next-generation scientific workflows. Significant improvements and innovation in compute, networks, storage, visualization and sensor technology continue to accelerate, generation after generation. These advancements add to the complexity of computation, data analysis and delivery, which now takes hundreds of steps as scientists continuously push the limits of technology.

At the heart of the Environmental Data Center are supercomputer-class machines ranging from large shared memory systems to tightly coupled clusters with and without Graphics Processing Unit-enabled acceleration providing a wide range of services, including compute, storage, application, print, project and scratch services. Our Digital Media Laboratory and Student facilities contain a heterogeneous mix of workstations specifically tuned for more demanding scientific needs. These include Linux/Unix based systems from Dell, Apple, Oracle/Sun. In addition, throughout the complex are high-end color printers, plotters, and scanners as well as digital postproduction tools for analyzing and creating visualizations targeted at streaming or DVD/Blu Ray distribution. A purpose-built visualization laboratory contains exceptional computing and video gear to produce high-definition 4k data visualizations and complete video presentations of research projects. An advanced geographic information system (GIS) Lab running on dedicated equipment is also available.

All these facilities feed a state-of-the-art seminar and presentation faculty enabling "one-touch" control of systems and data routing. These facilities are capable of delivering high definition scientific workflow experiences at a full 2 and 4K resolution.

A personal computer is provided for Dr. Hutchings. Basic computer support (access to the UNIX/Mac workstations) will also be provided for students visiting OSU. CEOAS routinely requests funding, as a percentage of proposed effort, to cover system administration, data back-up and system maintenance. Hutchings and the students have access to printers, scanners, and various statistics, numerical analysis and multimedia software for use during the proposed research. This software includes: IDL, Matlab, Microsoft office. Additional to the college provided computer support, Dr. Hutchings maintains a server that will be suitable for satellite image analysis and running numerical simulations.

Office

Dr. Hutchings is provided office space by CEOAS as well as the office space set aside for students and visitors. Desk space is provided in Dr. Hutchings laboratory for students and visitors to CEOAS. Students have access to various computer labs within CEOAS, detailed above.

Administrative Support

CEOAS administrative support includes a fully-staffed on-site business office to help administer the grant. Other CEOAS administrative support includes help with purchasing, travel arrangements, workshops, reception, mailing and shipping, office supplies for researchers, etc.

Collaborative Research: Ultra-Realistic Modeling and Simulation of Arctic Sea Ice

Data Management Plan

Since we use a variety of data types in this project, including in-situ observations, satellite remote sensing and model output, our data plan necessarily does not rely on one location for data management. All data required for this project would have been collected through other efforts, and are publically available. They are archived at nationally and internationally recognized repositories. The NASA IceBridge, ice chart, and passive microwave data to be used in this project is archived at the National Snow and Ice Data Center (NSIDC). Buoy data is archived at the International Arctic Buoy Program (IABP). Level 1-b satellite data for AVHRR, MODIS and LandSat are freely available from NOAA and NASA. An exception to free data access is for the NGA 40cm resolution satellite imagery. This is being provided by the Polar Geospatial Center through a current cooperative agreement with NSF, and can be shared with US collaborators. Citizen science data from the Ice Watch program are archived by Ice Watch and accessible on a webserver that is currently being transferred from University of Alaska Fairbanks to a permanent home at the Norwegian Meteorological Office.

MOSAiC data is being collected at the time of writing, and is shared freely among the MOSAiC contortion, for which Hutchings is the sea ice dynamics lead. We will request full membership of the MOSAiC collaborative as a new modeling effort should we be funded, which will ensure we can share our model output directly with other MOSAiC researchers and access all field data.

Higher-level, derived products may be extracted from the data sets we use. Such data sets will be provided to the NSF Arctic Data Center, and documented in publications. Model results will be documented and case studies that are developed for model intercomparison will be archived on git hub for use by other sea ice modelers.

If we do come across data sets that are not adequately archived, we will work with the authors to archive them. Possible locations for data archival will be the NSIDC, the International Arctic Buoy Program (IABP, for drifting buoy data), the Alfred Wegner Institute Pangea and the NSF Arctic Data Center.

Data products derived as part of this project will be documented through publications and archived with the NSF Arctic Data Center. Data location will be disseminated to sea ice modeling community broadly through word of mouth, in publication acknowledgements and ArcticInfo announcements.

POSTDOCTORAL MENTORING PLAN

The postdocs will be based at the University of Utah and UCLA and will work primarily with Golden and Teran, respectively. The primary mentor will make expectations clear at the outset. The postdoc will meet weekly (at least) with the mentor, and will write regular reports to the mentor, to enhance writing skills. The mentor will ensure that the postdoc is plugged-in to local mentoring and research activities, seeking out opportunities for the postdoc in leadership training, grant-writing development, teaching support, where applicable, giving and attending seminars, and other research collaborations related to the core issues.

Interdisciplinary Collaboration: Junior researchers will play a central role in the weekly discussions, where a focus on the big picture will be maintained. They will be involved in establishing frequent communication between institutions to help facilitate the interdisciplinary aspects of the proposed work. All participants in the proposed research will be encouraged to learn how to communicate and work with researchers from different fields. Our mix of field and theoretical scientists, with public participation and education is particularly well suited for developing these skills.

Working Groups and Mentoring Skills: All junior researchers will collaborate closely and informally with faculty and peers on a clearly defined research project. Senior faculty will provide research mentorship to the postdocs, and will guide the postdocs in mentoring students in the group. Similarly, graduate students will be guided in mentoring undergraduates, creating a rich network of support at all levels. Responsible conduct to maintain a supportive work environment is key, monitored by PIs, and training sought if needed.

Writing and Publishing: We will publish research results in top geoscience, applied math, mechanics, computational physics and computer graphics journals. The PIs will mentor junior researchers in their writing. Tasks will initially be managed primarily by the PIs with sections and subsections delegated and supervised, however in subsequent years junior researchers will take on more managerial roles. Attention will also be paid to writing for different audiences – communicating with the general public, writing a technical publication, writing a summary report on work accomplished, and so on.

Presentation Skills: Junior researchers will regularly present their work to their peers and mentors, at weekly local meetings, and at our partner institutions. They will also be encouraged to present at national and international meetings, as well as meetings geared toward younger investigators. We will establish a system for giving brief feedback about each presentation (e.g., clarity of visuals, clarity of explanations, flow of ideas, slide construction and layout, things that worked, points of confusion, suggestions for improvement, etc.), and the speakers will be encouraged to discuss this feedback with their working groups and local mentors, especially in cases of practice talks for conferences and interviews.

Software Development and Numerical Methods: Tutorials on MPM and related codes used in Teran's groups will be created to help introduce junior researchers to existing code bases and practices. Furthermore, these will cover less common aspects of theory and computational techniques related to nonlinear thermomechanical mixtures, elastoplasticity and continuum mechanics including aspects of GPU, many core CPU and distributed parallelism used to scale to large scale calculations. Emphasis is made in refining transferable skills for alternative career paths or developing new research directions.

Embracing Diversity: Women and minorities underrepresented in science and mathematics will be actively recruited for postdocs and student funding. Both Golden and Teran are currently working with a significant number of female and minority students and postdocs. This has helped create a diverse and welcoming work environment, with many role models, which can aid our recruiting efforts. Moreover, Golden has been active in programs to immerse young women at the high school and early university level in math and science research (see Bio), which in turn helps feed the pipeline for recruiting at higher levels. Junior researchers will be encouraged to attend national meetings like SACNAS and Blackwell/Tapia to encourage participation in this exciting new research.

THE UNIVERSITY OF UTAH

Scientific Computing and Imaging Institute

72 S. Central Campus Drive, 3750 WEB, Salt Lake City, Utah 84112

November 13, 2019

Dear Ken,

Thank you very much for telling us about your interesting proposed project on developing a mathematical and computational framework based on the Material Point Method (MPM) to simulate and visualize Arctic sea ice dynamics. If the proposal submitted by you, Dr. Kenneth Golden, entitled "Collaborative Research: Ultra-Realistic Modeling and Simulation of Arctic Sea Ice" is selected for funding by NSF, as Interim Director of the Scientific Computing and Imaging (SCI) Institute at the University of Utah, I am pleased to help support the success of this project through ensuring access to our extensive computing facilities (as outlined in the Facilities section) as well as by encouraging collaborations between you and various members of SCI. Both Professor Martin Berzins in SCI and myself have conducted research on the numerical properties of MPM, and Professor Berzins is currently focusing his energies on exascale computing – adapting his MPM-based *Uintah* code to modern architectures. We both would be very interested in seeing MPM's development for such an important problem as the future of our polar sea ice packs.

Good luck with the proposal.

Respectfully,

Robert M. (Mike) Kirby, Ph.D.
Interim Director, Scientific Computing and Imaging Institute
Professor of Computing
WEB 3602
Phone (801) 585-3421
director@sci.utah.edu

Biographical Information: Robert M. (Mike) Kirby, Ph.D. is the current (interim) Director of the Scientific Computing and Imaging (SCI) Institute at the University of Utah. Kirby is also a Professor of Computer Science and an Adjunct Professor in the Departments of Biomedical Engineering and Mathematics. He holds additional leadership roles as Associate Director of the School of Computing, as well as the Director of the Center for Multiscale Modeling of Electronic Materials (MSME). Kirby received the M.S. degree in applied mathematics, the M.S. degree in computer science, and the Ph.D. degree in applied mathematics from Brown University, Providence, RI, in 1999, 2001, and 2002, respectively. His current research interests include scientific and data computing, uncertainty quantification, high-performance computing (HPC), scientific and data visualization, as well as computational science and engineering (CS&E) applied to various applications.

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Pedro Ponte Castañeda
Professor and Raymond S. Markowitz Faculty Fellow

November 13, 2019

RE: NSF Proposal by Dr. Kenneth M. Golden to the Applied Math and Arctic Natural Sciences Programs

TO WHOM IT MAY CONCERN:

If the proposal submitted by Dr. Kenneth Golden, entitled "Collaborative Research: Ultra-Realistic Modeling and Simulation of Arctic Sea Ice" is selected for funding by NSF, it is my intent to collaborate with Dr. Golden and his colleagues on the rheology of polycrystalline media, as outlined in the Project Description.

I currently lead a project (No. N00014-17-1-2076) supported by the Applied Computational Analysis Program at ONR on the subject of "Homogenization models for the rheology and microstructure evolution of sea ice." This project has been concerned with the use of nonlinear homogenization methods to generate macroscopic constitutive models for intact sea ice accounting for the polycrystalline nature of ice, as well as for the presence of brine pockets embedded in this granular microstructure. In particular, the models account for the effects of ice single-crystal rheology, crystallographic texture, as well as for the volume fraction and average shape of the brine inclusions.

Among other issues, the project led by Dr. Golden is concerned with the modeling of sea ice at larger length scales to account for the interaction of (intact) sea ice floes separated by water leads and cracks. For this purpose, we envisage the possible use of the models that we are developing for intact sea ice as input into the larger scale models of the sea ice pack by the Material Point Method.

I'm looking forward to collaborating with Dr. Golden and co-PIs on this project.

Yours sincerely,

Pedro Ponte

Pedro Ponte Castañeda