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1 DECEMBER 1977

DEPARTMENT OF ATMOSPHERIC SCIENCES
UNIVERSITY OF WASHINGTON
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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

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MR. DONALD K. PEROVICH, Predoctoral Associate

MR. TERREN M. NIEDRAUER, Predoctoral Associate (terminated 15 July 1977)

MR. EDWARD JOSBERGER, Predoctoral Associate

MR. DAVID HEDRICK, Predoctoral Associate (from 15 September 1977)

INTRODUCTION

During the past year we have carried out theoretical studies on: (i) large-scale interactions between the ocean and atmosphere in the presence of an ice cover, (ii) radiative transfer in ice and snow, (iii) forecasting ice growth in leads and peripheral seas, and (iv) effects of transmitted short-wave radiation on the growth and decay of young ice. Laboratory experiments were conducted in the following areas: (i) the ablation of vertical and sloping ice walls submerged in warm sea water, (ii) the small-scale desalination of young growing sea ice, (iii) heat transfer processes within grease ice grown in a wave field, (iv) the optical properties of grease ice and young ice grown under quiescent conditions, and (v) scattering of short-wave radiation by inhomogeneities within the ice.

Two field experiments were successfully carried out - one in March 1977 to study the optical properties of cold first-year ice in the Beaufort Sea, and the other in June 1977 to study the salinity and temperature field around an iceberg in the North Atlantic. Fred Rigby completed his internal wave studies and wrote up the results in a Master's thesis entitled "Pressure Ridge Generated Internal Wave Wakes at the Base of the Mixed Layer in the Arctic Ocean". A Master's thesis entitled "Brine Drainage and Convection in Young Sea Ice" was also completed by Terren Niedrauer. Notable progress was made during the past year in two areas. First, in the large-scale interaction studies, a realistic treatment of young ice allowed us to obtain the first estimates of regional flux values in the Central Arctic. Second, in the grease ice experiments, we determined the physical relationship between heat transfer and wave damping which is needed for the development of a theoretical model. Scientific results from previous work include papers on the boundary

layers which form beneath a horizontal ice sheet floating on warm salty water, the optical properties of snow and ice, heat exchange over young sea ice, and observations of mass changes on a first-year pressure ridge keel.

DYNAMIC AND THERMODYNAMIC MODELING

Most of the efforts during this reporting period have been devoted to learning more about the behavior of young sea ice and its role in the overall interaction between the ocean and atmosphere in the Arctic. The work can be separated into four interrelated, but generally distinct, topics.

1.) Regional heat and mass balance in the Central Arctic. Numerous estimates of the heat and mass balance of the arctic ice pack have been made during the past few decades. In recent years, however, these estimates have become increasingly suspect because they are based largely on measurements taken over perennial ice and ignore contributions made by ice-covered leads. When the ice is less than about 1 m in thickness, surface temperature, albedo, turbulent heat exchange, ice production, salt rejection, and the transmission of short-wave radiation to the ocean all depend strongly on ice thickness - exchange rates over very thin ice being as much as 100 times those over the thicker ice. Since satellite data and other evidence now indicate that young ice usually comprises more than 10% of the ice pack in the Central Arctic, it is clear that we must take into account what happens over the young ice before we can quantitatively understand large-scale interactions.

In the past we have not been able to carry out regional (large-scale) calculations because we lacked information not only on the amount of thin ice and open water, but also on how various components of the heat balance

changed with ice thickness and season. Work supported by this contract during the last few years has addressed both of these problems. The thickness distribution model developed in collaboration with A. S. Thorndike and D. A. Rothrock now allows us to determine the amount of ice in any thickness category using strain and ice growth data as input. In addition, we have developed a thin ice model which predicts the rates of ice growth and salt rejection, all temperature dependent components of the surface heat balance, and the amount of solar heating in the upper ocean for any thickness of ice. The only input data required by this model are incoming long- and short-wave radiation and air temperatures; a recent modification now allows us to substitute cloudiness for the more difficult to obtain long-wave radiation. A preliminary description of this model was written up in the AIDJEX Bulletin last year. This paper has subsequently been expanded to show how the results can be used to calculate large-scale fluxes. Examples of regional heat balances during March are given for a theoretical thickness distribution and for a thickness distribution inferred from the satellite observations of Ahlmas and Wendler (1977). The expanded version has been submitted for publication to the Journal of Geophysical Research.

One of the primary motivations for the development of the thin ice model was its application in the thickness distribution model. Previously, we have been forced to rely on an empirical equation for the rates of thin ice growth needed in the calculation of the thickness distribution. In the last few months we have combined the two models, significantly improving the treatment of thermodynamics in the thickness distribution model. Thickness distributions can now be predicted taking into account such things as seasonal changes in the amount of short-wave radiation, oceanic heat flux,

and snow cover. Some changes were also made in the dynamic part of the model. By analyzing satellite imagery, D. A. Rothrock at AIDJEX found that less of the thicker ice is involved in ridging than we had previously estimated. Assumptions relating to the mechanical redistribution of the ice have therefore been modified to reflect these recent findings.

A program to determine regional values has also been written and added to the combined model. The complete model now operates as follows: (i) strains, incident radiation fluxes, and air temperatures are specified at each time step, (ii) growth rates for each thickness category are calculated, (iii) these growth rates are combined with the strain data to determine a new ice thickness distribution, (iv) fluxes of heat, mass, and salt are calculated for each thickness category, then (v) multiplied by the amount of ice in each category and integrated over thickness to find regional totals for each of the fluxes. This procedure is then repeated at each succeeding time step to obtain monthly and annual totals.

The complete model has recently been tested using the 2-year strain history from the T-3/ARLIS II/NP-10 triangle and climatological heat balance data. Thickness distributions predicted by the new model are somewhat different from those previously obtained, and we are presently analyzing the results to determine which changes are due to the improved thermodynamics and which are due to the different mechanical assumptions. Although different in magnitude, the regional flux totals are qualitatively similar to the cruder estimates we obtained last fall. Over the course of a year, there was a net ice production of about 70 cm in each unit area within the region - this can also be expressed as a volume change of 150 km^3 , an increase of 20-25% in the total amount of ice contained within the

triangle. The total amount of salt added to the mixed layer was about 3 times larger than would be expected from a uniform 3 m ice cover. Annual turbulent heat input to the atmospheric boundary layer over the region was about 10 times larger than that over the 3 m ice. The regionally averaged amount of short-wave radiation reaching the 3 m level in the ocean was nearly 2000 cal/cm², about 25% more than the heat input from the Atlantic layer. This suggests that the amount of ice melted from the underside of the ice pack is more than double present estimates. We suspect that pressure ridge ice and possibly false bottoms act as a sink for much of this heat. An abbreviated form of these results was presented in September at the ICSI/AIDJEX Symposium on Sea Ice in a paper entitled, "Estimates of the Regional Heat and Mass Balance of the Ice Cover in the Central Arctic".

2.) Forecasting ice growth in leads and peripheral seas. While testing the thin ice model, it was noted that predicted growth rates during the winter were substantially larger than those obtained from empirical ice growth equations. It was further noted that the various empirical equations did not agree well, suggesting that such equations may describe only a particular region (and/or year) and thus may not be applicable to general situations. In the future, satellites and buoys will provide basic data on cloudiness, ice movement, air temperatures, etc., but will not provide the complete data set needed to run sophisticated models. Instead, we must devise simplified ways to obtain information on ice growth and heat exchange from limited data. Techniques developed for this purpose should be flexible, in that they can be modified to take into account what may be

known about the local conditions. Present forecasting equations are quite limited in this respect.

We therefore decided to try and understand the physical basis of existing forecasting equations in order to see what improvements might be made. To do this, we first wrote down the complete equations describing the ice growth, then determined what simplifications would have to be made in order to obtain the particular form of the forecasting equation in question. We found that the empirical equations could be divided into two general classes: (i) those that equated air temperature and surface temperature, and (ii) those that assumed that all the heat conducted to the surface was lost to the atmosphere through turbulent dissipation. Both classes assumed that the net radiation balance at the surface was zero. Neither method accurately describes the growth of ice in leads - the first class fails because the surface temperature of thin ice does not bear a constant relationship to air temperature, while the second class fails because an increasing percentage of the heat conducted to the surface is lost via long-wave radiation as the ice thickens.

It was clear from our analysis that for forecasting equations to be improved, some simple way of treating long-wave radiation would have to be found. Fortunately, our radiation measurements at Barrow¹ have indicated that incoming long-wave radiation can be estimated quite well from air temperatures near the surface and cloudiness. With the relationship suggested by Maykut and Church, we linearized the fourth-order long-wave

¹Maykut, G. A. and P. E. Church, Radiation climate of Barrow, Alaska, 1962-66. Journal of Applied Meteorology, 12, 620-628, 1973.

radiation term in the heat balance equation and obtained an analytical expression for the ice growth which depended only on air temperature and cloudiness. Provision was also made to take into account a snow cover if such information were available. Predictions by the complete thin ice model and the new forecasting equation were compared, and good agreement obtained during the dark months.

The new forecasting equation should provide good estimates of ice growth in winter leads because the oceanic heat flux is very small compared with the heat conducted through the ice. It will, however, overestimate the fall growth of ice in the peripheral seas because large amounts of heat are still stored in the water when the ice begins to freeze. Lee and Simpson² have described a method of estimating how this stored heat would affect the ice growth, but they included the assumption that air temperatures and surface temperatures were the same. We therefore combined our treatment of the ice growth with their treatment of the oceanic heat flux to derive an equation which should be valid for seasonal ice in the peripheral seas.

While these equations should be adequate during much of the growth season, they are limited by the lack of a short-wave radiation term and, hence, cannot treat spring and summer conditions. As our data sets improve, it will be possible to improve ice forecasts by taking into account seasonal variations in the short-wave radiation. We are presently working on simplified ways of predicting summer melting and ice growth when the sun is high.

²A Practical Method of Predicting Sea Ice Formation and Growth, Technical

Report TR-4, U.S. Navy Hydrographic Office, Washington, D.C., 27 pp., 1954.

This case is somewhat more complicated than the winter case because the equations do not have simple analytical solutions, but it appears that fairly straightforward iterative procedures can be used to calculate the ice growth. We plan to write this work up and submit it for publication in the coming year.

3.) Effects of short-wave radiation on the growth and decay of young ice.

Between mid-April and the end of September, substantial amounts of short-wave radiation pass through young ice and are absorbed in the ocean. As a result of convection most of this energy rapidly returns to the bottom of the ice where it acts to retard the growth or to cause melting. From the optical measurements and theoretical calculations of T. C. Grenfell (see "Radiation in Ice" section), we now have good estimates of the amount of light penetrating the ice and can calculate how much of this energy is absorbed at a particular level in the ocean. The degree to which this energy affects young ice growth is still uncertain, although it is clearly different in the Central Arctic than in the seasonal ice of the peripheral seas. In the perennial ice, young ice is confined to refrozen leads. About 60-70% of the light passing through lead ice is absorbed below the bottom of the surrounding thick (3m) ice, and is then advected under the thicker ice where it does not directly affect the growth of the lead ice. Of the energy absorbed below the bottom of the lead ice and the surrounding ice, part must go into lateral melting on the lead walls, while the rest can move either up or down depending on the salinity of the surface waters. Beneath the thinner and more uniform ice cover in the peripheral seas, solar energy absorbed in the water should have a larger and more immediate effect on the growth.

Numerical experiments have been carried out to determine how various assumptions regarding the penetration of short-wave radiation influence the ice growth. The simulations show very different growth patterns for the different assumptions, indicating that the accurate treatment of penetrating short-wave radiation will be vital to predicting the growth and decay of young ice during the spring and summer months. One of the most interesting results obtained thus far is that, for a given set of incident fluxes, there can exist both a stable and an unstable equilibrium thickness - ice thinner than the unstable equilibrium melts away, while ice thicker than the unstable equilibrium will eventually grow to the stable equilibrium thickness. As far as we know, this behavior has not been noted previously. Whether or not there exists an unstable equilibrium thickness appears to depend on assumptions related to the amount of penetrating short-wave radiation. In the coming year, we plan to examine ice growth/ penetrating short-wave radiation interactions in more detail and to define more precisely the conditions necessary for the existence of an unstable equilibrium thickness.

4.) Positive feedback effects associated with the formation and growth of sea ice. The formation of ice can result in either positive or negative feedback, depending on a variety of factors. Heat losses from winter leads in the Central Arctic, for example, tend to warm the air and slow the ice growth; on the other hand, formation of ice in open seas allows the relatively warm air in the boundary layer to begin to cool, tending to enhance the ice growth. Treatment of feedback effects are an important step in the development of a good ice extent model. To learn more about

the magnitude and potential importance of feedback processes, we have begun to investigate the response of the ice in a number of different feedback situations.

The problem we are presently working on is this: would a thin layer of ice formed during the night or advected into a region of normally open water alter the heat balance sufficiently to cause continued growth of the ice? This situation applies in the early fall when enough short-wave radiation is absorbed by open water to keep it from freezing. The higher albedo of a thin ice cover reduces the net short-wave radiation and can, under suitable conditions, result in positive feedback. We have considered two cases where: (i) temperatures in the boundary layer remain essentially constant, as for example over leads in the perennial ice or coastal areas with prevailing offshore winds, and (ii) temperatures in the boundary layer follow the changing surface temperature of the ice. Results using the thin ice model indicate that one of the following will happen: (i) the ice may melt away, (ii) the ice may grow to a particular thickness and stop, or (iii) the ice may continue to grow indefinitely (within the range of validity of the thin ice model). The calculations have allowed us to define the combinations of air temperature and short-wave radiation needed for each of these possibilities to occur. As might be expected, the critical temperatures and short-wave radiation values depended strongly on what we assumed about the dependence of albedo and penetrating short-wave radiation on ice thickness. Probably the most serious limitation in the calculations carried out thus far was in the treatment of the atmospheric boundary layer. In the coming months we plan to try and improve this aspect of the model, and to look at feedback effects during other parts of the year.

RADIATION IN ICE

The paper entitled "The Optical Properties of Ice and Snow in the Arctic Basin" has been accepted for publication and is due to appear in the next issue of the Journal of Glaciology.

During the last two weeks of March we participated in a field experiment organized by Dr. S. Martin in connection with his studies for BLM/NOAA on the structure of sea ice in the shorefast ice zone near Prudhoe Bay, Alaska. This gave us an excellent opportunity to measure the optical properties of cold seasonal ice for which the physical parameters influencing the scattering and absorption (brine volume, bubble density, and crystal structure) were determined simultaneously. Because such ice has a low temperature and consequently a small brine volume, we expect its albedos and extinction coefficients to be larger than for warm melting ice of comparable thickness.

Spectrophotometer measurements of albedo, total transmission, and transmission profiles in the upper 50 cm of the ice were obtained together with total albedos determined at all locations with a pair of Kipp and Zonen radiometers. The measurements were carried out at about 50 sites from four different stations off the coast at varying distances from a few hundred meters offshore to about 1/2 km seaward of Narwhal Island. An attempt was also made to locate a refreezing lead in order to study thin growing ice; however, strong onshore winds had compressed the ice pack against the shore and no leads could be found within the range of the helicopter.

At temperatures of -35°C the new data recording system functioned very well and we have recovered about 90% of the raw measurements. As soon as we can compensate for the tape recorder slowdown which occurred during one run, we will have retrieved essentially all of the data. We are currently

in the process of decoding the data tapes and reducing the results. The final analysis will be written up for publication in conjunction with the interpretation of the structural and thermal results obtained by S. Martin.

Laboratory experiments conducted this past winter on the physics of ice grown in a wave field have provided us with the unique opportunity to study the optical properties of grease ice and pancake ice. In situ studies of these types of ice would be extremely difficult due to the adverse weather conditions accompanying their formation and to the lack of a stable platform.

The occurrence of grease ice and pancake ice is quite common in the seasonal ice zones as well as in refreezing leads and polynyas within the perennial ice pack due to the high winds prevalent in the Arctic Basin during most of the year. This ice layer can build up to more than 25 cm before it damps out the waves enough to freeze solid. Therefore, in many cases, the surface of young growing sea ice can have a much thicker layer of randomly oriented small crystals than would be formed under quiescent growth conditions. In view of the major role of thin ice in the energy balance of the arctic ice pack, it is important to understand how grease ice and pancake ice interact with solar radiation and the magnitude of differences in the optical properties of ice formed under calm and wavy conditions.

Our experiment was carried out as a joint project with S. Martin using the 2 m wave tank he had constructed. Fiber optics were mounted at 20 and 30 cm below the ice/water surface to measure transmitted irradiance, and a movable probe was positioned above the surface to record incident and reflected irradiance. Diffuse illumination was provided by mounting a

horizontal Plexiglas diffuser just above the ice surface with a set of lights about 1 m above the diffuser as the primary light source.

The wave field was generated by a power driven paddle and the air temperature was held at -25°C . Spectral irradiances were measured with the profiling spectrophotometer at intervals of 1.5 to 2 hours after ice growth began. When substantial pancakes had formed (typically 12 cm across and 13 cm thick), the paddle was stopped and the ice was allowed to solidify for the next few days. Two additional sets of measurements were made during this time to cover the transition of the surface from pancakes to hard ice.

With each set of optical measurements, physical data were obtained consisting of ice density, salinity, brine volume, temperature, and crystal structure. The experiment was completed successfully, and the data are in the process of reduction. As yet we have available only the spectral albedos. They show a continual rise at all wavelengths as the ice developed, beginning with values characteristic of specular reflection by water and rising to a curve which approaches the albedo for an old melt pond on multi-year ice. Data reduction should be completed in the next few months at which time the results will be prepared for publication in a comprehensive paper on the physical properties of grease ice.

Thin ice experiments in the cylindrical freezing tank are in progress. The fiber optics coupling apparatus has been tested and calibrated. An attenuation on the order of 20% is introduced by the coupling box together with the additional 30 cm fiber optics element it requires, but the light levels remain more than adequate for accurate transmission profiles. The operational amplifier in the profiling spectrophotometer has been replaced with a new low noise, low drift unit making it possible to increase the

sensitivity by a factor of 20. This is important for studies of snow and for laboratory measurements at short wavelengths where light levels can be quite low.

A thermistor array has been constructed and installed in the tank to measure temperature gradients in the ice in order to interpret growth rate data. Fourteen thermistors were mounted on a Plexiglas strip separated from each other by 2 cm to monitor growing ice sheets up to 25 cm in thickness.

To determine the brine volume of the ice as well as specific heats and thermal conductivities, vertical profiles of salinity are required. The most practical technique involves removing an ice sample and slicing it into horizontal sections which are then melted and their salinity determined. In order to minimize disturbances to the optical properties and thermal structure of the ice sheet, the samples must be quite small, and they must be extracted and processed quickly to minimize brine drainage. Both requirements have been satisfied by freezing into the ice a set of 1/2 inch diameter hollow plastic tubes which can be pulled out of the ice and the core extracted. Because the thermal diffusivity of the plastic is nearly equal to that of ice, the presence of the tubes should not greatly perturb the local temperature gradients.

Several complete experiments have been carried out to date at different air temperatures and water salinities in an attempt to isolate the effects of bubbles and brine volume on the optical properties of young ice. The ice was grown from filtered tap water with sodium chloride added for the salt ice cases. From 3 to 5 underwater fiber optics probes were used to record changes in total transmission as the ice thickened and to monitor localized variations within the ice as temperature and salinity changed.

An additional probe was positioned just above the surface to determine albedos and to monitor incident irradiance.

Two fresh ice runs were carried out at an air temperature of -15°C . Before the thickness of the ice layer reached 10 cm, bubble formation was negligible because at 0°C the water was not saturated with air. It was possible, therefore, to study both bubble free and bubbly ice in the same experiment. To the present limit of accuracy the optical properties of bubble free fresh ice are indistinguishable from those of the water. As the bubbly layer grew, the albedo maximum at 500 nm increased by about 30% with a corresponding transmission decrease of about 20% indicating an extinction coefficient on the order of $.025\text{ cm}^{-1}$.

Experiments with saline ice were conducted at air temperatures of -15°C and -20°C . Reflection and transmission of light by saline ice showed a marked dependence on ice thickness. At 500 nm, for example, the albedo increased from 0.18 for 7.4 cm of ice to 0.42 for 20.9 cm while the transmission decreased by 25%. A significant temperature effect was also noted. When the air temperature was raised to 0°C after the ice had reached maximum thickness, the albedo decreased to 0.28 due to surface melting and increased brine volume. Preliminary estimates indicate that extinction coefficients at 500 nm lie in the range 0.02 to 0.03 cm^{-1} , remaining relatively constant during ice growth but decreasing slightly during melting. Further experiments with different growth rates and water salinities will be carried out in the next few months.

Over the past few months we have developed a radiative model which allows us to apply the results of our field observations to the problem of the regional energy balance of the ice pack. The major difficulty was

to obtain an accurate description for thin ice in the range 2 to 40 cm. From our previous studies, we have a good understanding of the interaction of solar radiation with thick ice, but we do not yet have observational results for thin growing ice. Assuming, however, that the optical properties of young ice are similar to those of thicker blue ice, we can use a theoretical radiative transfer model to extend our results into the thin ice regime. This approach should give a good first approximation and was adopted for the present study. The thin ice model uses a modification of the Dunkle and Bevans theory which can include an ice layer with slowly varying optical properties together with an overlying layer of snow. The thickness of either layer can be as small as necessary. The model takes into account the effects of the snow-ice and ice-water interfaces, and it predicts the variation of albedo with ice thickness. These refinements are not usually included in the more common Beer's law approach used for thick ice, but they become quite significant when the ice is much thinner than 1 m. For example, 10 cm thick blue ice has a predicted albedo of approximately 0.12, about half the value for thick blue ice. Using the Dunkle-Bevans approach we also find that thin ice transmits substantially larger amounts of light than is predicted by the simple Beer's law. The calculations indicate, for example, that a 10 cm thick layer of young sea ice should transmit 50% more energy than the upper 10 cm of thick blue ice. About 20% of this is due to the change in albedo and the remainder is a result of the absence of a backscattering layer below the ice.

A series of calculations has been carried out for thin ice with up to 40 cm of snow cover to determine light absorption and transmission as a function of snow and ice thickness. The albedos and transmissivities have

been parameterized as simple exponential functions of ice thickness so that they can be incorporated conveniently and efficiently into our thermodynamic ice growth model. This model was then used to determine regional values of the radiative energy input to the ice and ocean (see Dynamic and Thermodynamic Modeling section). The results of the radiation calculations are being prepared for publication under the title "Radiative Energy Balance of Young Sea Ice". This paper will be submitted to the Journal of Glaciology in the near future.

In constructing a photometric model for sea ice or snow, the major difficulty involves specifying scattering functions for the various inhomogeneities which are present. Although scattering functions can be calculated accurately for a homogeneous distribution of spherical scattering centers, in actual ice the distribution of scattering centers is often inhomogeneous due to brine drainage and to variations in the freezing rate. In addition, only the vapor bubbles have spherical symmetry. Consequently, we are presently carrying out a series of laboratory experiments to determine empirically the scattering functions of different types of ice. The sensor currently in use is a filter photometer with a sensitivity range of more than 9 decades. This instrument is a simple modification of the ambient light photometer which was developed for field use, but with a greatly increased sensitivity range in order to measure the very weak scattering by bubble free ice. This case fixes the lower limit on scattering and thus provides a baseline against which to compare results from more complex ice types. We have examined several samples of bubble free ice and bubbly NaCl ice grown in the laboratory. The samples were about 1 cm thick so that they were optically thin in order to avoid complications due to multiple scattering

and reabsorption. The presently used sample geometry is a column about 20 cm tall with a square horizontal cross section. This configuration was chosen to allow the measurement of side scattering where the phase function has a minimum while avoiding "lensing" and internal reflection problems inherent with cylindrical samples.

Preliminary reductions for the bubble free ice show that the scattering is mainly due to specular reflection at the surfaces. Internal scattering at a particular angle is on the order of 10^{-6} of the incident intensity (I_0) indicating a volume scattering efficiency on the order of 2×10^{-5} at 400 nm. At longer wavelengths the efficiency is somewhat less. The angular scattering distribution (the phase function) is nearly symmetric about an axis perpendicular to the incident beam which suggests that the dominant process is Rayleigh scattering by very small inhomogeneities in the ice.

For the NaCl ice samples the scattering is much more efficient (on the order of 30 to 60% of I_0), and the phase function is strongly forward peaked, more characteristic of large scale inhomogeneities such as vapor bubbles and brine pockets. Vapor bubbles alone, however, do not adequately explain the observed phase function because of the strong backscattering component. Crystal boundaries and brine inclusions must, therefore, provide a significant contribution to the scattering. Further observations with bubbly fresh ice and bubble free saline ice will be obtained to determine the relative importance of the different types of scattering centers.

For all cases tested to date the phase functions were found to be nearly independent of wavelength over the entire range tested (400 to 800 nm). This indicates that the dominant scattering processes involve inhomogeneities which are much larger than the wavelength of the light and that the wavelength

dependence is determined by the refractive index of pure ice which is nearly independent of wavelength from 400 to 800 nm. This confirms our earlier assumption that complex Mie theory is not necessary to compute the scattering functions at wavelengths where light penetrates more than a few centimeters into sea ice.

In late April and early May we spent some time consulting on the instrumentation and design of an experiment to investigate the optical properties of a free floating ice floe in the Chuckchi and southwestern Beaufort Seas. The experiment, carried out under the direction of Mr. Tom Kozo and Dr. R. Francois of the Applied Physics Laboratory at the University of Washington, was designed to monitor changes throughout the spring and early summer in the optical transmission properties of the ice floe at four visible wavelengths using a set of filter photometers. Corresponding albedos were measured to allow the determination of extinction coefficients for the ice. In addition, total incident short-wave radiation was monitored with an irradiance pyrhelimeter. By combining results at the four wavelengths with our knowledge of the relative spectral dependence of the albedo and extinction coefficients, we should be able to determine the spectral variations in the optical properties over the entire visible wavelength range.

The data have been retrieved and are currently in the preliminary reduction stage. We hope to be able to use these results to obtain a record of the evolution of the optical properties of cold ice as it gradually warms up in response to increasing brine volume and surface ablation. This in turn would allow us to calculate quite accurately the amount of solar energy absorbed by seasonal sea ice during the months of

May through July when the incident radiation field is most intense. In addition, this investigation would also provide us with an independent comparison with the Prudhoe Bay experiment carried out last March.

Design of the scanning infrared photometer has begun. The instrument will be capable of scanning the visible and infrared spectrum from 0.4 to 2.5 microns using a circular variable interference filter together with a set of twelve individual interference filters. The spectral resolving power (wavelength \div bandpass) will range from 100 to about 250. The radiation detectors will be a PbS photoconductor for the infrared beyond 1 micron in conjunction with a blue enhanced silicon photodiode for visible and near infrared wavelengths. Initial estimates indicate that this system will detect spectral irradiances of less than $1 \mu\text{W}/\text{cm}^2/\text{nm}$ at all wavelengths - more than two orders of magnitude below the solar irradiance expected at 2.5μ on clear days in the Arctic.

The entire photometer as presently envisioned will be contained in an aluminum cylinder 25 cm in diameter and 30 cm tall weighing less than 35 lbs. The parts are presently being ordered and construction should begin early next year.

LABORATORY STUDIES OF SEA ICE

During the past year the article by S. Martin and P. Kauffman entitled "An Experimental and Theoretical Study of the Turbulent and Laminar Convection Generated under a Horizontal Ice Sheet Floating on Warm Salty Water" appeared in the Journal of Physical Oceanography. Second, Mr. Terren Niedrauer completed his laboratory study of the brine drainage of young sea ice and wrote up his results in both a Master's thesis and a scientific report entitled "Brine Drainage and Convection in Young Sea Ice". Third, Mr. Edward Josberger wrote up a summary of his work to date on the melting of ice walls in sea water as a paper presented at The First International Conference on Iceberg Utilization, held in Ames, Iowa, 2-6 October 1977. His paper will also appear in the proceedings of the conference.

Mr. Niedrauer's research documents the different kinds of convection which occur inside of sea ice. Namely, within the skeleton layer, convection takes the form of cusp-like features which form between the crystal platelets, and consist of small jet-like regions of downflow, and 10 mm wide regions of upflow. These features cause observable temperature perturbations within the ice. Second, within the brine channels, which form in the ice above the skeleton layer, Mr. Niedrauer shows that most of the brine which flows out of the young ice comes from sea water, which flows up into the ice, cools, then flows out. Additional brine outflow comes from the squeezing-off of small intercrystalline channels into brine pockets, the contents of which feed into brine channels. Niedrauer documents this process photographically in his report. The results of this research are presently being written up as a paper for the Journal

of Geophysical Research. This work concludes Mr. Niedrauer's association with the contract; on July 15 he began work with NOAA in Miami, Florida.

Mr. Josberger's research consists of a laboratory study of the turbulent boundary layer adjacent to a fresh ice wall suspended in warm salty water. Also, in cooperation with the U. S. Coast Guard, he designed and carried out a field study during June 1977 on the ablation of an iceberg in the North Atlantic. In other work S. Martin and P. Kauffman are carrying out a study of the heat transfer and wave damping processes within a field of grease ice, and have developed a physical model for how grease ice grows. We next discuss each of these topics in detail.

1.) The ablation of ice in the ocean. Using the laboratory apparatus which was built last year, Mr. Josberger has studied the case wherein the flow adjacent to a vertical ice wall becomes turbulent. The solution of this problem will lead to an understanding of the thickness and distribution of the low salinity boundary layers which form around icebergs and deep pressure ridges in warm salty water, to the prediction of ice ablation rates from the far field temperature and salinity, and to estimates of iceberg-driven upwelling caused by the presence of icebergs and ice shelves.

In the laboratory experiments, Josberger looks at the flow properties by several methods. First, thermistors are frozen into the ice, then as these melt out, he obtains the temperature immediately adjacent to the ice wall as a function of height. Second, small glass rods are frozen into the vertical walls of the ice such that they melt out perpendicular to the ice front. By using a precision transit to determine the distance

between the ends of the rods and the ice front, he measures melt rates as a function of height above the bottom of the ice. Third, by adding dye tracers to the fluid, he determines the boundary layer thickness and obtains estimates of the velocity profiles. The combination of these observations shows that once the boundary layer becomes turbulent, the ice wall temperature remains constant in the vertical, and the melt rate becomes nearly constant as well.

Using these experimental results, Mr. Josberger is developing an analytical model of the flow, based on the following assumptions: (i) constant wall temperature and salinity, (ii) the existence of a molecular sub-layer beneath the turbulent layer in which the salt, heat, and momentum each diffuse at their respective molecular diffusivities, and (iii) a turbulent outer layer with a constant eddy diffusivity which diffuses heat, salt and momentum at the same rate. These assumptions are analogous to those used in models of the planetary boundary layer.

The solutions in the turbulent and laminar regions are then matched by requiring that the velocity, temperature, and salinity fields and the fluxes of these quantities be continuous across the matching region. We then evaluate the unknown theoretical parameters such as the eddy diffusivity from the experimental data.

When the model is complete, it will be possible to predict ablation rates, wall conditions, turbulent entrainment velocities, eddy transfer coefficients, and vertical transport of heat, salt, and water from the far-field conditions. If the experimental results can be extrapolated to oceanic conditions, iceberg and pressure ridge lifetimes can be predicted along with the effect of the ablation on the adjacent water

column. Also, the importance of upwelling next to melting icebergs as a source of nutrients to the surface layer can be assessed. This work should be completed by 30 May 1978.

Mr. Josberger also participated in a U. S. Coast Guard International Ice Patrol cruise from 6-20 June 1977, aboard the USCG Evergreen in the Labrador Sea. On this cruise, Mr. Josberger looked at the effect of iceberg ablation on the water column, and attempted to determine the temperature at the ice-water interface.

The water column measurements consisted of 2 CTD sections, with six casts per section at distances of 2500 m, 1000 m, 200 m, 100 m, and 25 m from an iceberg which was approximately 100 m deep. The final cast of the section was made at a distance of 2 to 4 meters from the iceberg. The casts showed that within 200 m of the iceberg, the water temperatures were as much as 3°C colder in the upper 25 m than the temperatures at equivalent depths further away. Salinity variations were only of the order of 1 ‰ and occurred in the closest station. Probably as a result of the ablation boundary layers, the water at depth around the iceberg was cooled.

Mr. Josberger also took many photographs of the iceberg, and documented recent calving and roll-over. These observations combined with information provided by the crew suggest that calving is probably the main ablation mechanism, although the ablation boundary layers are important in that they affect the properties of the deeper water. Finally, Josberger attempted to measure the ice-water interfacial temperature of the iceberg, using a carefully-built thermistor probe mounted on a long rod. Because of the wave-induced ship motion, this technique did not work; however, inside the

pack ice, he was able to measure the interfacial temperatures of several bergy-bits. The results are described in greater detail in the paper submitted to the Iceberg Conference.

2.) Ice Growth in a Wave Field. Using our wave tank, S. Martin and P. Kauffman have recently carried out two series of experiments on ice growth in a wave field. The first was a joint project with T. C. Grenfell and D. Perovich on the optical properties of grease and pancake ice grown in both salt and fresh water. In these experiments, we grew ice, then stopped the paddle at intervals of about 1 hour to measure the reflection and transmission coefficients of the different kinds of ice. This data is in the process of analysis.

Second, we are presently doing a series of experiments on the heat transfer and wave attenuation properties of grease ice. To do these experiments, we have replaced our old drive motor with a more powerful one so that we now generate waves with amplitudes of 0.1-0.3 m. Using this motor in our existing 2 m long wavetank, we have obtained sufficient data to develop a physical theory for the interaction between grease ice growth and wave damping.

Our theory comes from the following observations. Using our apparatus, we grow grease ice layers up to 0.2 m in thickness in a strongly-damped wave field. At the grease ice surface, we observe from thermistor measurements that the temperature is only 0.1-0.01 degrees colder than the deep temperature, even when air at a temperature of -20°C blows across the surface. Also, to follow the velocity field within the grease ice, we use small plastic particles which are approximately the size and density of

the individual frazil ice crystals. We distribute these particles in the tank at different locations and depths in the grease ice, then follow their trajectories by taking motion pictures through the transparent side walls of the tank.

From observations such as these, we obtain a physical picture of how grease ice grows for the case of strong wave damping. In the Arctic, this case occurs both in leads and at the pack ice edge. For the case of leads over which cold air blows, the leads consist of an up-wind region of open water with wind waves on it, then a transition region of strong wave damping by the grease ice, and finally a third region of an unmoving layer of grease ice. As time progresses, the grease ice layer spreads across the lead. For the pack ice edge case, we have seen aerial photographs from the Bering Sea of strong damping of incident wind waves in grease ice.

In our laboratory tank the strong damping case also divides into three regions. First, adjacent to the paddle, the water is ice free; then the grease ice forms an elongated wedge with its thickness increasing as the wave amplitude decreases. Third, where the wave amplitude is zero, the grease ice has a uniform thickness.

The velocity field derived from observations of the particle motions within the grease ice wedge behaves as follows. At the grease ice surface, we observe superimposed on the wave motion strong horizontal velocities streaming away from the paddle, where the magnitude of the velocity decreases as the wave amplitude decreases. From conservation of mass, the decrease in the streaming velocity yields a downward vertical velocity, which we also observe. Finally, to close the circulation, there is both a weak countercurrent in the lower part of the grease ice and a turbulent

upwelling region at the point where the waves first encounter the grease ice.

The combination of our observations of the warm surface temperature, which means little heat is transferred through the ice by conduction, and the observed velocity field suggests that the grease ice grows by forced convection, in that the ice crystals form at the surface and then are driven below the surface by the downward velocity. Theoretical work shows that the strong wave damping, which is caused by the grease ice, drives the velocity field which makes the grease ice grow, for without the induced circulation, the ice would simply form at the surface and remain there. Therefore, the wave damping and the grease ice growth form a feedback loop, where grease ice causes damping, which yields a faster grease ice growth, which yields more damping, and so-forth.

In summary, the grease ice causes wave damping which generates an efficient form of heat transfer, wherein ice always forms at the sea surface and then is driven into the interior. This increases the wave damping and thereby causes more grease ice growth. This process continues until the waves are damped out, leaving a thick layer of grease ice behind. This efficient feedback mechanism may be one reason for the observed rapid rate of wave decay at the edge of the pack ice. These results also indicate that heat input to the atmospheric boundary layer will be larger if waves are present than if the water is still.

Finally, in the real ocean, the waves propagate into the grease ice with a range of frequencies. Our observations show that the long waves which propagate through the grease ice without much attenuation do not cause the circulation pattern described for the heavily damped waves.

For long waves, the grease ice surface freezes, and the convergent-divergent motion induced by the long waves divides the surface into pancakes. This transition from grease ice to pancakes as a function of wave frequency, amplitude, and grease ice thickness will hopefully also be resolved by our current research.

REPORTS PUBLISHED AND IN PRESS

1. Hall, R. T., G. A. Maykut, and D. A. Rothrock, Sea ice modeling: its testing with LANDSAT and potential use in FGGE. Proceedings of the Symposium on Meteorological Observations from Space: The Contribution to the First GARP Global Experiment, J. I. Kelly and S. Ruttenberg (editors), 104-109, National Center for Atmospheric Research, Boulder, Colorado, 1976.

The growth and movement of sea ice in the polar oceans is complicated by dynamic and thermodynamic interactions. Large-scale models of the ice cover are being developed, but testing of these models has proven to be difficult because of a lack of suitable data. Satellite imagery is now being utilized to test certain parts of these models. Analysis of LANDSAT data suggests that the ice pack behaves as a continuum on length scales greater than 100 km, which indicates that the large-scale properties of the ice cover should be defined on similar scales. Measurements of strain from sequential LANDSAT images have been used to test proposed stress-strain relationships for the ice, and to check certain assumptions related to the mechanical redistribution of ice thickness. Satellite photographs have also been used to compare observed amounts of thin ice and open water with predictions made by theoretical models. Methods by which remote sensing data can be used to estimate regional heat and mass balances over the polar oceans during FGGE are described.

2. Rigby, F. A. and A. M. Hanson, The evolution of a large arctic pressure ridge. AIDJEX Bulletin, 34, 43-71, 1976.

Extensive mass balance and structural observations were carried out on a large (10-12 m) pressure ridge during the summer of 1975 at the AIDJEX main camp. The authors drilled a large number of holes through the ridge and, by redrilling previously drilled areas and by monitoring thickness gauges, were able to examine ridge development over a period of several months. Some vertical temperature profiles were taken.

The mass loss from the ridge bottom proved to be several times that from the undeformed ice, apparently resulting as much from mechanical erosion as from melting. The lateral extent of the keel was substantially greater than that of the sail and the pattern of isostatic compensation of the ridge changed with time.

3. Martin, S. and P. Kauffman, An experimental and theoretical study of the turbulent convection generated under a horizontal ice sheet floating on warm salty water. Journal of Physical Oceanography, 7, 282-293, 1977.

In an experimental and theoretical study we model a phenomenon which occurs in the summer polar oceans; namely, the melting of flat sheets of either glacial ice or desalinated sea ice which float over sea water held at a temperature above freezing. Our laboratory results show when the solution salinity is such that the temperature of maximum density is below the freezing temperature, or for sea water salinities greater than 25 ‰, the heat transfer to the ice takes place in three regions. First, just beneath the ice, there is a boundary layer across which the salinity increases almost to its far-field value and the temperature increases linearly. Below this, there is an unstable convective boundary layer, which appears to be part double-diffusive, part pure thermal convection. Finally, there is a region of deep thermal convection. From comparison of a one-dimensional theoretical model of the heat transfer with the laboratory study, we find that the ice melts about twice as fast for this convective case as for a purely diffusive heat transfer model.

4. Rigby, F. A., Pressure ridge generated internal wave wakes at the base of the mixed layer in the Arctic Ocean. [M. S. Thesis, Geophysics Department, University of Washington, Seattle, Washington, 1977.]

The upper Arctic Ocean frequently displays strong density stratifications capable of propagating a variety of internal waves. When the ice moves relative to the ocean below it, large scale irregularities on the bottom of the ice, such as the keels of pressure ridges, might be expected to generate wakes of internal waves. In the summer of 1975 measurements were taken at the Arctic Ice Dynamics Joint Experiment main camp in an attempt to determine what effect the wave drag associated with these

wakes might have on the dynamics of the sea ice. In late July and August a number of waves were observed. These waves appeared to behave like interfacial waves on the sharp density change that occurred about 20 meters below the ice. The waves were the result of wake generation by the ice with the observed wave being a composite of the wakes of many obstacles. The amplitude of such a composite would be limited by the rate at which energy is dissipated from the waves. Resonant triad interactions involving the waves in the wakes is suggested as a possible dissipation mechanism. On the basis of this composite wake model the drag is estimated and found to be on the order of 5 to 25 percent of the total drag between ice and water for strong (22 cm/sec) currents and for ice conditions similar to those around the AIDJEX camp.

5. Niedrauer, T. M., Brine Drainage and Convection in Young Sea Ice.

Scientific Report No. 15, 67 p., ONR Contract N00014-76-C-0234,
University of Washington, Seattle, Washington, 1977.

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 skeleton layer and in the brine channels by the flow of dyed brine. Flow in the skeleton layer was cusp-like in appearance, consisting of narrow downflow regions separated by broad upflow regions. Several brine channels were 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 2%. 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. We also observed the formation of brine pockets from brine tubes.

6. Maykut, G. A., Estimates of the regional heat and mass balance of the ice cover in the Central Arctic. Sea Ice Processes and Models: I, Division of Marine Resources, University of Washington, Seattle, Washington, 65-74, 1977.

Previous estimates of ice production and heat exchange at the surface of the Arctic Ocean have ignored the large turbulent heat fluxes and rates of ice growth which occur in areas of thin ice and open water. To evaluate the seriousness of this omission, areally averaged totals for the fluxes of sensible and latent heat, ice production, solar heating in the upper ocean, and salt rejection from the growing ice were determined, taking into account the effects of thin ice and open water. These values were then compared with those which would be obtained if the ice pack were assumed to be a uniform 3 m cover. Amounts of thin ice and open water were calculated from the ice thickness distribution model developed by Thorndike *et al.* [1975], using as input climatological heat balance data and a two-year strain history derived from the movements of drifting stations ARLIS II, T-3, and NP-10. The results indicated that regional rates of ice production and salt rejection during the winter were 2-3 times larger than previously assumed. On an annual basis, the net ice production in the perennial ice was close to zero, whereas the net ice production in areas of young ice and open water was found to be equivalent to a layer roughly 70 cm in thickness covering the entire region. Turbulent heat losses for the year were found to be an order of magnitude larger when leads and thin ice were taken into account. Although the latent heat flux accounted for some of this difference, most of the change occurred in the sensible heat flux, particularly during the spring and fall. The amount of short-wave radiation absorbed below the 3 m level in the ocean was comparable with estimates of the amount of heat annually supplied to the mixed layer by the deeper Atlantic layer. Lateral melting due to solar energy absorption in leads was sufficient to increase the amount of open water by about 3%.

7. Grenfell, T. C. and G. A. Maykut, The optical properties of ice and snow in the Arctic Basin. Journal of Glaciology, 80 (in press).
8. Maykut, G. A., Energy exchange over young sea ice in the Central Arctic. Journal of Geophysical Research (submitted).

9. Josberger, Edward, A laboratory and field study of iceberg deterioration.

(Paper presented at the First International Conference on Iceberg Utilization, Ames, Iowa, 2-6 October 1977, and to appear in the proceedings from that conference.)

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