Fundamentals of Ocean Freezing

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LONG-TERM GOAL

For the last 10 years my goal has been to construct a quantitative understanding of the physical mechanisms responsible for the creation and evolution of the volumetric phase fraction of sea ice. Substantial advances in this regard have been made. In parallel with this direction, I have aimed to advance the coupling and interaction with electromagnetic signature modeling and to provide the basis upon which one can understand the assumptions made in thermodynamic modelling of sea ice. In particular, thin sea ice captures our interest because (a) of its central role in the wintertime surface heat balance and the salinity driven buoyancy flux, (b) shelf regions of the Arctic which are seasonal ice zones wherein dense water is formed over vast regions through freezing, and (c) sea ice models do not treat the buoyancy forcing caused by ice formation in a proper manner. Hence our refined understanding of the basic phase dynamics of the process underlies improving forecasting efforts.

OBJECTIVES

Our objective is to derive a basic understanding of the mechanisms of ice formation that exert a controlling influence on the brine flux at the surface of the polar oceans with a particular emphasis on thin ice formation in the Arctic. We would like to develop predictive theories of fluxes that properly account for the spatial variation in the phase fraction of sea ice, its influence on the flow permeability, and several instabilities that are driven by such interactions. We have found that even though ice growth may be continuous, the brine flux is not directly proportional to the growth rate for all stages of growth [1,2]. However, the latter has been assumed in numerical models. Therefore, models of ice growth, the most important buoyancy source for the polar oceans, and in particular the shelf regions, use incorrect boundary conditions. Two aspects of buoyancy forcing that are controlled by solidification dynamics have been of interest.

APPROACH

Our approach continues to marry theoretical, laboratory and field research. Most recently, we have brought the former two approaches to bear on field data to describe a basic instability in the brine dynamics of young sea ice [1]. This was accomplished by analyzing highly resolved temperature data taken through the air/sea/ice interface during the transition from an ice-free to an ice-covered Arctic Ocean surface during ONR's Lead Experiment. After the onset of this instability, the dominant controls on the brine flux change for the reasons described above.

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14. ABSTRACT
For the last 10 years my goal has been to construct a quantitative understanding of the physical mechanisms responsible for the creation and evolution of the volumetric phase fraction of sea ice. Substantial advances in this regard have been made. In parallel with this direction, I have aimed to advance the coupling and interaction with electromagnetic signature modeling and to provide the basis upon which one can understand the assumptions made in thermodynamic modelling of sea ice. In particular, thin sea ice captures our interest because (a) of its central role in the wintertime surface heat balance and the salinity driven buoyancy flux, (b) shelf regions of the Arctic which are seasonal ice zones wherein dense water is formed over vast regions through freezing, and (c) sea ice models do not treat the buoyancy forcing caused by ice formation in a proper manner. Hence our refined understanding of the basic phase dynamics of the process underlies improving forecasting efforts.

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WORK COMPLETED

Field evidence for our new theoretical predictions was sought during the Spring of 2001 under the support of an NSF project "Collaborative Study of Ice-Ocean Interaction in Svalbard", with J.H. Morison and M.G. McPhee. We have developed new instrumentation to observe in-situ brine volume profiles and will concurrently observe supercooling in the upper boundary layer using an ROV (modified by Morison). We deployed temperature- sensing instruments, similar to the freeze-in buoys deployed during the ONR LeadEx field experiment and during AnzFlux. These data formed a basis for extensions of our existing theoretical edifice in which we utilize modern techniques of applied mathematics [2]. This work extends the collaboration with H.E. Huppert, M.G. Worster.

RESULTS

First, previous to the instability described in [1] the brine volume profile is understood principally in terms of diffusion. After the onset of the instability, convection within the matrix becomes a fundamental mode of transport and hence buoyancy forcing in the upper ocean. We have examined theoretically and in the field what we believe to be a fallacious treatment of constitutional supercooling [3] in light of our recent results. Second, the interaction between the oceanic boundary layer and the morphological evolution of the underside of sea ice—its hydraulic roughness—is also basic to the boundary layer dynamics and hence the heat and mass fluxes at the ice-ocean interface. Therefore, uncovering potential mechanisms that underlie an increase or decrease of the hydraulic roughness of sea ice is of geophysical relevance. We have found a new mechanism whereby a sufficiently rapid oceanic flow can give rise to a corrugated sea-ice-ocean interface [4]. The mechanism relies on brine flows developing within the sea ice in response to Bernoulli suction caused by boundary layer flow adjacent to the interface. The resulting corrugation wavelength is approximately three to four times the thickness of the sea ice and hence, for relatively thin ice, will have a substantial influence on the hydraulic roughness. The conditions in which instability is most likely operative are found during storms in the central Arctic Ocean, in shelf seas, in ice-covered tidally driven fjords, or in coastal polynyas where the magnitude of the wind drift is large. Finally, we have discovered a premelting induced anamalous diffusion of soluble impurities through the ice matrix that is general to all polycrystalline ice [5], and a number of other basic advances in both crystal growth and interface dynamics that are listed in the publications.

IMPACT/APPLICATION

My approach is general so the results are broadly applicable and useful in understanding the phase evolution of any binary alloy undergoing unidirectional solidification, and hence there have been implications of the work that span fields from metallurgy to geophysics. I have shown that saltwater is an important transparent analogue for metallurgical systems, and that the phase behavior of this system is much broader than aqueous ammonium chloride, which has been used in metallurgy. This has direct relevance for other areas of materials research pursued at ONR. The spatial inhomogeneity of solid fraction has deleterious effects on the properties of technological materials. I have developed a fundamental understanding of how these processes control material properties, and this cuts across the boundaries of varied disciplines and hence addresses a broad range of the ONR's mission for the Navy. Our results have *commercial consequences* for metallurgical castings, the coarsening and annealing of ceramics and powders, and the nondestructive evaluation of polycrystalline alloys. Hence, while our sea ice studies offer a basic challenge to the geophysical agenda at the forefront of ONR's High

Latitude Program they act as a test bed for issues of relevance to a host of systems within the scope of other ONR departments.

TRANSITIONS

After ten years my research program has been terminated by the ONR and hence the principal transitions have to do with seeking support elsewhere.

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