Annotated Bibliography-Sea Ice Physics and Biology - S.F.Ackley
To accompany 2011 Lecture at MBI Workshop.

Lewis, M. J., Tison, J. L., Weissling, B., Delille, B., Ackley, S. F., Brabant, F., Xie, H., 2010. Sea ice and snow cover characteristics during the winter-spring transition in the Bellingshausen Sea: an overview of SIMBA 2007, ***Deep Sea Research II*** , doi:10.1016/j.dsr2.2010.10.027

This overview describes the results from the 3rd Antarctic Drift Station conducted during the International Polar Year in Sept 2007. Important parameters include the variation in temperature fields within the ice cover, leading to fluctuations in brine rejection and sea water upwelling in the sea ice. These time series were correlated with fluctuating levels of algal production and gas exchange within the ice cover, important parameters for coupling the ice cover to the atmospheric processes for CO2 and DMS/P. The characteristics of the ice cover also included widespread observed surface flooding with important consequences for the thermal regime of the ice cover and its eventual structure as the flooded snow refroze into sea ice of a different type than found from bottom freezing.

Golden, K.M., S.F. Ackley, V.I. Lytle 1998, The percolation phase transition in sea ice, ***Science*, **282, 2238-41. This paper showed the analogy of sea ice to other composite materials where the transition from permeable to impermeable takes place at a relatively low percentage of the brine volume, 5%, if the structural characteristics of the two materials satisfy certain mathematical criteria.

Fritsen, C.H., V.I. Lytle, S.F. Ackley and C.W. Sullivan, 1994, Autumn Bloom of Antarctic Pack Ice Algae, **Science**, 266, p.7824.

This (very cool) paper showed for the first time that a fall bloom of algae existed in Antarctic sea ice. The mechanism for creating the bloom was the addition of nutrients that were brought up from below, driven by convection. The convection was triggered by changes in brine composition when freezing in the upper layers caused salts to be rejected, densifying the brine which sank and was replaced by nutrient rich sea water from beneath the ice. The measurements were made from the first Antarctic sea ice drifting station, Ice Station Weddell.

Ackley, S.F., C.H. Fritsen, V.I. Lytle and C.W. Sullivan, 1996, Freezing Driven Upwelling in Antarctic Sea Ice Biological Systems, **Proceedings of XVII Symposium on Polar Biology**, No. 9, 45-59, NIPR, Tokyo, Japan. This paper was a follow-on and expanded version to the Fritsen et al 1994 Science paper. While that paper showed an indirect measure of the overturning by computing how much seawater nutrients were needed to grow the observed algae, this paper included independent evidence from thermistor strings that showed pulses of temperature within the ice, cold when brine descended and warm when seawater ascended.

Thomas,,D.N. And G.S. Dieckmann,**Sea Ice** 2nd Edition, Wiley-Blackwell. 2010
Chapters 1,2,8,12
Chapter1 provides an overview of the importance of sea ice: The changes, particularly in Arctic sea ice summer extent with five years of record lows seen after 2007 have revised the prediction of the possible disappearance of summer sea ice from about 2100 to before 2050.
Chapter 2 on the growth, structure and properties of sea ice sets the stage for how the large-scale behavior of sea ice in its response to climate forcing, and the micro-scale behavior derived from ice growth and structure, are linked together. Ultimately, the sub-millimeter scale is the habitat for microscopic life that is described in other chapters, so these properties are fundamental to the structure of the biological environment and provide the substrates for biogeochemical processes. Key physics for these other discussions is in this chapter.
Chapter 8 on primary production and sea ice points out that despite lower rates of primary production

by sea ice algae compared to phytoplankton, they are virtually the sole source of fixed carbon for higher trophic levels in ice-covered waters. Sea-ice algae have been shown to sustain a wide variety of organisms, including krill, throughout the winter season when other sources of food are absent. Chapter 12 is on biogeochemistry of sea ice and reviews the important links between the chemical and biological environments within sea ice. While driven by molecular scale interactions, biogeochemical cycles are far-reaching in their impacts on the carbon cycle, DMS production, and the mediation of biology by trace nutrients such as iron.

Ackley, S.F. et al 2003 A Top-down Multidisciplinary Study of the structure and function of the pack-ice ecosystem in the eastern Ross Sea, Antarctica **Polar Record** 39 (210): 219–230. This overview paper describes the relationship of pack ice to the polar ecosystem based on the Antarctic Pack Ice Seals cruise into the Ross Sea. It is fairly unique in including studies of the seals and penguins and their major food supply, Antarctic krill, in relation to the large and small scales of sea ice characteristics in the Antarctic.

Weeks, W. F. **On Sea Ice**, Univ of Alaska Press 2011,
Chapters 5,6, 7 ,8
Chapter 5 Components, The phases of sea ice are described as water, seawater and brine, ice, and solid salts. Although relatively few, these important constituents are assigned their appropriate temperature ranges, structures, and (for the salts) eutectic temperature, the temperature that they precipitate as solid from brine.
Chapter 6. First sentence reads: 'In order to understand sea ice, one must have a general understanding of the so-called sea ice phase diagram, which specifies the amounts and compositions of the phases that exist at different temperatures when one freezes sea ice to form sea ice." This chapter describes the evolution of the sea ice phase diagram by first considering the NaCl-H20 phase diagram and progressing to the NaCl-H20-Na2S04 system. This then leads to the phase diagram for "standard" sea ice developed by Assur (1958). A useful addition to the phase diagram is the table of phase relations numerical values with temperatures, salinities and salt amounts as tabulated by Assur (1958), used in the construction of the phase diagram.
Chapter 7. Sea Ice Structure. How sea ice evolves and the pathways are described either in slow growth, calm conditions where one-dimensional conduction of heat determines the structure, or under conditions of appreciable swell, waves, wind and blowing snow produce forms of ice controlled by these small scale dynamics. Other processes forming snow ice structures and platelet ice are also described, accounting for more minority components of sea ice structures observed in the field.
Chapter 8 Sea Ice Salinity Characteristics of the ice salinity field in sea ice as observe from cores is reviewed here. Included are generalizations of the structures observed in both Arctic and Antarctic regions. Relationships of ice thickness to ice salinity compiled from field data is given along with the form of general equations relating these two. Finally, theories used to describe the evolution of the sea ice salinity are given and some of their performance characteristics in their predictions.

Weeks, W.F. and S.F. Ackley 1986 Growth, Structure and Properties of Sea Ice, in **The Geophysics of Sea Ice** (N. Untersteiner, ed.), Plenum NATOAS1 Series 3, v. 146, p. 9-153, 1986. This chapter, also published as a CRREL monograph, while largely superseded and updated by Weeks, W.F. On Sea Ice contains detailed information on ice structure, salinity and some of the electrical, thermal and mechanical properties that were investigated up until that time. In some areas this review still contains the complete information as some of the experiments have not been extended or repeated.

Ackley, S.F., M.J. Lewis, C.H. Fritsen, and H. Xie, 2008, Internal melting in Antarcticsea ice: development of "Gap Layers", **Geophysical Research Letters**,doi:10.1029/2008GL033644. This paper was a simple 1-D model study which showed how an important biological habitat for sea ice algae, internal melted or "Gap" layers could develop during Antarctic summer in pack ice regions. In relating the physics to the biology, an important aspect of this model is that it is testable, unlike much of the previous work, which were descriptive and subject to speculation as to cause.

Perovich, D.K., B.C. Elder, K.J. Claffey, S. Stammerjohn, R. Smith, S.F. Ackley, H.R. Krouse and A.J. Gow, 2004, Winter sea-ice properties in Marguerite Bay, Antarctica, **Deep-Sea Research** II, 51, p. 2023-2039. In this relatively warmer region of the Antarctic pack ice zone, measurements from remote buoys of ice and snow temperatures showed that, even in winter, when areas became flooded under a thick snow cover, little refreezing took place so that slush layers of flooded snow were widespread. A physical consequence is that less snow ice could form here than might be otherwise expected if the layer froze back. As spring warming progressed, these slush layers (from other studies) are regions where high levels of biological matter are found, suggesting they are significant growth regimes for sea ice algae.

Dieckmann, G.S., M. Spindler, M.A. Lange, H. Sicken, S.F. Ackley,1991, Antarctic Sea Ice, A Habitat for the Foraminifer Neogloboquadrina Pachyderma, **J of Foram Res.**, 2 It p. 184-91 . Forams are relatively large heterotrophs that become trapped within the ice during freezing processes. Structurally they were found in greater numbers in frazil ice, a small-grained ice type usually associated with some turbulence in the water column. The higher concentrations found in the ice relative to the water column also suggested they found the ice habitat a more benign environment.

Shen H.T. And N. Ackermann,Wave incorporation of sediment and algae Sea Ice Properties and Processes, Proc. of the W.F. Weeks Sea Ice Symposium, S.F.Ackley and W.F. Weeks (eds.), **CRREL Monograph 90-1**,.300 pgs, 1990. This laboratory study used a wave generator to show how wave pumping could concentrate algae or sediment into pack ice. Since frazil ice is found primarily where waves were present, it provided the principal mechanism needed for the higher concentration of forams found in the Dieckmann et al 1991 study.

Homer, R. S.F. Ackley, G.S. Dieckmann, B. Guiliksen, T. Hoshial, L. Legendre, LA. Melnikov, W. S. Reeburgh, M. Spindler and C. W. Sullivan, 1992, Ecology of sea ice biota 1. Habitat, terminology and methodology, **Polar Biology**, 12, 41-27
Legendre, L., S.F. Ackley, G.S. Dieckmann, B. Gulliksen, R. Homer, T. Hoshial, I.A. Meinikov, W. S. Reeburgh, M. Spindler and C. W. Sullivan, 1992, Ecology of sea ice biota, 2. Global significance. **Polar Biology**, 12, 429.44
These two review papers established the basic terminology and methodology for sea ice biota. It described how to classify the habitats so that comparative studies could be made, appropriately differentiating the habitats so that confusion over mechanisms, such as bottom freezing or surface flooding, could be reduced. The second paper used the observations of the habitats known until that time to develop "back of the envelope" estimates as to the contribution of sea ice algae to the total production in polar seas. These estimates served a useful purpose in later calculations that refined the

estimates numerically, where different processes of formation could be more quantitatively derived and based on physical conditions.

Ackley, S.F. and C.W. Sullivan,1994, Physical Controls on the development and characteristics of Antarctic sea ice biological communities--a review and synthesis, **Deep-Sea Research**, Vol. 41,. p. 1583-1604 This paper summarized several of the physical mechanisms, e.g. wave action, surface flooding, gap layers, etc, responsible for the variety of sea ice habitats that are observed in Antarctic sea ice. It importantly showed that several of these habitats are at least much more prevalent, if not unique, to the Antarctic environment. These habitats, their physical causes, and generally higher productivity than Arctic sea ice environments are one element of global climate change that may impact the Antarctic in a way not seen in the Arctic.

Lytle, V.I. and S.F. Ackley, 1996, Heat Flux through Sea Ice in the Western Weddell Sea: Convective and Conductive Transfer Processes, **Journal of Geophysical Research**,v.101,8853-8868. This paper resulted from time series, first time measurements, of pack ice temperatures from the first Antarctic drifting station, Ice Station Weddell. It showed the importance of convective heat flux, driven by freezing from above, in the ocean interaction with the overlying ice cover. These results, along with related biological results are still being used as the principal validation data sets for physical and biological models of the Antarctic pack ice, nearly twenty years after they were taken.