

UNIVERSITY OF WASHINGTON

DIVISION OF MARINE RESOURCES

DEPARTMENT OF
ATMOSPHERIC SCIENCES

DEPARTMENT OF
OCEANOGRAPHY

A I D J E X

ARCTIC ICE DYNAMICS JOINT EXPERIMENT

PART 1: SCIENTIFIC PLAN

MAY 1970

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Arctic Ice Dynamics Joint Experiment

Part I: Scientific Plan (Second Draft)

*The attempt and not the deed,
confounds us.*

Macbeth, II, ii.12

May 1970

PREFACE

The concept of AIDJEX, as it had evolved in numerous discussions and studies since IGY by a wide range of investigators, was advanced in a Final Report on ONR Contract N00014-67-A-0103-0004, dated 7 July 1969 (by Norbert Untersteiner and Kenneth L. Hunkins). Through the offices of the Arctic Institute of North America, and funded by the Office of Naval Research (Arctic Program), a meeting of experts in the field was convened on 7 November 1969 to discuss and evaluate this report. At this meeting the general idea of AIDJEX, its timeliness, and the distribution of emphases was endorsed by that group. J. O. Fletcher, upon request of the group, accepted the task of co-ordinating the production of an expanded version of the AIDJEX plan that would contain not only the numerous useful suggestions made by the group but also a survey of some preliminary studies in the context of AIDJEX, and an outline of the operational and logistic requirements for the conduct of the experiment. The National Research Council, through AINA, made available a modest but welcome fund to facilitate this task.

It soon became apparent that the deadline we had set for the production of the second draft of the AIDJEX Plan, May 1970, could not possibly be met if Operations and Logistics were to be included. Therefore, we decided to produce this second draft in two parts; Part I, Scientific Plan, and Part II, Operations, Management, and Logistics. The first part is presented herewith.

The undersigned owe particular gratitude to J. O. Fletcher (Rand) for his advice and numerous contributions at all stages of progress. Substantial written contributions were made by L. Coachman (University of Washington) toward expanding and modifying the original oceanographic section, and by W. Wittmann and colleagues (Navoceano) on various topics in remote sensing and ice morphology. In addition, we gratefully acknowledge the help and counsel of W. Campbell (USGS), J. D. Smith (University of Washington), H. Solomon (Rand), R. J. Evans (University of Washington), W. F. Weeks (CRREL), and many others.

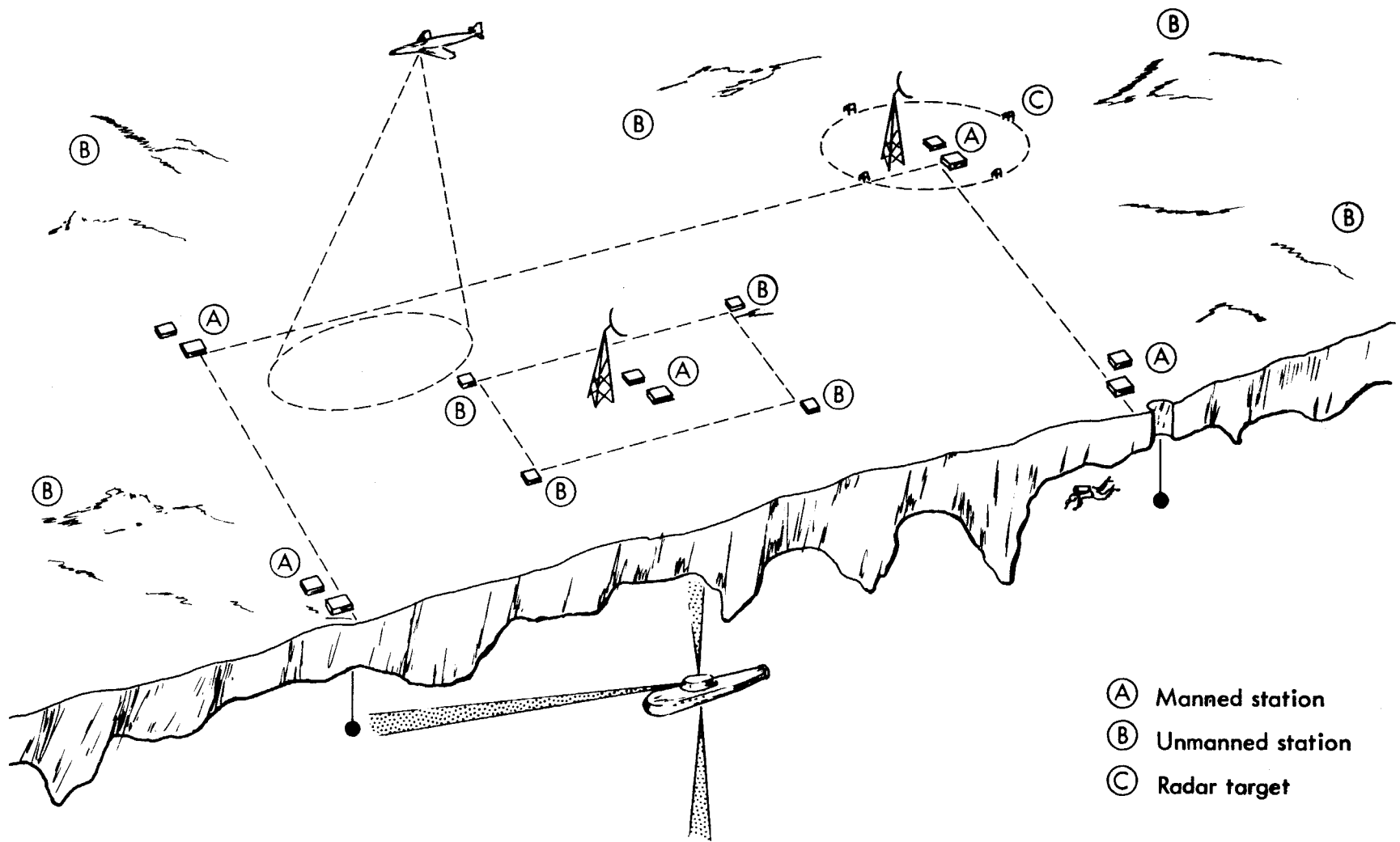
If AIDJEX is to be launched successfully, it must be a multi-agency, multi-disciplinary enterprise, transcending parochial interest. The generous way in which the above contributors have given of their time and expertise promises that this will be the spirit of AIDJEX.

Seattle, 4 May 1970

N. Untersteiner
G. A. Maykut
A. S. Thorndike

ABSTRACT

An understanding of the large-scale response of sea ice to its environment is needed for solving many important theoretical and practical problems, ranging from the interaction between ice cover and global circulation to the passage of ships in ice-covered seas. Observations from single stations are intrinsically inadequate for this purpose. It is therefore proposed to conduct measurements from an array of drifting stations in the Arctic Ocean. The proposed array consists of a central manned station surrounded by four unmanned stations forming a square 20 km on a side, and four manned stations forming a square 100 km on a side. Additional unmanned stations will be deployed outside the main array. A logistic headquarters based on a secure location (such as a nearby ice island), is required. Position, atmospheric pressure, and wind speed will be determined regularly at all stations. In addition, observations at the manned stations will include meteorological conditions, wind stress, water stress, and ice conditions. To determine the areas of open water, pressure ridges, melt ponds, and other features, surface observations will be supplemented by regular airborne surveys of the test area by means of photography, side-looking radar, laser profiler, and infrared imagery. Under-ice topography must be obtained by submarine transits. These data should yield new information on the rheology of sea ice, the relationship of the heat balance to large-scale ice strain, and a variety of current and wave phenomena in the oceanic boundary layer. Logistical support must include medium or light aircraft for transport between the Base Station and satellite stations, and helicopters, particularly for summer flying and rescue. The manned stations will be occupied for extended periods during two years, with several weeks of intensified studies during selected periods in each season when large seasonal fluctuations in the ice and environment require synchronized observations at all stations. A pilot study is proposed to begin March 1971 with the full-scale field project to follow in 1972 and 1973.



AIDJEX Configuration

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Part II

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 Special operational considerations

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 Station facilities

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Arrangement

 Pilot experiments

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 Allocation of responsibilities

PROGRAM OBJECTIVES

Two thirds of the present terrestrial ice cover consists of sea ice. The belt of sea ice surrounding the Antarctic continent may cover as much as 8% of the hemisphere in winter but shrinks to a narrow rim at the end of the austral summer. The ice covering the Arctic Ocean is largely perennial and undergoes much smaller variations in extent during the course of a year.

Unlike the massive continental ice caps of Antarctica and Greenland, whose variations occur on a time-scale of millennia, sea ice is a thin veneer of frozen sea water whose extent responds with great sensitivity to environmental changes on a time-scale of months to years. The southern boundary of sea ice in the North Atlantic Ocean has shifted hundreds of miles in historic times and, on the whole, it appears that sea ice cover is one of the most important climate-related variables of the earth's surface.

The role of sea ice in modifying the global circulations of the atmosphere and the oceans is not quantitatively understood. An ice cover greatly reduces the transfer of momentum from air to water and suppresses drift currents and wind mixing. The ice cover effectively reduces heat exchange between the atmosphere and the ocean by reflecting solar radiation during summer and by suppressing heat loss of the ocean to the atmosphere during winter. Therefore, it is evident that the presence or absence of sea ice critically affects the dynamic and thermodynamic interaction of atmosphere and ocean not only in the polar regions but probably on a much larger, and perhaps global, scale.

Large sheets of sea ice are in almost continual motion that causes fracturing, ridging and the formation of regions of open water. Neither the physical mechanisms controlling these processes nor their role in maintaining the overall size of the ice cover is adequately understood. Experience from single drifting stations indicates that the complex interactions of the sea-ice-air system can best be analyzed by means of a network of simultaneously operated stations.

Answers to the specific questions discussed in detail in the subsequent sections would produce numerous basic and practical benefits:

- 1) They would provide the parameters relating air and water stresses to ice strain, necessary for further development

of dynamic models of large-scale sea ice motion. Since forecasts of future ice conditions are based on forecasts of wind fields and their influence on ice movement, clarification of these relationships is fundamental to the improvement of such forecasts.

- 2) They would provide much of the information needed to evaluate the participation of sea ice in air-sea interaction and climatic change. An understanding of this interaction is necessary to assess the purported instability of the ice cover on the Arctic Ocean.
- 3) They would provide information on the general morphology of sea ice, its relation to past strain, and the mechanisms producing the morphological features.
- 4) They would enable us to relate ice strain and particularly the amount of open water to the heat balance and production of new ice.
- 5) They would provide environmental data useful in understanding primary production and other biological phenomena in the ocean under conditions different from today's, and in evaluating the possibility of damage to the arctic environment from expanded economic activity in the area.
- 6) They would greatly enhance our knowledge of the structure and dynamic behavior of arctic water masses and the attendant features of sound propagation.
- 7) They would provide crucial information on the feasibility and desirability of large-scale artificial removal of sea ice.

PROBLEMS TO BE INVESTIGATED

Background

It has long been known from observations made at drifting stations that the ice deformation visible to the observer at the surface (shearing, ridging, opening of leads) often has no obvious connection to the wind. Dramatic shear deformations lasting for more than a day were observed at IGY-Station Alpha in August 1958 during a period of almost perfect calm.

The stress caused by friction of wind on the upper surface of the ice is only one of several forces which drive the pack ice. The complete list of forces includes: wind stress, water stress, coriolis force, pressure gradient force due to tilting of the sea surface, and internal forces arising from the constitutive properties of the ice and the mutual interactions of ice floes.

Observations of water stress have been reported by Untersteiner and Badgley (1965; see also Suzuki, 1967), who measured current profiles to a depth of four meters. These results were interpreted in terms of Prandtl boundary layer theory. Hunkins (1966) measured current velocities to a depth of 32 meters which he interpreted in terms of Ekman layer theory, with a thin Prandtl-type layer immediately below the ice. This Prandtl-type layer gave a roughness length in close agreement with Untersteiner and Badgley's results. Soviet workers have measured Reynolds stresses beneath an ice floe using a hot wire instrument (Kolesnikov, et al., 1965). Their values of tangential stress bracket the value found by Hunkins with a profile technique.

Reed and Campbell (1962) analyzed periods of unaccelerated drift of Station Alpha and generally corroborated Shuleikin's (1938) conclusion that the ice drifts about 45° to the right of the surface wind direction at about $1/50$ of the wind speed. However, individual data points show a very large degree of scatter, partially attributable to internal stresses in the ice. These stresses arise from the internal transmission of wind and water stresses through the ice. Thus, the ice movement observed at a given location is dependent not only on the stresses applied at that point,

but also on the stresses applied to the surrounding areas.

Campbell (1965) developed a numerical model of the mean annual pattern of ice drift in the Arctic Ocean, including the effects of air and water stresses, coriolis force, gradient currents, and internal ice stress. The latter was modeled by assuming the ice to be a Newtonian liquid of extremely high horizontal eddy viscosity. These calculations were successful in that they resulted in realistic average drift velocities and a correct position of the ice gyre in the Canadian Basin. However, the rate of convergence in the gyre was unrealistically high (50% per year). The three major deficiencies of the model were identified by Campbell:

- a) the necessarily unrealistic assumption about internal ice stress,
- b) uncertainty about the external stresses, and
- c) limitations of a steady-state solution.

Even though it is feasible to obtain time-dependent solutions of Campbell's model with its present parameterizations, such solutions would be hardly meaningful until a) and b) are resolved.

In addition to being moved about by mechanical forces, sea ice undergoes changes in thickness due to thermodynamic processes. A recent study (Maykut and Untersteiner, 1969) has clearly defined the effects of various components of the energy budget on ice thickness. Excluding dynamic effects, the ice would achieve an equilibrium thickness determined only by the heat exchange between the ocean, ice, and atmosphere. Figure 1 shows in nomographic form how the ice, under steady climatic conditions and no dynamic motions, would thicken or thin, depending on the initial deviation from the equilibrium thickness.

Basic Questions to be Answered

Natural sea ice in the Arctic Ocean varies from centimeters to tens of meters in thickness. Individual floes range from meters to kilometers in diameter, and are separated by open leads or pressure ridges. This heterogeneous layer interacts thermodynamically, as well as dynamically, with the atmosphere and ocean. A study of the dynamics of sea ice requires simultaneous observations of stress and strain over a large area. Because of the difficulties involved in such an observational program, most research-

ers have emphasized thermodynamic problems and neglected the dynamics of the system.

However, thermodynamic processes alone cannot describe the heat exchange between the atmosphere and ocean, the frequency distribution of ice thickness, or the mass budget of the ice pack. The principal heat exchange occurs between the ocean and atmosphere, with the ice regulating the rate of exchange. By altering the distribution of leads and pressure ridges, ice movements may significantly influence the heat budget. Badgley (1966) found that the heat loss from small areas of open water is at least two orders of magnitude greater than that from old ice. If, as some studies indicate (Wittmann and Schule, 1966), the percent of open water is 10% rather than the commonly believed 1%, then the heat exchange between the ocean and atmosphere occurs principally through leads.

Furthermore, the observed frequency distribution of ice thickness cannot be explained thermodynamically. A strictly thermodynamic treatment would predict that all the ice would achieve equilibrium thickness within a period of a few decades (Figure 1). In reality, a certain frequency distribution of ice thickness exists (Figure 2). This distribution must be maintained by the dynamic forces counteracting the equalizing effect of the thermodynamics. If the dynamic forces were removed, the ice thickness would attain, after two years, a new frequency distribution given by the dashed curve in Figure 2.

Ice deformation also affects the mass budget. For instance, the formation of leads creates sources of rapid ice production during the winter. Thus, the total volume of ice in an area changes as the difference of the thermodynamic growth and the dynamic divergence of the velocity field. This may be expressed formally:

$$\begin{array}{l} \text{rate of volume increase} \\ \text{per unit area moving} \\ \text{with the ice} \end{array} = \sum_{i=0}^{\infty} a_i \left[\left(\frac{\partial h_i}{\partial t} \right)_Q - h_i \nabla \cdot \vec{V} \right] \quad (1)$$

where, for convenience, the ice assumes only discrete thicknesses h_i . \vec{V} is the (horizontal) ice velocity and $(\partial h_i / \partial t)_Q$ expresses the thickness change due to thermodynamic processes. If the thickness and velocity fields are known, this equation can be used to compute the ice production.

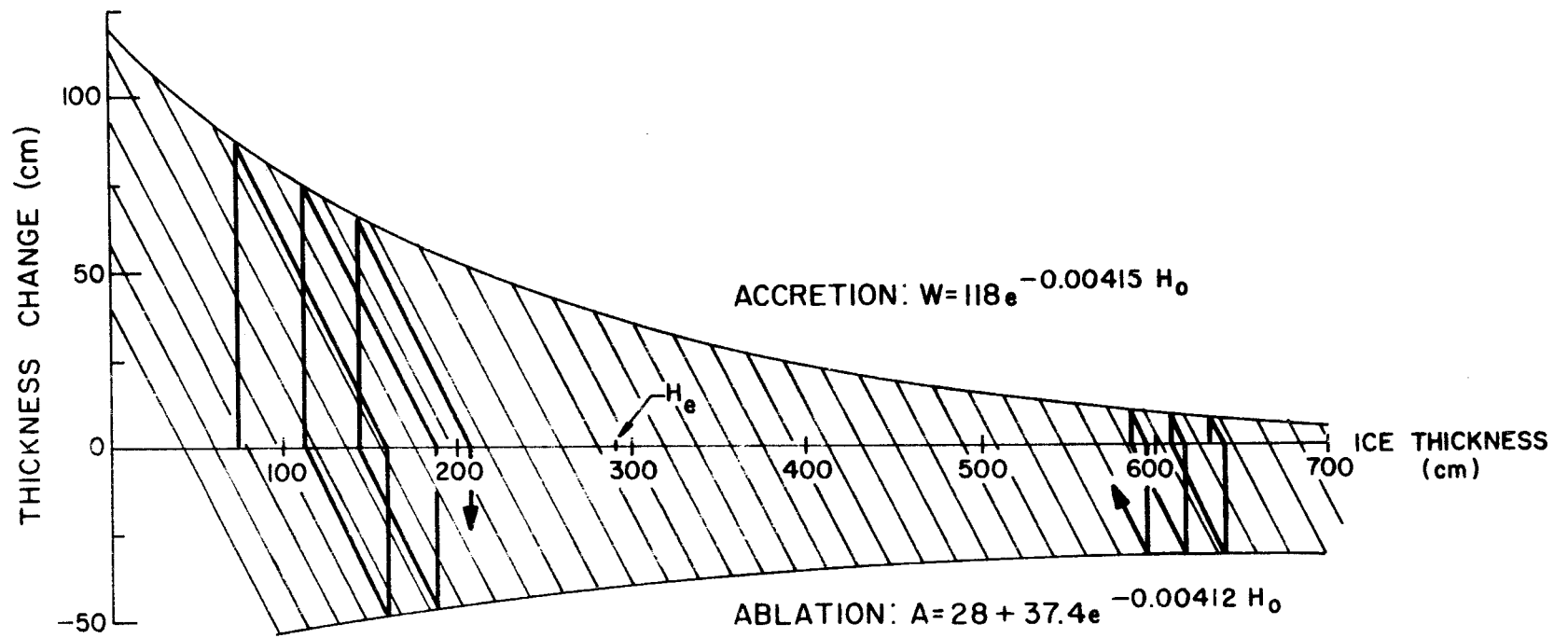


Figure 1. Nomogram showing the theoretical dependence of accretion (September-May) and ablation (June-August) on ice thickness under present climatic conditions. Starting from any point on the x-axis (ice thickness) and following the lines as shown by the examples (heavy lines), it is seen how the ice approaches the equilibrium thickness, H_e (after Untersteiner, 1962; Untersteiner and Maykut, 1969).

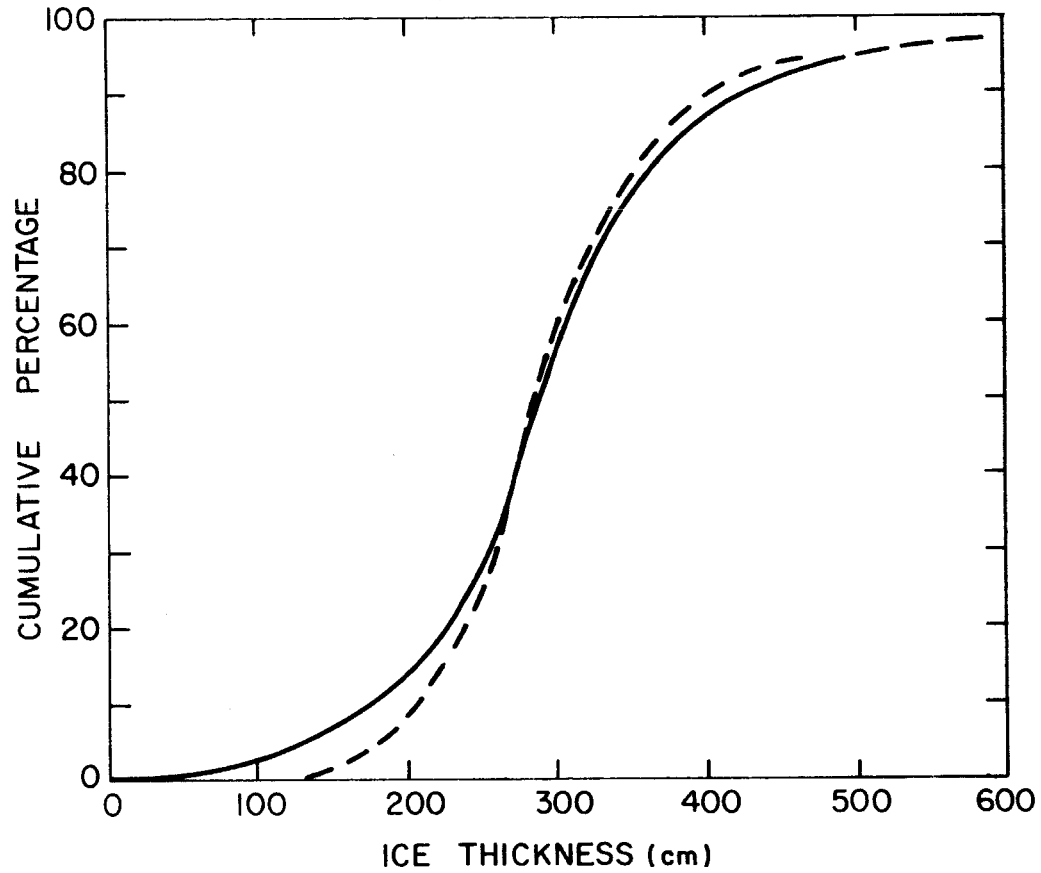


Figure 2. Solid line: Cumulative frequency distribution of ice thickness in the Central Arctic (estimated after Wittman and Schule, 1966)
Dashed line: Ice thickness frequency distribution after two years, under the assumption that no ice deformation is taking place. (After a large number of years only ice of equilibrium thickness, 290 cm, would exist.)

To describe (and hence predict) this system in quantitative terms it would be necessary to know the initial states of all three media, as well as the physical laws describing their behavior and interaction. Neither of these requirements can be met today. This difficulty is common to studies of geophysical systems, but it has been demonstrated that considerable insight can be gained by limiting the analyses to phenomena of certain scales. Accordingly, AIDJEX has been designed to answer three basic questions:

1. How is large-scale ice deformation related to the external stress fields?

Sea ice as a substance has been thoroughly investigated in the laboratory, but practically no quantitative knowledge exists on the large-scale physical properties of sea ice as a geophysical phenomenon. It seems impossible at present to devise a theoretical method by which both the inhomogeneous nature of the ice and the dependence of its strength on strain history can be adequately represented. The only acceptable alternative is to acquire an empirical understanding of the stress-strain relationship for sea ice. Such an understanding would be essential in formulating and testing various models to describe sea ice dynamics.

Average, large-scale, horizontal divergences in the atmosphere range from 10^{-6} to 10^{-5} sec^{-1} . Dunbar and Wittmann (1963) published a preliminary analysis of the positions of four drifting stations and found the ice divergence to be on the order of 10^{-7} sec^{-1} . This is roughly in keeping with Shuleikin's rule of thumb that the ice moves at about one-fiftieth of the surface wind velocity. But this fact alone reveals little about the actual stress-strain relationship for the ice. Due to its rigidity, the ice responds not only to the local external stress, but also to the regional stress field. The internal stress at a point arises from the propagation of the regional stress field through the ice and, consequently, is influenced by the distribution of leads and ice topography. Ice movement, internal stress, and external stress must all be known in order to determine an empirical stress-strain relationship. The force (\vec{I}) due to the internal stress is the only term in the equation relating ice movement to applied forces which cannot be measured directly, and it must therefore be found as a residual. This equation expresses Newton's Second Law in the form:

$$\rho h \frac{d\vec{V}}{dt} = \vec{\tau}_A + \vec{\tau}_W + \vec{C} + \vec{G} + \vec{I}, \quad (2)$$

where ρ is the ice density, h is ice thickness, and \vec{V} is the two-dimensional velocity vector. The measurable forces acting on the ice are forces arising from wind stress ($\vec{\tau}_A$) and water stress ($\vec{\tau}_W$), the coriolis force (\vec{C}), and the pressure gradient force (\vec{G}). The latter two forces involve no conceptual difficulties, since the coriolis force depends only on the velocity of the ice and on the latitude, and the pressure gradient force, in this context, is simply the component of gravity parallel to the slope of the sea surface. However, treatment of the wind and water stresses poses certain problems.

The atmosphere and the ocean exert stresses on the ice due to frictional drag. This frictional drag results from fluid flow over the uneven top and bottom surfaces of the ice, and can be artificially resolved into two components: form drag, resulting from flow over obstacles of order greater than one centimeter, and skin drag, resulting from flow over obstacles less than one centimeter. Skin drag is believed to usually dominate the wind stress, whereas form drag may dominate the water stress. Only preliminary measurements have been made of the form or pressure drag on pack ice (see under "Pilot Studies"). The pressure drag on a ridge can be calculated if the ice speed, water speed, and the shape of the ridge are known, but the calculations will be complicated in the case of deep draft ridges which extend downward through the Ekman layer because internal waves may arise which exchange energy with the deeper layers of the ocean. So-called roughness lengths are frequently used to model the frictional coupling between the atmosphere and the ice, and between the ice and the ocean, but the relationship between these parameters and surface topography is obscure. The rule of thumb (roughness parameter = 1/30 typical obstacle size) is of little value for sea ice, where several interpretations of "typical obstacle" are possible.

It has been recognized since the time of Nansen, that wind stress usually makes the largest contribution to the acceleration of sea ice. In the equation relating the acceleration of the ice to the sum of the forces acting on it, wind stress is typically on the order of a few dynes/cm², while the water stress is on the order of one dyne/cm² or less. The coriolis force is almost always smaller than the water stress, and the component of gravity parallel to the surface gradient is comparable to the coriolis force. These forces add vectorially with the internal stress term to accelerate the ice. Thus each determination of the internal stress term as the

difference between the ice acceleration term and the external stresses, incorporates all of the errors associated with these measured quantities. The probable error of the internal stress is therefore of the order of the largest probable error of the measured terms. Errors in the estimates of the acceleration term and the external stress terms are due primarily to measurement errors in navigation and average ice thickness, and to our incomplete understanding of the frictional coupling of the ice to the atmosphere and the ocean. The navigational errors will presumably vary randomly about zero, and their importance can be estimated from the scatter of observations at a known location. Realistically, navigational errors may prove to be so large that direct measurement of the acceleration will be necessary. Errors arising from incomplete wind and water stress theories can only be estimated roughly. Since these errors will not average out in time, they are contained in, and indistinguishable from, the internal stress term.

Fundamental to an understanding of the dynamic behavior of sea ice is a description of the interaction between the large-scale stress and strain fields. Since neither ice strain nor the propagation of stresses through the ice can be determined from observations at a single station, simultaneous data must be acquired from an array of stations. A major barrier to the understanding of ice dynamics is our present inability to predict, or even to measure directly, the internal ice stress. The force due to internal stress at a point can be determined as a residual when the external stresses and the ice movement are known; this in itself would be of significance, but would provide no new insight into the origin and transmission of internal stress. With an array of stations, it should be possible to find a causal relationship between the internal stress at a point and the regional stress and strain fields. However, the propagation of stress is complicated by nonuniformities in the ice such as leads and pressure ridges. In order to incorporate these effects into the above causal relationship, it is necessary to obtain a detailed morphological description of the ice within the test area. Frequent aerial survey flights, using current remote sensing techniques, will therefore be required. Such data would not only furnish new information on the role of leads and pressure ridges in large-scale ice deformation, but would also provide the input necessary for a parameterization of the ice cover. The immediate goal is the development of a functional relationship between the internal stress at

a point and the regional stress and strain fields, a relationship which must include the regional strain history and a parameterization of the characteristics of the ice. Such a relationship is required in any predictive model of large-scale ice deformation.

2. How does ice topography interact with the large-scale stress and strain fields?

The transfer of momentum between the atmosphere and the ice, and between the ice and the ocean, is regulated by the roughness of the ice topography, however the topography is itself modified by the strains generated from the wind and water stresses. Our ability to answer Question 1 relies on achieving at least an empirical understanding of the dual nature of this interaction. Specifically, we must first be able to describe in simple terms the frictional coupling between components of the system, and to identify the various mechanisms involved in the deformation of the ice, before any useful model can be formulated.

An important objective of AIDJEX is to devise methods by which the stresses on the ice can be related to simple variables obtained by remote sensing techniques. The wind stress at a point could be calculated from observations of the wind vector at a given level, if an appropriate roughness length were known; however, at present, no direct method exists for finding the roughness length characteristic of a particular type of surface. The wind stress can also be calculated without resorting to roughness lengths by using the gradient method (see Wind Observations). These values of stress can be used in conjunction with an assumed logarithmic wind profile to produce a roughness length. During AIDJEX, this method will be used to catalog the roughness lengths appropriate to a variety of surface topographies. Surfaces should be categorized according to their statistical properties. In particular, portions of the spatial spectral density are expected to correlate well with the aerodynamic roughness lengths. Accurate profiles of surface elevation would be needed to perform the spectral analysis. If a good correlation can be established, aerial surveys would be sufficient to estimate roughness lengths.

Analogous to the wind stress, the water stress depends on the relative velocity of the ice over the water and upon the roughness of the lower surface. Current profiles obtained during AIDJEX will be used to calculate stresses and roughness lengths under the ice. These data will then be used

to relate ice velocity and bottom roughness to water stress. Ultimately, however, it will be necessary to devise a valid way of relating the total water stress to ice velocity and to easily observed morphological features of the ice.

Determinations of the roughness lengths at the bottom of the ice will be of limited value in the long-range objectives of AIDJEX, unless they can be related to the under-ice topography. If a statistically valid scheme for relating top and bottom profiles is found, then it will be possible to estimate bottom roughness on the basis of airborne observations of the top surface.

On a large enough scale, pack ice must be in hydrostatic equilibrium. Locally, however, hummocks may exist without compensating bummocks, and subsurface protrusions may exist with no topside expression. Nevertheless, on a regional scale, the gross bottom topography (which regulates the form drag) must be correlated with the major deformities of the upper surface. To establish such a correlation, simultaneous top and bottom profiles will be required.

Of primary concern to AIDJEX is the way in which stress is transmitted through the ice pack. The propagation of stress is directly related to the formation and development of inhomogeneities in the ice. These features serve to relieve accumulated stresses within the ice cover, but little quantitative information is available on the energy required to produce the observed deformation or on the mechanisms involved. Determinations of the internal stresses at the manned stations will therefore enhance the understanding of stress transmission only if they are interpreted in light of surrounding deformational features.

Despite the seemingly chaotic way in which sea ice ruptures, certain generic types of fractures can be identified:

- a) Parallel-edge cracks, caused by the weight of ice piled on the edge of a floe,
- b) Perpendicular-edge cracks, caused by the buoyancy of ice pushed below the edge of a floe,
- c) Long-wave cracks, caused by bending of the ice due to local atmospheric pressure gradients, or swell created by storms. These cracks appear in parallel series and cross ice of all thicknesses in nearly straight lines (Assur, 1963),

- d) Thermal cracks, caused by cooling and contraction of parallel slabs of ice.

It can be shown by a simple quantitative estimate that the forces resulting from divergence and shear normally occurring in the atmosphere and ocean are far too small to break a homogeneous, plane parallel slab of ice of more than a meter in thickness. Therefore, pre-existing inhomogeneities in the ice must contribute to localized stress concentrations causing the observed deformation. In thick ice, ridging is always preceded by the formation of a jagged tension crack. Subsequent motion with a shear component then causes the ice to part along certain parts of the crack while ridges form along others (by overthrusting and parallel-edge cracking). Thermal cracks may be particularly important in this context. Bennington (1967) reports that in reasonably level ice, major thermal cracks appear, as one might expect, with some regularity, at a spacing of a few hundred meters. In the absence of external stresses they often fill with water and refreeze, but if an external stress field is present at the time, these cracks may influence the development of a statistically recognizable "normal" floe size distribution.

It can frequently be observed that the young ice covering a lead is compressed into a high pressure ridge by the convergence of the two adjacent heavy floes. However, we do not know the relative importance of any of the processes identified, and we do not know the percentage contribution of ice of different thicknesses to the total of existing ridges.

A detailed description of the geometry of ice floes and pressure ridges will render insight into the physical processes by which the ice pack is deformed. The spacing, orientation, and length of pressure ridges should be observed, together with their relationship to fracture patterns within the surrounding ice. Present efforts (Weeks and Kovacs, 1970) to obtain profiles of individual ridges should be expanded to include a study of the life cycle of pressure ridges.

3. How do ice deformation and morphology affect the heat balance?

According to Badgley (1966) the heat loss from open leads during winter is at least two orders of magnitude more rapid than from thin ice. Local differences of this magnitude are probably greater than those found over any other kind of natural terrestrial surface.

Diverging ice motion has three important consequences:

- a) It causes heating of the atmosphere by exposing the warm water surface.
- b) It causes the rapid formation of new, relatively thin ice, which, by subsequent converging motion, can form pressure ridges.
- c) It causes convection in the ocean by the brine rejected from the growing ice.

Thus, the dynamic behavior of the ice and its heat balance are closely related. In their report, "Glaciology in the Arctic," the Glaciology Panel of the Committee on Polar Research, National Academy of Sciences (1967), identify this relationship as crucial to an understanding of long-term ice variations:

"The important scientific problems of the interaction among oceanic circulation, sea ice, and the atmospheric heat balance and circulation are related to the practical possibility of artificially influencing climate on a large scale. Although the scope of these problems extends well beyond the field of glaciology, the Glaciology Panel believes that ice is a pivotal factor.

Arctic Sea-Ice Cover: Stable or Unstable:

An inherent instability of the arctic sea-ice cover would have important implications: removal of the sea-ice cover might be triggered by natural or human influences. Removal of an unstable sea-ice cover would, in turn, presumably have profound influences on the climate of the northern hemisphere. At least three conflicting views exist on this question, namely:

- a) That there is an alternation between an ice-free and ice-covered Arctic Ocean as a result of various influences, including change of sea level.
- b) That the sea-ice cover is unstable: if it were destroyed, the arctic heat balance would be altered toward conditions that would prevent reforming of the sea-ice cover.
- c) That the sea-ice cover is stable, that is, that equilibrium conditions favor a sea-ice cover. If

the cover were removed, it would re-establish itself within a few years.

These hypotheses cannot be conclusively proven or disproven without consideration of the entire ocean-atmosphere circulation with all its ramifications. For instance, it seems possible that increased heat advection into the Arctic, instead of causing more ice to melt, might lead to a greater production of ice: increased circulation (higher wind velocities) causes more ice deformation, divergence, and a greater number of open leads. During most of the year, the heat loss from open water is two orders of magnitude greater than from thick ice. If the increase of the area of open water is substantial, even an excessive anomaly of heat advection cannot compensate for the local loss, and the result will be an increased ice production"

During the winter, the rate at which heat is transferred between the ocean and the atmosphere is highly sensitive to the extent of open water. The area of open water depends upon the dynamic behavior of the ice pack, which, in turn, depends upon the orientation and spacing of leads and polynyas. Therefore, not only the total area of open water, but also the geometry of major fracture systems, should be observed. The production of new ice in leads acts as a valve which greatly reduces the sensible heat flux from the ocean to the atmosphere. The data required to deduce the sensible heat flux are identical to those required to deduce the wind stress (see Atmospheric Observations).

The transfer of heat through the pack ice itself is regulated by ice thickness and by the thickness of the snow blanket. Since snow is an effective barrier to heat transfer, regions of anomalous snow depths, for instance on the lee side of ridges and over summer drainage features, must be considered in any attempt to evaluate a regional energy balance. Thus, in addition to providing data on the distributions of leads and ice thickness, AIDJEX will attempt to determine relationships between snow depth and ice topography.

In the summer, the upper portion of the ice is essentially isothermal and there are only small temperature differences between ice and open water. Thermodynamic distinctions between leads, pressure ridges, and undeformed ice are therefore concealed during this period; however, knowledge

of the areal extent of leads is still necessary in order to calculate the amount of radiant energy absorbed by the ocean (Fletcher, 1965).

The only morphological features of significance to the summer energy balance are melt ponds. Because of the disparity between the albedos of ice and water, summer melt ponds absorb much greater amounts of short-wave radiation than the surrounding ice. The prevalence of melt ponds (greater than 50% coverage during certain periods of the ablation season) accounts for the low areal albedo averages which have been observed from aircraft and high towers (Hanson, 1963; Langleben, 1968). The low integrated albedos indicate a rate of energy absorption at the surface which is too large to be consistent with mass balance studies. In some unknown way, the melt ponds must dispose of this excess of energy (Maykut and Untersteiner, 1969). As a first step towards an understanding of the role of melt ponds in the regional energy balance, AIDJEX will furnish data on the geometry (coverage, shape, and depth) of melt ponds and their relationship to deformational features.

EXPERIMENT DESIGN

Station Array

It is proposed that an array of drifting stations be established in the Arctic Ocean to observe the dynamic response of sea ice to its environment. The array will consist of a number of observation stations, five of which will be manned. The size and shape of the array are designed to give measurements which will be of maximum use in the calculation of the stress-strain relationship. The number of stations necessarily represents a compromise between the desire for accuracy and statistical reliability on the one hand, and financial and logistic considerations on the other.

The main array will consist of the five manned stations, with four initially arranged in a square around a central station. Typically, major ice features (such as leads, ridges and individual floes), have a scale of several kilometers, and atmospheric pressure systems have a scale of thousands of kilometers. It is desired that the square should be large compared to the ice features but small compared to the atmospheric pressure systems. Therefore, the initial square of manned stations should be 100 km on a side. It is desirable to minimize shoreline effects, which are a complication. It is the consensus of opinion among workers in the field of ice drift that this can be accomplished by locating the main array several hundred kilometers from shore (Fig. 3).

Additional unmanned (or occasionally manned) stations will be placed outside of the main array, in a continuation of the 100 km grid of which the four outer manned stations will form the basic unit. These stations are necessary because (among other reasons) there is evidence (Browne and Crary, 1958; Bushuyev et al, 1964) that the ice drift at any point depends on the winds over an area of at least 20,000 km²; this is larger than the main array. These unmanned outer stations will extend to a coast in at least one direction, so that it will be possible to estimate how far shore effects penetrate into the interior of the Arctic Ocean.

It is desirable to include some measurements of the ice drift on a smaller scale than the main array. From experience in other oceans, it

appears that the scale of inertial and other wave motions that may contribute to ice deformation is on the order of 10 km. It is suggested that, as a first try, there should be a square of four unmanned (or occasionally manned) stations 20 km on a side around the central manned station. Depending on the initial results, it may prove desirable to relocate the unmanned stations or to establish a number of additional stations to increase the statistical reliability of the results, to permit the calculation of higher order velocity differences, or to permit intensive study of especially active regions. The plan now calls for observations at the unmanned stations to include only position, wind velocity, and atmospheric pressure. Additional meteorological and oceanographical observations may be added if they are easily automated and sufficiently valuable.

A base station will be needed to serve as a logistic headquarters for the project. It is essential that this base station have a reliable airstrip, since frequent logistic and scientific flights will be required. Experience on previous drifting stations has shown that air strips established on sea ice tend to develop cracks and break up. The useful lifetime of such an airstrip is measured in months and hence the pack ice does not provide a platform of sufficient permanence or dependability for a project of this magnitude. Therefore, the only sites considered suitable for establishing a base station are ice islands.

Situating the logistic base at the central station would minimize flying time and conserve personnel and supplies. This will probably only be possible if an ice island whose area is small compared to the area of the inner square can be found in a suitable location. In this way the anomalous size, strength, and movement of the ice island will have only a small effect on the drift patterns of the surrounding pack ice. A larger ice island, such as T-3, could be used as a base station provided it is well outside of the inner square of unmanned stations. An exception might occur if suitable techniques can be found to determine the position of unmanned stations from a considerable distance. It might then be possible to locate the entire array of unmanned stations away from the exact center of the larger square, and still use a large ice island as the center manned observing station. Otherwise, it will be necessary to establish a central manned station on the pack ice, and have a separate base station on an ice island. If no ice island meets the necessary requirements, the project should be postponed, rather than risk a pack ice airstrip.

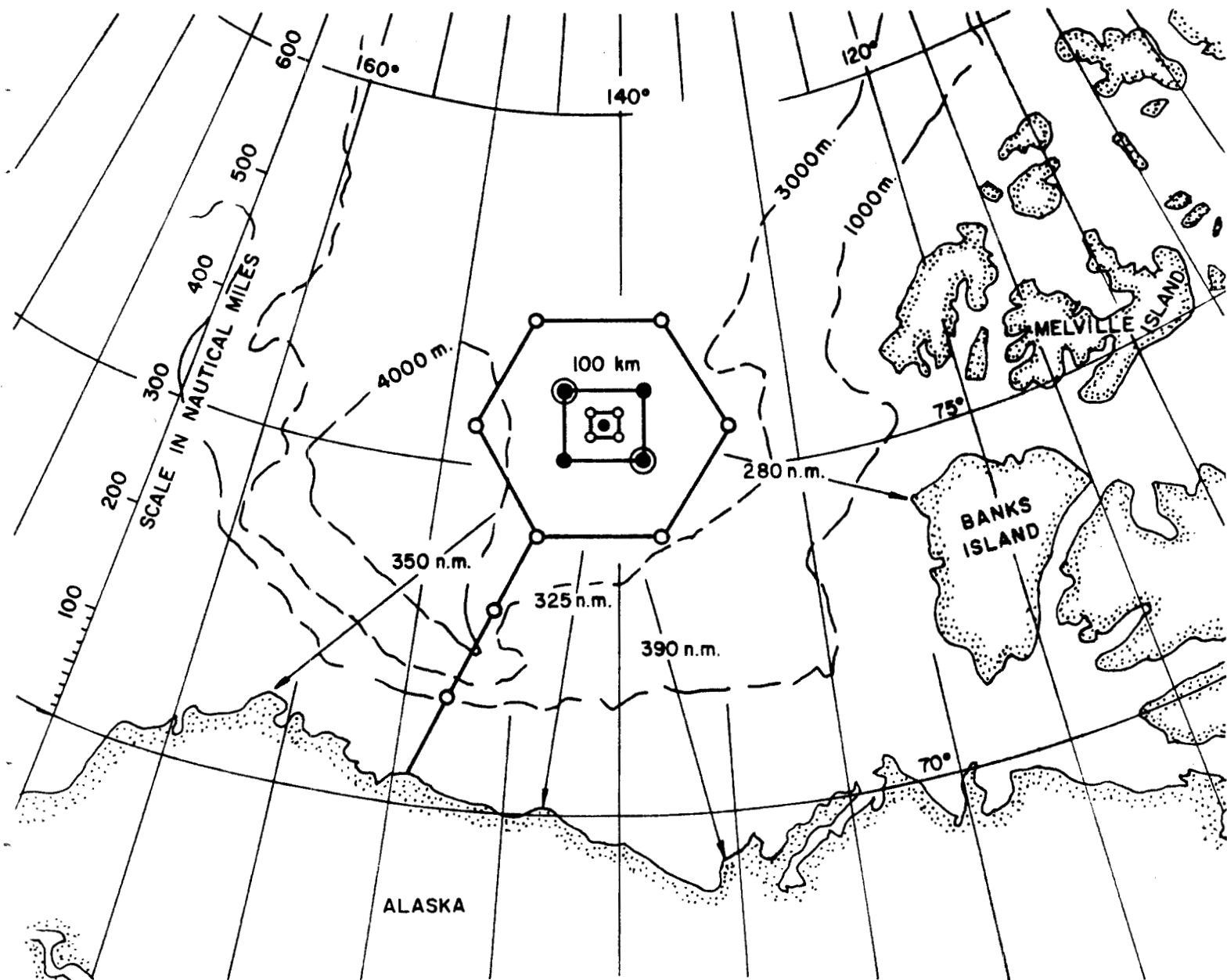


Figure 3. Tentative station array and approximate location, showing manned stations (full circles) and unmanned stations (open circles). The additional circles around two of the manned stations indicate local (1-km-scale) strain networks.

Instruments and Observations

The discussion below outlines the measurements that are needed to investigate the questions raised in the previous section, and identifies some of the appropriate instruments for these measurements. The limitations of individual instruments are mentioned as they apply to arctic conditions. Details of instrumentation and procedure have been left flexible as field experience may demand considerable modifications.

Sea ice observations

The area of the inner square (containing the Central Station) and a strip at least 20 kilometers wide (connecting the four manned outer stations) should be surveyed regularly during those intervals when observations are being taken at the surface. The systems used for these surveys must record surface temperatures and morphological features. Ideally, such systems should be capable of detecting narrow leads, melt ponds, pressure ridges with height estimates, surface roughness, and, if possible, ice thickness. Instrumentation will be mounted aboard aircraft, submarines, and satellites. Existing observational programs will be exploited whenever possible.

Imagery. The successful development of airborne sensors such as the infrared scanner (IRS), the sidelooking radar (SLR), and the optical laser, suggests their application to the studies proposed in AIDJEX. Passive microwave (PMS) and scatterometry systems presently being studied and developed within the NASA Earth Resources program also might ultimately be used in the remote sensing of sea ice. Ground verification parties will provide data to calibrate and check the remote systems.

Special emphasis will be placed on obtaining aerial photographs of the experimental area. Both the equipment and the interpretive techniques used in aerial photogrammetry are highly developed. Photographic mapping offers the advantages of high resolution, low distortion, and large area coverage, but its use is restricted to periods of clear weather. Aerial photographs will be used as a guide in interpreting the results from other remote systems.

The infrared scanner measures effective surface temperatures. During the winter, it can be used to detect the presence of leads, thin ice, and possibly pressure ridges. During the summer, however, the surface is nearly

isothermal and this system is of limited value. Although useful under all light conditions, the IRS cannot be relied on when clouds or fog exist below the aircraft.

Sidelooking radar is roughly the all-weather equivalent of aerial photography. Images from SLR show ridge and fracture systems in the ice pack; however, no consistent key is yet available to permit detailed identification of other ice features. With such a key it may be possible, for instance, to distinguish newly frozen ice from thicker ice.

Passive microwave sensors may be useful for distinguishing open leads and melt ponds from newly frozen ice. Since the microwave emissivities of ice and water are significantly different, the PMS can distinguish between a water surface and an ice surface, even when the ice is near the melting point. The PMS is an all-weather system. The scatterometer measures radar backscatter at various grazing angles, and has, to a limited extent, been used to identify ice types.

Satellite imagery, both vidicon and high resolution infrared, currently in use on the NIMBUS III vehicle, will be collected over the entire AIDJEX test area. These data are expected to be largely qualitative and of much lower resolution than the airborne imagery.

Deployment of all the above systems would result in significant overlap in the observed data. But, in view of the many ambiguities and uncertainties in interpretation, such redundancy is essential to insure a complete and accurate picture of the ice cover.

Profiling. None of the above systems are capable of measuring ice thickness. At present, simultaneous top and bottom profiles offer the best hope for obtaining these measurements. Analysis of such profiles should clarify the relationship between the top and bottom surface topographies. If a statistical relationship between the top and bottom surfaces can be established, it would be possible to determine ice thickness on the basis of aerial observations alone. It is also possible that top surface profiles could be used to obtain an index of roughness that relates directly to turbulent roughness lengths.

Top surface profiles will be observed with an airborne optical laser altimeter. The laser system has a resolution of approximately a centimeter, but is unreliable if fog or clouds are present beneath the aircraft. Since its accuracy increases with decreasing altitude, low level (500 feet) flights avoid much of the preclusive weather and promise increased resolution.

In addition to measuring ice roughness, the laser system may be used to detect ice which visual observations and high quality photography are unable to distinguish from open water. Techniques presently being studied indicate that laser imagery may also be capable of identifying major pack ice types (Ketchum, 1970). Surface topography is one of the basic criteria for visually identifying stages of ice development. Very early stages of ice development generally have smooth, level surfaces with only minor pressure ice formations. Later stages maintain a generally level surface but have frequent, more pronounced pressure formations, such as ridges and hummocks. Old sea ice has an uneven, gradually rolling surface caused by weathering. Since these parameters are revealed in the laser terrain profile, identification of ice types can usually be made through interpretation of the character of the profile.

Under-ice profiles will be taken with the submarine acoustical ice canopy profiling system described by Lyon (1964). The resolution of this system is much lower than the laser system and, in the immediate vicinity of the stations, it may be necessary to supplement the data with observations of the local ice profile taken by other means. In a pilot project in the spring of 1970 (Smith, 1970) substantial success was achieved in obtaining profiles of a limited area using scuba divers. Boreholes through the ice and small submersibles may also be exploited for this purpose.

Positioning and acceleration. Essential to the success of AIDJEX is the ability to obtain accurate relative positioning of the manned and unmanned stations. Without this ability, no reliable computations of ice strain and strain rate would be possible. Since the sampling interval must be small compared to the typical period of atmospheric systems, hourly observations are indicated. Total large-scale strains exceeding 10% over a period of a day or so are not expected. Relative positions, obtained hourly, should be accurate to at least 0.1% of the total distance between stations; that is, to ± 50 meters in the outer square and to ± 10 meters in the inner square. During periods of large strain rates, satellite positioning of the manned stations would be adequate; however, during relatively quiet periods, the inaccuracies inherent in this system would be comparable to the expected deformation and more accurate positioning techniques will be required.

It is expected that accelerations (needed for the evaluation of Eq. 2) of large magnitude and low frequency can be determined as second order differences of navigational fixes. Higher frequency accelerations will have to

be observed directly by means of accelerometers. The technical problems involved in these measurements have not been studied in detail and should be given high priority in the projected pilot experiment in spring 1971.

Positions of stations should be determined as follows:

<u>Station</u>	<u>Period</u>	<u>Method</u> (tentative)
Manned stations	Hourly	Transit satellite LORAN rho rho DECCA HI-FIX Other?
Unmanned stations		
Inner array	at least hourly	IRLS
Outer array	2-hourly	radar tellurometer Other?

Procedures. This section outlines some of the procedures to be followed in taking the "Sea Ice Observations." One major aircraft will be flown at an altitude high enough to permit rapid coverage of the test area with sidelooking radar and aerial photography. Surface-mounted radar transponders or reflectors will provide control necessary to align the images of adjacent flight paths. The frequency of flights will be determined by the occurrence of significant deformation events during those intervals when intensive observations are being taken at the surface.

Another major aircraft will carry both laser and infrared sensors and will be flown at low altitude since signals from these sensors are attenuated by atmospheric moisture. The combined infrared-laser flights will cover the perimeter of the quadrilateral when conditions permit, but at least every several days during the periods of intensive data collection. Special flights will be conducted following storms or other significant events.

Nuclear submarines are the only feasible platforms for obtaining ice canopy data over sections extending for hundreds of kilometers. Ideally, submarine surveys should be conducted with the same frequency as airborne surveys.

Atmospheric observations

Wind stress. All observations of wind stress are fraught with two fundamental difficulties: One is the problem of representativeness in a terrain of irregular topography, the other is the variable stability of the boundary layer. To make a point measurement representative in terms of features of the surface topography, it should be taken as high as possible.

To reduce the effects of density stratification, it should be taken as low as possible. The only feasible approach is a compromise.

Two methods of measuring wind stress should be considered: the profile method and the eddy flux method. The profile method has the advantage of low initial cost and easy maintenance, and the disadvantage of being somewhat empirical in concept. The eddy flux method involves sophisticated electronics and high cost, but also high accuracy. The following procedure seems to offer an optimal compromise between the various techniques and requirements:

Wind velocity and temperature are measured at two levels and used to determine the effect of the density stratification, expressed by the Richardson number.

$$Ri = \frac{\partial\theta/\partial z}{(\partial u/\partial z)^2} \frac{g}{T} \approx \frac{\Delta\theta\Delta z}{(\Delta u)^2} \frac{g}{T} \quad (3)$$

The stress τ is then

$$(\tau/\rho)^{1/2} \equiv u_* = f(Ri) k \frac{\Delta u}{\Delta \ln z} \quad (4)$$

where $f(Ri) = \begin{cases} (1 - \gamma Ri)^{1/4} & \text{for unstable conditions (Ri < 0)} \\ (1 - \alpha Ri)^{1/2} & \text{for stable conditions (Ri > 0)} \end{cases}$

$$\gamma \approx 16, \alpha \approx 7$$

(Businger, 1966; Paulson, 1967).

Anemometers and temperature sensors should be mounted at 4 and 8 meters above the ground, with provisions for easy height adjustment and switching of anemometers. The sensor outputs should be converted to wind stress by means of analog circuits, according to equation 4. A switch, activated by a change in sign of the Richardson number (temperature gradient), will select the appropriate circuit for $f(Ri)$. The stress values should be averaged and printed out for 10-minute intervals. In addition, wind and temperature values should be monitored on ordinary stripchart recorders with integrating devices.

It is desirable to check the accuracy of the stress observations obtained by means of the gradient method. Since it is now known that sonic anemometers can be operated effectively under arctic conditions (Thorndike, 1970), one station will be equipped with a one-dimensional sonic anemometer plus a fast-response cup anemometer, mounted halfway between the other anemometers. These instruments give the stress according to

$$\tau = -\rho \overline{u'w'} . \quad (5)$$

The eddy velocities u' and w' are measured by the fast-response anemometer and the sonic anemometer, respectively. Multiplication and averaging are accomplished electronically. Stress data from this method should also be printed out at 10-minute intervals.

Wind stress measurements by the profile method should be maintained at each of the outer stations and at the Central Station. One sonic flux meter should be moved from station to station for comparisons.

Heat flux. The data necessary to obtain wind stress (equations 3, 4, and 5) can also be used to calculate the flux of sensible heat. No further observations are necessary. For the profile method, the heat flux is given by

$$F_h = \frac{\rho c_p k^2}{(\Delta \ln z)^2} \Delta u \Delta \theta \phi(Ri), \quad (6)$$

where $\phi(Ri) = (1 - \gamma Ri)^{3/4}$ for unstable conditions,

and $\phi(Ri) = (1 - \alpha Ri)$ for stable conditions.

The left-hand side of equation 6 can be computed by appropriate analog circuits, corresponding to those used for computation of the stress.

The eddy flux method describes heat transfer as

$$F_h = c_p \rho \overline{w'T'} \quad (7)$$

which can also be recorded directly.

Wind vector. Wind direction should be recorded continuously at the outer stations. A windvane with high damping should be mounted at the same, or a somewhat higher, level where wind velocity for stress computation is observed. Integrated (averaged) wind directions should be recorded at the

same time intervals for which stress is recorded. Accurate monitoring of ice floe rotation is therefore important.

Observations of wind direction and velocity at the inner stations are desirable and should be contemplated if azimuth control is feasible for an unmanned station. If not, wind velocity alone should be recorded at the standard height (as above) and for the standard time interval. Wind data from the Inner Stations should be telemetered to the Central Station.

Radiation. Radiant energy fluxes are the most important components of the heat budget. AIDJEX will afford a unique opportunity to observe their local variability and relationship to ice deformation (see "Basic Question 3").

The elements to be measured continuously at all manned stations are: incoming long-wave radiation, outgoing long-wave radiation, incoming short-wave radiation, and albedo. Since meltwater ponds absorb at least twice as much incoming short-wave radiation as clean ice, it will be essential that, during the melting season, the percentage area covered by ponds be surveyed as frequently as possible (see also chapter on Imagery). The effective surface temperature will be monitored by infrared radiometer at selected periods on all types of surfaces (snow, ice, ponds, leads, pressure ridges, etc.). Airborne radiation measurements and cloud observations from an all-sky camera will be made to obtain a complete picture of the radiative energy balance.

Although several types of all-wave and short-wave radiometers of comparable quality are commercially available, it is paramount that the same type of radiometers be used at all stations.

Atmospheric pressure. Atmospheric surface pressure should be recorded at all stations and averaged automatically over the standard time interval. Pressure averages should be accurate to within ± 0.05 mb. Unless the sensors are mercury barometers, periodic calibrations, requiring visits to the unmanned stations, will be necessary.

Upper air. The logistic base station should be equipped with a radar-tracked radio-sonde that provides high resolution vertical profiles in the lowest few hundred meters. These observations are not only needed for the heat balance work, but would also be of considerable value for both survey and supply flights.

The frequency of upper air observations should follow the standard synoptic schedule, with provisions for more ascents when deemed necessary.

Oceanographic Observations

Water stress. The water stress, due to the relative motion of ice and water, can be resolved into contributions from skin friction and form drag. Past measurement of friction drag have been made at locations chosen more for their convenience than for their representation of typical arctic pack ice. As in the case of wind stress, either a profile method or an eddy flux method may be employed. The profile method is simpler and more reliable for field use. This method requires measurements of vertical velocity profiles. Near each of the manned stations, current meters will be installed at depths of 0.5 m, 1 m, 2 m, 4 m, 8 m, 16 m, and 32 m. The sites should be chosen as carefully as possible to insure that no anomalous local ice conditions influence the measurements. The current meter data must have the ice drift subtracted vectorially to give true currents. Ice drift will have to be obtained from the navigational data. If a reliable hot wire or sonic current meter becomes available, it may be preferable to use the eddy flux method and measure the Reynolds stresses directly.

Measurements in the frictional boundary layer may be interpreted according to Prandtl theory to give a local value of stress. Measurements in the planetary boundary layer may be interpreted in terms of Ekman theory to yield a stress which is integrated over a wider area. In addition to the routine measurements of the frictional stress at each site, a series of experiments should be conducted to find roughness lengths characteristic of the bottom surface of various types of pack ice. Observations of the under-ice topography, current measurements, and ice velocity are needed for the calculation of form drag. A detailed description of the under-ice surface must be obtained on two scales:

- a) Gross scale, encompassing an area on the order of that enclosed by the four outer manned stations. This is best accomplished by a submarine with upward-beaming sonar and inertial navigation, running an appropriate survey grid. This survey needs to be repeated from time to time, since the nature of the major under-ice features (leads and deep pressure ridges) within the study area will undoubtedly change.
- b) Micro-scale, covering the areas in which the detailed boundary layer experiments are performed. These surveys

must be conducted before and during the experiments. The submarine might be able to accomplish these surveys in sufficient detail if acoustic beacons are located below the ice for reference; however, other methods may prove more feasible. One possibility would be a small submersible equipped with the mapping sonar, and its position controlled by an array of sound transducers.

The use of scuba divers (see under "Pilot Studies") or side-scanning sonar should be considered as possibilities in case submersibles are not available.

The current measurements needed for the form drag calculations must also be made on two scales. On the micro-scale, measurements will be needed which will permit the detailed calculation of the form drag on individual pressure ridges. One method of measuring the form drag of individual features is presently under development (J. D. Smith, 1970). This method utilizes an array of about two dozen specially designed current probes, which can resolve the currents in three dimensions. The array is located under the ice in different positions relative to a pressure ridge. Divers will probably be required for locating and mooring the array. More sophisticated versions of this system will be incorporated into the AIDJEX program; however, it will not be possible to make direct measurements of the form drag at each station. Perhaps techniques can be developed to compute the form drag on the basis of the current measurements used to determine the friction drag.

The problem of measuring form drag will be a formidable one, and as many methods as possible should be used for cross checking. One possibility would be to measure pressure on both sides of the ridge, using sensitive manometers.

Tilt. Another force acting on sea ice is the pressure gradient force resulting from the component of gravity parallel to the sea surface. Measurements of the slope of the sea surface should be recorded continuously at each of the manned stations. Estimates of the sea surface slope can be obtained directly from hydrostatic leveling of the sea surface.

Observations of ice tilt offer the simplest method of obtaining the pressure gradient force but they require occasional calibration by direct hydrostatic leveling, since they involve the assumption that ice tilt

corresponds to sea surface slope. The tiltmeter is basically a pendulum device which responds both to the ice tilt and to horizontal accelerations. There is no method of separating the two effects in the data recorded by such an instrument. Accelerations must therefore be determined independently from navigational data or accelerometers and then subtracted from the tiltmeter readings to give the ice tilt. Preliminary experiments need to be made to find the relative magnitudes of the two effects under actual field conditions.

Hydrostatic leveling of the sea surface is theoretically the best technique to obtain the absolute tilt of the sea surface (Weber, 1969). However, a practical hydrostatic system with continuous recording has not been developed. Therefore, absolute hydrostatic tilt measurements should be supplemented with continuous relative observations from a tiltmeter.

Transient ocean currents. In most cases, water stress, created by the movement of the ice over the ocean surface, retards ice drift. However, after long periods of unaccelerated drift a sizeable boundary layer, moving along with the ice, will develop in the ocean. The momentum of this layer may continue to drive the ice when the other driving forces have subsided. Furthermore, other transient ocean currents, which may or may not be induced by ice movement, could exchange momentum with the ice cover and, in doing so, affect its motion. An understanding of the interaction of transient currents with the ice cover is needed for the development of reliable forecasting models. AIDJEX offers, for the first time, the necessary network of stations to properly observe such transient phenomena as internal waves, inertial oscillations, and planetary waves. Observations will include profiles of salinity, temperature, and velocity. It is likely that these observations will also yield new information on the transfer of heat between the deep ocean and the ice cover.

Frequent vertical profiles of temperature and salinity will be obtained with commercially available salinity-temperature-depth recorders (STD). An STD will be operated at each of the manned stations. The instrument will normally be left at a fixed depth in the main halocline to record time variations due to internal waves and turbulence. Twice a day the STD will be raised and lowered to obtain a vertical profile. A number of Nansen bottles with reversing thermometers should be available at each station as an independent check on the STD, and as a backup in case of an STD failure. They would also allow for other measurements such as dissolved oxygen and nutrients.

Previous data from the Arctic indicate that significant horizontal variations in hydrographical conditions may occur on small as well as large scales. Provision should therefore be made for special experiments to study the smaller scale variations. Consideration should be given to the installation of continuously recording thermographs and salinographs at the unmanned stations for measurements near the surface during selected periods.

In addition to the shallow current profiles used to calculate the water stress, current observations should be taken down to depths of at least several hundred meters for studying internal waves. Two specific distributions of current meters deserve consideration. The first would provide data at 10 meter intervals, below the boundary layer, down to a depth of 400 meters. The other would provide measurements at less frequent intervals, but would extend as deep as 2000 meters. It may be cheaper in the long run to measure on a dense spacing at depths extending into deep water.

It is advisable to sample currents as continuously as possible for as long as the experiment continues. This procedure will insure that the complete spectrum of currents existing during the experiment will have been sampled. Sampling must be sufficiently rapid to avoid contamination from high-frequency processes, otherwise the well-known problem of "aliasing" occurs. Past experience has shown that a sampling interval of about one minute is adequate to resolve high frequency motions below 50 meters depth, but that a sampling rate of 5 to 10 readings per minute is necessary in the mixed layer above 50 meters. Preliminary experiments using different sampling rates and different depths are needed to determine the optimum spacings and sampling rates.

It may also be desirable to extend the measurements of internal waves to intermediate horizontal scales to check horizontal coherence. This would require the establishment of a temporary current meter installation at one of the unmanned stations on the inner square for a period of one or two weeks.

Data Considerations

All oceanic and atmospheric measurements should be recorded by analog and digital methods. Analog records will be used for monitoring data and system performance in the field. Digital output will be recorded on magnetic

tape in uniform format suitable for computer analysis.

In a project of this scope, it is expected that modifications in observational procedures and instrumental systems will be required as the data begin to emerge. Preliminary analysis of the data, requiring a small digital computer, is therefore necessary. This computer will be situated at the Base station and will receive telemetered data from the surrounding array of stations.

Project Stages

AIDJEX will consist of four stages: planning, pilot studies, field program, and analysis. It is expected that, during the planning stage, investigators from a number of organizations will prepare detailed proposals for participation in the research outlined in this general plan.

Pilot experiments. The magnitude of effort involved in AIDJEX requires that as many of its elements as possible be tested before the combined experiment is begun. A number of recent, independent studies can be identified as direct contributions to the preparation for AIDJEX. A selection of such studies is given below.

An activity of long standing and special value to AIDJEX are the airborne ice surveys and remote sensing studies by W. Wittmann and collaborators (Naval Oceanographic Office).

W. F. Weeks and A. Kovacs (CRREL) published an exhaustive report of their investigations of pressure ridges off the Alaskan coast near Barrow, and a review of all existing literature on the subject.

A series of advanced experiments concerned with ice drift in the Gulf of St. Lawrence have been reported by S. D. Smith (Beford Institute) and O. M. Johannessen (McGill U.) and their collaborators. Wind drag coefficients of ice floes under neutral and unstable conditions were measured by means of a three-dimensional sonic anemometer.

The diversified, continuing project of K. Hunkins and collaborators (Lamont), especially their work on internal waves, Ekman drift, and satellite navigation has provided much of the basic information for the planning of AIDJEX.

Probably the most sophisticated array of instruments for the measurement of momentum and heat transfer in the boundary layer exists at the Arctic

Submarine Laboratory, Naval Undersea R & D Center, San Diego. Results of field experiments are being prepared for publication by J. H. Brown and collaborators.

An experiment by L. Coachman and collaborators (U. Wash.) in spring 1970 was aimed at examining deviations from geostrophic flow to a depth of 500 meters at closely spaced stations, as well as the spatial coherence of currents simultaneously observed at spacings of 3, 10, and 20 km. During the same experiment, J. D. Smith and collaborators (U. Wash.) mapped the bottom topography of a small (40 by 40 m) area of ice to investigate the effect of bottom topography on Reynolds stresses in the Ekman layer, while W. J. Campbell (USGS) conducted preliminary tests of ranging devices for the continuous observation of small-scale ice strain.

Also in spring 1970, A. Thorndike (U. Wash.) tested the performance of sonic anemometers at low temperature (to -50°C) and obtained satisfactory results, including direct print-outs of Richardson numbers.

A theoretical study by R. J. Evans and N. Untersteiner (U. Wash.) verifies the empirical observation that major thermal cracks in perennial sea ice occur at an average spacing on the order of 10^2 meters.

In addition to these preparatory projects it is planned to conduct, as an integral part of AIDJEX, a pilot experiment in spring 1971. In this experiment, a "manned station", as fully equipped as possible, will be deployed to test sensors, recording apparatus, camp facilities, and whatever remote sensing and automatic equipment will be available at the time.

Main field program. The main field program will have a duration of at least one year in order to observe seasonal changes in the state of the ice cover. Although it would be desirable to run the experiment continuously throughout this period, such an approach seems inefficient and involves numerous technical difficulties. A more practical approach is to select several periods of special interest during which all systems would operate simultaneously. These periods of intensive data collection will each last approximately one month and will be chosen to provide representative data on conditions within the test area during the height of the melt season, the middle of the winter, the fall freeze-up, and, possibly, the spring transition from snow-covered to bare ice. Maintenance crews will occupy the manned stations between the periods of intensive observations. Routine navigation,

certain oceanographic observations, and aerial surveys will be maintained throughout the year. Other observational programs would be continued according to the specific needs of individual projects. This phase of AIDJEX is tentatively scheduled to begin in the spring of 1972. Upon completion of the field work, AIDJEX will coordinate the reduction, distribution, and analysis of the data. The total duration of AIDJEX is expected to be six years.

DEVELOPMENT OF NUMERICAL SIMULATION MODELS

Background

Our present knowledge about ice drift in the Arctic Ocean comes from a number of observations of single points, starting with Nansen's voyage on the "Fram". There are three main regions of ice drift in the Arctic Ocean: (1) A large clockwise gyre in the Beaufort Sea; (2) A broad steady drift toward the Greenland Sea on the Siberian side of the Arctic Ocean, and; (3) A stagnant region north of Greenland and Ellesmere Island. The drift of a single ice floe can be highly irregular for short periods of time, but tends to follow one of the main drift patterns over a longer period. The general features of this drift have been explained (Campbell, 1965) as a result closely related to the mean atmospheric circulation over the Arctic Basin. Non-steady effects, whether they arise from a variable wind field, or variable ocean currents (including possibly long Rossby waves as investigated by LeBlond, 1964, and Farmer, 1966) are the subject of AIDJEX.

On one previous occasion an array of drift stations was established to study the simultaneous motion of several points on the ice pack. This was done by the Soviet Union in the northwestern part of the Laptev Sea. In general, the points of the main Soviet array, which were initially placed in a square, drifted together in the direction of the Greenland Sea, but some relative motion was observed. An excellent qualitative discussion of the features of the motion has been given by Bushuyev et al (1964), but a detailed theoretical analysis has apparently not been carried out.

Current Status

Theoretical modeling of the ice drift and ocean circulation will be carried out in parallel with the field work. The theoretical analysis of the early results from AIDJEX field work will serve as a guide in adjusting the design of the experiment.

The following is a list of such "modelling" efforts that are either presently under way or deserve special priority:

- 1) Morphology interpretation

Ridges, hummocks, leads, and many other morphological features of the ice reflect past strains. If the ice were a more durable substance and its rheology better understood, its past deformations could be inferred from its present state with some accuracy, much as the petrofabrics of rocks are used to analyze their tectonic history. In reality, unfortunately, there are several processes working continuously to erase the signatures of past strains:

- a) Ice is a visco-plastic material and creeps rapidly when near the melting point,
- b) Ridges and other surface features produce an uneven distribution of snow, causing an uneven distribution of surface ablation,
- c) Irregular ice accretion can occur at the surface by flooding of areas depressed below free-board level, and by lateral movement and refreezing of surficial meltwater,
- d) Wherever the ice is not at equilibrium thickness, mass is not being conserved.

These processes tend to obscure the effects of strain but, generally, they occur on a time scale of years while the strain features are produced on a time scale of days to months. Therefore, it should be possible to establish some relationships between the observed ice topography and past strains. Efforts in this direction will be made as soon as the necessary statistical data on ice morphology become available.

2) Constitutive Law

Ideally, a constitutive law for large-scale elements of sea ice, relating strain (ϵ) and stress (σ), i.e.

$$\epsilon = F(\sigma) \quad (8)$$

should be found. For reasons which are discussed in Appendix I, it is possible only under certain circumstances to find this law on the basis of AIDJEX data. However, it should be possible to find the divergences of both strain and stress, which will suffice for use in the predictive equation (2).

The large-scale stress-strain relationship is, of course, the integrated result of many small-scale interactions between individual blocks and plates of ice. Therefore, it seems important that, concomitant with large-scale experiments, efforts should be made to investigate the details of

small-scale collision and ice failure, using model experiments, local ice strain data, aerial photographs, and other suitable airborne observations. One such study is presently being planned by J. D. Smith and L. Coachman (U. of Wash.)

3) Ice bottom drag coefficient

A study by J. D. Smith (U. of Wash.) is aimed at separating skin drag from form drag at the underside of the ice. Smith was able to show that a slope of 1/20 contributed no less than 50% to the total water drag on a solid surface. Hence it can be expected that bottom topography will be a determining factor in the overall momentum transfer between ice and water. The desired end result of this study is to identify a bulk drag coefficient as a function of statistical parameters which describe the local variation of ice thickness. It is hoped that once the statistical relationship between top and bottom profiles is established by airborne laser and submarine profiling, only the former will be required to attach a certain bulk drag coefficient to a given area of sea ice.

4) Transient ocean currents

The assumption that ice and water of the Arctic Ocean are in a steady circulation suffices only as a first approximation. Actual drift tracks of floes are highly convoluted and are not repeated in detail. Even though two ice floes may pass through the same geographical position at different times their paths will not be the same. To understand this time-dependent motion, non-steady models are required. Although a general theory of time-dependent, wind-driven ocean currents has not yet been developed, some progress has been made in formulating models which will be of use in the overall context of AIDJEX. K. H. Hunkins (Lamont) developed an analytical model of forced internal waves driven by a divergent wind field acting through an Ekman layer. In this model, the upper ocean is exponentially stratified, with an upper mixed layer, and is forced by a sinusoidal wind field. The model gives insight into the mechanics of transient currents and provides both a basis for, and a check on, future numerical models of oceanic response to non-steady wind fields.

5) Non-isotropic ice viscosity

As an intermediate step, and in continuation of their previous work, W. Campbell and A. Rasmussen (USGS) have developed a model that treats the

ice as a viscous fluid (as did the earlier version of their model) however, with a viscosity dependent upon the flow field. After a first estimate of the ice velocity field, the viscosity is adjusted to be high in regions of convergence and shear and low in regions of divergence. Then a new velocity field is computed, and so on. By this iterative process, an ice velocity field is obtained for the given stress field, which represents a mechanically anisotropic sheet of sea ice. Actual numbers for the respective viscosities are, of course, not available, but the computational technique and the preliminary results obtained will be useful in applying the results of AIDJEX.

Future Models

The primary goal of AIDJEX is the formulation of a predictive model which will yield forecasts of ice deformation and drift on the basis of a few easily measured quantities. The model presently envisioned computes each of the stresses from observations of wind, position, pressure, and surface characteristics. Wind stress is computed from observations of the wind vector at a given level, assuming a logarithmic profile and a roughness length characteristic of the surface. Water stress is computed from the velocity of the ice and a roughness length appropriate to the underside of the ice. This roughness length will be computed using a statistical relationship between the top surface topography and the bottom surface topography. The treatment of the internal stress, pressure gradient force, and coriolis force have been described above. The successful application of this model depends on several relationships, especially those pertaining to internal stress, transient ocean currents, and roughness lengths, which have yet to be established. It is possible that some small laboratory experiments may be performed to verify some of the theoretical ideas.

Such a model, aside from providing insight into the mechanics of ice deformation, will make it possible to estimate, from a given atmospheric pressure field, what the ice conditions in a given location will be. Forecasts will be possible to the same extent that atmospheric pressure can be forecast. From a practical point of view, "ice forecasting" is

concerned with the following six features: drift fields, shear zones, open water, thick level ice, deformed ice, and thin ice. A measure of the probable occurrence of all of these features can be forecast with a functional model of the kind outlined above.

The next step will be to relate, in quantitative terms, the ice strain field and heat balance, i.e. ice production. Only estimates of unknown reliability exist on the amount of ice exported from the Arctic Basin into the Greenland Sea and the Atlantic Ocean. Also unknown is the the role and contribution of young ice in the formation of pressure ridges. The ability to relate ice strain and the formation of new ice would provide an approach to both problems. When a given area of pack ice undergoes repeated extension and compression, the new ice forming during the periods of extension will be later compressed into ridges, but will prevent the complete restoration of the previous area. This will result in an outward flux of ice. The effects of ice strain on the heat budget will also be needed for a refinement of the input parameters to models of the large-scale atmospheric circulation over the Arctic.

Ultimately, all empirical relationships and models developed in the context of AIDJEX should be incorporated into the modelling of atmospheric and oceanic circulations on a global scale. Only then will it be possible to examine the global consequences of natural or artificial modifications in the extent, thickness, or circulation of the arctic ice cover.

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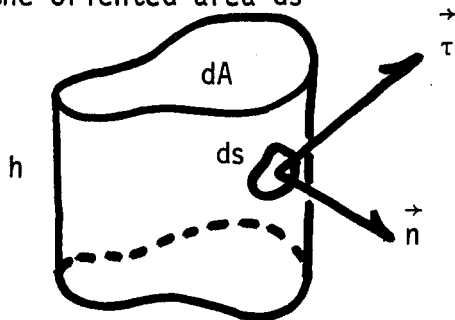
APPENDIX I

Consider an infinitesimal, vertical column of sea ice of thickness h and area dA . This volume element has mass $\rho h dA$. Any acceleration experienced by this mass element must be caused by the action of body forces on the center of mass, and by surface forces acting on the surface of this volume. Hence, in two dimensions,

$$\rho h dA \frac{d\vec{v}}{dt} = \rho h dA [\text{body forces per unit mass}] + \int_{\text{surface}} \vec{\tau} ds, \quad A(1)$$

where \vec{v} is the velocity and $\vec{\tau}$ is the surface traction. The only body forces are the coriolis force and a component of gravity parallel to the sea surface. The coriolis force per unit mass is $-2\vec{\Omega} \times \vec{v}$ where $\vec{\Omega}$ is the rotation vector of the earth. The horizontal component is $f\vec{v} \times \vec{k}$ where $f \equiv 2\omega \sin(\text{latitude})$, and $\omega \equiv$ angular velocity of the earth. The component of gravity acting parallel to the sea surface is $g \sin(\text{slope of sea surface})$.

The surface traction $\vec{\tau}$ is the component of the stress tensor $\vec{\tau}$ acting on the oriented area ds



$$\vec{\tau} = \vec{\tau} \cdot \vec{n} ds. \quad A(2)$$

The surface integral in (1) may be decomposed as follows:

$$\int_S \vec{\tau} ds = \int_{\text{top surface}} \vec{\tau} dA + \int_{\text{bottom surface}} \vec{\tau} dA + \int_{\text{vertical surfaces}} \vec{\tau} ds. \quad A(3)$$

Neglecting normal stresses on the top and bottom surfaces, we may label $\vec{\tau}$ top surface as $\vec{\tau}_a$, the air stress arising from frictional drag by the

wind blowing across the surface, and $\vec{\tau}$ bottom surface as $\vec{\tau}_w$, the water stress. Equation (1) now has the form

$$\rho h dA \frac{d\vec{v}}{dt} = \rho h dA [f\vec{v} \times \vec{k} + g\sin\alpha] + \vec{\tau}_a dA + \vec{\tau}_w dA + \int_{\text{vertical}} \vec{\tau} ds \quad A(4)$$

If, in the last term of equation (4), we assume that the vertical component of $\vec{\tau}$ vanishes and that the horizontal components are independent of the vertical coordinate -- i.e. if we reduce the problem to two dimensions -- then we may write

$$\int_{\text{Vertical Surfaces}} \vec{\tau} ds = h \int_C \vec{\tau} dl = h \int_C \vec{\tau} \cdot \vec{n} dl = h \int \nabla \cdot \vec{\tau} da = h dA \nabla \cdot \vec{\tau} \quad A(5)$$

Vertical Surfaces C C Area

Equation (4) now becomes

$$\rho h \frac{d\vec{v}}{dt} = \rho h f \vec{v} \times \vec{k} + \rho h g \sin\alpha + \vec{\tau}_a + \vec{\tau}_w + h \nabla \cdot \vec{\tau} \quad A(6)$$

In equation (6), only $\nabla \cdot \vec{\tau}$ cannot be measured directly and must therefore be determined as a residual when the other terms are known. The $\nabla \cdot \vec{\tau}$ term arises from the constitutive properties of the ice. Since $\nabla \cdot \vec{\tau}$ has only two components and the stress tensor itself has three independent components, it is not possible to use the results anticipated from AIDJEX ($\nabla \cdot \vec{\tau}$) to derive a complete constitutive equation, i.e. we cannot find a relationship $\vec{\tau} = F(\epsilon)$, however, the large-scale strain observations should enable us to establish

$$\nabla \cdot \vec{\tau} = F(\nabla \cdot \epsilon)$$

Since ϵ is a combination of derivatives of \vec{v} , equation (7) can be written as $\nabla \cdot \vec{\tau} = F[G(\vec{v})]$ and substituted into equation (1) to yield an equation

that relates v and its derivatives to measurable quantities. If it were ever possible to specify the stresses applied to the outer margins of the entire ice sheet covering the Arctic Ocean, as well as the wind and water stresses, then it would, in principle, be possible to solve for the state of stress everywhere within the ice, and to relate stress and strain by a complete constitutive law.