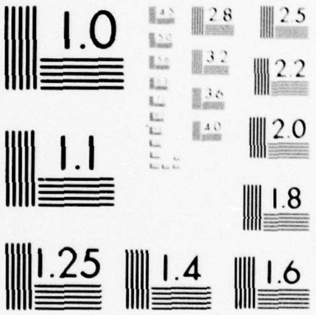
AD-A079 527 WASHINGTON UNIV SEATTLE DEPT OF ATMOSPHERIC SCIENCES F/G 8/12
ANNUAL REPORT NUMBER 11.(U)
DEC 79 S MARTIN, G MAYKUT N00014-76-C-0234
UNCLASSIFIED NL

1 OF 1
AD
A079 527

END
DATE
FILMED
2-80
DDC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

12

A063023

SC

ANNUAL REPORT NO. 11

CONTRACT N00014-76-C-0234
NR 307-252

1 DECEMBER 1979

DEPARTMENT OF ATMOSPHERIC SCIENCES
UNIVERSITY OF WASHINGTON
SEATTLE, WASHINGTON 98195

REPRODUCTION IN WHOLE OR IN PART IS
PERMITTED FOR ANY PURPOSE OF THE
UNITED STATES GOVERNMENT

DISTRIBUTION UNLIMITED

(12)

ANNUAL REPORT NO. 11

CONTRACT N00014-76-C-0234
NR 307-252

1 DECEMBER 1979

See 1473 in back

DEPARTMENT OF ATMOSPHERIC SCIENCES
UNIVERSITY OF WASHINGTON
SEATTLE, WASHINGTON 98195

REPRODUCTION IN WHOLE OR IN PART IS
PERMITTED FOR ANY PURPOSE OF THE
UNITED STATES GOVERNMENT

DISTRIBUTION UNLIMITED

CONTENTS

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. SEELYE MARTIN, Co-Principal Investigator
DR. GARY MAYKUT, Co-Principal Investigator
DR. THOMAS GRENFELL, Research Associate
MR. PETER KAUFFMAN, Electronics Technician
MR. DONALD K. PEROVICH, Predoctoral Associate
MR. EDWARD JOSBERGER, Predoctoral Associate (terminated Nov. 1978)
MS. JANE BAUER, Predoctoral Associate

INTRODUCTION

During the past year two of our students completed research projects. Edward Josberger finished his Ph.D. thesis on the ablation of vertical ice walls submerged in warm sea water, and Donald Perovich finished his M.S. thesis on the optical properties of young sea ice. Scientific reports on both topics have been prepared and distributed. Calculations of the large-scale heat and mass balance over the AIDJEX array have been carried out and compared with values in the central part of the Basin as inferred from earlier drifting station data. The sensitivity of regional fluxes to processes associated with ice deformation was also investigated. Laboratory measurements of light scattering by sea ice have been concluded. Results indicate that the scattering coefficient depends on both temperature and growth rate, while the phase function was found to be unexpectedly insensitive to these quantities. Analysis of laboratory and field work on the interaction of waves and grease ice has been completed, leading to the formulation of an empirical equation for wave damping by grease ice. A theoretical model of solar heating in leads is being developed. Preliminary work suggests that the rate of lateral melting responds directly to changes in lead width, if the lead is narrow; however, increases in width above about 100 m have little effect because the greater heat input is balanced by greater heat loss to the atmosphere.

A spring cruise on the NOAA ship SURVEYOR was carried out in the Bering Sea. Wave attenuation at the ice edge and the relative motions of ice bands which break free from the pack were investigated. The new infrared scanning photometer was completed in April and successfully field tested at Barrow during May and June. Changes in spectral albedos and incident irradiance as a function of cloudiness were recorded through the early melt stages. Experimental methods for measuring lateral ablation in leads were also tested.

Scientific results from previous work include papers on the effects of ice thickness on the absorption of solar radiation, brine drainage and convection in young ice, the melting of vertical ice walls in warm salty water, the optical properties of young ice, ice edge phenomena, and wave damping by grease ice.

DYNAMIC AND THERMODYNAMIC MODELING

Heat and Mass Balance Studies. Our goals here are: (i) to understand large-scale ice production and surface heat exchange over the Arctic Ocean, and (ii) to determine the sensitivity of these quantities to processes associated with the deformation of the ice pack. During the past year we have been engaged in a comprehensive study of this problem, utilizing all available data. The basic tool for this work is our regional averaging model which requires: (i) ice strain data to calculate the thickness distribution and (ii) incident energy fluxes to calculate ice growth and the surface heat balance for each thickness of ice. Since the early calculations, the model has been improved through the addition of improved numerical techniques and more realistic ridging parameters. Testing these improvements with the T-3/ARLIS II/ NP-10 strain data produced a substantial increase in the predicted fluxes. Regional fluxes have also been calculated using high quality AIDJEX strain data and were found to be significantly different than those from the T-3 triangle. For example, annual totals of sensible heat loss were two and a half times larger over the AIDJEX manned array, while ice production was 35% greater. The latent heat flux, on the other hand, differed by only 8%. AIDJEX strains tended to put more ice in the 20-40 cm thickness category and less into the 40-80 cm category, causing area-weighted turbulent flux values to peak in the 20-40 cm range rather than the 40-80 cm range found with the T-3 data. It is not clear whether these large differences result from normal year-to-year changes in ice movement, differences in ice flow between the Beaufort Sea and the Central Arctic, improvements in measurement accuracy, differences in the scale of the two sets of strain measurements, or some combination of the above. Upcoming data from the FGGE buoy array should be helpful in resolving this question.

In the second phase of this work, we have carried out over a dozen additional simulations in order to learn more about how the above results are affected by strain field characteristics and by assumptions regarding the ridging parameters. We found that setting the shear to zero and leaving the divergence unchanged in either the T-3 or AIDJEX data caused about a 50% reduction in the amount of open water during the winter months. Thus, although shear dominates the strain field of the ice pack, such motions are responsible for no more than about half of the winter open water production. During the summer, divergence and lateral melting completely determine the amount of open water. Despite decreases in the amount of open water and young ice when shear was neglected, there was only about a 10% decrease in the winter rates of ice production. This was because of substantially larger amounts of thick first-year ice which partially compensated for the ice production lost in the thinner categories. The sensible heat flux, on the other hand, responded strongly to the decrease in thin ice; the magnitude of the change depended on season, but for the year there was over a 60% decrease in the sensible heat input to the atmospheric boundary layer. Other calculations indicated that the regional heat balance is quite sensitive to assumptions regarding which thicknesses of ice participate in ridging, but is insensitive to the way in which this ice is redistributed. An unexpected result was that the large-scale heat fluxes generated from daily AIDJEX strain data were essentially unaffected when recalculated with strains which were passed through a 5 day filter. This suggests that motions with a period of less than 5 days are unimportant in terms of ice production and heat exchange. We are carrying out additional calculations to see if this is reasonable.

The final case we are studying is a comparison of the AIDJEX manned array and the AIDJEX buoy array to see if there are any consistent differences in heat exchange between the 100 and 500 km space scales. A paper describing the results of this work should be completed shortly.

The techniques and models developed for the above work have so far been applied only to the case of uniform strain across some area. It should also be possible to approach the more general problem of a large region containing many strain elements in much the same way. A solution to this general problem is needed before we can effectively utilize data from large arrays of buoys. We are therefore working on the design of a program which will simultaneously calculate area-averaged heat exchange over many grid elements, using as input only ice motion, temperature, and cloudiness data. The most difficult part of the problem is to deduce the various components of the heat and mass balance from such scanty information. Fortunately, our previous work on improved ice forecasting equations indicates that we should be able to obtain reasonable estimates of all the fluxes, with the possible exception of incoming shortwave radiation. We suspect that parameterizations presently used in large-scale models are appropriate for thick lower latitude clouds, but tend to underestimate solar radiation over the Arctic. We are looking into this possibility and, if necessary, will develop a more suitable parameterization. We are also trying to resolve some questions regarding the advection of ice thickness distribution between adjacent grid elements. The ultimate results of these efforts should be a model which will allow us to determine both spatial and temporal changes in the heat and mass balance across the entire Arctic Basin.

Response of the Ice to Temperature Changes. Recent concern about the increasing levels of carbon dioxide in the atmosphere and predictions of a possible 5-10°C increase in air temperatures in the polar regions led us to examine the effects of such changes on the ice pack. Our calculations indicate that winter temperature anomalies have a relatively small effect on the ice. Summer temperature anomalies, on the other hand, produced dramatic changes in the ice cover. For example, a 1°C increase in the 10 meter air temperature during the melt season caused roughly a 60% decrease in average ice thickness - an increase of 2-3°C caused the eventual disappearance of the ice.

The above results point up a weakness implicit in this approach. While it is reasonable to expect that changes in climate can change winter air temperatures by several degrees, it is not clear that summer air temperatures near the surface of the melting ice could be maintained much above the freezing point. Yet it is the summer temperatures which seem to be critical in determining the long-term response of the ice. The question which now needs to be considered is how changes in upper level temperatures (e.g. at the top of the planetary boundary layer) would affect the ice cover. To address this question we plan to combine a suitable boundary layer model with our ice growth model.

Summer Decay of the Ice Pack. Solar radiation absorbed in the upper ocean appears to be an important factor in the summer retreat of the ice edge and in the general decay of the interior pack. However, precise details of the processes involved are not known. Lateral melting on floe edges has received some attention because of the positive feedback potential - lateral melting causes a decrease in ice concentration which allows more shortwave radiation absorption in the water and a continuing acceleration in the rate of lateral melting. Simple models of this process have been formulated by Zubov and by Langleben. A serious drawback with both these models is their assumption that all the absorbed radiation goes into lateral melting. In reality some of the energy is absorbed beneath the ice where it contributes to bottom ablation, while some fraction of the remainder is lost to the atmosphere through longwave radiation and turbulent heat exchange.

As the first step in a combined theoretical and experimental study of the problem, we have developed a simple, but more realistic, lateral melting model. We assume that: (i) water in the lead is well mixed, (ii) energy absorbed below the ice contributes exclusively to melting on the bottom rather than on lead walls, and (iii) energy deposited in the layer between the surface of the water and the bottom of the ice goes into lateral melting, warming of the water, and heat input to the atmospheric boundary layer. An energy balance equation which includes all the heat fluxes is applied at the air/water interface, while lateral melting rates are determined from predicted far-field temperatures using the parameterization developed by Ed Josberger (see "Reports Published and In Press" section).

The major difference between the results of this model and those of earlier ones is in how the lateral melting is affected by lead width. The older models implicitly assume that melt rates depend linearly on lead width; our model, however, predicts a rapid increase in melt rate only up to a lead width of about 100 meters, after which melting becomes increasingly insensitive to lead width. Intuitively this seems correct, suggesting that the Zubov/Langleben models may seriously overestimate the speed at which ice concentration decreases.

The problem with our present model is that it ignores the details of heat transport in the water. If the water salinity is above 25 $^{o}/_{oo}$, radiative heating increases the stability of the layer resulting in a much greater eddy diffusivity in the horizontal than in the vertical. Whether this tends to increase or decrease lateral melting is not entirely clear. Another problem is that, as lead area increases, there will necessarily be more exchange of energy between water in the lead and water below the ice. Again, we don't know whether this exchange will have a positive or negative effect on the lateral melting. Our next step in the improvement of the model will thus be to include a more realistic treatment of the water in the stable case. This will be done through the introduction of a two-dimensional heat diffusion equation. Such an approach has been tried by Soviet investigators (e.g. Doronin) with questionable success, probably due to inadequate attention to heat exchange at the surface. Ultimately, we plan to treat the unstable case and explicitly examine water motion in leads.

Numerous other mechanisms are potentially important in the decay of the ice cover, but there seems to be no way to assess their importance theoretically. We therefore plan to carry out a summer field program to determine in detail how solar radiation affects the interaction between the ice cover and upper part of the ocean. During the spring field experiment (see Radiative Transfer section) several days were devoted to testing techniques to measure lateral ablation and heat exchange in summer leads. In mid-June an ablation array was set up in a small lead which had opened through a section of first-year ice within easy access from shore. Scuba diving was carried out in the lead, enabling us to study the cross-sectional profile of the ice at several locations.

The lead closed before useful ablation data could be obtained, however, we found that scuba diving and snorkeling under melt season conditions was less difficult than anticipated. Unlike cold weather diving, a portable tent was ample shelter for the divers, freezeup was not a problem, and all equipment could easily be transported on hand pulled sleds. Thus we feel that the only serious obstacle to a successful summer lead experiment is the problem of locating a suitable site.

RADIATIVE TRANSFER STUDIES

A paper entitled "The Effects of Ice Thickness on the Exchange of Solar Radiation over the Polar Oceans" was published in the Journal of Glaciology. The paper describes theoretical calculations of the absorption and transmission of solar radiation by young growing sea ice. Two distinct types of ice are considered. Of primary importance is young growing ice which occurs throughout the Arctic Basin during most of the year. Such ice has a high salinity, is relatively homogeneous, and is usually covered with dry windpacked snow. The second type, white ice, consists of a highly scattering granular surface layer above a thin transition zone and a consolidated lower layer. Although white ice does not constitute a major fraction of the thin ice during most of the year, substantial quantities can be produced by ablation of first-year ice at the margin of the ice pack during the summer. White ice does not develop until the overlying snow layer has melted away.

Calculations of spectral and total transmission, absorption, and albedo were carried out for ice from 2-80 cm in thickness, with up to 40 cm of snow cover. Energy absorption in the ice was sensitive to the spectral behavior of the albedo over the entire solar spectrum (400 to 3000 nm), as well as to the effects of cloudiness on the spectral composition of the incident irradiance. Since it was assumed that clouds remove essentially all the radiation beyond 1200 nm, total albedos calculated for a particular ice type varied by up to 30% depending on the degree of cloudiness. Radiative energy absorption was also sensitive to cloud cover - on clear days it was as much as 50 times larger in the upper 10 cm of the ice than on cloudy days. Below 10 cm most of the infrared wavelengths had been removed and the energy absorption was about twice as large on clear days. In addition, total transmission to the ocean was 2 to 2.5 times as large under clear skies.

Depth profiles of net irradiance showed that, for ice thinner than 80 cm, Beer's law provides a poor description of the radiation field. Melting white ice, for example, transmitted up to 3 times as much energy to the ocean as Beer's law would predict. To incorporate the results of the present study into our thermodynamic ice growth model without using an involved radiation model, the albedo and transmission results have been parameterized as functions of snow and ice thickness.

Laboratory Studies of Young Ice. Experiments on the optical properties of thin salty ice have been completed. The objective of the investigation was to study variations in the albedos and extinction coefficients of young ice in response to changes in ice thickness, growth rate, salinity, and temperature. Ten experiments were carried out. These included two runs with fresh water at -15°C air temperature, six runs with saline water (32 $^{0}/_{00}$ initial salinity) at air temperatures ranging from -10°C to -37°C, and two experiments with water of intermediate salinity (16 $^{0}/_{00}$) at -10°C and -20°C. Each run lasted from 10 to 15 days and included measurements of spectral albedos and transmission profiles as the ice grew. Concurrent measurements of the physical state of the ice included vertical temperature and salinity profiles, and ice thickness. After the ice growth was completed 12 cm cores were extracted and sectioned into thin vertical and horizontal slabs. Close-up photographs of these slabs were taken to illustrate variations in the bubble density profile and to show brine drainage features. Additional photographs in polarized light were used to delineate the crystal structure of the ice.

In each of the fresh ice experiments we were able to study both bubble-free and bubbly ice. Since the water was not initially saturated with air, the ice grew to about 80 mm before significant bubble nucleation took place.

As the ice grew thicker, densely packed bubbles formed in long vertical columns rather than as discrete spheres which one commonly finds in salty ice. To the present limits of accuracy, the optical properties of bubble-free fresh ice are indistinguishable from those of pure water. As the bubbly layer grew, spectral albedos increased by only a few percent, and the total transmission decreased only slightly, indicating an extinction coefficient at 500 nm of less than 0.1 m^{-1}. Because the vertical sides of the columnar bubbles introduced very little backscattering, neither the albedo nor the attenuation was strongly affected even though the vapor volume was quite large. If the same vapor volume were distributed as a large number of spheres with about the same diameter as the cylinders, backscattering would be much greater. Thus, the fresh ice results are more representative of lake and river ice, and provide only a lower limit for the influence of bubbles on the optical properties of salty ice.

Albedos of salty ice increased much more rapidly with ice thickness than those of fresh ice. Values at the end of the growth phase ranged from 0.4 to 0.9 depending on the ice temperature and initial growth rate. A significant temperature dependence was also found. For example, the albedo at 500 nm of 25 cm ice grown at an air temperature of -10°C was 0.55, but when the ice was warmed to -2°C, the albedo decreased by 20%. In another run the ice surface was cooled below the eutectic temperature (-21°C) causing solid salt to crystallize out of the brine, forming a surface crust. The albedo was then as large as that of dry snow. Raising the surface temperature above -21°C caused the salt to redissolve, and the albedo dropped by about 30%.

Growth rate dependence was tested by comparing ice samples of the same thickness and temperature, but which were grown at different air temperatures between -10°C and -37°C. Spectral albedos at all wavelengths were larger for ice which had grown faster. A difference of about 40% was observed between the extreme cases at all wavelengths.

Surprisingly, spectral albedos from the intermediate salinity experiments were the same or slightly higher (up to 20%) than those from the corresponding high salinity (32 $^{0}/_{00}$) cases. This was caused by the formation of a thin brine skim on the surface which was not present on the intermediate salinity ice. The skim filled in surface irregularities and reduced backscattering in the uppermost ice layers. This effect was most pronounced for an air temperature of -20°C; at an air temperature of -10°C the skim was barely noticeable and albedos for the 16 $^{0}/_{00}$ and 32 $^{0}/_{00}$ cases were nearly the same.

Spectral extinction coefficients (κ_λ) observed for growing young ice were from 1.5 to 15 times greater than for the thick summer ice studied in our field experiments. To check these results the ice was heated with the artificial sun and bulk extinction coefficients were determined from changes in the vertical temperature profiles. Results from the two methods agreed to within 5%, supporting the accuracy of the optical data. As with the albedos, spectral extinction coefficients were larger for higher growth rates and decreased with increasing temperature. At 500 nm, κ_λ ranged from about 2 m^{-1} for ice grown at an air temperature of -10°C to 12 m^{-1} at -37°C. When the air temperature was raised to -2°C and the ice allowed to equilibrate, κ_{500} decreased by as much as 8 m^{-1}. The changes in extinction with temperature and growth rate appeared to be smooth except when the upper layers of the ice crossed the eutectic temperature.

Since the absorption coefficients of brine and pure ice are essentially independent of temperature, the optical properties of sea ice are governed by the effectiveness of scattering in the ice. Enhanced scattering results in higher albedos; it also increases the extinction coefficient because the optical path length is greatly increased by multiple scattering with a corresponding increase in the probability that the light will be absorbed within the ice. Scattering in turn is determined primarily by the platelet structure and the distribution of brine between the platelets. The amount of scattering is inversely related to the temperature. As brine pockets and channels open up with increasing temperature, the brine/ice interfaces coalesce and become more rounded. If the ice temperature drops below the eutectic point, salt crystals are precipitated out causing a sudden increase in the scattering. Growth rate is important because it determines the platelet and crystal sizes and the initial distribution of brine in the ice. Albedo is also influenced by changes in surface conditions. Flooding of the surface due to melting or to concentrated brine being squeezed out gives a smooth surface and lowers the albedo, and melting followed by drainage leaves a crumbly surface with a higher albedo.

From these results it appears that the extinction coefficient of natural sea ice will vary with depth and time since the optical properties respond to changes in the temperature and salinity of the ice. Thus, the optical properties of sea ice should be in a continual state of change. In the Arctic this involves a transient phase for the first two years until the salinity profile stabilizes followed by a cyclic variation with seasonal environmental changes.

While the results of the present experiments isolate the effects which influence the optical properties, further work is necessary to give a quantitative connection between α and κ and the ice structure. The weak dependence of the optical properties on water salinity should be examined in more detail. Finally, the effects of vapor bubbles have not been studied here, but should be included in any general theory of the optical properties of sea ice. Several of these problems have been studied in the scattering experiments described below.

The complete results of this work have been released as Scientific Report No. 17, and a condensed version submitted to the Journal of Glaciology for publication. We also plan to write an additional paper describing the theoretical part of the work.

Scanning Photometer. Construction and testing of the scanning photometer has been completed. The instrument scans over visible and infrared wavelengths from 400 to 2500 nm using a circular variable interference filter, together with a set of twelve fixed band interference filters. The spectral resolving power (wavelength/bandpass) ranges from about 25 at 400 nm to 46 at 1300 nm. Thus, in addition to extending the wavelength region to cover more than 98% of the solar spectrum, the new system has almost 20 times greater spectral resolution between 800 and 1000 nm than do our previous instruments. The radiation detectors include two lead sulfide photoconductors for the infrared beyond 1000 nm and a blue-enhanced, ultra-low-leakage photodiode for visible and near infrared wavelengths. The system will detect spectral irradiances of less than 0.1 $\mu W/cm^2/nm$, giving 2-3% accuracy in the incident irradiance at 2.5 microns on a heavily overcast summer day in the Arctic.

The entire photometer is contained in an aluminum cylinder 20 cm in diameter and 20 cm in height and weighs less than 35 pounds including batteries. To eliminate A.C. noise problems, only D.C. power supplies which run off rechargeable lead acid batteries are used. C-MOS electronics have been installed where possible for low power drain and low temperature operation. The photometer is intended primarily for measuring incident spectral irradiance and infrared spectral albedos, but it has a fiber optics attachment if measurements within the ice are required.

A field experiment was carried out at Point Barrow from mid-May until the end of June 1979. Most of the observations were made on the seasonal sea ice between 1/2 and 2 miles offshore near the Naval Arctic Research Laboratory. The goals of the experiment were: (i) to determine spectral albedos of different surface types during the onset of the melt season, (ii) to study incident spectral irradiance versus cloudiness, and (iii) to do some initial testing of our methods for the summer lead experiment.

After some initial adjustments the photometer performed extremely well. A broken ground wire was the only serious problem encountered. At an ambient temperature of -10°C the instrument would run for 3 to 4 hours on one charge of the battery pack. Measurements of incident spectral irradiance were digitized and recorded on magnetic tape, which was much faster than hand logging, in order to measure entire spectra quickly before cloud conditions could change appreciably. The scans were played back through an XY plotter at NARL in case the digitized data were later lost. Initial calibrations of instrument sensitivity were carried out at the lab at +20°C as insurance against possible instrument damage in shipping. Since the sensitivity is temperature dependent and a suitable controlled temperature environment was not available at Point Barrow, a complete set of calibrations was carried out this September in our own cold rooms.

Incident and reflected irradiances were obtained at 40 different sites, ranging from dry wind-packed snow to well developed melt ponds. Simultaneous Kipp radiometer measurements were taken both to provide total albedos as a check for the spectral data, and to monitor fluctuations in the incident radiation due to changes in cloud conditions.

The albedo data were recorded by hand at 52 wavelengths and were reduced each evening. The results are consistent with our previous data from 400 to 800 nm and with the Kipp albedos. Considerable improvement was achieved from 800 to 1000 nm with the higher resolution and good spectral detail was observed at longer wavelengths. Although some differences exist as we expected, our data for snow appear to be consistent with reflectances measured by O'Brien and Munis in the laboratory.

Computer processing of the results is now nearly complete, and the data have been recovered from all sites but one. From the XY plots it is evident that clouds do absorb much of the infrared radiation; however, a good deal more infrared energy reaches the ground than we originally estimated. Reduction and interpretation of the data will be completed next year and the results will then be written up for publication.

A short talk on the design and operation of the photometer was presented before the Northwest Glaciological Society this November. This information will also be written up in a short paper for the Instruments and Methods section of the Journal of Glaciology.

Scattering Experiments. Measurements of the light scattering properties of sea ice have been completed. Fifty-eight cases have been studied including bubble-free ice, fresh bubbly ice (glacier ice), salt ice grown at various temperatures in the cylindrical tank, and grease ice.

Light scattering is characterized by a coefficient, σ, defined as the fraction of light scattered per unit length out of a collimated beam incident on the test sample, and by the phase function which describes the angular distribution of the scattered radiation. These two parameters define the role of scattering in the transfer of radiation through sea ice.

For bubble-free ice the apparatus originally detected faint scattering from surface irregularities. When these were removed by polishing the sample faces, no scattered light could be detected; thus the scattering coefficient was less than 10^{-5} m^{-1} and a much larger sample would be needed to measure the scattering. However, since the absorption coefficient is several orders of magnitude larger (more than 4×10^{-2} m^{-1}) than σ, scattering can be ignored.

For sea ice the scattering is much more efficient; measured values of σ lie between 0.03 and 0.4 m^{-1}. The phase functions show strong forward scattering with a minimum near 120° and a slight increase for larger deflection angles. The phase function is independent of wavelength from 400 nm to at least 800 nm which suggests that scattering is controlled by the refractive indices of salt water, ice, and air, none of which are strongly wavelength dependent.

Substantial variations in the scattering coefficients and phase functions were observed for different salt ice samples. A strong temperature dependence between -10°C and -30°C was found where scattering coefficients for the colder samples were 2 to 3 times larger. The phase functions showed some increase in forward and backscattering with decreasing temperature as well as a weak dependence on sample orientation. Large increases in σ occurred when the ice was cooled below the eutectic point and the scattering became nearly isotropic.

Scattering coefficients for grease ice which had been frozen solid were somewhat larger than for samples from the thin ice experiments at the same temperature and showed more sidescattering and backscattering. This is reasonable since the grease ice is made up of many randomly oriented small crystals rather than a smaller number of large columnar crystals characteristic of the interior of the thin ice.

Results thus indicate that the scattering coefficient depends on both the freezing rate and the temperature of the samples. The phase function, however, is not strongly influenced by these quantities. This should simplify the parameterization of the scattering properties. Final analysis is in progress and the results are being prepared for publication in the Journal of Geophysical Research.

Optical Properties of Cold Seasonal Ice and Grease Ice. The data from the spring field experiment carried out near Prudhoe Bay have been reduced. This study gave us the opportunity to measure the optical properties of cold, thick first-year ice which had not undergone a melt season. Spectral albedos between 400 and 1000 nm for cold ice with the snow scraped from the surface were quite high, even though no surface granular layer was present. They lie between our previous results for melting first-year white ice and melting multiyear white ice. The total albedo was 0.55 as compared with 0.47 and 0.57 for first-year and multiyear ice, respectively.

Extinction coefficients (κ_λ) for cold ice were larger than for the interior of summer ice, but smaller than for the young ice grown in the laboratory. Values of κ_λ at 500 nm ranged from 1.3 to 2.0 m^{-1} as compared with 0.6 to 1.2 m^{-1} for summer ice and 2.5 to 12 m^{-1} for young ice. In one case, however, κ_{500} was comparable (0.85 m^{-1}) to the summer values. At this site the uppermost 16 cm consisted of nearly fresh ice from the nearby Shaviovik River.

The present results are consistent with the findings of the thin ice experiments which show that α and κ are larger for colder more rapidly grown ice. Thus, since the average growth rate of thick cold first-year ice is slower than for thin young ice, its extinction coefficients and hence light scattering within the ice should be less than for the young ice but greater than for melting summer ice. The corresponding comparison for albedos is not as simple because variations in the surface conditions such as flooding on the formation of a drained granular layer cause large changes in the albedos. While a quantitative analysis will be required to compare albedos for ice of different thicknesses, the present albedos also appear to be consistent with our previous results.

The laboratory studies of grease ice indicate that the albedos are considerably lower than for the same thickness of solid ice grown in the cylindrical tank at similar air temperatures. The extinction coefficients on the other hand are only slightly smaller. This suggests that, in addition to the influence of the very high "brine volume" of grease ice, its light scattering properties are significantly different from those of ice grown at the bottom of an existing ice layer. A quantitative investigation of the comparison of cold young ice, grease ice, and thick summer ice will be an important part of the parameter study planned for next year. We intend to use the scattering data in conjunction with the 16-stream radiative transfer model to determine how varying the concentrations of the different scattering inhomogeneities affects the albedo and transmission.

FLUID MECHANICS AND SEA ICE

During the past year graduate student Edward Josberger completed his thesis on the ablation of vertical ice walls submerged in warm seawater. S. Martin and P. Kauffman completed an analysis of the laboratory studies of the interaction of waves and grease ice, and carried out a cooperative field program in March 1979 on the properties of the Bering Sea ice edge with NOAA and the Scott Polar Research Institute. Another graduate student supported on the contract, Ms. Jane Bauer, began a series of laboratory experiments on the melting of ice floes in a wave field.

Our reports and papers during the past year include the technical report by Edward Josberger entitled "Laminar and Turbulent Boundary Layers Adjacent to Melting Vertical Ice Walls in Salt Water". This has been revised by Josberger and Martin into the paper entitled "A Laboratory and Theoretical Study of the Boundary Layer Adjacent to a Vertical Melting Ice Wall in Salt Water" and submitted to the Journal of Fluid Mechanics. S. Martin and P. Kauffman have in the final stages of preparation a manuscript entitled "A Field and Laboratory Study of Wave Damping by Grease Ice" which will shortly be submitted to the Journal of Glaciology. This is an account of our laboratory experiments and field observations on wave damping by sea ice, and gives as complete an account as we are able to provide of the role of grease ice in the marginal seas.

Our major effort during the past year was the organization of an ice edge cruise on the NOAA ship SURVEYOR. Although this work was primarily supported by the OCSEAP program, the present ONR contract contributed to the cruise in two ways. First, the contract paid for the costs related to the borrowing, insuring, and repair of a wave-rider buoy, which was deployed from the ship to gather wave data in support of a wave attenuation study carried out by Dr. Vernon Squire and Mr. Stuart Moore of the Scott Polar Research Institute. Squire and Moore have written up part of this Bering Sea work in a paper entitled "Direct Measurement of the Attenuation of Ocean Waves by Pack Ice", which is in press at Nature.

Second, Ms. Bauer carried out a study on the cruise of the relative motion of the bands of ice which form at the ice edge. These bands measure about 1 km wide by 10 km long, and form during periods of off-ice winds. In Bauer's study she mounted six visual targets on different ice floes within 1 km of the edge following a period of easterly winds which compacted the ice edge. When the winds shifted to the northeast, the ice moved to the southwest with ice bands starting to form. She then tracked the motion of the targets from helicopter overflights with the Global Navigation System over a 23 hour period. Her results showed that the band moved to the southwest at about 4% of the wind speed and at 35° to the right of the wind. At the beginning of her observations the ice in the bands was part of the pack; after 23 hours the ice was at least 25 km to the southwest of the pack.

Our observations show that these bands form because the ice floes near the edge have a greater aerodynamic roughness than the interior ice. The cause of the roughness increase is that the floes near the edge are rafted and ridged by the action of ocean swell. When the winds blow off the ice, the rough ice moves south faster than the interior ice, which leads to the formation of the bands. Bauer and Martin include a discussion of this work in a chapter entitled "Bering Sea Ice Edge Phenomena", which is written for a proposed Bureau of Land Management book. We plan to rewrite this chapter in a more technical manner for submission to the Journal of Geophysical Research.

Finally, we completed construction of our new 1 m deep by 1 m wide by 5 m long wave tank. Using this tank, Ms. Bauer has begun a series of experiments on how ice floes melt when they are placed in warm salt water through which waves propagate. The purpose of this experiment is to discover how the wave-induced boundary layer under the ice floe enhances the ice ablation, then to compare the experimental results with theory.

REPORTS PUBLISHED AND IN PRESS

1. Grenfell, T. C., The effects of ice thickness on the exchange of solar radiation over the polar oceans. Journal of Glaciology, 22, 87, 305-20, 1979.

Total transmission, absorption, and reflection of solar radiation have been determined for bare blue and white ice between 0.02 and 0.8 m in thickness as well as for blue ice covered with 0.01 to 0.4 m of dry packed snow. The calculations were performed at 45 wavelengths between 400 nm and 2150 nm using a two-stream model to account for the finite thickness of the ice and snow layers. Total radiative energies were found by numerical integration over wavelength. The results were compared with corresponding calculations for optically thick ice of the same types. Albedos increase from about 0.05 for open water to a maximum of 0.9 for thick snow. For 0.8 m blue and white ice, predicted albedos on cloudy days are 0.28 and 0.67 respectively. Under clear skies these albedos decrease by 10 to 30%. Total transmission through thin ice (less than 0.8 m) is from 50% to 300% greater than is predicted by Beer's law depending on ice type and cloud cover. Radiative energy absorption at the surface is independent of thickness, but significant departures from Beer's law of as much as 200% are evident in all cases below a depth of 2.5 mm. A parameterization scheme is presented for incorporating these results into heat- and mass-balance studies.

2. Niedrauer, T. M., and S. Martin, An experimental study of brine drainage and convection in young sea ice. Journal of Geophysical Research, 84, C3, 1176-86, 1979.

In a series of experiments using a 1.6-mm-thick freezing tank, thin sections of salt water ice were grown which exhibit the same drainage features as natural sea ice. The tank design permitted photographs to be taken, while thermocouples mounted in the tank walls recorded the temperature profiles within the ice. Convection was observed in both the skeletal layer and in the brine channels by the flow of dyed brine. Flow in the skeletal layer was cusplike in appearance, consisting of narrow downflow regions separated by broad upflow regions. Above the skeletal layer, several brine channels were also usually present in the ice, and convective overturning occurred in these channels. The convection caused temperature fluctuations of 0.05°C, which calculations show increase the vertical heat flux by 1%. The brine drainage channels, which were usually sloped 30° to 60° to the horizontal, always had isotherms tilted from 0° to 13° in the same direction. The brine channels move both horizontally and vertically through the ice by melting their lower walls and freezing on the upper walls. An analysis based on the heat flux due to brine channel convection shows that convection can drive these wall movements. Our observations suggest that most of the brine movement in the channels is caused by recirculation of water from below the ice. On a small scale we also observed the formation of brine pockets from brine tubes.

3. Josberger, E. G., Laminar and turbulent boundary layers adjacent to melting vertical ice walls in salt water. Scientific Report No. 16, Office of Naval Research, Contract N00014-76-C-0234, Department of Atmospheric Sciences, University of Washington, Seattle, Washington, 185 pp., 1979.

A laboratory study of melting vertical ice sheets immersed in sodium chloride solutions of oceanic temperatures and salinities found that the convective motions generated by the melting consist of two regions confined to a boundary layer adjacent to the ice. The first region, at the bottom of the ice, is laminar and bidirectional, with a 2 to 3 mm thick upward flowing layer next to the ice inside of a 10 mm thick outer downward flowing layer. This bidirectionality results from the large difference between the thermal and saline diffusivities which contain dilute water near the ice and allows the cooling to diffuse further from the ice. Near the ice, dilute cold water rises; while away from the ice, cold saline water sinks. Second, further up the ice, the inner layer goes through a region of transition and becomes fully turbulent when the saline Grashof number reaches 2×10^8. The turbulent flow is upward, unidirectional and the dominant flow in the oceans.

Ice-water interface temperature measurements over the ice surface show a vertically varying temperature in the laminar region and a uniform temperature in the turbulent region. The measured melt rates were highest in the transition region, lowest in the laminar region, and had a slow vertical variation in the turbulent region. For water temperatures greater than 25°C, the turbulent flow reversed direction and a laminar bidirectional region formed at the top of the ice.

In a theoretical study of the turbulent flow, an eddy diffusivity models the turbulent transport of momentum, salt and heat in the conservation equations and the laboratory measurements determine the model parameters. The turbulent model consists of three regions: a laminar inner region, an intermediate region where the eddy diffusivity increases linearly with distance from the ice and an outer region of constant eddy diffusivity. A similarity transformation reduces the governing partial differential equations to a system of ordinary differential equations which are then numerically integrated.

The numerical results show the following: The eddy diffusivity depends parabolically on the density difference across the boundary layer. The major effect of the turbulence is to increase the transport of dilute water away from the interface. The dilution effect overwhelms the thermal effect on density to produce a unidirectional upward flow. Finally, the injection of melt water into the boundary layer reduces the salt flux to the ice which lowers the interface salinity as the water temperature increases. Use of the results to form a zero net buoyancy condition on the buoyancy integrated across the boundary layer predicts the reversal of the turbulent flow which accurately fits all of the known data.

Salinity and temperature measurements with depth in the vicinity of an iceberg in the North Atlantic Ocean show variations in these quantities near the iceberg that may be the result of the upward flowing turbulent boundary layer.

4. Perovich, D. K., The optical properties of young sea ice. Scientific Report No. 17, Office of Naval Research, Contract N00014-76-C-0234, Department of Atmospheric Sciences, University of Washington, Seattle, Washington, 151 pp., 1979.

Eight laboratory experiments were performed to determine the optical properties of young salt ice and to examine correlations between the optical properties and the state of the ice. Ice grown at different temperatures (-10, -20, -30, and -37°C) and from water of different salinities (0, 16, and 31 $^{o}/_{oo}$) was investigated. The experiments were conducted using a tank system which was designed to grow ice similar to that found in nature, allow an accurate determination of the state and structure of the ice, and permit in situ optical measurements to be made. Measurements of incident, reflected, and transmitted irradiances were used in conjunction with a modified Dunkle and Bevans photometric model to determine spectral albedos and extinction coefficients. The thin cold ice of these experiments had albedos which were comparable to the values for the thicker warmer ice examined by previous researchers; however, extinction coefficients were 1.5 to 15 times greater. Qualitative relationships between the optical properties and the physical state of the ice were observed. As the ice temperature decreased (and the brine volume decreased) both albedo and extinction coefficient increased; when the ice temperature dropped below the eutectic point the increase was drastic. The dependence of albedo and extinction coefficient on the brine content of the ice was found to be complex with both the brine volume and its vertical distribution being significant. Variations in ice salinity over the range 4 $^{0}/_{00}$ to 14 $^{0}/_{00}$ did not influence the optical properties. Increases in albedo and extinction coefficient were primarily a result of changes in the ice structure which enhanced scattering.

A four stream discrete ordinates photometric model was developed to treat the case of a floating ice slab. The model included both anisotropic scattering and refraction at the boundaries. The effects on albedo and transmittance of variations in such model parameters as the single scattering albedo and the phase function were investigated. Using one and two layer models, theoretical albedos and transmittances were compared to experimental values. The four stream model was further applied to investigate such topics as the depth dependence of irradiance, cases of direct beam incident radiation, the spectral dependence of albedo and transmittance, and the effects of surface layers. It was suggested that future laboratory research be oriented towards determination of single scattering albedos and phase functions for an extensive range of ice types.

5. Martin, S., A field study of brine drainage and oil entrainment in first-year sea ice. Journal of Glaciology (in press).

6. Josberger, E. G., The effect of bubbles released from a melting ice wall on the melt-driven convection in salt water. Journal of Physical Oceanography (in press).

7. Squire, V. A., and S. C. Moore, Direct measurement of the attenuation of ocean waves by pack ice. Nature (in press) (partial support).

8. Neshyba, S., and E. Josberger, An estimation of antarctic iceberg melt rates. Journal of Physical Oceanography (submitted).

9. Perovich, D. K., and T. C. Grenfell, Laboratory studies of the optical properties of young NaCl ice. Journal of Glaciology (submitted).

10. Josberger, E., and S. Martin, A laboratory and theoretical study of the boundary layer adjacent to a vertical melting ice wall in salt water. Journal of Fluid Mechanics (submitted).

11. Martin, S., and J. Bauer, Bering Sea ice edge phenomena. Bureau of Land Management (submitted) (partial support).

12. Martin, S., and P. Kauffman, A field and laboratory study of wave damping by grease ice. Journal of Glaciology (in preparation).

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) 29

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
ANNUAL REPORT NO. 11

2. GOVT ACCESSION NO.

3. RECIPIENT'S ~~CATALOG NUMBER~~
⑨ Rept. for

4. TITLE (and Subtitle)
⑥ ANNUAL REPORT ~~NO.~~ Number 11,

5. TYPE OF REPORT & PERIOD COVERED
INTERIM REPORT 1 OCT 78-30 SEP 79,

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
CONTRACT N00014-76-C-0234

8. CONTRACT OR GRANT NUMBER(s)
⑮ N00014-76-C-0234

9. PERFORMING ORGANIZATION NAME AND ADDRESS
ARCTIC SEA AIR INTERACTION
DEPARTMENT OF ATMOSPHERIC SCIENCES AK-40
UNIVERSITY OF WASHINGTON, SEATTLE, WA 98195

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
NR 307-252
⑫ 37

11. CONTROLLING OFFICE NAME AND ADDRESS
OFFICE OF NAVAL RESEARCH
CODE 461, ARCTIC PROGRAM
ARLINGTON, VA 22217

12. REPORT DATE
⑪ 1 DECEMBER 1979

13. NUMBER OF PAGES
33

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
THE DISTRIBUTION OF THIS REPORT IS UNLIMITED

⑩ Seeyle /Martin
Gary /Maykut

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES
Research topics studied during this report period

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

ARCTIC OCEAN	SEA ICE	
Heat Balance	Grease Ice	Light Scattering
Ice Edge	Growth	Optical Properties
Ice Production	Lateral Melting	Thickness Distribution
Sea Ice		

④ ③ ⑤ ②

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The report summarizes research performed under Contract N00014-76-C-0234, NR 307-252, during the year 1 October 1978 - 30 September 1979. Research topics include: (1) large-scale heat and mass balance of the ice pack; (~~ii~~) effects of ice deformation on regional heat fluxes; (~~iii~~) light scattering and optical properties of sea ice; (~~iv~~) lateral melting in leads; (~~v~~) wave damping by grease ice; (~~vi~~) ice edge phenomena; and (~~vii~~) effects of arctic clouds on incident solar radiation in the near infrared. ⑦

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

⑥

370 270 JOB

DISTRIBUTION LIST

CONTRACT N00014-76-C-0234
NR 307-252

DEFENSE DOCUMENTATION CENTER
CAMERON STATION
ALEXANDRIA, VA 22314

US NAVAL RESEARCH LABORATORY
CODE 2627
WASHINGTON, DC 20375

WOODS HOLE OCEANOGRAPHIC INST
DOCUMENT LIBRARY LO-206
WOODS HOLE, MA 02543

COLD REGIONS RES & ENG LAB
PO BOX 282
HANOVER, NH 03755

CAPT D C NUTT, USN (RET)
DEPARTMENT OF GEOGRAPHY
DARTMOUTH COLLEGE
HANOVER, NH 03755

DR JOHN C F TEDROW
DEPT OF SOILS, LIPMAN HALL
RUTGERS UNIVERSITY
NEW BRUNSWICK, NJ 08903

DR KENNETH L HUNKINS
LAMONT-DOHERTY GEOLOGICAL OBSY
TORRY CLIFFE
PALISADES, NY 10964

CHIEF OF ENGINEERS
ATTN DAEN-MCE-D
DEPARTMENT OF THE ARMY
WASHINGTON, DC 20314

DEPARTMENT OF THE ARMY
OFFICE CHIEF OF ENGINEERS
ATTN DAEN-RDM
WASHINGTON, DC 20314

MR M R HERRMAN
NAVAL FACILITIES ENG COMMAND
CODE 032 A, YARDS & DOCKS ANNEX
ROOM 2B1
WASHINGTON, DC 20390

MR ROBERT D KETCHUM JR
BLDG 70, CODE 8050
NAVAL RESEARCH LABORATORY
WASHINGTON, DC 20390

MR LOUIS DEGOES, EXEC SECTY
POLAR RESEARCH BOARD
NATL ACADEMY OF SCIENCES
2101 CONSTITUTION AVENUE, NW
WASHINGTON, DC 20418

POLAR INFORMATION SERVICE
OFFICE OF POLAR PROGRAMS
NATIONAL SCIENCE FOUNDATION
WASHINGTON, DC 20550

DR GEORGE A LLANO
ACTING CHIEF SCIENTIST
OFFICE OF POLAR PROGRAMS
NATIONAL SCIENCE FOUNDATION
WASHINGTON, DC 20550

MR M M KLEINERMAN
PROJECT MANAGER FOR ARCTIC ASW
US NAVAL ORDNANCE LABORATORY
WHITE OAK, MD 20910

MR PAUL P LAUVER, PUBLICATIONS
ARCTIC INST OF NORTH AMERICA
3426 NO WASHINGTON BLVD
ARLINGTON, VA 22201

DR G LEONARD JOHNSON
CODE 461, ARCTIC PROGRAMS
OFFICE OF NAVAL RESEARCH
ARLINGTON, VA 22217

DR NORBERT UNTERSTEINER
SCI ADV FOR ARCTIC & POLAR AFFAIRS
OFFICE OF NAVAL RESEARCH
CODE 400P
ARLINGTON, VA 22217

CHIEF OF NAVAL RESEARCH
OFFICE OF NAVAL RESEARCH
CODE 412
ARLINGTON, VA 22217

CHIEF OF NAVAL RESEARCH
OFFICE OF NAVAL RESEARCH
CODE 414
ARLINGTON, VA 22217

CHIEF OF NAVAL RESEARCH
OFFICE OF NAVAL RESEARCH
CODE 480D
ARLINGTON, VA 22217

US NAVAL OCEANOGRAPHIC OFFICE
LIBRARY (CODE 8160)
NSTL STATION
BAY ST LOUIS, MS 39522

DIRECTOR, INST OF POLAR STUDIES
OHIO STATE UNIVERSITY
125 SOUTH OVAL DRIVE
COLUMBUS, OH 43210

DR ALBERT H JACKMAN
CHAIRMAN, DEPT OF GEOGRAPHY
WESTERN MICHIGAN UNIVERSITY
KALAMAZOO, MI 49001

DR REID A BRYSON
INST FOR ENVIRONMENTAL STUDIES
UNIVERSITY OF WISCONSIN
MADISON, WI 53706

DR DAVID CLARK
DEPARTMENT OF GEOLOGY
UNIVERSITY OF WISCONSIN
MADISON, WI 53706

PROF RICHARD S TANKIN
DEPT OF MECH ENGINEERING
NORTHWESTERN UNIVERSITY
EVANSTON, IL 60201

PROF WILLIAM MCINTIRE
COASTAL STUDIES INSTITUTE
LOUISIANA STATE UNIVERSITY
BATON ROUGE, LA 70803

DR HARLEY J WALKER
DEPARTMENT OF GEOGRAPHY
LOUISIANA STATE UNIVERSITY
BATON ROUGE, LA 70803

DR V P HESSLER
4230 EUTAW STREET
BOULDER, CO 80302

WORLD DATA CENTER: A FOR GLAC
INST OF ARCTIC & ALPINE RESEARCH
UNIVERSITY OF COLORADO
BOULDER, CO 80309

CONTRACT ADMINISTRATOR
OFFICE OF NAVAL RESEARCH BRANCH OFC
1030 EAST GREEN STREET
PASADENA, CA 91106

COMMANDER
NAVAL UNDERSEA CENTER
ATTN TECHNICAL LIBRARY, CODE 1311
SAN DIEGO, CA 92132

RESEARCH LIBRARY
NAVAL ELECTRONICS LAB CENTRE
SAN DIEGO, CA 92152

LIBRARIAN
TECHNICAL LIBRARY DIVISION
NAVAL CIVIL ENGINEERING LABORATORY
PORT HUENEME, CA 93041

COMMANDING OFFICER
CODE L61
NAVAL CIVIL ENGINEERING LABORATORY
PORT HUENEME, CA 93043

MR BEAUMONT BUCK
POLAR RESEARCH LABORATORY ING
123 SANTA BARBARA STREET
SANTA BARBARA, CA 93101

SUPERINTENDENT
NAVAL POSTGRADUATE SCHOOL
LIBRARY CODE 2124
MONTEREY, CA 93940

DR ARTHUR LACHENBRUCH
BRANCH OF GEOPHYSICS
US GEOLOGICAL SURVEY
345 MIDDLEFIELD ROAD
MENLO PARK, CA 94025

DR W M SACKINGER
DEPT OF ELECTRICAL ENGINEERING
UNIVERSITY OF ALASKA
FAIRBANKS, AK 99701

DR KEITH MATHER
705 GRUENING BUILDING
UNIVERSITY OF ALASKA
FAIRBANKS, AK 99701

DR CHARLES E BEHLKE, DIRECTOR
INST OF ARCTIC ENVIRONMENTAL ENG
UNIVERSITY OF ALASKA
COLLEGE, AK 99701

DR DONALD W HOOD
INST FOR MARINE SCIENCE
UNIVERSITY OF ALASKA
FAIRBANKS, AK 99701

DR GUNTER WELLER
GEOPHYSICAL INSTITUTE
UNIVERSITY OF ALASKA
COLLEGE, AK 99701

LIBRARIAN
NAVAL ARCTIC RESEARCH LABORATORY
BARROW, AK 99723

MGR INUVIK RESEARCH LABORATORY
BOX 1430
INUVIK, NORTHWEST TERRITORIES
XOE OTO CANADA

DR SVENN ORVIG
MCGILL UNIVERSITY
DEPT OF METEOROLOGY
PO BOX 6070
MONTREAL 101, PQ, CANADA

MARINE SCIENCE CENTRE LIBRARY
MCGILL UNIVERSITY
PO BOX 6070
MONTREAL 101, PQ, CANADA

DR E R POUNDER
RUTHERFORD PHYSICS BUILDING
MCGILL UNIVERSITY
3600 UNIVERSITY STREET
MONTREAL, PQ H3A 2T8, CANADA

MRS GAIL HORWOOD
METEOROLOGY LIBRARY
MCGILL UNIVERSITY
MONTREAL 101, PQ, CANADA

DR WESTON BLAKE JR
GEOLOGICAL SURVEY OF CANADA
DEPT OF ENERGY MINES RESOURCES
601 BOOTH STREET
OTTAWA, ONTARIO K1A 0E8 CANADA

DEPARTMENTAL LIBRARY-SERIALS
DEPT OF THE ENVIRONMENT
OTTAWA, ONTARIO K1A 0H3 CANADA

DEFENCE RESEARCH BOARD
DEPT OF NATIONAL DEFENCE
190 O'CONNOR STREET
OTTAWA, ONTARIO K1A 0Z3, CANADA

MISS MOIRA DUNBAR
DEFENCE RESEARCH ESTABLISHMENT
OTTAWA, NATL DEFENCE HEADQUARTERS
OTTAWA, ONTARIO K1A 0Z4, CANADA

DR ROBERT L RAUSCH
DEPT OF MICROBIOLOGY
W COLLEGE OF VET MEDICINE
UNIVERSITY OF SASKATCHEWAN
SASKATOON, SASK S7N 0W0, CANADA

DR E L LEWIS
FROZEN SEA RESEARCH GROUP
INSTITUTE OF OCEAN SCIENCES
9860 W SAANICH ROAD, PO BOX 6000
SIDNEY, BC V8L 4B2, CANADA

DR A R MILNE
DEFENCE RES ESTABLISHMENT PAC
FLEET MAIL OFFICE
VICTORIA, BC, CANADA

METEOROLOGICAL OFFICE LIBRARY
LONDON ROAD
BRACKNELL, BERKSHIRE, ENGLAND

DR T E ARMSTRONG
SCOTT POLAR RESEARCH INSTITUTE
CAMBRIDGE, CB 2 1ER, ENGLAND

THE LIBRARIAN
SCOTT POLAR RESEARCH INSTITUTE
CAMBRIDGE CB2 1ER, ENGLAND

DR MICHAEL KELLY
SCHOOL OF ENVIRONMENTAL SCIENCES
UNIVERSITY OF EAST ANGLIA
NORWICH NR4 7TJ, ENGLAND

NATIONAL INST OF OCEANOGRAPHY
WORMLEY, GODALMING
SURREY, ENGLAND

CENTRE NATL DE LA RECHERCHE SCI
LABORATOIRE DE GLACIOLOGIE
UNIVERSITE DE GRENOBLE 1
SERV DE GEOPHYS, 2, RUE TRES
CLOITRES 38-GRENOBLE, FRANCE

CENTRE D'ETUDES ARCTIQUES
ECOLE PARTIQUE DES HAUTES ETUDES
VI SECTION (SORBONNE)
6, RUE DE TOURNON, PARIS -6
FRANCE

DR KOU KUSUNOKI
POLAR RESEARCH CENTER
NATIONAL SCIENCE MUSEUM
KAGA 1-9-10, ITABASHI-KU
TOKYO, JAPAN

NORSK POLARINSTITUTT
ROLFSTANGVN 12, POSTBOKS 158
1330 OSLO LUFTHAVN
NORWAY

PROF DR ALEXSANDER KOSIBA
KATEFRA I OBSERWATORIUM
METEOROLOGI I KLIMATOLOGII
UNIWERSYTETN WROCLAWSKIEGO
WROCLAW 9, U CMENTARNA 8
POLAND

STOCKHOLMS UNIVERSITET
NATURGEOGRAFISKA INSTITUTIONEN
BOX 6801
113 86 STOCKHOLM, SWEDEN

DR ING O MAGGIOLO
FACULTAD DEINGENIERIA
HERRERA Y REISSIG 585
MONTEVIDIO, URUGUAY

LIBRARY-CENTRE FOR NORTHERN
STUDIES AND RESEARCH
MCGILL UNIVERSITY
1020 PINE AVENUE WEST
MONTREAL, PQ H3A 1A2
CANADA

UNIVERSITY ARCHIVES
UNIVERSITY RECORDS SECTION BL-10
UNIVERSITY OF WASHINGTON
SEATTLE, WA 98195

RESIDENT REPRESENTATIVE
OFFICE OF NAVAL RESEARCH
ROOM 422, UNIV DISTRICT BLDG JD-27
UNIVERSITY OF WASHINGTON
SEATTLE, WA 98105

DR LAWRENCE COACHMAN
DEPARTMENT OF OCEANOGRAPHY WB-10
UNIVERSITY OF WASHINGTON
SEATTLE, WA 98195

DR T SAUNDERS ENGLISH
DEPARTMENT OF OCEANOGRAPHY WB-10
UNIVERSITY OF WASHINGTON
SEATTLE, WA 98195

DR KNUT AAGARD
DEPARTMENT OF OCEANOGRAPHY WB-10
UNIVERSITY OF WASHINGTON
SEATTLE, WA 98195