Sea Ice and Heat Budget

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In April 1957 a group of scientists arrived at Ladd Air Force Base to man the first long-term U.S. drifting station on sea ice. Considering how much, twelve years later, we still have not found out, our innocence at that time might have been disheartening. But, luckily, innocence never is.

I am sure that our small research group at the University of Washington had a thoroughly thought-out program at the time, and the questions to ask might have been the following:

1) What are the properties of sea ice?
2) Why is the Arctic Ocean ice-covered?
3) Under what circumstances could the present ice cover change?

Needless to say, these three questions are closely connected, especially the second and the third.

In dealing with the first question, properties of sea ice, an important distinction is to be made between the small-scale (sample size) properties and the properties of a large, natural sheet of sea ice, or in other words, between sea ice as a material and sea ice as a geophysical phenomenon.

A great deal of work has been done on the properties of sea ice as a material. Owing to the work of Weeks and Assur (1967), Peyton (1963), Schwerdtfeger (1963), and many others we have now accumulated a substantial amount of knowledge on the crystallographic structure of sea ice and on its mechanical and thermal properties. We also have a fair amount of knowledge of the radiative properties although here considerably more work remains to be done, for instance, on the attenuation of light in sea ice and on radiative properties in the microwave region.

All properties of sea ice are profoundly affected by its salt content. From the work of Assur and Weeks we have now a fairly clear idea of how the partition of ice and salt occurs during the freezing process and how the brine is distributed in the initially formed ice. We also have known for a long time that the ice, which originally has a salinity of several parts per thousand, becomes practically fresh after a few years. This process of desalination, however, is still largely unknown and offers a field of fascinating and useful research.

In general, it seems fair to say that sea ice as a material is reasonably well known and that those points that are to be cleared up are easily identified and will no doubt be taken care of in the near future.

Much less favourable is the situation in regard to the properties of large, composite sheets of natural sea ice. In the present context of the general heat and ice budget of the Arctic Ocean there are three parameters that are most important:

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strength, roughness, and albedo. None of them do we know accurately enough to be confident in making the calculations that will be discussed later. And all three of them have a common requisite: knowledge of the actual morphology of the ice. What the shape and size of a sample are for the experimenter in the laboratory, distribution of ice thickness, leads, and ridges are for the geophysicist in the field. It is our lack of knowledge of the morphology of the ice that makes it so difficult to evaluate its properties.

Strength: This is the most problematic parameter. It is needed for calculations and predictions of the movement of the ice. More specifically, we need to know how a large sheet of natural sea ice is deformed by stress under the action of wind and water currents that contain areas of convergence, divergence, and shear. It is hopeless to theorize on this problem, and even the design of a meaningful experiment, relating the distributions of air and water stresses to ice strains, contains fundamental difficulties that will not be overcome without the execution of a rather vast observational project.

Roughness: This is the parameter that describes the efficiency of the frictional coupling between the air and water flows and the ice. We have some idea what the roughness length of smooth, undisturbed ice is. But the drag on those areas may be outweighed by the form drag on ridges and hummocks at both sides of the ice, and we cannot hope to calculate accurately the stress to which the ice is subjected if we don't know its topography.

Albedo: The annual total of incoming short-wave solar radiation is of the order of 70 kcal. cm.$^{-2}$. About 25 or 30 per cent of that is absorbed at the ice surface. The absorption coefficient is very sensitive to the areal extent of water puddles in the summer and of open leads (which are nearly black). A decrease of the albedo of only 2 per cent would cause an increase in absorption equivalent to 20 cm. of ice melted. Of course, the albedo has been measured by numerous investigators but most of these measurements were made too close to the ground and do not accurately represent areal averages. Nothing is known about the range of year-to-year variations of average albedos.

There are, of course, other large-scale parameters that are important as, for instance, the transmission of light through the ice into the ocean, but those mentioned are the most crucial in the present context.

The second main question is concerned with the explanation of the existence of the present ice cover. Since the presence or absence of ice is determined by the temperature at the surface, and since the temperature at the surface is determined by the fluxes of energy into and out of the surface, the determination of these energy fluxes is the only approach to an explanation of what happens at the surface. It is trivial to say this now, but it was not until the 1930's that this approach, or the so-called heat balance method, became commonly adopted.

To explain sea ice we first have to establish a number of observational facts. From the numerous observations made at the drifting stations we know that the total accumulation of snow is about 40 cm. with a density of 0.35 g. cm.$^{-3}$, that the mean monthly surface temperatures range from about 0° in July to about -32°C. in February, that the snow usually begins to melt around the tenth of June, that it is melted away by the end of June, and that subsequently about

40 cm. of ice are melted away, balanced by an equal amount of new ice formed at the bottom during the winter months. Thus an "equilibrium ice thickness" is established that is generally believed to be around 3 m. These observations have been fairly easy to make, and they established what it is that has to be explained.

The next set of observations concerns the energy fluxes. These observations are much more laborious and, since the International Geophysical Year they have been a major part of the activities of our group at the University of Washington. They consist of measurements of radiative fluxes, both visible and infrared, albedos, wind and water flow profiles in the boundary layers, temperature profiles in the air and in the ice, and evaporation or condensation. These observations are fraught with a long list of difficulties, ranging from plain instrumental inaccuracies to problems of sampling and representativeness. The most extensive and thorough efforts in combining all this information into a coherent picture of the overall heat balance have been made by Fletcher (1965) at the Rand Corporation and by Vowinckel and Orvig (1966) at McGill University. The picture that evolves is, of course, not free of unexplained inconsistencies but, in general, they are minor and we now have at least a working knowledge of the thermodynamic behaviour of the ice and of the energy fluxes that cause it. To tie these two together and to develop a formal, mathematical way to describe thickness and temperature changes of the ice as a result of climatic and oceanic forcing functions has been our main effort during the past five years.

The details of our numerical model cannot be described here (Maykut and Untersteiner 1969). In brief, the model predicts surface temperature, surface ablation, bottom ablation or accretion, internal temperature, and snow or ice thickness, caused by a given set of input functions consisting of incoming short and long-wave radiation, turbulent fluxes in the air, and snowfall. With Fletcher's heat balance values as input functions, the model produces a sheet of ice that behaves, in its thermodynamic aspects, almost exactly the way it is observed in nature. In other words, it seems that our second main question, "Why is the Arctic Ocean ice-covered?", has been answered at least partially. Even though we have not said how the ice got there, we have explained in quantitative terms what keeps it there.

The third main question, "Under what circumstances could the present ice-cover change?", leads us not only to the heart of the problem but also into a vast area of unresolved and exceedingly complex questions.

The real ice cover is only very crudely approximated by the simple, semi-infinite sheet of ice that we have described in our model. In reality, the forces of wind and water currents act on the ice and cause the contorted drift patterns that we know from our stations, the large stream of ice that is continuously pushed out into the Greenland Sea, and the open leads and pressure ridges that modify the heat exchange to an unknown degree.

A numerical model for the drift of sea ice under the influence of wind and water currents has been developed by Campbell (1965) at the University of Washington, but this model cannot be used for actual drift predictions as long as the internal stress parameters, mentioned earlier, are unknown.

Given the interaction between the thermodynamic and the dynamic behaviour of the ice, and given the fact that any major variation in the extent of the ice cover would also influence the atmosphere, which in turn interacts thermodynamically with the ice, it becomes clear that we have here a three-phase-system of air, ice, and ocean, that interacts on a global scale with a built-in variety of multiple feedbacks. Our ability to parameterize such a problem is deficient and our computers are still too slow, but there is no doubt that it will be solved since the present limitations are in data and data-processing rather than in concepts and ideas.

The "heart of the problem" mentioned earlier in this section is the purported "instability" of the arctic sea-ice cover. On the basis of some rather qualitative arguments it has been theorized that this ice cover, once removed by some climatic anomaly (natural or artificial), would not return. The drastically lowered albedo of an open Arctic Ocean would result in an amount of heat storage during the summer that would prevent the formation of more than a thin skim of winter ice. The historical record speaks against such an instability. The work of Hunkins and Kutschale (1967) and Ku and Broecker (1967) at Columbia University indicates that the Arctic Ocean has been ice-covered for at least 150,000 years. Recent work done at the University of Wisconsin (Steuerwald *et al.,* 1968) suggests that this might have been so throughout the entire Quaternary, if it is true that the present rate of sedimentation is indicative of an ice cover and low productivity in the ocean. However, the interpretation of these findings still seems to leave some room for doubt, and even the remote possibility that the arctic ice cover might be unstable in the above sense makes this problem one of extreme importance from a scientific, economic, and even political point of view.

When our project started in IGY 1957, logistical support was provided by the Alaskan Air Command. Perhaps there are records of the cost of this operation. If there are, it is best not to look at them because they would be misleading. Station Alpha was a "first" and a conspicuous success, whatever price was paid, and I doubt that the relative economy and efficiency of the later drifting stations would have been possible without the experience gained by the first one.

Since 1959 we have been logistically supported by the Naval Arctic Research Laboratory, and this seems an appropriate time to thank Max Brewer and his staff for their efforts and hospitality. I should add that NARL not only supported the field activities mentioned earlier but also an extensive program in air chemistry and radiation climatology at Barrow.

Speaking for the thirty-odd people that have worked for our project and who have, in part, gone on to either greater or lesser things, I should like to direct an expression of particular gratitude to two addresses: one is Phil Church, who initiated our whole project and saw it through its first turbulent years, and the other is Max Britton and the Office of Naval Research, who have been staunchly supporting us with money and encouragement, and who have given us the new Naval Arctic Research Laboratory.

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