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Norbert Untersteiner, et al

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13. ABSTRACT The report summarizes research performed under Contract N00014-67-A-0103-0007, NR 307-252, during the year 1 October 1973 - 30 September 1974. Research topics include: (i) growth and ablation of sea ice, (ii) sea ice dynamics, (iii) optical properties of sea ice, (iv) desalination of sea ice, (v) thickness distribution of sea ice, and (vi) generation of internal waves in the ocean by pressure ridge keels.

14. KEY WORDS

ARCTIC OCEAN
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- Thickness Distribution
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- Wave Drag



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## PERSONNEL

The following scientific and technical personnel have been employed by the Contract during part or all of the period covered by this report:

DR. NORBERT UNTERSTEINER, Principal Investigator

DR. GARY MAYKUT, Co-Principal Investigator

DR. SEELYE MARTIN, Co-Principal Investigator

DR. THOMAS GRENFELL, Research Associate

MR. RONALD ROULET, Assistant Physicist (deceased February 1974)

MR. PETER KAUFFMAN, Electronics Technician

MR. FRED A. RIGBY, Predoctoral Associate

MR. DONALD K. PEROVICH, Predoctoral Associate (from 15 June 1974)

MR. TERREN M. NIEDRAUER, Graduate Assistant (from 15 June 1973)

## INTRODUCTION

This report describes activities under Contract N00014-67-A-0103-0007 during the period 1 October 1973 to September 1974, at the Department of Atmospheric Sciences, University of Washington.

During the past year, our research efforts have been concentrated in three general areas: (i) desalination and entrainment processes in growing sea ice, (ii) optical properties of sea ice and consequent effects on down-welling irradiance in the Arctic Ocean, and (iii) theoretical modeling. Laboratory observations were made of brine drainage from sea ice, lateral melting of ice walls, interaction of petroleum with sea ice, and the movement of large brine pockets under strong temperature gradients. Scientific results from previous laboratory work on the growth of ice stalactites, the evolution of under-ice melt ponds, and the desalination of young sea ice have been written up and are now either in print or in press. In connection with the radiation in ice program, analysis of the Barrow data has been completed and a paper describing the spectral distribution of light beneath first-year sea ice has been submitted to a journal for formal publication; a paper describing the spectrophotometers and their operational characteristics has also been published. A field program to investigate the interaction of solar radiation with perennial sea ice and the ocean was carried out at T-3 during the summer. Spectral data on albedos, attenuation within the ice and snow, and the irradiance field beneath the ice were obtained. In the area of numerical modeling, rapid progress has been made in developing the theoretical framework needed to combine dynamic and thermodynamic effects in a single ice model. Formulation of the ice thickness distribution theory is essentially complete and has been incorporated into the AIDJEX ice model. A complete description of this model, together with the results from construed motion calculations, appeared as a joint paper in a recent AIDJEX Bulletin. In addition, a theoretical study of the conditions under which internal wave drag effects could be important to the motion of arctic pack ice has been made and a description of the results published in the AIDJEX Bulletin. Preliminary observations downstream from a moderate pressure ridge keel near T-3 during September verified the presence of standing internal waves near the pycnocline. A detailed field study of such waves is planned for summer 1975.

DYNAMIC AND THERMODYNAMIC MODELING

Work in this area has concentrated almost entirely upon generalizing and improving our theoretical treatment of the ice thickness distribution (G) and its relationship to the dynamics and thermodynamics of the arctic ice pack. A fundamental problem in calculating changes in the thickness distribution lies in describing the redistribution of ice during ridge building. Our initial treatment was one-dimensional, in that it considered only the effects of convergence or divergence and assumed that only the thinnest ice in a given region went into ridging. However, strain measurements from the 1972 AIDJEX Pilot Study indicated that shear was as large or larger than the divergence, and examination of aerial photographs suggested that shear ridges were a common feature in the ice pack. Last fall the model was expanded to take into account the effects of shear as well as convergence. One consequence of shearing motions is that ridges can be formed from ice of almost any thickness, and therefore the thinnest ice first assumption cannot be used in a two-dimensional treatment. Hence, for a given state of strain, it is necessary to specify the range of thicknesses and the relative amounts of ice consumed in the ridging process together with how this ice is redistributed into pressure ice. Few field data are available on this subject; however, conservation of area and conservation of mass place strong constraints on the redistribution process. A general theoretical framework has been developed which incorporates these constraints and defines the range of acceptable functions which characterize the ridging process.

Although we obtained a number of analytical and numerical solutions to the thickness distribution equation last fall, these solutions were not realistic, rather they served only to provide insight into the behavior of the governing equation and the sensitivity of G to our basic assumptions. What was lacking was a way to relate the thickness distribution to the large-scale strength of the ice. This was finally accomplished by D. A. Rothrock from the AIDJEX Modeling Group through conservation of energy considerations. In cooperation with members of the AIDJEX Modeling Group, realistic calculations of the thickness distribution were then begun using: (i) the elastic-plastic material properties of the ice postulated by M. D. Coon, (ii) thermodynamic growth rates predicted by the Maykut/Untersteiner model, and (iii) specified strains comparable in magnitude to those observed during the AIDJEX pilot studies. A series of cases were run using different initial assumptions regarding the shape of G for a variety of strain histories. In addition to showing how the thickness distribution changed with time, the results also provided time-dependent information on yield strength, potential energy, and the plastic work performed on the ice. The model was also driven using real strain data gathered during the 1972 AIDJEX Pilot Study; results from this calculation yielded estimates of G and the stress components during the forty day period. The calculations demonstrated that, because it is the distribution of the thin ice which determines the overall strength of the ice pack, thermodynamics plays a central role in determining the material properties of the ice and its dynamic behavior. Since growth rates define the characteristics of the ice thickness equation, the thermodynamics also determine the relative importance of the initial conditions. For example, in the situations considered above, it was found that the yield strength of the ice was strongly dependent upon the initial choice of G for the first 20-30 days, after which time it was primarily dependent on the strain history. This suggests that, in the winter at least, it may not be as critical to know the exact ice thickness distribution as we had previously thought. A comprehensive description of the thickness distribution work and the elastic-plastic approach, together with results from the construed motion studies, was prepared jointly with members of the AIDJEX Modeling Group and published in a recent AIDJEX Bulletin under the title, "Modeling the Pack Ice as an Elastic-Plastic Material".

Recently, we have used the model to analyze macroscale (1000 kilometer) strain data taken from the triangle formed by ARLIS II, T-3, and NP-10 during the two year period from May 1962 to May 1964. The velocity field of the ice for this case proved to be quite similar to that observed on a much smaller scale (100 kilometers) during the 1972 AIDJEX Pilot Experiment; the motion was generally diverging with the shear component of the strain tensor being comparable in magnitude with the divergence. This suggests that results obtained on the 100 kilometer scale chosen for the AIDJEX Experiment should indeed be representative of the large-scale behavior of the ice pack. Using growth rates derived from climatological heat flux averages together with the model, we were able to calculate how the thickness distribution within the T-3/ARLIS II/NP-10 array changed during the two year period. Predicted seasonal changes in G conformed to our intuition and the final form of G was in reasonable agreement with submarine data. The only obvious problem which showed up as a result of the calculations was that the model apparently does not create enough thick (greater than 8-10 meters) pressure ice. We plan to look more carefully at the problem of dynamic redistribution of the ice to try and come up with a rational way of describing the production of very thick pressure ridges. The 1000 kilometer strain data were also used to evaluate the sensitivity of the model to assumptions regarding the redistribution process and the initial conditions. In general, we found that the yield strength underwent large fluctuations in time and was significantly affected by our initial assumptions. The shape of G, on the other hand, was only mildly affected by these assumptions and it appears that the strain history is the dominant factor in determining how ice thickness is distributed. A paper describing the formal development of the thickness distribution concepts and these recent results is being prepared jointly with A. S. Thorndike and D. A. Rothrock for submission to the Journal of Geophysical Research.

The thickness distribution calculations carried out to date have relied on rather crude data, however, the Main AIDJEX Experiment should provide us with a detailed data set of high quality. We hope to be able to use these data for the final test of the G model. While the thermodynamic growth rates used in the previous calculations may be considered typical of ice in the Central Arctic, there is no reason to expect that conditions over any specified area in the ice pack will conform to climatological averages. For a proper test of the model we must have growth rates which are representative of the AIDJEX strain array. Since it is impractical to measure growth rates under all ice thicknesses during the entire 14 month period, we have devised a combined theoretical-experimental program to obtain the needed information. AIDJEX personnel will periodically make thickness measurements under six different ice categories, including leads and pressure ice. These results will be used to verify growth rates predicted by the thermodynamic model on the basis of actual temperature and heat flux data. Because the turbulent heat exchange over thin ice is substantially larger than that over thick ice, it will be necessary to alter the upper boundary condition in the ice growth model so that the fluxes of sensible and latent heat appear explicitly as function of wind speed and the gradients of temperature and moisture in the lower part of the atmospheric boundary layer. Suitable parameterizations have been found, but we have not yet tested them.

One problem limiting the general applicability of the thermodynamic model is that it must be driven by sophisticated heat flux data which are not routinely available. For thicker ice where growth rates are small and not very sensitive to short term departures from the mean, this is not a serious problem since climatological averages can be used without introducing large errors. This is not the case for thin ice growth and it would be useful to have a model which utilizes simpler and more easily obtainable data. To remedy this we have recently reformulated the ice growth model so that it can be operated using only data on air temperature, wind speed, and snow depth. This "simplified" model would be used primarily to describe the growth of first year ice and would not be capable of predicting summer ablation at the upper surface. It would, however, represent a great improvement over empirical methods of predicting ice growth. In the future we hope to be able to use the complete model to parameterize, to some extent, the transport of heat within the ice. This would reduce the complexity of the "simplified" model still further so that it could be coupled directly with other models of the ice or atmosphere.

RADIATION IN ICE

Analysis of the Barrow data has been completed and the transmission results submitted to Limnology and Oceanography under the title, "The Spectral Distribution of Light beneath First-Year Sea Ice in the Arctic". This paper deals primarily with the amount and spectral composition of the short-wave radiation which would typically be available for primary production under sea ice in the coastal portions of the Arctic Basin. While the underlying first-year ice appears to be fairly homogeneous, surface conditions were found to have a large effect on total transmission through ice of equivalent thicknesses. Three main types of ice were considered in this study: (i) white ice which was above the local water table and was continuously drained, (ii) ice covered by shallow melt ponds, and (iii) snow-covered ice. The radiative properties of a fourth type of ice, blue ice which was saturated by melt water at the local water table, were found to be indistinguishable from those of the melt pond ice. Examples are given in the text showing absolute transmission and percent transmission as a function of wavelength for each of these surface types.

Analysis of the transmission data has definitely established the presence of algae within the lower part of the ice. Examination of the data sequence revealed time-dependent changes in the shape of the transmission spectra which we suspected were due to decreased algal loading as the underside of the ice melted. By differencing transmission spectra obtained on different days beneath ice of similar type and thickness, we were able to determine a measure of the spectral absorption of the contaminant. We found a strong absorption peak at 435 nm with a secondary peak at 670 nm. The curve has almost exactly the same shape as those obtained by Lorentzen (1972) in the laboratory with cultured brown algae. There seems to be little doubt, then, that there were algae within the lower part of the ice, presumably living in brine channels between ice crystals. Following two weeks of intense melting at the surface, the average ice thickness had decreased to about 120 cm and effects from the algae were no longer discernible in the transmission spectra. It is not clear whether melting at the bottom or flushing by surface melt water contributed to the demise of the algae, but, in any case, they do not appear to be able to withstand vigorous periods of melting.

Using the Barrow data in conjunction with a two-layer photometric model based on the theory of Dunkle and Bevans, we were able to obtain predictions of light transmission beneath first-year white ice and melt pond/blue ice as a function of ice thickness (0-300 cm) and wavelength (400-800 nm). By assuming that the spectral distribution of the incident radiation at the surface is similar to that observed at Barrow, we also produced contour plots which will allow cruder estimates based only on knowledge of total global short-wave radiation. For the snow-covered ice, we showed total transmission as a function of both snow thickness and ice thickness. Insofar as possible, all effects of the algae were removed from these estimates. Thus, the graphs should allow biological oceanographers to calculate the energy available for primary production at the bottom of the ice, but they provide no information as to whether that production takes place in the ocean or the ice.

Because of the extensive preparations necessary for the summer field trip, we did not have time to prepare a report on spectral albedos and attenuation coefficients in first-year sea ice before the field party left for T-3. At the present time our plans are to combine these data with similar results from multi-year ice to produce a comprehensive description of the optical properties of arctic sea ice.

## SUMMER FIELD PROGRAM

The field program was carried out at T-3 during a four mon period spanning the melt season. The work closely followed the plan set forth in our 1974 proposal. Most of the observations were made on sea ice, about one to two miles from the edge of the island. The actual site was on the opposite side of the island from the camp. While choosing the site this far from camp compounded the logistic difficulties, there were a number of important advantages; easy access to the sea ice, minimal contamination of the test area with oil and particulate matter from the main camp, and sufficient separation from the island to avoid anomalous ice thickening and water runoff problems. Details of the individual projects are as follows:

1. Albedo Observations - Spectral albedos were determined using the submersible spectrophotometer with an opal glass diffuser to measure incident and reflected irradiance directly. A pair of Kipp radiometers was employed to simultaneously obtain total albedos. Albedo data were taken systematically throughout the melt season and provide comparative records from many locations over the time interval when the surface of the ice pack was undergoing drastic changes. Supportive measurements of grain size, snow density, and thickness of the surface scattering layer were made to assist the interpretation of observed albedo changes. Data are still being reduced but we find, for example, that white ice in June had an albedo of about .85 at 500 nm, dropping down to about .40 at 1000 nm; the corresponding Kipp albedo was close to .60. For windpacked snow the albedo at 500 nm was just above .90, dropping to about .80 at 1000 nm.

2. Underice Radiation - The spectral distribution of downwelling irradiance beneath perennial sea ice was measured with the submersible spectrophotometer at about fifty-five different sites. Data were recorded beneath white ice and adjacent melt ponds over a thickness range of 115 cm to 250 cm. The angular distribution of the light beneath the ice was measured in a number of instances by varying the attitude of the instrument. We found that the variation in light intensity was less than 5% over a 45° tilt range, indicating that the light beneath thicker ice (at least) is nearly isotropic in the downward hemisphere. We do not yet know whether algae were present in our test area during the underice measurements. We saw no indication of algae in the cores, but we expect the shape of the spectral irradiance curves to be the ultimate test of their presence. Preliminary extinction coefficients for white ice have been calculated and show a minimum value of approximately .0074 $cm^{-1}$ at 500 nm, suggesting the absence of algae in observable quantities.

3. Attenuation within Ice and Snow - Because of internal melting and refreezing over several annual cycles, we expect multi-year ice to have attenuation coefficients which are substantially different than those of homogeneous first-year ice. Multi-year ice typically exhibits a pronounced scattering layer near the surface which is not present in first-year ice; penetrating short-wave radiation also modifies its internal structure giving in a different distribution of brine volume, bubble density, and salinity with depth. During the summer field experiment we attempted to determine how these factors affect the optical properties of the ice. Vertical profiles of forward-scattered and backward-scattered radiation were taken in the upper meter of the ice and snow with the profiling spectrophotometer. While backscatter measurements could be made simply by inserting the fiber optics probe

down small vertical bore holes, the forwardscatter measurements involved somewhat more effort. Trenches were dug in the ice and spring snow and horizontal holes bored about 1 meter into the side walls at various depths. The fiber optics probe was then mounted so that it looked straight up and inserted to the end of each of these holes. In the sea ice, observations were made beneath both the natural decomposed surface layer and an artificially scraped surface. Variations in grain size and crystal structure with depth were also recorded. From these observations we should be able to determine the extent to which the highly scattering surface layer modifies the optical properties of the ice and, when used in conjunction with the underice data, to infer attenuation coefficients deep within the ice.

4. Ablation Program - As part of the ablation program, a photographic survey of the areal coverage of melt ponds was carried on throughout the melt season. We had also hoped to be able to conduct systematic observations of ablation on the top and bottom of a moderately large pressure ridge. A suitable ridge was finally located and an array of ablation stakes set up across the sail, but before the thickness holes could be drilled a system of leads opened and separated it from the camp. Because access to the area was hazardous and time-consuming and because there were no other suitable ridges nearby, it was decided to abandon the program. This data is important, however, to large-scale studies of the mass balance of the ice pack and we have therefore written it up as part of a suggested program of growth rate observations to be carried out during AIDJEX.

5. Internal Ice Structure - The objective of this study was to monitor the changes in internal ice structure (brine volume, bubble density, and grain size) which occur as a result of interaction with solar radiation. During early July the ice became saturated with water resulting in the development of a local water table, usually 10-15 cm below the surface. Cores from melt ponds and adjacent bare ice showed no appreciable differences in either brine volume or bubble density below the water table during the early part of the melt season. Above the water table the ice was white, granular, and partially decomposed; below the water table the structure of the ice was complex with irregular bubble layers appearing throughout the cores. During the later part of the melt season, these layers had a larger brine volume than the surrounding ice, indicating selective absorption of short-wave radiation. Many of the melt ponds exhibited near-surface bubble layers which ranged in thickness from 1-15 cm during the early part of the melt season. All but the thickest of these bubble sheets were ablated away by the end of July. Quantitative measurements involving slabbing and photographing ice cores began in August when the samples could be drained, prepared, and measured without appreciable melting in the open air. Cross-sections 1 to 2 cm in thickness were photographed against a background grid of known dimensions to determine bubble densities and distributions in the upper meter of the ice; samples were taken from beneath melt ponds, white ice and newly frozen lead ice. For the white ice, no strong systematic trend with depth was noted below the local water table. Values ranged from 2-6%. In melt pond ice, however, the brine volume was strongly dependent on depth by the end of July; at the end of the melt season, the liquid volume ranged from 40% or more at the surface down to 10 or 15% at 1 m. Thus the brine volume beneath melt ponds is 5 to 10 times that beneath the bare ice,

indicating a significant storage of short-wave energy beneath the melt ponds in the form of latent heat.

Spectrophotometer data were routinely recorded both on magnetic tape and in the form of X-Y plots. The X-Y plots were intended to function primarily as a backup in case of failure in the magnetic tape records. Data tapes produced in the early part of the melt season were of good quality and have already been reduced; however, the tape recorder appears to have undergone progressive deterioration during the course of the summer and later tapes show an increasing number of sporadic coding errors and blank spots. By the end of the experiment the tape recorder was generating essentially only unrecognizable characters and blanks. Much of the data from the middle tapes can be recovered by hand, but the final few tapes contain no useful information. Although X-Y plots could not be made at every site due to occasional plotter malfunctions, we do have plots from many of the sites where the magnetic record was lost. We are presently transcribing magnetic tape data from the middle of the melt season for subsequent keypunching and computer reduction. Because of these processing problems the data reduction will be slower than originally planned, but we should ultimately be able to recover a substantial portion of the missing data. For future experimental work we are constructing a state-of-the-art data acquisition unit in which the information is recorded on a cheap, battery powered, cassette tape recorder.

The radiation related observations were terminated at the end of August and the month of September devoted to a study of the generation of internal waves in the ocean by pressure ridge keels. A theoretical study of the problem (see next section) had indicated that, under the proper conditions, standing internal waves should be present near the pycnocline downstream from pressure ridge keels. No previous measurements of these waves are known to have been made. At the beginning of the study we were not optimistic about our chances for success for a number of reasons: (i) the part of the ocean where T-3 was located was fairly stagnant with low relative current speeds, (ii) the only large ridge (about 15 meters) in the area was the one chosen for the ablation measurements which was still cut off from the island, necessitating the transport of equipment across the ice choked leads in a small boat, and (iii) we would be able to get only a rough idea of the velocity and density structure of the ocean near the keel. Nevertheless, thermistors were lowered to the pycnocline during the first week of September and observations taken for a two week period. Internal waves were detected on several occasions, with the largest having an amplitude of 3-4 meters. The pycnocline was relatively shallow in the area, occurring at a depth of only 30 meters as compared to 40-50 meters in most parts of the Arctic Ocean, and this may have contributed to the unexpectedly large size of the waves. While the data were too crude in time and space to determine how the wavelength and amplitude of the waves were related to keel geometry, current speed, or strength of the pycnocline, the observations suggest that such waves should be a frequent occurrence throughout the Arctic Basin. Given the observed ridge frequency of several ridges per kilometer, it appears likely that keel generated internal waves could play a significant role in the upper part of the Arctic Ocean, and perhaps in the motion of the ice itself.

## INTERNAL WAVE DRAG

A simple theoretical model describing the internal wave drag on a pressure ridge keel has been developed by F. Rigby. The treatment assumes that the upper part of the Arctic Ocean can be described by a two-layer model with a sharp density discontinuity near the pycnocline. Mathematically this situation is analogous to one described by Lamb (1932) involving the formation of waves on the surface of a stream which are induced by an obstacle on the bed of the stream. With some modification of the Lamb approach, analytical solutions were obtained and a description of the results submitted to the AIDJEX Bulletin under the title, "Theoretical Calculations of Internal Wave Drag on Sea Ice".

Calculations were carried out to determine the dependence of internal wave drag on: (i) depth and shape of the keel, (ii) relative current velocity, (iii) depth of the interface between the two layers (h'), and (iv) size of the density jump across the interface ($\Delta\rho$). Two keel shapes were considered; a semi-circular keel and a semi-elliptical keel with its major axis three times as long as its minor axis. This semi-elliptical keel was very similar in cross-section to one studied by Kovacs et al. (1973). The results show that, whereas form drag on the semi-elliptical keel is substantially smaller than on the semi-circular keel, wave drag at high current speeds is much larger on the semi-elliptical keel than on the semi-circular keel. In general, the results indicated that wave drag is negligible below current speeds of about 25-30 cm/sec; in the 30-40 cm/sec range, wave drag increases rapidly and can become the dominant component of the water drag for the larger (>20 meters) keels.

Recently, the model has been extended to treat the case of a homogeneous mixed layer of constant density overlaying a layer with a constant density gradient. This is a closer approximation to the true situation in the Arctic Ocean. At present we are still checking over the details of this development and have not compared predictions from this model with those of the simple two density model.

It is evident from the model calculations that the wave drag is very sensitive to assumptions regarding the depth of the interface and, to a lesser extent, the magnitude of the density jump across the interface. At this point, it is not clear what values for h' and $\Delta\rho$ are most appropriate. It is important to settle this question as the applicability of our results to the Arctic depend on the proper choice of these two quantities; however, it appears likely that wave drag is not negligible near large keels when the current is flowing strongly. Even if wave drag proves to be important for some keels in some situations, it is not yet clear whether this effect would appreciably alter large-scale values of water stress. Direct field observations appear to be the only practical way to definitely establish the role of internal wave drag in the dynamic behavior of the ice. The preliminary measurements made near T-3 in September 1974 verified the presence of these waves and demonstrated that they could be detected with relatively simple and inexpensive apparatus. The observations also suggested that significant internal waves could be generated without extremely high current velocities. Although smaller internal waves might not greatly influence the drag, they could be important to understanding processes in the upper 100 meters of the Arctic Ocean. We are hoping to be able to conduct detailed observations at an AIDJEX camp during the summer of 1975 in an effort to obtain more quantitative information on how these waves interact with the ocean and ice cover.

LABORATORY STUDIES OF SEA ICE

During this reporting period, we completed, wrote up, and edited the results of the following four projects. First, our ice stalactite research under the title "Ice stalactites: Comparison of a laminar flow theory with experiment" by S. Martin appeared in the March 1974 issue of the Journal of Fluid Mechanics. Second, S. Martin and P. Kauffman completed their joint research on under-ice melt ponds, which described the observed laboratory formation of ice in these ponds in terms of three one-dimensional mathematical models. This work, under the title "The evolution of under-ice melt ponds, or double diffusion at the freezing point", appeared in the July 1974 issue of the Journal of Fluid Mechanics.

Third, S. Martin and L. Eide analyzed the data from Eide's experiments on the growth and desalination of a thin sheet of laboratory sea ice. This material, under the title "The formation of brine drainage features in young sea ice", will appear shortly in the Journal of Glaciology. Finally, S. Martin and W. Campbell wrote a reply to a critique of their earlier article on the interaction of oil spills with the large scale motion of the arctic pack ice. This is scheduled to appear in the 29 November 1974 issue of Science.

In addition to the work described in the above papers, our present research is concentrated in four areas; namely, the drainage of salt from sea ice, the lateral melting of pressure ridge keels and other ice blocks, the interaction of petroleum with sea ice and the migration of large brine droplets. We will next discuss these four in the above order.

1. Drainage Studies - A third year graduate student, Mr. Terren Niedrauer, as part of his Ph.D. research, is doing a laboratory study of the convective

drainage of brine from the skeletal layer of sea ice. His apparatus consists of a small freezing cell with the inner dimensions of 10 cm wide, 20 cm deep, and only 1.5 mm thick. This small freezing cell is insulated with several layers of thermopane, while the flow inside the cell is recorded by time-lapse movies, still photographs, and small thermocouples with a thermal resolution of $10^{-2}$ degrees Celsius.

Using this apparatus, Mr. Niedrauer observes the following phenomena: (1) A spatially periodic convective drainage pattern which occurs between the crystal platelets. The pattern consists of narrow downward jets of brine separated by broad regions of upflow. The wavelength of the pattern is about 5 mm. (2) The formation of brine drainage channels from the joining together of large brine pockets. (3) The expulsion of brine from very small brine tubes with a diameter of 50 microns into larger channels and the subsequent closing off of these brine tubes into brine pockets. At the present time, Mr. Niedrauer is both working on theoretical models of the above phenomena and designing as a control some simple three-dimensional experiments.

2. <u>The Ablation of Ice in the Ocean</u> - The problem of estimating the 'lifetime' of both pressure ridge keels and icebergs in the ocean involves the study of the laminar and turbulent boundary layers which occur on both vertical and horizontal ice walls submerged in warm sea water. During the past six months, a fourth year graduate student, Mr. Edward Josberger, who is supported by AIDJEX, has been studying the behavior of these boundary layers both theoretically and in the laboratory as part of his Ph.D. research. His preliminary results show that the ablation occurs in a complicated double convective boundary layer.

To describe briefly the physics of this double boundary layer, consider a vertical ice wall in a salt water solution held at a temperature above freezing. At the ice wall, the boundary condition is that the salinity and temperature of the salt water must lie on the freezing curve. Therefore, the wall must melt to cool and dilute the adjacent warm water down to the freezing curve. From a simple steady-state mathematical model, because heat diffuses much faster than salt, the temperature boundary layer is about 30 times thicker than the salinity boundary layer. This difference in the boundary layer thicknesses has the following effect, depending on whether the sea water salinity is less than or greater than about 25 $^{0}/oo$. When the oceanic salinity is less than 25 $^{0}/oo$ and the oceanic temperature is below the temperature of maximum density, then the melting wall generates cold, less-saline water relative to the ocean. The less-saline water generates a narrow upward boundary layer jet, while the colder, thicker temperature boundary layer also yields a broad upward jet, so that the boundary layer flow is one-directional.

When the salinity is greater than 25 $^{0}/oo$ and the sea water temperature is above the temperature of maximum density, then the salinity boundary layer still flows upward, while the flow in the temperature boundary layer is now downward, so that a two-directional flow is produced in the vertical. There is also a gray area for salinities less that 25 $^{0}/oo$ and temperatures greater than the temperature of maximum density where the flow regime is a combination of those previously discussed.

Our preliminary experimental results show for the first case described above that the boundary layer becomes turbulent for temperature elevations above the freezing point of order 1 degree Celsius in a length of order 1 meter. The transition to turbulence increases the melting rate by about a factor of 5.

During the coming year, we plan to study both the laminar and turbulent regimes for the various cases described above and see if our results will lead to theoretical models. We also hope to apply our results to the proposed observations of pressure ridge melting which will be carried out during the Main AIDJEX Experiment.

3. Oil under Sea Ice - Because of the increasing possibility that off-shore oil drilling will soon begin in the Beaufort Sea, and the subsequent interaction of this oil with the sea ice through either spills or blow-outs, we have done several simple experiments on how sea ice absorbs oil. Through the offices of Imperial Oil in Canada and Atlantic-Richfield in Alaska, we obtained free samples of both Norman Wells crude oil and Prudhoe Bay crude oil. Using these samples and diesel fuel, P. Kauffman and S. Martin examined in our thin ice tanks how the entrainment proceeds.

Our preliminary experiments show that a small fraction of the oil will be entrained by the brine channels, whereas the rest of the oil will be trapped in a layer at the ice front. This trapped oil apparently has several effects. First, because the thermal conductivity of crude oil is about $6 \times 10^{-2}$ that of ice, the ice below the oil layer grows more slowly. Second, the oil appears to completely block the brine drainage from the sea ice above the oil layer. The blocking of the drainage and entrapment of brine in the ice above the oil will prevent the natural increase of both strength and conductivity in the ice. We also discovered during the melting of these ice sheets that the oil rose to the surface through the brine channels which were expanded in size by the heat. This provides a mechanism for bringing the oil to the ice surface in one season. P. Kauffman and S. Martin are presently attempting to organize the results of these simple experiments for publication. Also, S. Martin and W. Campbell have extended their comments on the interaction of large oil spills with the pack ice dynamics in a recent short article in Science.

4. Migration of Large Brine Drops - Experimental studies of the migration rates of macroscopic brine droplets by F. Rigby have led to three general conclusions. First, brine droplets with a diameter on the order of one millimeter or larger can, and generally do, migrate by a convective mechanism. The droplets display speeds as much as two orders of magnitude greater than those predicted theoretically on the basis of salt diffusion, the only mechanism previously considered. Observed velocities ranged from 0.2 to 1.5 mm/hr. Convective brine pocket migration thus could be an effective desalination mechanism in sea ice with substantial numbers of large brine drops. Secondly, convective brine pocket migration is characterized by a trail of flawed, porous ice in the wake of the moving droplet. The trail is physically weak and represents a path along which subsequent brine droplets can migrate at even higher rates. This observation suggests at least one possible mechanism by which brine channels can initially form; however, there is no experimental evidence to indicate that this is indeed the case. Finally, the data indicate that convection takes place in brine pockets only if the temperature is above about -5°C; below this temperature, diffusive behavior is observed. Thus, convective brine pocket migration can be expected to occur only in the lower part of the ice or during the summer.

Analysis of the observational data has been hampered by the fact that the results do not appear to be reproducible. While a particular brine pocket usually migrates in a reasonably consistent fashion, a second drop placed in another piece of ice under similar conditions can exhibit a radically different rate of migration. It appears that the migration is either very sensitive to small temperature fluctuations or to microfractures within the block. Careful experiments are needed to determine the origin of the velocity variations, but it seems possible that the density of cracks and flaws in the ice may be at least as important as the size of the temperature gradient.

## REPORTS PUBLISHED AND IN PRESS

1. Martin, S., Ice stalactites: Comparison of a laminar flow theory with experiment. Journal of Fluid Mechanics, 63, 51-86, 1974.

Recent field observations in the polar oceans show that the hollow tubes of ice called ice stalactites form around streamers of cold brine rejected by the growing sea ice. In a laboratory study of this process, we inject cold, dense brine at a constant salinity, temperature and volume flux into an insulated tank of sea water held at its freezing point, then photograph the resultant stalactite growth. Because the inner wall temperature of the stalactite remains on the salinity-determined freezing curve, as the stalactite grows and the temperature deficit of the brine goes into the growth of ice, the inner wall melts to dilute and cool the adjacent brine back to its freezing point. This melting means that both the inner and outer stalactite radii increase with time. The radius of the stalactite tip, which is constant for each experiment, is shown to be controlled by the onset of a convective instability. If the tip becomes too large, overturning occurs and the sea-water intrusion freezes, reducing the radius of the tip so that the flow leaving the tip is marginally stable. Inside the stalactite, since the inner radius increases with time, both theory and experiment show the interior flow to be convectively unstable. The present study also derives a solution from the constant-heat-flux Graetz solution for the growth in both length and side-wall area of the stalactite. The experiments show that away from the stalactite base and the very beginning of the experiment this solution, with convection accounted for by an adjustable coefficient, describes the experimental growth. Finally, analysis of the experiments shows that as much as 50% of the ice represented by the cold brine does not go into the stalactite, rather the ice goes directly into the ocean as loose crystals.

2. Coon, M. D., G. A. Maykut, R. S. Pritchard, D. A. Rothrock, and A. S. Thorndike, Modeling the pack ice as an elastic-plastic material, AIDJEX Bulletin, 24, 1-106, 1974.

A model of the motion of drifting pack ice in the Arctic Ocean is presented, treating explicitly, if not with consistent rigor, the growth and melt rates of the ice, the formation of leads and pressure ridges, and a mechanical response which is elastic at low stress levels and plastic at some higher, critical state of stress.

The strength of the ice is determined by its thickness distribution, and therefore varies because of both thermal and mechanical effects. To examine the behavior of the model, several artificial calculations were made by specifying the strain rate history of a single element of pack ice and solving for the ice thickness distribution and the states of stress in the ice.

3. Thorndike, A. S., Strain calculations using AIDJEX 1972 position data. AIDJEX Bulletin, 24, 108-130, 1974.

Strain and strain rate calculations are presented based on measurements of the positions of three drifting sea ice stations. The measurements were made using the Navy Navigation Satellite System. In processing the data, time derivatives were calculated by Kalman smoothing techniques, and space derivatives by simple finite differences.

4. Martin, S. and F. Kauffman, The evolution of under-ice melt ponds, or double diffusion at the freezing point. Journal of Fluid Mechanics, 64, 507-531, 1974.

In an experimental and theoretical study, we model a phenomenon observed in the summer Arctic, where a fresh-water layer at a temperature of 0°C floats both over a sea-water layer at its freezing point and under an ice layer. Our results show that the ice growth in this system takes place in three phases. First, because the fresh-water density decreases upon supercooling, the rapid diffusion of heat relative to salt from the fresh to the salt water causes a density inversion and thereby generates a high Rayleigh number convection in the fresh water. In this convection, supercooled water rises to the ice layer, where it nucleates into thin vertical interlocking ice crystals. When these sheets grow down to the interface, supercooling ceases. Second, the presence of the vertical ice sheets both constrains the temperature T and salinity s to lie on the freezing curve and allows them to diffuse in the vertical. In the interfacial region, the combination of these processes generates a lateral crystal growth, which continues until a horizontal ice sheet forms. Third, because of the T and s gradients in the sea water below this ice sheet, the horizontal sheet both migrates upwards and increases in thickness. From one-dimensional theoretical models of the first two phases, we find that the heat-transfer rates are 5-10 times those calculated for classic thermal diffusion.

5. Roulet, R. R., G. A. Maykut, and T. C. Grenfell, Spectrophotometers for the measurement of light in polar ice and snow. Journal of Applied Optics, 13, 1652-1659, 1974.

Two portable spectrophotometers have been designed to record light scattering and absorption in polar ice and snow. In the first instrument optical fibers are used to transmit light from the interior of the ice to the spectrophotometer. Such an arrangement allows light measurements up to 2 m away from the instrumentation with minimal disturbance of the natural environment. A miniaturized, submersible spectrophotometer was also built for in situ measurements under floating sea ice. This version, except for the recording apparatus, is entirely self-contained and is housed in a cylindrical tube 9 cm in diameter and 60 cm in length. The unit can be lowered into the ocean through a small borehole in the ice; position and orientation are controlled from the surface. Both spectrophotometers are designed to measure light intensities in the visible spectrum (400-1000 nm). Wavelength resolution is adjustable down to 5 nm at a wavelength of 400 nm, with a field of view of less than 3°. Sensitivities in the present versions are sufficient for measurements through several meters of sea ice with a relative accuracy of 1%. Instrument operation has been tested in the Arctic down to temperatures of -25°C.

6. Rigby, F., Theoretical calculations of internal wave drag on sea ice. AIDJEX Bulletin, 26, 129-140, 1974.

Because of the density stratification in the upper part of the Arctic Ocean, the movement of pressure ridge keels through the mixed layer can create internal waves in the vicinity of the pycnocline. These waves transport energy away from the keels and thereby generate drag on the ice. This study defines the conditions under which wave drag could contribute significantly to the total water stress. The development of internal waves downstream from a semielliptical keel is described by a simple two-dimensional, two-layer ocean model. Results calculated from the model show the dependence of wave drag on keel depth, current speed, depth of the upper layer, and density change across the interface between the layers. Comparison of the relative magnitudes of form drag and wave drag suggests that wave drag is not negligible near large keels when the current is flowing strongly.

7. Mohaghegh, M. M. and M. D. Coon, Bearing capacity of a plate on an elastic foundation with application to floating ice sheets. Journal of Applied Mechanics (in press).

8. Eide, L. and S. Martin, The formation of brine drainage features in young sea ice. Journal of Glaciology (in press).

9. Rothrock, D. A., The steady drift of an incompressible arctic ice cover. Journal of Geophysical Research (in press).

10. Martin, S. and W. J. Campbell, Reply to Ayers et. al., Science (in press).

11. Maykut, G. A. and T. C. Grenfell, The spectral distribution of light beneath first-year sea ice in the Arctic. Limnology and Oceanography (submitted).

12. Coon, M. D. and M. M. Mohaghegh, Limit analysis of Coulomb sandwich plates. International Journal of Mechanical Sciences (submitted).