Sea Ice Solidification: The Physical Origin Of Macroscopic Properties

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LONG-TERM GOALS

The long term goals of this project are to derive a quantitative understanding of the physical mechanisms responsible for the creation and evolution of the important thermodynamic properties of sea ice, and the relevant coupling with electromagnetic signature modeling. The approach is basic and hence the results are broadly applicable and useful in studies of all unidirectionally growing binary alloys. The focus is on saltwater and the implications influence fields from metallurgy to geophysics.

OBJECTIVES

Oceanic freezing captures our interest because its central role in the thermohaline circulations associated with leads. The outstanding puzzle concerns the relationship between local lead scale dynamics, whose timescales are short relative to seasonal timescales, and the large scale hydrography of the Arctic Ocean (Badgley, 1966). In order to understand the lead scale dynamics attention must be paid to the coupling between salt fluxes and solidification dynamics. Our principal objective is to develop a quantitative and predictive understanding of this coupling.

APPROACH

The approach relies on theory, laboratory and field experimentation. The theoretical work is centered on effective medium descriptions with a thermodynamic basis and is done in collaboration with Drs. H.E. Huppert and M.G. Worster at the University of Cambridge. The laboratory work has been designed to model the leading order effects of the system and is also done in collaboration with the Cambridge group. The field work began with the ONR Lead Experiment and has recently focused on the analysis of the data, obtained by autonomous buoys designed at APL/UW, in the context of the theoretical and laboratory treatments.

WORK COMPLETED

During this year we completed the application of an algorithm (derived and tested last year) that tracks solidification fronts to the field data from LeadEx. This study was highly successful and correlated our previously derived critical porous medium Rayleigh number analysis with direct oceanographic measurements in the water column.

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RESULTS

We demonstrated the controlling influence that the internal phase evolution of sea ice has on heat and mass fluxes in the field. We had previously examined the stability of the brine trapped in a growing sea ice matrix both theoretically and experimentally (Wettlaufer et al., 1997 a,b, and Worster and Wettlaufer, 1997) and now find that haline convection, driven from within the growing sea ice in the field, is consistent with this previous work and with the nature of direct turbulence measurements. The importance of this process is that, although ice growth is continuous, the local brine flux commences abruptly, only after some time, in contrast to what had previously been supposed. Hence, the ice growth process itself is a source of intermittence in oceanic boundary layer turbulence. Furthermore, we found that, in this particular situation, the sea--ice growth is not simply a square root function of time, in contrast to the model typically used in numerical simulations. This work will be published soon (Wettlaufer et al., 1999).

We have quantified how the microscopic kinetics that control the crystallographic orientation at the advancing ice/ocean interface (Dash et al., 1999) are related to the growth drive in the system. We have derived a basic theory of how particles are redistributed in the ice cover under the influence of thermomolecular pressure gradients (Worster and Wettlaufer, 1999; Wettlaufer 1999a,b) and how these gradients depend on the nature and concentration of impurities in the ice cover (Wettlaufer 1999c).

IMPACT/APPLICATION

By far the most practical methods of studying lead convection are numerical simulations and laboratory models, and a strong conclusion of our research is the importance of the proper treatment of the boundary conditions describing the buoyancy flux. We have shown quite clearly that saltwater is an important transparent analogue for metallurgical systems, and that the phase behavior of this system is a superb test bed for materials properties in general. The approach is receiving broad attention and we will publish an article in Scientific American on the topic (Wettlaufer and Dash 2000). This has direct relevance for other areas of materials research pursued in ONR's Department of Engineering, Materials, and Physical Science.

TRANSITIONS

We are actively pursuing both the large scale geophysical implications of our understanding of local brine flux dynamics, but also how our understanding of thermomolecular pressure gradients sheds light on other materials systems; in particular solid rare gases (Zhu et al., 1999).

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., V.A. Hodgkin and J.S. Wettlaufer, Dynamics of faceted grain boundary grooves, *J. Stat. Phys.* **95**, 1311 (1999).

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., Ice Surfaces: Macroscopic effects of microscopic structure, *Phil. Trans. Roy. Soc. A*, **357** 1-23 (1999a).

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, 1999b), p. 39-68.

Wettlaufer, J.S., Impurity effects in the premelting of ice, *Phys. Rev. Lett.*, **82**, 2516 (1999c).

Wettlaufer, J. S., M. G. Worster and H. E. Huppert, The solidification of leads: theory, experiment and field observations, *J. Geophys. Res.*, in press, (1999).

Wettlaufer, J. S. and J.G. Dash, Mysteries of ice surfaces, *Scientific American*, February (2000).

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, 1999, p. 339).

Zhu, D-M., J.G. Dash, B. Sing, O.E. Vilches and J.S. Wettlaufer, Frost heave in Argon, (subjudice) *Science* (1999).

PUBLICATIONS

Wettlaufer, J. S. and J.G. Dash, Melting below zero, *Scientific American*, February (2000).

Wettlaufer, J.S., Impurity effects in the premelting of ice, *Phys. Rev. Lett.*, **82**, 2516 (1999).

Wettlaufer, J. S., Ice Surfaces: Macroscopic effects of microscopic structure, *Phil. Trans. Roy. Soc. A*, **357** 1-23 (1999).

Wettlaufer, J. S., M. G. Worster and H. E. Huppert, The solidification of leads: theory, experiment and field observations, *J. Geophys. Res.*, in press, (1999).

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, 1999, p. 339).

Dash, J.G., V.A. Hodgkin and J.S. Wettlaufer, Dynamics of faceted grain boundary grooves, *J. Stat. Phys.* **95**, 1311 (1999).

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, 1999), 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, 1999), 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.