

# InfoNorth

## AIDJEX Revisited: A Look Back at the U.S.-Canadian Arctic Ice Dynamics Joint Experiment 1970–78

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### INTRODUCTION

**T**HE ARCTIC ICE DYNAMICS JOINT EXPERIMENT (AIDJEX) was an American-Canadian project to develop a comprehensive model of sea ice cover under the combined influences of the atmosphere and the ocean. From sea ice modeling studies in the 1950s and early 1960s, it had become clear that the “missing link” in resolving the momentum equation was the flow law for sea ice, that is, the law describing internal ice stress and its spatial propagation (Doronoin and Kheisin, 1975). The central idea of AIDJEX was that a realistic formulation of this law would eventually permit the construction of a sea ice model that could be built into the global climate models being developed at that time.

The momentum equation, also known as Newton’s Second Law, states that the acceleration of a body, multiplied by its mass, is proportional to the sum of all forces acting on it. In the case of sea ice cover as it exists on the Arctic Ocean, the acceleration is negligibly small, so the sum of all forces acting upon the ice must be zero. These forces are the tangential forces exerted by the wind and ocean currents, a force resulting from the rotation of the earth (the Coriolis force), and a small component of gravity resulting from the dynamic tilt of the sea surface. These external forces are counteracted by an internal stress with which the ice resists deformation. This relationship is expressed by a “flow law” that relates the external stress to the rate of deformation.

The four external stress terms in the momentum equation lend themselves to direct observation, but the internal stress cannot be measured directly and must be deduced from the deformation of an array of points (marked by stations or ice camps). Given the scale of air and water stress, this measurement clearly required multiple manned stations. The notion had been discussed at various meetings and workshops held by the Arctic Institute of North America and the National Research Council’s Polar Research Board, but as yet there was no concerted effort within the sea ice community to develop a scientific plan for a project.

The first “embryonic” plan was formulated in 1965, but the actual impetus to develop a serious project plan came in 1968, with a phone call to one of us (N.U.) from Walt Wittmann of the Navy Hydrographic Office. Reminding us that we had discussed the need for a multiple-station project, Wittmann offered seed funding for the development of a scientific plan. The first version of such a plan was submitted to the Office of Naval Research in July 1969.

While it is difficult in retrospect to unravel the multitude of personal recollections, individual biases, and historical facts, it is clear that this first scientific plan was the right seed planted in the right soil, because within the next two years AIDJEX was off and running.

Between 1970 and 1978, the Project Office published 40 issues of the *AIDJEX Bulletin*: in total, more than 4000 pages of original scientific papers, field reports, data reports, workshop reports, and translations of relevant Russian papers. Thanks to the generous effort by colleagues at NASA’s Jet Propulsion Laboratory, the entire collection and the 1972 and 1975 Operations Manuals are now available on the Internet at <<http://psc.apl.washington.edu/aidjex/>>.

### THE SCIENTIFIC PLAN

In May 1970, an improved and expanded version of the scientific plan was submitted to the National Science Foundation and the Office of Naval Research by N. Untersteiner, G.A. Maykut, and A.S. Thorndike. The revised plan addressed three questions:

1. How is large-scale ice deformation related to external stress fields?
2. How does ice topography interact with large-scale stress and strain fields?
3. How do ice deformation and morphology affect heat balance?

The authors looked at the ice pack as a mechanical system responding to forces applied by the wind and ocean

currents. Work conducted during the International Geophysical Year 1957–58 and subsequent model developments had established the basic functioning of sea ice as a thermodynamic system responding to heat fluxes from above and below. There was a consensus in the community that the thermal questions had been solved, and that the remaining questions concerned the mechanical behavior of the ice. At the same time, glaciologists had begun to understand the dynamics of glaciers and ice sheets by applying principles of continuum mechanics. The mechanical properties of ice entered these theories in the form of a relationship between stress and strain. The relationship was either based on laboratory measurements of the deformation of a specimen of ice under a known load, or simply hypothesized. Having understood the processes that control the temperature, growth, and melting of sea ice, the natural next step was to study those that control its motion and deformation. And so it was proposed to investigate the relationship between stress and strain for natural sea ice, and to use the results as the foundation for a continuum mechanical model.

Of course it was recognized that sea ice is not a continuous medium. It is riddled with fractures that partition it into many floes of all sizes and shapes. The scientific plan took it as an article of faith that there was some length-scale that separated the smooth, continuous, large-scale response to the wind from the granular fine structure of individual ice floes. The idea was to develop a stress-strain relationship that worked for the large-scale motion, and which might contain parameters that depended on a statistical description of the granular fine structure.

There was not much evidence to support the separation-of-scales assumption. One piece of evidence was the drift tracks of previous ice stations. When the drift tracks from many years were superimposed on the same map, there emerged a flow field with two features—a clockwise circulation in the Beaufort Sea, and a broad stream of ice flowing from the Siberian coast to the Fram Strait. When only drift tracks from simultaneous stations were plotted, they showed large departures from the long-term mean, which exhibited spatial correlations over distances of 1000 km. These observations suggested a basin-wide mean flow driven by the mean oceanic and atmospheric circulation, with fluctuations caused by synoptic-scale winds superimposed upon it. A scale of 100 km was adopted as an “infinitesimal” element: small compared to the scale of the ocean currents and atmospheric pressure field, yet big enough to present a meaningful average over the granular structure.

As the second question emphasizes, it was believed that the geometric properties of the ice pack—the partition into floes of various sizes and shapes, and the existence of pressure ridges and rubble fields—were consequences of ice deformation and at the same time modulated the coupling between the ice and the oceanic and atmospheric boundary layers. So the conceptual model developed in the scientific plan included two linked sets of processes, as schematically depicted in

Figure 1: 1) Ice motion: External forces and internal stresses determine the ice motion, with parameters such as ice strength and drag coefficients depending on geometric properties of the ice; and 2) Geometric properties: Ice thickness, pressure ridging, surface roughness, and floe size evolve in time. The geometric properties would be represented by statistical distribution functions.

The largest gap in this conceptual model was our poor understanding of how the stresses in the ice pack were related to its deformation. To address this problem, we proposed to observe the deformation of the ice from the motion of several points that lined an “infinitesimal element” about 100 km in size. At the same time, the stress gradient could be inferred from the balance of forces at each point, assuming that the acceleration and all the other forces were measured. For example, if the ice were not moving despite a strong wind, one would say that the stress gradient was equal to and opposite to the wind stress. It was hoped that from a large sample of different conditions, some rule relating the stress to the kinematic quantities would emerge. Precisely how this emergence would occur was not revealed in the scientific plan.

The strategy just sketched was vulnerable on at least two fronts. First, only the spatial derivatives of ice stress appear in the momentum balance, not the stress itself. Second, to deduce the stress gradient term indirectly by measuring all the other forces in the momentum equation is a noisy proposition, the error in the estimated stress term being the sum of the errors in the other terms. The stress term is impossible to measure directly and difficult to estimate indirectly. And even if you knew it exactly, it would not be straightforward to relate it to the deformation.

In rebuttal, it was asserted that over a year-long experiment there would surely be times when the stress term was large and times when it was small. It would be possible to test proposed stress-strain relationships by using them in a numerical simulation of the ice motion. So the plan was to use measured wind and water stresses and a postulated stress-strain law to drive a time- and space-dependent model of ice motion and the evolution of its geometric properties. The results were to be compared to measured ice motion, with the expectation that some stress-strain laws would work better than others.

#### FAVORABLE CIRCUMSTANCES

A number of circumstances fortuitously converged:

- The scientific merit of the plan was widely recognized, and it reflected a common view of a scientific community that was eager to participate.
- U.S. agencies had not conducted a major scientific effort in the Arctic since the International Geophysical Year 1957–58.
- Both the Office of Naval Research and the National Science Foundation had well-funded Arctic programs.

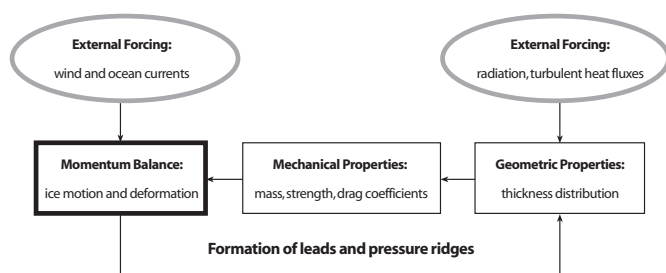


FIG. 1. Schematic relationship of the external forcing on the sea ice cover and its motion and thickness distribution.

- An especially appointed joint panel of the National Academy of Sciences and the National Research Council fully supported the project and helped to convince the National Science Board to authorize funding.
- A new generation of observing technologies was coming on line, including satellite navigation to replace celestial observation, battery-powered automatic data buoys that telemeter their positions and other data via satellite, accurate salinity-temperature-depth probes to replace Nansen bottles, quartz oscillator barometers to replace aneroid and mercury barometers, laser ranging to measure mesoscale ice deformation, and digital recording devices instead of paper strip charts and log-books.

#### PILOT STUDIES AND PREPARATIONS FOR THE MAIN EXPERIMENT

In March 1970, an exploratory study was conducted north of Tuktoyaktuk to test oceanographic instruments and techniques of observing water stress (AIDJEX Bull. 4, 1971). The first pilot study, from February to April 1971, was designed to test the various observing systems. It used a single station, called Camp 200, on an ice floe 200 km north of Tuktoyaktuk, with Fletcher's Ice Island T-3 in the Beaufort Sea as a secondary base. The second pilot study, from February to April 1972, employed a main camp 500 km north of Barrow and two satellite camps that formed a triangle with sides about 100 km in length. This pilot study served as the dress rehearsal for the main experiment and employed the complete set of instruments and techniques for measuring air and water stress, remote sensing by airborne instruments, and unattended data buoys (AIDJEX Bull. 14, 1972; Bull. 18, 1973).

It was a mild shock for us when, some time before the second pilot study, the late Thomas B. Owen, NSF's Assistant Director for National and International Programs, asked us when we would submit our "Operations Manual." Owens was a former admiral and chief of naval research. For us civilian scientists, it was a novel, challenging, and beneficial experience to prepare these manuals. The second pilot study was the first for which such a manual had been prepared. Another "first" was that the program managers in the leading American and Canadian

funding agencies manifested their commitment to support the project by their signatures in the Operations Manual.

#### Automatic Data Buoys

Soviet scientists and engineers pioneered the development of automatic weather stations for use in the Arctic pack ice. Between the early 1950s and late 1960s, their Drifting Automatic Radio-Meteorological Station (DARMS) program deployed more than 300 such buoys in a sector between Franz Josef Land and the Bering Strait. Data from these buoys were transmitted by HF radio signals, which were also used to locate the buoys by radio triangulation from coastal receiving stations.

The advent of satellite-borne methods of earth location and data transmission allowed us to skip the relatively low-tech approach taken by DARMS. With the support of the National Data Buoy Program office, National Oceanic and Atmospheric Administration (NOAA), and the help of a commercial contractor, AIDJEX acquired six different designs of data buoys. They employed the Interrogation, Readout, and Location System (IRLS) and the Random Access Measurement System (RAMS), both based on the Nimbus satellite series, and the Navy Satellite Positioning (NavSat) system. All data buoys recorded their geographical coordinates, as well as atmospheric pressure and temperature, several times per day. Earth locations were accurate to about 100 m if measured by NavSat, and to about 2 km using the other systems (AIDJEX Bull. 7, 1971; Bull. 40, 1978). This technology was of course rendered obsolete in the early 1990s, when the Global Positioning System (GPS) became widely accessible.

#### LOGISTICS

Throughout the pilot studies and the main experiment, the Canadian Polar Continental Shelf Project, the Naval Arctic Research Laboratory, and private contractors provided logistical support by means of small aircraft: Twin-engine DeHavilland Otter, Bristol Freighter, and helicopters. In spring 1972, a milestone event of aircraft operation on sea ice occurred when a C-130 Hercules aircraft landed on a runway of 2 m ice, prepared by no more than dragging a heavy wooden frame over the ice to spread the snow. Since then, such operations have become routine.

After the 1972 pilot study, the new regime at NARL gave us the virtually unlimited use of the facilities and support services at Barrow, including building materials, fuel, construction workers, and support for a full-time resident logistics manager who worked directly for the project. The evolving equal rights legislation of the time ended the long history of drifting ice camps as an exclusively male domain, and the AIDJEX camps were the first fully co-ed establishments on the ice.

AIDJEX was given sufficient funding to acquire logistical capabilities previously not available at ice camps.

On-station helicopters and small fixed-wing aircraft were used to deploy data buoys. After the breakup of the main camp ("Big Bear") in October 1975, helicopters enabled us to airlift buildings and equipment to the satellite camp "Caribou," which then served as the main camp until the project ended in May 1976. Previous ice camps had had to rely on HF radio communication, with the attendant difficulties caused by ionospheric disturbances. During the main experiment, Big Bear was able to communicate with both Barrow and Seattle by satellite telephone. Our presence on the ice during the main experiment amounted to a total of approximately 39 person-years. It seems remarkable that during this time no serious illnesses or injury accidents occurred. In two instances, navigation errors took helicopters off course and forced them down for lack of fuel, but in both cases they were found and were able to return safely with air-dropped fuel.

Contrary to the common belief that the remoteness of the Arctic Basin and its cold and darkness pose the most logistical problems, it is in fact the summer melt season that causes the greatest difficulties. Even if runways remain free of cracks, melt ponds severely limit their use, typically between early June and early September. The typical low stratus clouds and the frequent fog and icing conditions magnify the logistical difficulties. For that reason, most of the field observations of Arctic pack ice come from the period February to May, and summer observations are rare and valuable. In modern times, Russian observers have spent a total of about 30 summers on the pack ice, while Western observers have spent summer on the ice only four times: twice during the International Geophysical Years 1957 and 1958 at Station Alpha, once during AIDJEX in 1975, and once during SHEBA in 1998.

#### THE MAIN EXPERIMENT, MARCH 1975 TO MAY 1976

It was a hallmark of AIDJEX that, well before the beginning of the main experiment, the scientific plan had been sharpened to the extent that a firm and well-defined observational program had been established: a program deemed to be both feasible and sufficient to achieve the objectives of the project.

The overall responsibility for the project was assigned to the project director and his staff at the University of Washington (Fig. 2), which included a manager of field operations and a base manager of field operations located at the Naval Arctic Research Laboratory at Barrow. Principal investigators for the different disciplines were identified and represented in the AIDJEX steering committee. While the customary process of submitting proposals to the funding agencies was maintained, it was the uncommon and difficult task of the steering committee to pre-select only those proposals that would contribute directly to the overall purpose of the project as stated in the scientific plan.

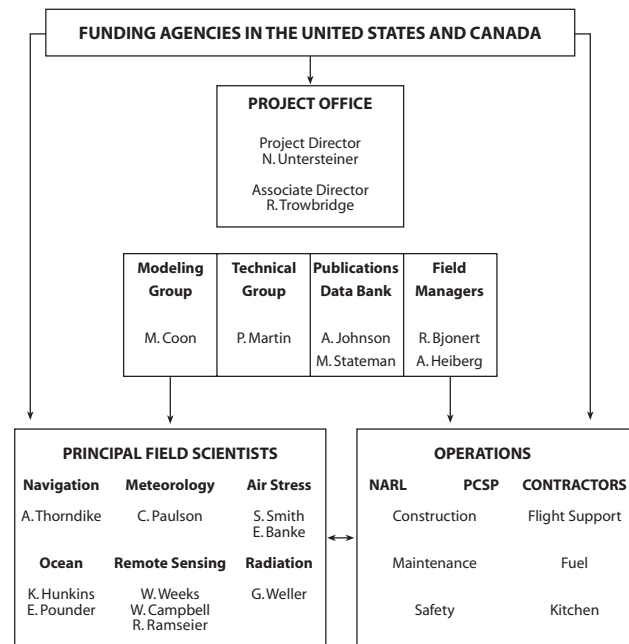


FIG. 2. Organization of the main experiment, 1975–76. The project office was located at the University of Washington in Seattle. NARL = Naval Arctic Research Laboratory (Barrow, Alaska); PCSP = Polar Continental Shelf Program (Ottawa, Ontario).

Since all installations on drifting pack ice are prone to damage or destruction by cracking, shearing, and ridging, the experimental design called for a measure of redundancy in the observations of the ice strain field: the initial station array consisted of a central main camp surrounded by satellite camps, arranged in a triangle with sides about 150 km long. The manned station arrays were to be surrounded by a polygon of data buoys at a distance of about 300 km from the main camp.

After numerous flights to locate a suitably large, thick, and smooth piece of ice, deployment of the central main camp began in mid-March 1975. By mid-April, this main camp, three satellite camps, and eight data buoys were in place and had started the observational routines (Figs. 3, 4, 5, 6).

The core observational program produced data on the geographical coordinates of data buoys and manned camps and the barometric pressure and air temperature at these locations. At the manned camps, vertical arrays of anemometers and thermometers were used to deduce the horizontal stress exerted by the wind. Similarly, arrays of current meters below the ice yielded data for the water stress. The dynamic tilt of the sea surface was calculated from deep profiles of ocean temperature and salinity. Routine three-hourly weather observations were taken in support of flight operations (for a full description of the observational program, see the 1975 Operations Manual). This program was designed to measure the external forcing on the ice and its motion and deformation, which were required to realize the scheme outlined in Figure 1. In addition to the core program of AIDJEX, a number of special geophysical studies were



FIG. 3. The AIDJEX main camp near completion in April 1975.



FIG. 4. Satellite camp in spring 1975.

conducted that used the existence of a manned station array as a logistical base of opportunity. These studies are also described in the Operations Manual.

Routine operation of the camps and buoys progressed throughout the summer without significant mishaps (Fig. 7). Another unprecedented benefit was that we had a helicopter on station throughout the summer. Despite the well-known and feared icing condition typical of the Arctic summer, we were able to move personnel and equipment between the camps.

For obvious reasons, the probability that an ice camp will break up increases with its size. The main camp, which covered an area of about 100 m across, had 22 huts and several science installations, including a mast 25 m tall and stacks of fuel drums. So it was no surprise that finally, on 1 October 1975, a long, straight crack split the camp area in two. Over the next 10 days, shearing motion along the crack separated the two halves of the camp by several hundred meters, bringing the observational program at the main camp to a halt (Figs. 8, 9, 10).

Through a massive effort of slinging buildings by helicopter (Fig. 11) and transporting equipment by twin-engine aircraft, we were able to convert one of the satellite



FIG. 5. Observations of wind and temperature profiles in the boundary layer.

camps (Fig. 12) to the new main camp, and by early November the program was back to full-scale operation. It continued to operate without further interruption until the end of the project in mid-May 1976.

The number of people working at the pack-ice stations ranged from 22 to 58. The total presence of workers in the field was 14350 person-days, or 39 person-years. The successive locations and shapes of the manned-camp triangle and the polygons of data buoys in May 1975 and May 1976 are shown in Figure 13.

## SUCCESSSES

### *Ice Thickness Distribution Theory*

From a great distance, for instance from an observatory on the moon, the Arctic Ocean might appear to be covered by a uniform sheet of ice, but the reality is quite different. The ice pack is rough, broken, and irregular. The ice thickness may range from zero to tens of meters over



FIG. 6. NavSat data buoy.

horizontal distances of a few meters. Because the ice thickness affects the dynamics of the ice, it was necessary in AIDJEX to confront the chaotic ice geometry. The result was a conceptual model based on the assumptions that:

1. Ice thickness is the most important geometric property.
2. Ice thickness is a random function of space and time, and only its statistical properties have any geophysical significance.
3. Regions of scale 100 km or so are large enough to provide a statistically significant sample of thickness and small enough to capture the large-scale variations in the ice pack.
4. The statistical properties of the ice thickness respond deterministically to thermal and mechanical forcing. A model of the ice pack might hope to simulate the statistical properties.
5. Mechanical properties, such as the failure strength of the ice pack, are sensitive functions of the thickness statistics.



FIG. 7. Summer on the pack ice.



FIG. 8. In early October 1975, a crack through the middle of the main camp was followed by a 400 m shear that rendered the camp inoperable.

In this conceptual model, the evolution of the ice pack was represented as a competition of thermal and mechanical effects. The thermal processes determined the mean thickness. Over a time scale of years, the thin ice grew more in the winter than it melted in the summer, whereas the thick ice melted more in the summer than it grew in winter. So the net effect was that all ice approached equilibrium thickness. Opposing this relaxation toward an equilibrium thickness, the mechanical processes act as sources of open water and pressure ridges at the extremities of the distribution. Finally, the model linked the thickness distribution to the mechanical behavior of the system by allowing the ice strength to depend on the thickness distribution.

A skeptic might have pointed out that the model was mostly guesswork, with little empirical support. There were so many degrees of freedom in the model that the strategy of optimizing the model by varying the parameters was unlikely to converge on truth.

Ultimately, what we had to work with was a well-defined atmospheric pressure field and a poorly resolved,



FIG. 9. More cracks and dislocations in late October 1975.

large-scale deformation based on the motion of a few buoys. These data sufficed to drive a model calculation. Among the many model outputs were the ice velocities at a grid of points, which could be compared to precisely measured motion at three or four points. In retrospect, it was naïve to expect the measured motions to tell us much about the model parameters.

What did we learn? Much of the time the ice motion at a point was approximately proportional to the geostrophic wind. This is to say that the thickness distribution and ice mechanics have only a small effect on the measured motion. Therefore, measuring the motion is unlikely to tell us much about those processes. At times when the ice mechanics played a greater role, the deformation field was not adequately resolved by the motion of only three or four points. Finally, to study the way the thickness distribution controls the mechanics, one would need to monitor the behavior of different regions having significantly different thickness distributions, and one would need to know those distributions.

Looking back, one wonders why the AIDJEX plan was not criticized more ruthlessly. Perhaps the fact that the plan was logically complete, with no loose ends, nothing missing, and nothing extra led us to overlook some of the practical difficulties. And perhaps the community was carried along by the optimism of the times, associated with rapidly expanding computational power, recent advances in satellite positioning, remote sensing, and automated measurement systems. Or perhaps those who might have seen weaknesses in the strategy also saw the potential for collecting a wealth of new observations about the Arctic environment and held their tongues.

#### *Air Stress from the Atmospheric Pressure Field*

Contrary to the mildly pessimistic prediction of a standing advisory committee in NSF, the derivation of surface air stress from the geostrophic wind field was an unqualified success. The geostrophic wind, derived from the atmospheric pressure field, is turned toward the low pressure



FIG. 10. Kitchen and mess hall building in October 1975. For some reason, people did not linger over dinner.

at an angle that increases with decreasing height above the surface. This angle is modified by the thermal stratification in the atmospheric boundary layer. With the observations taken according to plan, and with the application of a simple boundary layer model, a whole year's worth of surface stress observations were obtained and used in many subsequent studies.

#### *Water Stress and the Discovery of Ubiquitous Baroclinic Eddies*

The objectives of the AIDJEX program were further exploration of the oceanic boundary layer and measurement of ice-water stress. Measurements of current profiles during the AIDJEX pilot program in 1972 demonstrated again the existence of modified Ekman spirals in the upper 25 m during rapid ice drift. A momentum-integral method was developed for determining ice-water stress on pack ice. The method involves few assumptions and includes the effects of both friction and form drag. A more unexpected result of the 1972 observations was the discovery of the widespread occurrence of subsurface mesoscale eddies.

Swift transient undercurrents in the Arctic Ocean had been observed as early as 1937 with short-term current measurements, but their structure was not understood. The extended duration and the multiple camps of the 1975–76 experiment gave ample opportunity to collect data on these features and to show that they are indeed baroclinic eddies. These eddies have diameters of 10 to 20 km and are confined to depths between 50 and 300 m. Current profiles to a depth of 200 m were taken daily from the four manned camps. Temperature and salinity profiles were also taken daily from the surface to 750 m depth. The combined temperature, salinity, and current data over the extended tracks of the stations provided details on the structure, statistics, and behavior of these eddies. Most remarkable was their widespread occurrence. During the 14-month observation period, 146 eddies were crossed, of which 19 represented second crossings. Current velocity in the high-



FIG. 11. More than half of the buildings from the main camp were airlifted to satellite camp “Caribou.”

speed cores of the eddies ranges up to 60 cm/s. This contrasts with velocities of less than 10 cm/s in surrounding waters.

### Stress-Strain Law

As AIDJEX was developing, one of the central questions was how best to represent the resistance of the ice to being deformed. The current idea was that ice is in some way viscous, so that it flows progressively faster as stresses increase. But treating the ice as a viscous material was unsatisfying in a formal continuum mechanical framework, and it had the glaring deficiency that it did not allow the ice, as actually observed, to “lock up”—that is, to get wedged into a coastal “corner” and stop moving. Early on, the analogy was made with granular materials and with plastic yield, which means that the material resists increasing loads without moving until the load reaches some failure criterion, at which point it flows “catastrophically” and can support no greater load.

The idea was put forward that the stress-strain law and the thickness distribution were linked: the work against stresses in deforming the ice cover could be matched to the energy required to modify the thickness distribution in the building of pressure ridges and in the grinding of floes against each other, but it seems that this idea has lost traction. But these forms of rheologies incorporating plastic failure were introduced into sea ice modeling and remain to this day.



FIG. 12. Camp “Caribou” upgraded to main camp. It continued to operate from November 1975 until the end of the project in May 1976.

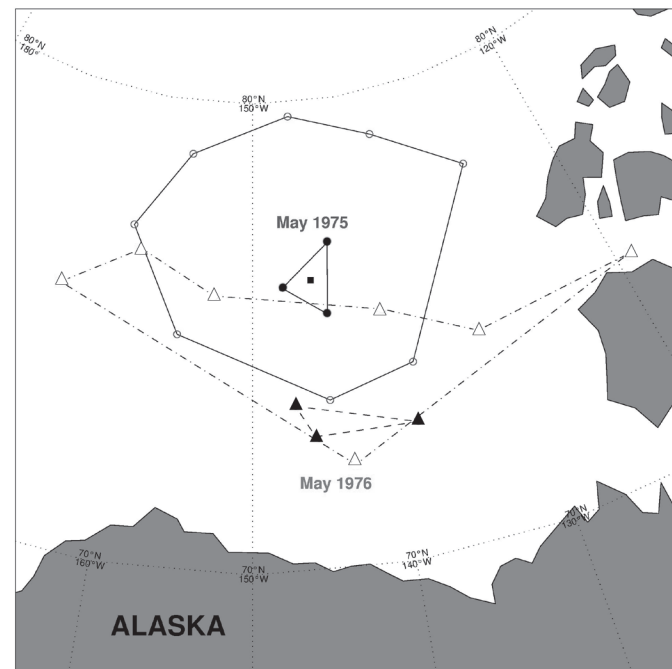


FIG. 13. Initial (dot) and final (triangle) arrays of manned camps (full dots and triangles) and data buoys (open dots and triangles). The location of the original main camp is marked by a black square.

### Buoy Program

At the very beginning, the funding agencies made it clear that AIDJEX was a finite-duration study, and that we could not expect to see it “institutionalized” upon its completion. Many post-AIDJEX proposals for continued work were declined, and it took several years for the Polar Science Center at the University of Washington to emerge as a “Son-of-AIDJEX” research group consisting of several principal investigators pursuing individual topics. However, our convincing success in obtaining data on ice deformation and air stress by means of buoys enabled us to



secure continued funding, which ultimately led to the International Arctic Buoy Program (see below).

### *Ice Draft Data from Submarines*

It was another great coup of AIDJEX that it won participation by the U.S. Navy, which sent a submarine cruise under the AIDJEX camps in April 1976 to measure ice draft along a 1400 km long pattern under our station array. A submarine had never before participated in a civilian expedition. The cruise was unique in that the ship, the U.S.S. *Gurnard*, had two new instruments undergoing their first trials: a narrow-beam sonar and a digital recording device. From that time forward, both devices were standard equipment on Arctic submarine cruises. In another first, the Navy released to the public the actual profile of draft and the approximate geographic cruise track. Papers quantifying the thickness distribution, illustrating the fractal properties of such a profile, and exploring statistics of ridges and leads showed the value of making such data public. Two decades later, toward the end of the Cold War, the Navy orchestrated more cruises with civilian scientists as players and began to release large amounts of previously secret draft profile data. These data are now available as a public archive from the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado.

### *The AIDJEX Data Bank*

Given the stated overall purpose of the project and the number of individual investigators, a novel approach had to be taken with regard to a common data bank. Routine data, such as weather, barometric pressure, station location, and standard oceanographic casts had to be submitted to the data bank prior to further analysis. Specialized data, which had required development of new instruments or techniques to be collected, were “protected” from outside access for one or two years while the principal investigator performed scientific analyses.

After the end of the main experiment, the routine data were processed and submitted to the NSIDC. Additional sets of specialized data were submitted by principal investigators in subsequent years.

The follow-up at the end of an exciting field project—the careful processing of all data, quality control, annotations of metadata, and systematic archiving—is perceived as being less glamorous than the fieldwork itself, and therefore these tasks are often more difficult to fund. What we know is that, in subsequent years, the NSIDC distributed AIDJEX data to many users (see Pritchard, 1980 for an early summary of the results of AIDJEX).

### MISSED OPPORTUNITIES

Despite our preoccupation with ice dynamics, and given the large number of people on the ice, it might have been easy to conduct a comprehensive ice mass and heat balance

study, similar to those conducted at NP-2 and at IGY-Station Alpha. Observations of radiation and turbulent heat fluxes were conducted, but in the absence of systematic measurements of ice albedo, temperature, and ablation/accretion, these could not be related to the mass balance.

Similarly, it might have been easy (and would have required little manpower) to take systematic summertime aerial pictures of the ice from the helicopter on station to study the evolution of melt ponds related to small-scale surface topography, the distribution of meltwater, and the composite ice/melt pond albedo. In fact, there remains to this day a severe shortage of observations of the regional albedo and its evolution through the summer. At the same time, the composite ice/meltwater albedo is still the premier tuning parameter and source of uncertainty in present models of sea ice.

Clearly, a missed opportunity was that we made only a minimal effort to observe the melt rate of pressure ridge keels, which is an item of speculation to this day.

Upward-looking sonar to measure the draft (thickness) of floating ice and the technology to deploy and recover instruments moored at the sea floor existed during AIDJEX, but they were not applied until 10 years later.

### LASTING IMPACT

#### *Upper Ocean Structure*

Mesoscale eddies appear most prevalent in the Beaufort Sea (Canada Basin). Observations during AIDJEX led us to believe that the eddies developed primarily by baroclinic instability of the shelf break circulation in the southern Beaufort Sea. This hypothesis appears to be supported by recent expeditions along the edge of the continental shelf north of Alaska. The role of these eddies in ice-water interaction is still a subject for investigation. They are not being resolved in ocean models, and their cumulative effect on the upper ocean structure and ocean heat flux remains to be elucidated.

#### *Buoy Program*

Our successful use of automatic data buoys to obtain data on ice deformation and air stress enabled us to secure post-AIDJEX funding, first from the National Science Foundation and the Canadian Atmospheric Environment Service in 1978, and later from NOAA’s Global Atmospheric Research Program (GARP) and the United States Navy (Office of Naval Research and the Naval Oceanographic Office). Germany, France, Japan, Norway, and Russia joined to participate in the program, and since 1991, there has been an International Arctic Buoy Programme (IABP), deploying an annual average of 25 buoys of different designs and a growing level of sophistication and producing valuable and widely used data. The published literature contains more than 500 citations of the

IABP data, which includes buoy locations and time derivatives, sea level pressure and temperature and, for selected locations, ocean temperature and salinity. The data can be found on the Internet at <http://iabp.apl.washington.edu/>.

### *Ice Kinematics from Satellites*

To test the idea that ice deformation changed the ice-thickness distribution in quantifiable ways, AIDJEX pioneered the idea of carefully measuring both the deformation and the changes in leads and ridges in sequential LANDSAT images. This germ of a methodology grew into the routine and large-scale measurement of deformation, first from SAR imagery and later from passive microwave imagery. These techniques are commonplace today. The initial deployment of SeaSat in 1978 was followed by a succession of other satellites carrying Synthetic Aperture Radar (SAR) equipment, and these are collecting enormous amounts of data from the Arctic. In 1989, NASA built a facility on the University of Alaska campus in Fairbanks that routinely collects SAR data from over the Arctic Basin and processes them into kinematic sea ice data. Such data strongly complement kinematic data from buoy tracks for testing modeled ice motion and for assimilation into model hindcasts.

### *Sea Ice Model Development*

Cutting-edge ice models today contain two common vestiges of AIDJEX model development: plastic failure and a thickness distribution. Today's modelers are always up against the limits of finite computing resources. Their art is one of balancing how finely to resolve thickness, how accurately to solve the non-linear plastic flow equations, and how realistically to represent the surface heat balance and conduction of heat through the ice cover. On the other hand, what was learned three decades ago about air and water drag coefficients and their seasonal variation with stability seems, peculiarly, not to have ever been incorporated into high-end ice models.

With regard to sea ice in interactive global climate models, it appears that the thermodynamic-dynamic sea ice models have reached a level of sophistication far greater than can be used in global climate models. While most of the current climate models include sea ice, the modeled extent and thickness vary widely, and most models achieve an approximately correct contemporary ice

cover only by purposeful tuning, most commonly by tuning the ice albedo.

The daunting ice/climate problem is the extreme sensitivity of sea ice to thermodynamic forcing by the atmosphere and the ocean. Current climate models produce cloud and down-welling radiation fields differing by such large amounts that they allow calculations of ice thickness ranging from zero to more than 10 m. It seems unclear at this point how the model predictions of future climates can be improved to include credible predictions of the sea ice cover.

### ACKNOWLEDGEMENTS

We are grateful to Ron Kwok, Jet Propulsion Laboratory, for scanning all 40 issues of the AIDJEX Bulletin and making them available on the web, and to Ignatius Rigor for making Figure 13. Most of all, our gratitude is due to all the people who made AIDJEX happen, most notably to the late Richard Trowbridge, Associate Project Director; Max Coon, head of the Modeling Group; Patrick Martin, Technical Manager and head of the Buoy Program; Rolf Bjornert and Andreas Heiberg, Managers of Field Operations; Alma Johnson, editor of the AIDJEX Bulletin; and all the dedicated principal investigators and other scientists and helpers in the field, at the project office, and at their home institutions. We also thank Joseph Fletcher, the first director of the project office in 1970–71, and Richard Goody, who chaired the Joint Panel for AIDJEX of the National Research Council and who championed our cause before the National Science Board.

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