Sea Ice Solidification: The Physical Origin of Macroscopic Properties

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LONG-TERM GOAL

Our long term goals are to construct a quantitative understanding of the physical mechanisms responsible for the creation and evolution of the volumetric phase fraction of sea ice. In parallel with the development of solidification research, we aim to advance the coupling and interaction with electromagnetic signature modeling. Our approach is general so the results are broadly applicable and useful in understanding the phase evolution of any binary alloy undergoing unidirectional solidification. Although we emphasize the saltwater system, the implications for the mechanical and thermophysical properties span fields from metallurgy to geophysics.

OBJECTIVES

The main geophysical scientific hypothesis driving the study of rapid oceanic freezing is that the very uniform mixed layer structure observed in the Arctic is created entirely from a relatively small area of leads (Badgley, 1966). Therefore these events, whose timescales are short relative to seasonal timescales, and which occur throughout the Arctic, may be responsible for the creation and maintenance of the large scale hydrography. Our results in studying the theoretical basis, and the experimental and field evidence for the phase evolution of sea ice, address this issue directly. We continue to tease out the underlying mechanisms that are generically responsible for the phase evolution of any unidirectionally solidified alloy which have until now, escaped quantitative understanding (Wettlaufer, 1998a). For sea ice, quantitative analysis is required to evaluate the insulative efficiency, mechanical integrity, electromagnetic and acoustic properties, biological productivity and pollutant scavenging capacity of sea ice, all controlled by the brine volume and its evolution.

APPROACH

We have used basic mixture theory, laboratory experimentation and have analyzed field data all centered around rapid solidification of the ocean initiated by the ONR sponsored Lead Experiment (The LeadEx Group, 1993). Under additional support from the British Natural Environmental Research Council, over thirty laboratory experiments were performed at Dept. of Applied Mathematics & Theoretical Physics, University of Cambridge, in collaboration with Professor H.E. Huppert and Dr. M.G. Worster. Using these laboratory data, we have developed a theoretical understanding of phase fraction dynamics, which treats the heretofore untractable interaction between solidification and fluid mechanics that are essential to understanding the systems evolution.

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The signature component draws upon recent advances in inverting the electromagnetic equations describing the scattering through the material (Sylvester et al., 1996). The work uses as a guide airborne synthetic aperature radar and surface based observations. The theory has been aided substantially by previously funded ONR research to develop a model that treats scattering from surface roughness which overlies a region having a vertical profile of dielectric properties. A model was developed to treat sea ice in the relevant lower range of microwave frequencies (Winebrenner et al., 1995). This model is now poised to treat the recently analyzed LeadEx field data.

WORK COMPLETED

As of a year ago, we had developed the mean field mixture theory relevant to the solidification from above of a sub-eutectic binary alloy and had completed the analysis of laboratory experiments involving saltwater and have applied the general theory to find two modes of instability are relevant to the system. During this year we developed an algorithm to track solidification fronts from temperature data taken through the mixed phase/liquid interface and we tested this algorithm using well controlled laboratory data. Success here allowed us to apply the algorithm to the field data from LeadEx, a task just completed. We have begun using this data as input to the scattering theory.

RESULTS

From the laboratory data we found a dramatic universal discontinuity of the solid fraction that is associated with a critical ice thickness and hence a striking jump in the magnitude, and time evolution of, the heat flux has implications in the polar regions *and* in materials processing (Wettlaufer et al., 1997 a,b, and Worster and Wettlaufer, 1997). The system offers an attractive transparent metallurgical analogue and the results are first order relevant to the control of the formation of undesirable defects in castings. More immediately, these findings have just been translated into the geophysical context through a thorough analysis of the field data (Wettlaufer et al., 1998 a). This analysis has shown that the instability and associated brine fluxes that we have observed in the laboratory, have taken place in the Arctic as measured directly by oceanographic techniques (Morison and McPhee, 1998).
This is the first rigorous quantification of convection in sea ice and its coupling to brine flux under a rapidly freezing lead. It changes the interpretation of an old problem and provides the basis for new boundary conditions for thermohaline models. We have continued to quantify a new mechanism for the upward transport of brine in a polycrystal based on the ideas of *grain boundary melting* (Dash et al., 1995; Wettlaufer et al., 1997c, Wettlaufer, 1998) and have further quantified the mechanisms associated with the transport of soil particles through the ice, the basis for sediment migration (Worster and Wettlaufer, 1998b). Inverse theory (Sylvester et al., 1996, and Sylvester and Winebrenner, 1998) has led to a new method to directly estimate thickness for electromagnetically lossless problems. Extending these results to a more lossy model for sea ice will allow a direct coupling to solidification theory. We have discovered the microscopic kinetics that control the crystallographic orientation at the advancing ice/ocean interface (Dash et al., 1998).

IMPACT/APPLICATION

We 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 in ONR's

Department of Engineering, Materials, and Physical Science. The spatial inhomogeneity of solid fraction has deleterious effects on the properties of technological materials. We address the basic coupling of microscopic and macroscopic phenomena, and a have developed a fundamental understanding of how these couplings control material properties constitutes a research priority that cuts across the boundaries of varied disciplines and hence address a broad range of the ONR's mission for the Navy. Our results have *commercial consequences* for the casting of ingots (Worster, 1997), the coarsening and annealing of ceramics and powders, and the nondestructive evaluation of polycrystalline alloys. The work advances the role that new materials and efficient materials processing play in the country's agenda for technological competitiveness. 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 other materials and applications within the mandate of other ONR departments.

TRANSITIONS

We are actively pursuing how our understanding of microscopic effects of ice surfaces influences macroscopic environmental phenomena of importance in many fields (Wettlaufer and Dash, 1999; Wettlaufer et al.,1998b). This has led to a broad based set of studies that use sea ice as a test bed for both environmental and materials science settings.

REFERENCES

Badgley, F.I., Heat budget at the surface of the Arctic Ocean, in *Proc. Symp. Arctic Heat Budget and Atmospheric Circulation*, ed. J.O. Fletcher, p. 267-78, The Rand Corp., Santa Monica, CA. 1966.

Dash, J. G., H-Y. Fu, and J. S. Wettlaufer, The premelting of ice and its environmental consequences, *Rep. Prog. Phys*. **58,** 115 (1995).

Dash, J.G., V.A. Hodgkin and J.S. Wettlaufer, Dynamics of faceted grain boundary grooves, *J. Stat. Phys.*, in press, (1998).

Morison, J.H., and M.G. McPhee, Lead convection measured with an autonomous underwater vehicle, *J. Geophys. Res*., **103**, 3257-81, 1998.

Morison, J., et al., The LeadEx Group, The LeadEx Experiment, *Eos Trans.*, **74,** 393, (1993).

Sylvester, J., D.P. Winebrenner and F. Glys-Colwell, "Layer-Stripping for the Helmholtz Equation," *SIAM Journal of Applied Mathematics*, **56** 736 (1996).

Sylvester, J., D.P. Winebrenner, "Linear and nonlinear inverse scattering," *SIAM Journal of Applied Mathematics,*To Appear (1998).

Wettlaufer, J. S., M. G. Worster and H. E. Huppert, The phase evolution of young sea ice, *Geophys. Res. Lett.* **24**, 1251 (1997)a.

Wettlaufer, J. S., M. G. Worster and H. E. Huppert, Natural convection during solidification of an alloy from above with application to the evolution of sea ice, *J. Fluid Mech.* **344**, 291-316 (1997)b.

Wettlaufer, J. S., M. G. Worster and L. Wilen, Premelting Dynamics: Geometry and Interactions, *J. Phys. Chem. B* **101**, 6137-41 (1997)c.

Wettlaufer, J. S., Introduction to Crystallization Phenomena in sea ice, in *Physics of Ice-Covered Seas*, edited by M. Leppäranta, (University of Helsinki Press, Helsinki, 1998a), p. 105-194.

Wettlaufer, J.S., Impurity effects in interfacial melting, *Nature,* subjudice (1998)b.

Wettlaufer, J. S., M. G. Worster and H. E. Huppert, The solidification of leads: Theory, experiment and field observations, *J. Geophys. Res.* subjudice (1998)a.

Wettlaufer, J. S., J.G. Dash and N. Untersteiner, eds. *Ice Physics and the Natural Environment,* NATO/ASI **56**, Series I, (Springer-Verlag, New York, 1998)b.

Wettlaufer, J. S. and J.G. Dash, Ice surfaces: Macroscropic effects of microscopic structure, *Scientific American*, To appear (1999).

Worster, M.G., Convection in Mushy Layers, *Ann. Rev. Fl. Mech*. **29** 91-122 (1997).

Worster, M. G. and J.S. Wettlaufer, Natural convection, solute trapping and channel formation during solidification of salt water, *J. Phys. Chem. B* **101**, 6132-36 (1997).

Worster, M.G., and J.S. Wettlaufer, The fluid mechanics of premelted liquid films, in *Fluid Dynamics at Interfaces*, ed. Wei Shyy (Cambridge University Press, Cambridge, 1998).

PUBLICATIONS

Wettlaufer, J.S., Impurity effects in interfacial melting, *Nature*, subjudice (1998).

Wettlaufer, J. S. and J.G. Dash, Ice surfaces: Macroscropic effects of microscopic structure, solicited by *Scientific American*, To Appear (1999).

Wettlaufer, J. S., M. G. Worster and H. E. Huppert, The solidification of leads: Theory, experiment and field observations, *J. Geophys. Res.* subjudice (1998)a.

Worster, M.G., and J.S. Wettlaufer, The fluid mechanics of premelted liquid films, in *Fluid Dynamics at Interfaces*, ed. Wei Shyy (Cambridge University Press, Cambridge, 1998).

Dash, J.G., V.A. Hodgkin and J.S. Wettlaufer, Dynamics of faceted grain boundary grooves, *J. Stat. Phys.*, in press, (1998).

Wettlaufer, J.S., Crystal growth, surface phase transitions and thermomolecular pressure, in *Ice Physics and the Natural Environment,* NATO/ASI **56**, Series I, eds J.S. Wettlaufer, J.G. Dash and N. Untersteiner, (Springer-Verlag, New York, 1998), p. 39-68.

Hodgkin, V.A., J.G. Dash, and J.S. Wettlaufer, Geometric selection in ice polycrystals: concavity, faceting and kinetics in *Ice Physics and the Natural Environment*, NATO/ASI **56**, Series I, eds J.S. Wettlaufer, J.G. Dash and N. Untersteiner, (Springer-Verlag, New York, 1998), p. 295-6.

Wettlaufer, J. S., Introduction to Crystallization Phenomena in sea ice, in *Physics of Ice-Covered Seas*, edited by M. Leppäranta, (University of Helsinki Press, Helsinki, 1998), p. 105-194.

Wettlaufer, J. S., M. G. Worster and L. Wilen, Premelting Dynamics: Geometry and Interactions, *J. Phys. Chem. B* **101**, 6137-41 (1997).

Wettlaufer, J. S., M. G. Worster and H. E. Huppert, The phase evolution of young sea ice, *Geophys. Res. Lett.* **24**, 1251 (1997).

Wettlaufer, J. S., M. G. Worster and H. E. Huppert, Natural convection during solidification of an alloy from above with application to the evolution of sea ice, *J. Fluid Mech.* **344**, 291-316 (1997).

Worster, M. G. and J.S. Wettlaufer, Natural convection, solute trapping and channel formation during solidification of salt water, *J. Phys. Chem. B* **101**, 6132-36 (1997).