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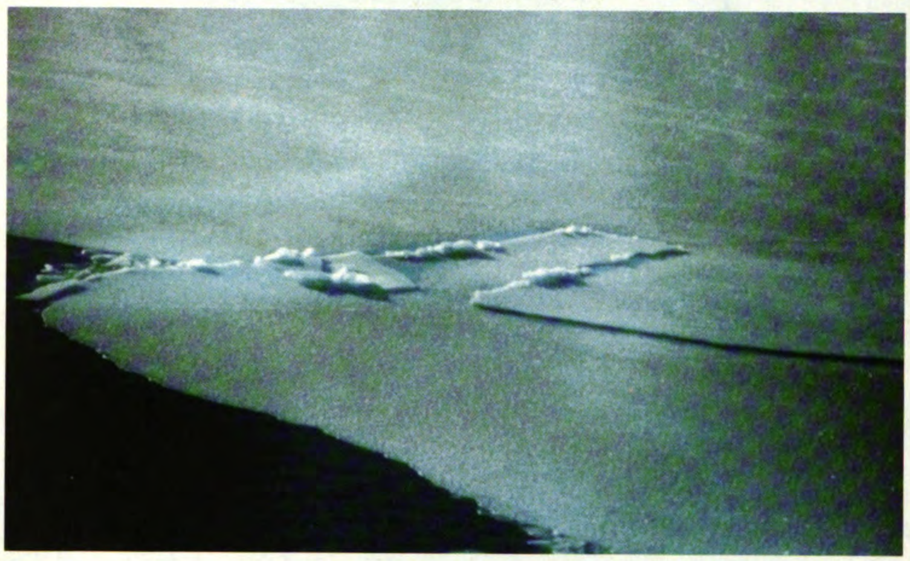
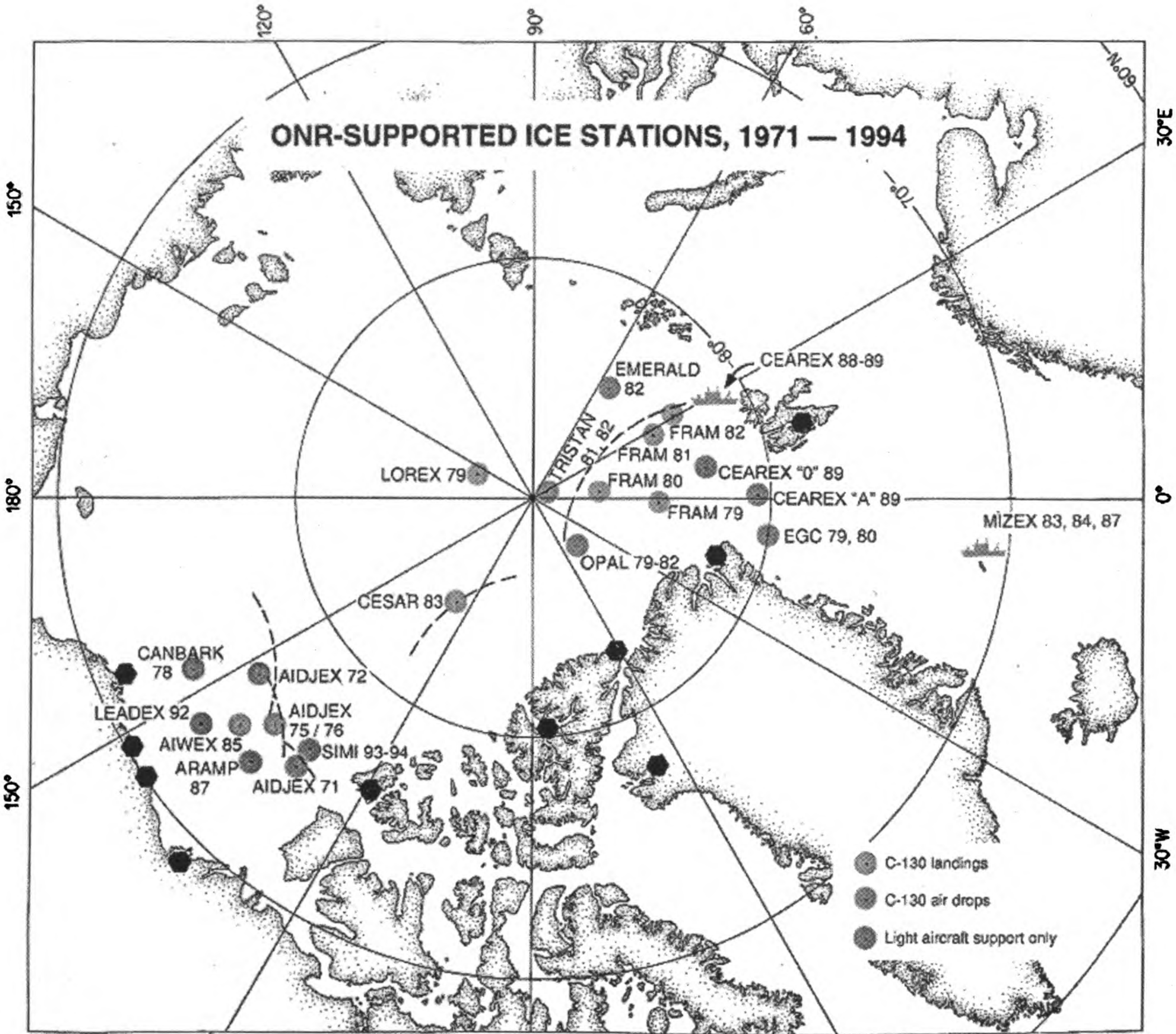


Arctic Studies



Office of Naval Research (ONR) sponsored a program of manned ice camps in the late 1940's where scientists worked and lived for long periods of time. Initially the camps were situated on thick pieces of glacial ice (100 or more feet thick) which were stable and lasted for decades. Such ice islands were rare because very few glaciers drift into the Arctic Ocean.

Starting in the 1970's, ONR shifted to manned camps on thinner mobile sea ice. Logistic and support techniques have been perfected to the point that such camps are now routine for Arctic research and are used to support under-ice naval operations. Ice camps are the research and equipment platforms for studying large scale sea ice in its environment.

Up-to-date information on the extent, position, thickness and break up characteristics of sea ice are vital for Arctic naval missions. An understanding of the large scale response of sea ice to its environment is needed for solving many important practical and theoretical problems ranging from the interaction between the ice cover and global circulation to navigation on and under the ice-covered sea.

Picture courtesy of A. Heiberg.

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About the cover
Finger rafting is a common phenomenon in ice covered regions. Individual fingers range in scale from centimeters to hundreds of meters, and usually occur in regular patterns. The finger shown here is about three meters long. The precise mechanism for finger rafting is not well understood.

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History of the ONR Chair in Arctic Marine Science

Robert H. Bourke, Department of Oceanography, Naval Postgraduate School, Monterey, CA

The polar marine science community is a small segment of the much larger and broader U.S. and international marine science community. It is a close knit community as attested that most of us gathered in this room this afternoon know a considerable number of the attendees. We may be small in numbers but we are truly global in our interests as many of us study phenomena and processes associated with both the Arctic and Antarctic polar regions. The polar oceanography community is truly international in its make up with most U.S., Canadian and European scientists having worked together over the years. In the past 15 years this international cooperation has flourished with meetings and workshops being held in the U.S. and Europe and attended by members from many countries including colleagues from Asia. As an example, think back and recall how many different countries were represented on the Polarstern during the MIZEX experiments. Another example is to note that over 15 countries had scientists present at the Nansen Centennial Symposium in Bergen in 1993.

Today this diverse group, encompassing members from a broad spectrum of the geophysical sciences, is gathered to honor both the U.S. Navy, in particular the Office of Naval Research, for having the wisdom and foresight to establish a research Chair in Arctic Marine Science and the scientists who have occupied the Chair. In 1976, 20 years ago, the Chair was founded through the efforts of Warren Denner and Ron McGregor. Twenty years later the occupants of the Chair read like a who's who in polar marine science with representatives from universities, government and research laboratories, a variety disciplines and five different countries (Table 1). Today we will hear from 13 of these Chair alumni.

Before I introduce our honored colleagues and speakers, let me digress and tell you of the early history of the Chair, its formation and evolution.

In the years after WWII during the 1950s and 1960s, the U.S. Navy exhibited little interest in the Arctic region, i.e., the Navy didn't expect to conduct war fighting operations there. However, scientists from various universities

Table 1:
Occupants of the ONR Arctic Marine Sciences Chair

1976-77: PROFESSOR WARREN W. DENNER Naval Postgraduate School (Ice Dynamics/Mechanics)	1983-84: PROFESSOR WALKER O. SMITH University of Tennessee (Ice Edge Biology)	1990-91: PROFESSOR JOHN L. NEWTON Consulting Scientist (Arctic ASW)
1977-78: PROFESSOR ALLAN M. BEAL Arctic Sub Lab (Sea Floor Bathymetry)	1984-85: PROFESSOR H. JOSEPH NIEBAUER University of Alaska (Ice Dynamics)	1991-92: PROFESSOR ALAN S. THORNDIKE University of Puget Sound (Sea Ice Physics)
1978-79: PROFESSOR WILFORD F. WEEKS CRREL (Ice Mechanics)	1985-86: PROFESSOR STEPHEN A. ACKLEY CRREL (Ice Mechanics)	1992-94: PROFESSOR JAMES H. WILSON Consulting Scientist (Arctic Ambient Noise and ASW)
1979-80: PROFESSOR ALLAN R. MILNE IOS (CANADA) (Ambient Noise)	1986-87: PROFESSOR JOHN E. WALSH University of Illinois (Sea Ice Variability)	1994-95: PROFESSOR ARNOLD L. GORDON Lamont-Doherty Earth Observatory (Antarctic Circulation)
1980-81: PROFESSOR PETER WADHAMS Scott Polar Research Institute (Ice-Wave Interaction)	1987-88: PROFESSOR ROBERT S. PRITCHARD Consulting Scientist (Arctic Sea-Ice Dynamics)	1996-97: PROFESSOR LAWSON W. BRIGHAM Cambridge University, USCG (Ret) (Remote Sensing, Ice Operations)
1981-82: PROFESSOR OLA M. JOHANNESSEN University of Bergen (Marginal Ice Zone)	1988-89: PROFESSOR ARNE FOLDVIK University of Bergen (Ocean-Ice Shelf Interaction)	
1982-83: PROFESSOR MILES G. MCPHEE Private Consultant (Ice-Water Boundary Layer)	1989-90: PROFESSOR JAMES H. MORISON University of Washington (Under-Ice Boundary Layer Dynamics)	

were interested in studying a broad range of topics related to the Arctic environment. In 1947 the Naval Arctic Research Laboratory (NARL) was established at Pt Barrow in Alaska to provide a base of operations for these scientists. When Warren Denner joined the faculty of NPS in 1963, he inherited and expanded a course in Polar Oceanography based mainly on the venerable Russian work of Zubov. Warren recognized the need to get these naval officer students into the field to experience the harsh realities of the polar environment so he arranged to have the class taught at NARL in 1964/65. The class continued to be offered twice a year at NARL until the lab closed in 1978.

During the late 60s, early 70s, when the ARLIS and T-3 ice camps were in operation, Warren got to know Ron McGregor who was the Polar Program Manager at ONR. In 1973 Warren was selected to be the Director of NARL where he remained until 1976. It was during these years that Warren and Ron recognized the need to increase the Navy's awareness of polar science. The reluctance to consider polar operations as a potential warfare theater was one mainly borne of ignorance, with the important exception of the submarine force who recognized its significance after the successful trans-Arctic voyage of NAUTILUS in 1958.

When Warren Denner returned to NPS in 1976, he convinced the NPS administration to establish a research Chair supported by ONR. This was no easy task as Chairs were a new entity to NPS at that time. Warren was the first Chairholder and worked to establish its foundations of providing a means to make the civilian polar science community aware of the Navy's needs and capability to conduct operations in, above and beneath ice-covered waters. The objectives of the Chair, as defined 20 years ago, are still valid today: (1) the Chairholders are to conduct polar research and assist in translating basic knowledge into operational products and (2) to inculcate a love of polar science in NPS students and students from their own institutions in order to provide the Navy with a cadre of officer and civilian polar experts.

In 1977-78 Alan Beal held the Chair. Alan had a long, illustrious career at the Arctic Submarine Laboratory working with its founder, Waldo Lyon. He served as Chief Scientist on many of the icebreaker cruises that my colleague, Bob Paquette, and I participated in. Alan passed away several years ago, the only deceased Chairholder among the Chair alumni.

In 1978, when Warren left NPS, Bob Paquette took over the duties of Chair Administrator during which time he recruited Willy Weeks, Allen Milne, Peter Wadhams, Ola Johannessen and Miles McPhee to the Chair. I took over as the Chair Administrator in 1983/4 upon the retirement of Bob Paquette and have had the good fortune to recruit and work with 12 more Chairholders since then.

As I said earlier, the Chairholders represent a broad spectrum of countries, universities and labs and disciplines. Four have come from other countries: Allen Milne from Canada, Peter Wadhams from England, Ola Johannessen and Arne Foldvik from Norway. Government labs are represented by Alan Beal from ASL, Willy Weeks and Steve Ackley from CRREL, and John Newton from NRAD. Private consulting companies are represented by Miles McPhee, Bob Pritchard and Jim Wilson.

When categorized by scientific discipline, the largest preponderance is, perhaps not surprisingly, associated with sea ice, the all pervasive medium that defines the polar regime. In this category I have included Warren Denner, Willy Weeks, Peter Wadhams, Steve Ackley, Bob Pritchard and Alan Thorndike. Their studies mainly concern ice mechanics, its properties, strength, thickness and temporal and spatial distribution. The study of the ocean underlying the ice cover, i.e., its physical oceanography has been conducted on micro to macro scales by Arnold Gordon, Arne Foldvik, Joe Niebauer, Jamie Morison, Miles McPhee and, if we fold in the specialty of remote sensing, we include Ola Johannessen and Lawson Brigham. The Navy has long had an interest in acoustic propagation and noise generation in the polar seas tied to submarine operations in ice-covered waters and the conduct of ASW missions to counter the submarine threat. This group of applied scientists includes John Newton (who has ridden on most of the SUBICEX boats and participated in many ice camps), Jim Wilson, Allen Milne, Alan Beal and Warren Denner.

We have two remaining Chairholders whose specialty is not in either of these three preceding groups. Walker Smith is the lone biological oceanographer but is well known for his interaction with the physical oceanographers. Indeed, he and Joe Niebauer have teamed up over the years in large part because their tenure in the Chair overlapped and opened the door for a shared view of the oceanography near the ice edge. Our lone mid-westerner and atmospheric scientist, John Walsh, has shown how climate variability affects the ice distribution on seasonal, annual and longer time scales.

Although the Chair was initially set up to further our knowledge and understanding of the processes affecting the Arctic Ocean and its peripheral seas, it soon broadened to polar seas in general. Like many of you in the room today, many of our Chairholders have conducted research in Antarctic waters, notably Arnold Gordon, Steve Ackley, Willy Weeks, Arne Foldvik, Peter Wadhams, Walker Smith, Jamie Morison, and Miles McPhee. In their talks this afternoon you will hear of the similarities and differences between these two ice-covered oceans.

Table 2
Technological Advances

GPS
- provides precise navigational accuracy

Satellites
- visual, infrared, microwave, radar
- frequent, wide area remotely sensed observation

Arctic Buoy Program
- surface pressure/winds and temperature throughout Arctic basin

SUBICEX/SCICEX
- submarine science measurement programs

Icebreakers
- deep penetration into Arctic Ocean
- North Pole and Trans-Arctic voyages "routine"

CTD
- continuous observations in the vertical, increased speed and accuracy

ADCP
- ship/moored current observations over large segments of the water column

Computer Power
- in situ data processing/analysis
- high resolution forecast/simulation models developed

Acoustic Sensors
- horizontal and vertical directionality
- upward looking sonars for ice draft observations

Data Sets
- longer records, higher quality

My initial intent was to include some anecdotal remarks for each Chairholder relative to their stay in Monterey. However, the compacted schedule prevents me from doing this. I can say that all have enthusiastically enjoyed their time at NPS and found it highly productive. Most finally found time to complete long over due manuscripts, thoughtfully examine old and recent data sets or participate in planning for future field projects. In this latter regard, ONR actively involved the Chairholders in much of the early planning for the MIZEX series of experiments and follow on experiments such as CEAREX and LEADEX. Many acted as thesis advisors for our Naval Officer students; their expertise was highly sought after by both our faculty and students. One of the side benefits of the Chair has been the continued interaction with NPS faculty long after their departure from the Chair. The collegial relationships developed at NPS have lead to joint partnerships on research projects and scholarly papers. I am also appreciative of the help they gave me in providing lectures in the Polar Oceanography course.

An important and integral part of the Arctic Chair team are the ONR Polar/High Latitude Program Managers who have provided guidance and financial support for the Chair. Leonard Johnson took over from Ron McGregor in the late 1970s and he and Tom Curtin have since been the mainstays of program support for the Chair, and Arctic marine science in general, for the past two decades. To them we owe a debt of gratitude for steering numerous field programs from inception to successful completion. Tom Curtin, in the next talk, will highlight the purpose and scientific advances of some of these major programs. Today Mike Van Woert heads up the ONR High Latitude program. He sends his regards to our honored alumni. Unfortunately, he is unable to join us this afternoon as he is on a long awaited trip to Antarctica at this moment.

We have chosen the theme of this anniversary session to look back upon the advances we have made in the past twenty years, and they are indeed impressive, and to suggest where we might focus our attention, resources and effort for the next 5 to 10 years. Each of our Chairholders will address the accomplishments and potential future direction for the various disciplines they represent. It is our intention to publish their talks as a collection of extended abstracts.

In order to kick off this theme I have prepared the two following tables which illustrate some of the technological advances (Table 2) of the past 25 years and the scientific advances (Table 3) that have resulted from this improved technology. The lists are by no means complete but do serve to illustrate how far we have pushed the scope of our understanding of Arctic processes.

As we look back over the past 20 years, I think we would all agree that indeed we have made substantial progress in our understanding of the processes that drive the Arctic atmosphere ice-ocean environment. They have been years filled with challenging and exciting field programs, mostly conducted in the Alaskan-Canadian-Greenland sector of the Arctic. We can look forward to increased mutual cooperation with our Russian colleagues and perhaps joint observational programs conducted in the Siberian Arctic. Much data exchange has recently take place with Russian scientists and even more is anticipated. Instead of field programs conducted mainly in the spring and summer seasons, we can anticipate data collection efforts year 'round as remote or autonomous instruments will relay their data via satellite or internet back to our labs. This may be the route that we will take if we are to set up a continuous monitoring program to observe the remarkable changes that have been taking place in the Arctic Ocean since the start of this decade.

I think we can say that the goals of the Chair have been met. The Navy has developed a pool of officers who have a strong appreciation for the impact of the Arctic environment on all aspects of naval operations. These officers occupy positions of technical and strategic importance at the National/Naval Ice Center, ONR, the Naval Research Lab and other commands. On the other hand, the operational forecasts they routinely produce and interpret were for the most part developed and continuously improved by the collective efforts of many of you sitting in the audience this afternoon.

Table 3
Scientific Advances

Circulation
- improved knowledge of surface, intermediate, deep waters
- seasonal, interannual and decadal variability
- role of continental shelves, convective cells, canyons

Ice Rheology
- improved models relating to ice deformation processes

Ice Concentration/Thickness
- temporal and spatial distribution
- long term trends

Heat Flux
- albedo, leads/polynyas, cloud cover, boundary layer

Geochemistry
- water mass, circulation tracers

Acoustic Propagation
- underice scattering models
- signal processing to reduce reverberation, improve target recognition

Russian Data/Collaboration
- access to Russian arctic
- historical data bases of many parameters

Climate Models
- dominant role of arctic region in global circulation, climate studies

Because of the breadth and visibility that the Chair brings to the study of polar marine science, I am pleased to report that ONR will continue to support the Chair for the foreseeable future. Announcements and advertisements in EOS have gone out for next year's Chair. So, if you are interested in spending a year at Monterey, starting next fall, or perhaps sometime in the next few years, please contact me.

Now as we commence our program to celebrate the Arctic Chair's 20th anniversary, I salute our former Chairholders and ONR program sponsors. I look forward to welcoming many more of you to the Chair in the coming years.

Historical Perspectives on the Arctic Program at the Office of Naval Research

Thomas B. Curtin, Office of Naval Research, Arlington, VA

"In the history of exploration of the North country, the United States Navy has played a most significant and exciting role. The names of Admiral Robert E. Perry, Admiral Richard E Byrd, Commander Donald B. MacMillan, Commander Richard Cruzen, Commander Lincoln Elllsworth and of Dr. Elisha Kent Kane, a naval medical officer who led his expedition in search of a lost Sir John Franklin expedition, immediately make one realize how great has been the role that the United States Navy has played in searching the mysteries of the North." (Shelesnyak, M.C. and V. Stefansson, 1947)

For more than fifty years, the Office of Naval Research has continued the tradition of scientific inquiry by maintaining an active, multi-disciplinary, Arctic basic research program. The tenets of the program, set forth in 1947, remain valid today:

"Specifically, however, the Office of Naval Research is interested in precise information regarding the meteorology, geology, and environmental influences of the North country on man and to that end is getting underway a program for the scientific information of Arctic conditions in the United States' own Arctic territory, the northern slopes of Alaska. With this basis of information and the possibility of exchange of information from other sources, the Navy should have a complete picture of the true north and therefore be able to use it to its fullest possible extent.

"This last frontier of exploration presents an exciting field not alone in terms of the old geographical exploration, but more in terms of the utilization of our finest and newest techniques in geophysical and biological science applied to a large and vast area of relatively unknown territory. It is a true challenge to the research-minded youth of our country." (ibid., 1947)

In addition to high quality investigations across a range of scientific disciplines, key elements of the program, established at inception and maintained for over a half century, are international collaboration, bold field experiments, development and use of innovative technology, and support of graduate students.

Singular among federal research programs in any field, the Arctic Program at the Office of Naval Research has been managed by just seven people spanning over fifty years (Figure 1). The tradition of proactive, involved managers was established early as documented in one of the program's first publications:

The Office of Naval Research has many Arctic experts working on various phases of its Arctic research program. Several of these men have contributed to this pamphlet. Sir Hubert Wilkins has written a valuable introduction and Dr. Vilhjalmur Stefansson has compiled a useful bibliography on Arctic literature. The main article of the pamphlet was written by Dr. M.C. Shelesnyak, Head of the Environmental Physiology Branch, Office of Naval Research.

"Dr. Shelesnyak gathered material about the Arctic as United States Naval Observer with the Moving Forces, Canadian Army Winter Arctic Expedition, Operation Musk-Ox, in 1945. The expedition traveled by motorized, tracked vehicles 3100 miles across the Canadian Arctic prairies, Queen Maude Gulf, Coronation Gulf and southward from Coppermine to Port Radium, across Great Bear Lake and down through the bush country along the Alaskan-Canadian Highway to Edmonton. Dr. Shelesnyak's first-hand knowledge of the Arctic was further broadened by his experiences in traveling by dog sled from Coppermine N.W.T. to Cambridge Bay, Victoria Island, having left the Moving Forces to rejoin them later." (ibid., 1947)

Measures of the fifty years of research supported by the program are the associated cumulative scientific literature and the strategy and tactical procedures, both military and commercial, influenced by that knowledge. A comprehensive bibliography has not been compiled. To do so would be a major task, and no doubt the result would be impressive. A few of of the major insights achieved over the years are highlighted in Figure 2. Atmospheric circulation patterns and pollutant (haze) pathways are now well established. The mechanical, electrical and chemical properties of sea ice as well as its dynamics and thermodynamics over a hierarchy of scales are known well enough to enable predictive models with some skill. The statistics of sea ice extent, variability, drift, and to some degree its thickness have been determined. Propagation of sound, both at low and high frequencies, including scattering and transformation into a rich class of plate waves some of which were discovered initially in the Arctic, can now be modeled accurately. Ambient noise mechanisms have been established. The Ekman spiral, derived theoretically, was first observed in the Arctic, as was thermal microstructure. The ocean circulation, including water mass residence times and mesoscale eddy distributions, is now generally known. Unique aspects of the internal wave spectrum have been documented. The high primary productivity in the marginal ice zone has been quantified and its mechanisms elucidated. The Nordic Seas have been determined to be carbonate vice silicate dominated oceans, leading to a role in global carbon sequestration. Near surface bacterial abundance at high latitude is far greater than previously thought. The properties of permafrost are known and were used to great advantage in pipeline construction. Bathymetric, magnetic and gravity fields have been mapped to useful, but not high, resolution. Understanding how much there is yet to be understood is always sobering. However, contrasting man's knowledge of the Arctic marine environment from a view in 1945 to one in 1998 gives an appreciation of how much has been accomplished.

Logistics has always been inextricable from science in the Arctic. Ice stations or camps have been central ways of doing business since Nansen pioneered the method with the Fram. A relative ice station activity index for the program is plotted at the bottom of Figure 2. During peak years, logistics costs typically consumed 20-40% of the program budget. The locations of ice stations since 1971 are shown in the inside front cover of this issue. From the mid sixties to the late seventies, many expeditions in the western Arctic were staged from the Naval Arctic Research Laboratory (NARL) at Point Barrow, Alaska. Eastern Arctic stations were staged from Greenland or Norway. Since the Navy's divestiture of NARL to the North Slope Borough in the late seventies, there has been a slow but steady trend toward autonomous instrumentation. That trend is expected to accelerate in the coming years with advances in microprocessors, navigation and communication technology. Considering the number and diversity of people involved, the variability and extremes of nature, the remote and Spartan accommodations on the ice, and the invariably tight budgets, it is a notable tribute to the operations managers over the years that all have returned safely to analyze their data.

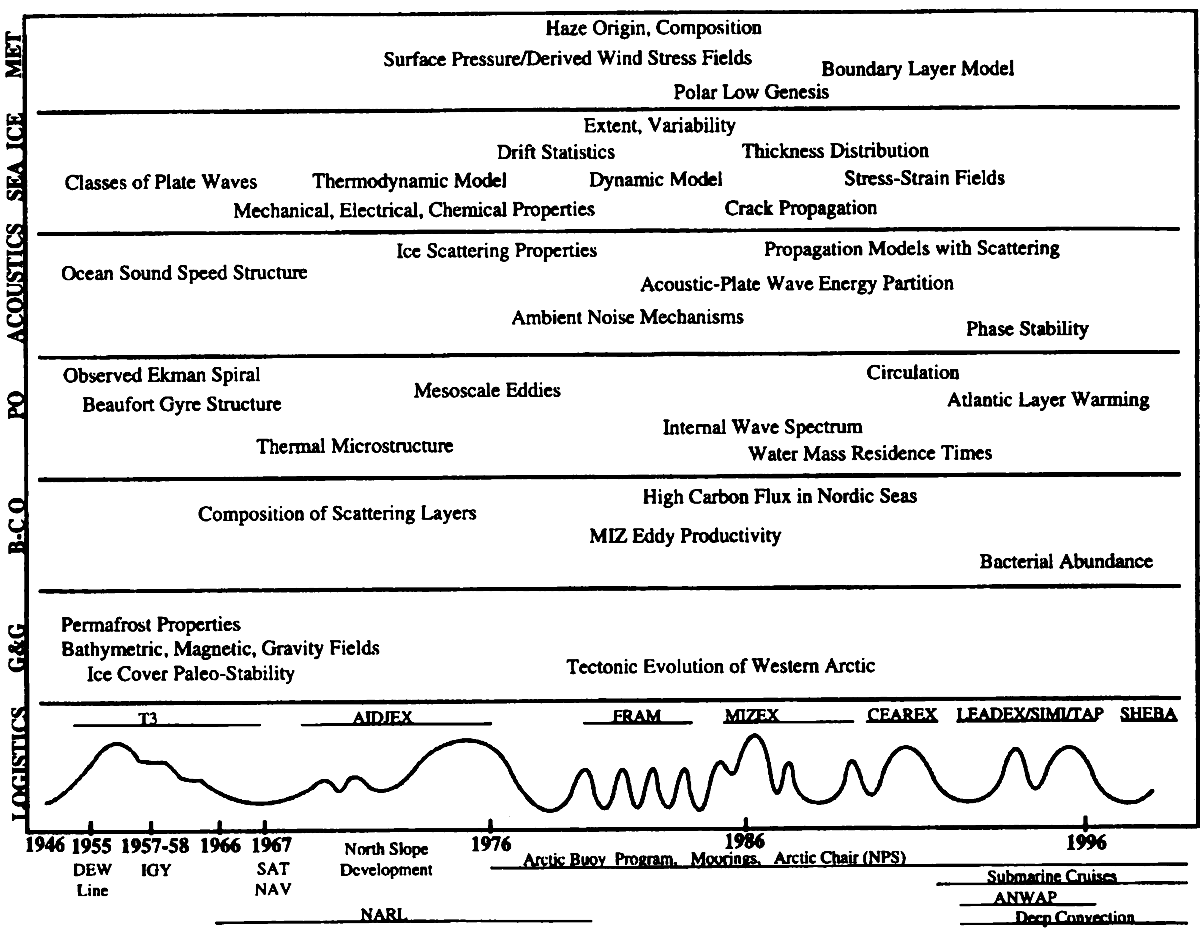
From a historical perspective, there have been three stages of United States Naval interest in the Arctic. The first stage was marked by exploration, driven by personalities like

Figure 1
Program managers of the Arctic Program since its inception at the Office of Naval Research.

1947 - 1954	M.C. Shelesnyak
1954 - 1970	M.E. Britton
1970 - 1975	R. McGregor
1975 - 1984	G.L. Johnson
1984 - 1994	T.B. Curtin
1994 - 1996	M. Van Woert
1998 -	Dennis Conlon

Figure 2

A few of the major insights by discipline achieved over the years of the Arctic Program at the Office of Naval Research.



Perry, Byrd, Ellsworth and Kane. The second stage was characterized by more calculated investigations and classified operations, framed by the cold war and the advent of the nuclear submarine. The Office of Naval Research was established at the beginning of this second stage, and the Arctic program has existed only in this context until recently. The third stage began with the end of the cold war. The investment strategy and method of operation for the current stage are evolving now. This evolution is in many ways unprecedented.

Acknowledgments

The collective principal investigators spanning fifty years are the essence of the ONR Arctic Program. The complete history of the Program lies in their accomplishments reflected both in the scientific literature and in numerous unrecorded, successful naval missions accomplished. Art Baggeroer, Andy Heiberg, Ken Hunkins, Leonard Johnson, Ned Ostenso, Norbert Untersteiner and Willy Weeks contributed significantly to this article.

REFERENCES

Shelesnyak, M.C. and V. Stefansson, 1947. Across the Top of the World, A Discussion of the Arctic. Office of Naval Research, Navy Department, NAVEXOS P-489, Washington, D.C., 71 p.

Arctic Climate Variability: Observations and Model Simulations

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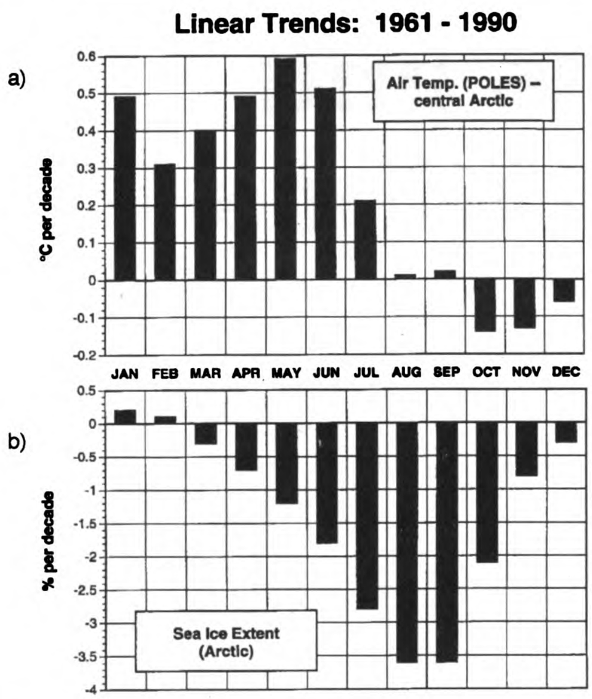
It is well-known that global climate models show a polar amplification of the near-surface warming of the atmosphere in response to increased concentrations of greenhouse gases. While the Arctic warming is diminished somewhat when the climate models include sulfate aerosol effects and coupling to a deep ocean, the polar amplification is a pervasive feature of model-projected greenhouse warming, especially in the Northern Hemisphere. The model-projected warming is associated with a retreat of sea ice and is generally accompanied by an increase of precipitation in high latitudes (IPCC, 1996, p. 307-309). If the models are correct about the amplification of greenhouse effects in the polar regions, then the recent build-up of greenhouse gas concentrations (an increase of equivalent CO_2 by approximately 50% since the mid-eighteenth century) should be producing a detectable response in the polar regions. Unfortunately, detection of such signals is hampered by the short record lengths of datasets describing the polar atmospheres in a systematic way. Many polar datasets are not only limited to the past several decades, but are often extremely limited in spatial coverage over the Arctic Ocean, the subpolar seas, and most of Antarctica. In the present summary, we examine several datasets depicting Arctic variability over short climatic timescales: the most recent several decades. Such timescales are likely inadequate for unambiguous detection of greenhouse effects in the Arctic. Nevertheless, these datasets illustrate the magnitudes of the Arctic's multidecadal variability (natural or otherwise), and they will point to several regions, seasons, and variables that may merit close monitoring in the coming decades. In addition, an examination of data-derived variations in the context of climate model simulations will point to several observational issues relevant to climate signal detection in the polar regions.

In general, station data show a near-surface warming in the Arctic over the past several decades (Chapman and Walsh, 1993). This warming is apparent even when stations suspected of having urban influence are removed from the

Figure 1
Linear trends (1961-1990) of (a) Arctic Ocean surface air temperature, °C per decade, from POLES data (S. Martin, Univ. of Washington); (b) Arctic sea ice extent, % per decade (from Chapman and Walsh, 1993). In both (a) and (b), data are pooled into three-month periods centered on indicated months.

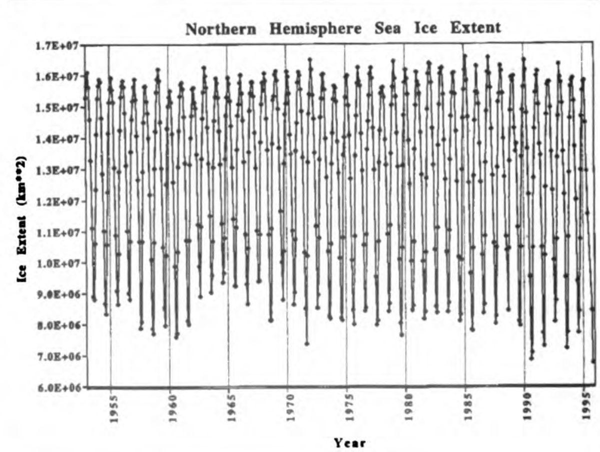


dataset (e.g., Jones, 1994). The warming is most apparent over northwestern North America and northern Eurasia. Although the absence of permanent stations over the Arctic Ocean makes it difficult to map the recent temperature variations poleward of the northern continental margins, an analysis by Martin et al. (1997) of temperatures from drifting ice stations suggests that the Arctic Ocean's surface air temperatures have indeed increased since 1960 during the winter and spring (Fig. la). This seasonality is consistent with the warming over the northern continents. However, this seasonality does not match the seasonality of climate models' greenhouse warming, which is generally strongest in autumn. There is a general compatibility in the spatial patterns of the annual mean warming obtained from models and observational data, although the tendency for the northern continental areas to warm the most is also consistent with the natural variability found in climate model simulations. The observed warming over northern high latitudes also appears to be at least partially attributable to recent shifts in the atmospheric circulation and its temperature advection pattern (e.g., Trenberth, 1990). In addition, the associated sea ice trends are different in the observational data and in the model simulations of climate change. Thus any attribution of the recent multidecadal warming to the greenhouse effect of increased CO_2 is open to question.

Figure 2 is a monthly time series of Northern Hemisphere sea ice extent for the years 1953 1995, inclusive. The wintertime maximum of sea ice extent has remained remarkably constant through the period. However, there is a noticeable tendency for more frequent extreme summer minima in recent years. The three lowest values of summer ice extent in the period of record occurred during the 1990s, in agreement with the recent findings of Maslanik et al. (1996). The linear trends of sea ice extent (Fig. lb) are consistent with the time series of Fig. 2: negative trends are largest in the summer and essentially nonexistent in the winter. The extent to which this seasonality disagrees with all the greenhouse projections of climate models will likely depend on the rapidity of the recovery of the extent of sea ice, perhaps only of small thickness, to its "historical" winter maximum after an extreme summer melt. Regionally, the decrease of summer sea ice has been largest in the Asian Arctic; there has been no decrease (and even a slight increase) in the Labrador and Greenland Seas.

Observational data (IPCC, 1996, p. 152-155) also suggest that precipitation has increased over northern land areas in recent decades, although the spatial scatter of precipitation reduces the statistical significance of these increases. Correspondence with the increases projected by models must be tempered by the apparent biases in the model simulations of present-day precipitation, as well as by the considerable uncertainty in observational measurements of precipitation in cold windy environments. There is a definite tendency for the climate models to oversimulate Arctic precipitation. The model biases are typically 25-75%. This

Figure 2
Time series of end-of-month sea ice extent, 1953-1995, for the Northern Hemisphere. Data are from Chapman and Walsh (1993), updated through 1995 using data from National Ice Center.



bias extends to the northern terrestrial regions and to P-E (precipitation minus evaporation), based on comparisons of observed river discharge and the areally-integrated P-E from climate model simulations (Walsh, et al., 1997).

In summary, recent decadal-scale variations of Arctic climate are generally consistent across variables, at least in the annual mean: the Arctic has become warmer, wetter, and more likely to experience extreme summer minima of sea ice extent. An exception appears to be the North Atlantic, including the Labrador and Greenland Seas. However, given that the warming has been relatively strong in winter, it is unclear why there has not been a more notable decrease of wintertime sea ice extent. Claims of compatibility between the recent variations and model-derived greenhouse projections appear to be premature for several reasons. First, the seasonally of key features such as the polar warming is different in the data (winter/spring warming) and the models (autumn/winter warming). Second, there are large differences among models in their simulations of variables such as precipitation and cloudiness for the present climate. For those variables for which direct observational comparisons can be made, there are often substantial biases of the simulated quantities relative to their observational counterparts. Explanations of the scatter and elimination of the polar biases will require systematic mode experiments.

The next 5-10 years will likely provide unprecedented opportunities for the detection of the climate-change signals in the Arctic. Not only are such changes anticipated (and arguably, overdue), but there are likely to be observational and modeling opportunities that significantly enhance our knowledge of the Arctic climate system's temporal evolution. The availability of a nuclear submarine dedicated to science missions (SCICEX) will permit the measurement of sea ice thickness in a more systematic manner than has heretofore been possible. Given the ambiguities in the recent record of sea ice extent, ice thickness may well be the variable of choice for sea ice monitoring. In addition, the length of the Arctic buoy network's database is now approaching 20 years, permitting meaningful determination of trends in the basin-wide fields of atmospheric pressure (circulation), ice motion/deformation, and air temperature. Improved sensors of temperature will allow the mapping of this key variable with much greater confidence than in the past. Coordinated field programs such as SHEBA, ARM and FIRE will provide not only their suites of intensive measurements, but also process studies that will enhance our understanding and modeling capabilities with regard to key Arctic processes (especially those involving the surface energy budget and clouds). The resulting model improvements should add credibility to model-based data assimilation efforts, e.g., reanalyses, which will likely emerge as useful tools for the documentation of changes in the Arctic climate system.

REFERENCES

Chapman, W. L., and J. E. Walsh, 1993: Recent variations of sea ice and air temperature in high latitudes. *Bull. Amer. Meteor. Soc.*, **74**, 33-47.

IPCC, 1996: *Climate Change 1995: The Science of Climate Change* (J. T. Houghton- L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell, Eds.), Intergovernmental Panel on Climate Change, Cambridge Univ. Press, 572 pp.

Jones, P. D., 1994: Hemispheric surface air temperature variations: A reanalysis and an update to 1993. *J. Clim.*, **7**, 1794-1802.

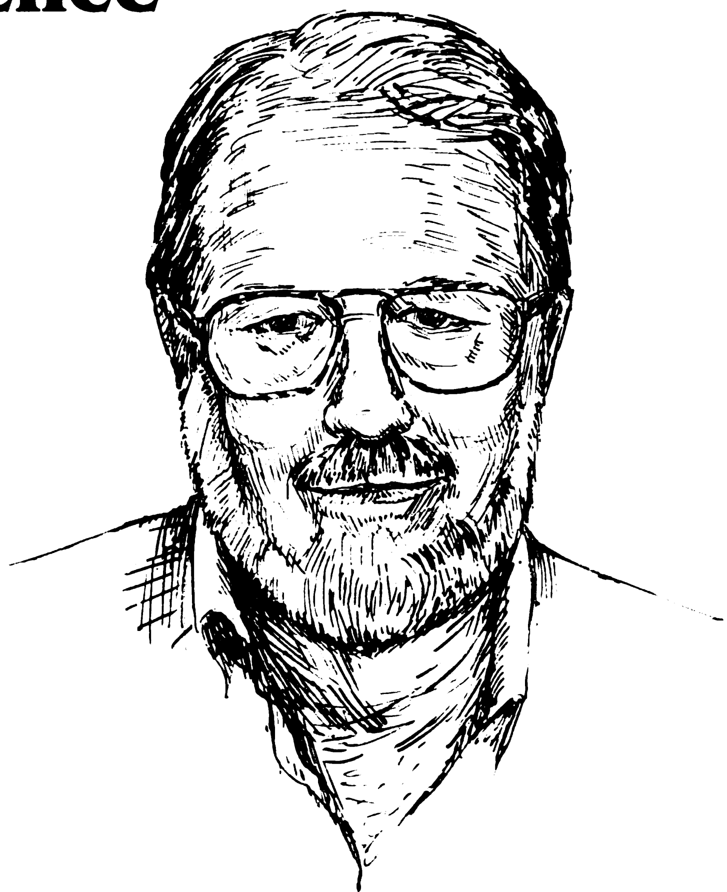
Martin, S., E. Muñoz, and R. Drucker, 1997: Recent observations of a spring-summer warming over the Arctic Ocean. *Nature*, submitted.

Maslanik, J. A., M. C. Serreze, and R. . Barry, 16: Recent decreases in Arctic summer ice cover and linkages to atmospheric circulation anomalies. *Geophys. Res. Lett.*, **23**, 1677-1680.

Trenberth, K. E., 1990: Recent observed inter-decadal climate changes in the Northern Hemisphere. *Bull. Amer. Meteor. Soc.*, **71**, 988-993.

Walsh, J. E., V. Kattsov, D. Portis, and V. Meleshko, 1997: Arctic precipitation and evapotranspiration: Model results and observational estimates. *J. Clim.*, submitted.

Profiles in Science



Wilford "Willy" Weeks

Dr. Wilford "Willy" Weeks has been a Principal Investigator of the Office of Naval Research (ONR) for many years focusing his research efforts on the iced covers of the world's polar oceans. He retired in 1996 from the University of Alaska but remains active as a consultant to the Federal Government on ice problems associated with the Polar Regions. His career in snow and ice began in 1955 when he was an Air Force Research and Development Officer leading a field operation along the Labrador coast studying the properties and behavior of sea ice.

After teaching geology for five years at Washington University, he joined the staff of the Snow and Ice Branch of the Army Cold Regions Research and Engineering Laboratory in Hanover, New Hampshire. He was at the Laboratory for 26 years and was also an Adjunct Professor of Earth Sciences at Dartmouth College. In 1986, he became Chief Scientist at the Alaska Synthetic Aperture Radar Facility and Professor of Geophysics at the Geophysical Institute of the University of Alaska in Fairbanks.

Dr. Weeks has participated in 35 field operations in the Arctic, three in the Antarctic, and five winter operations in more temperate regions. Colleagues recognized his outstanding work by electing him to the National Academy of Engineering and to the Presidency of the International Glaciological Society. He was also honored as the ONR Chair in Arctic Marine Science at the Naval Postgraduate School, Monterey, California. Recently, he was named an honorary member of the American Polar Society, a Fellow of the American Geophysical Union, and a Fellow of the Arctic Institute of North America. He was awarded the U.S. Army Research and Development Achievement Award on two occasions, the Army award for Meritorious Civilian Service, and the Navy Meritorious Unit Commendation for his part in field operations in the Arctic Ocean.

Bottom Water Formation and Distribution in the Weddell Sea

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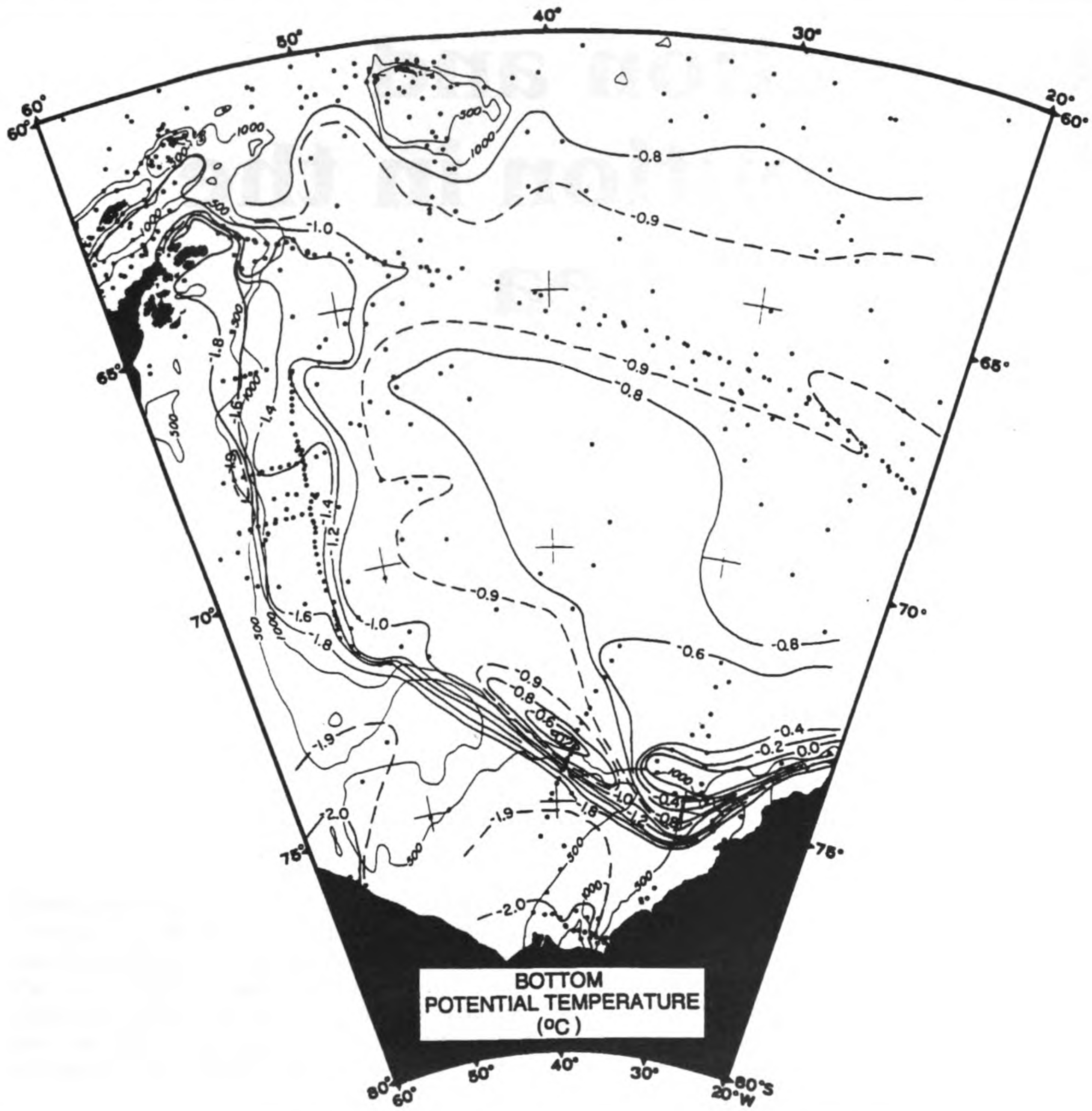
As we collect more observational data it is becoming increasingly evident that the ocean varies both spatially and temporally far more energetically than previously thought. So is the case in the Weddell Sea, where detailed observations within its western rim from the Ice Station Weddell (ISW Group, 1993) exposed the co-existence of two types of bottom water, one relatively fresh, the other more saline. Often these two types are observed within a single station, forming a highly stratified benthic layer (Gordon, et al., 1993). Using the ISW data and that of other recent data in the Weddell Sea a more detailed map of bottom potential temperature and salinity is constructed (Fig. 1, 2).

Within the deeper central part of the Weddell Sea the bottom potential temperature pattern (Fig. 1) reveals the presence of relatively warm bottom water, above -0.8°C. This broad feature forms as >-0.8°C water shifts towards the deeper center of the basin upon encountering the outflow of very cold and dense Ice Shelf Water from the Weddell Sea Shelf, channeled within the Filchner Depression (Foldvik, et al., 1985). The warm bottom water approaching from the east at depths below the mouth of the Filchner Depression (between 600 to 650 m; map 567 from the AWI bathymetry series, in prep) is pushed towards the central basin, while the warmer bottom water of the upper slope, first undercut by the colder water, reappears along the upper slope to the west of the cold water plume, which drops to deeper levels while advecting westward.

A major export of cold shelf water appears to occur just west of General Belgrano Bank (72.5 to 73.5°S and 47° to 50°W). From that point the areal extent of the sea floor deeper than 1000 m covered with cold bottom water (<-1.0°C) grows progressively larger along the general flow path of the Weddell Gyre towards the west and north (Muench and Gordon, 1995). Most of the Ice Station Weddell bottom temperatures in the western Weddell Sea at depths of 2500 to 3000 m, south of 67°S is well below -1.2°C. North of 67°S the width of the <-1.4°C bottom layer abruptly narrows, which may be a product of increased vertical mixing

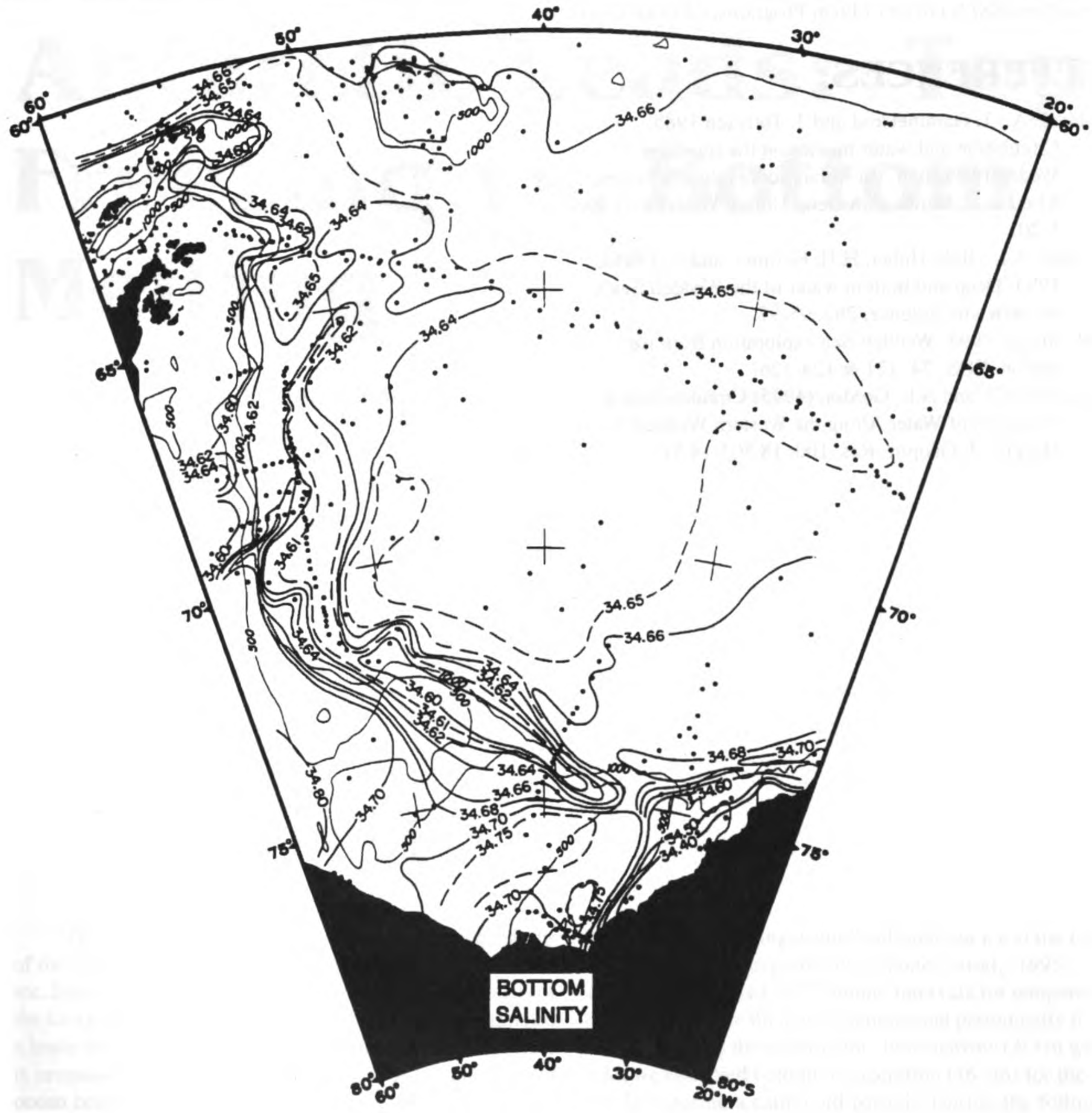
Figure 1
Bottom potential temperature pattern of the Weddell Sea.



with slightly warmer overlying water (Gordon, et al., 1993). In the northwestern Weddell Sea cold bottom water turns towards the east as <-1.0°C water near 64°S and continues eastward as <-0.9°C water between 64° and 66 °S.

The bottom salinity distribution (Fig. 2) in the western Weddell Sea reveals the spatial distribution of the two types of bottom waters. A plume of <34.62 bottom water emanates from just west of General Belgrano Bank, winding itself along a path of 700 km towards the north, ending near 65°S and 50°W. The saline shelf water of the western Weddell Sea (Western Shelf Water, Foldvik, et al., 1985), migrates northward, escaping from the shelf near 69°S, forming a saline plume just landward of the <34.62 plume. The Ice Station Weddell stations (Gordon, et al., 1993) shows that this salty bottom water lifts the lower salinity bottom water off the sea floor, inducing a very stratified double layer slope plume. It is suspected that slope canyon near 70°S directs the saline shelf water into the deep ocean.

Figure 2
Bottom salinity distribution in the western Weddell Sea.



Seaward of the elongated <34.62 plume, there is a suggestion of a plume of >34.65 water. It is expected that the Filchner Depression outflow of Ice Shelf Water entrains some of the older more saline bottom water advected in from the east. This mixture is still colder than the -0.8°C water of the central Weddell Basin.

In summary: bottom water characteristics reveal major export of low salinity shelf water near 72°S 51°W immediately west of General Belgrano Bank. It is joined downstream by high salinity bottom water just north of 70°S. The low salinity bottom water is expected to be derived from Ice Shelf Water, similar to the export from Filchner Depression; the high salinity bottom water is derived from the mass of Western Shelf Water, a product of sea ice formation. Only in the western Weddell Sea do these two types of bottom stratify to occupy the same water column. One wonders if the ratio of low to high salinity bottom water changes with time, perhaps in response to sea ice changes.

Acknowledgment

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REFERENCES:

Foldvik, A., T. Gammelsrod and T. Torresen 1985: Circulation and water masses on the southern Weddell Sea shelf. In Antarctic Res. Series Volume 43 ed. S.S. Jacobs, Am Geop Union, Wash DC, pages 5-20.

Gordon, A.L., B.A. Huber, H.H. Hellmer, and A. Ffield, 1993: Deep and bottom water of the Weddell Sea's western rim. Science, 262, 95-97.

ISW Group, 1993: Weddell Sea exploration from ice station. EOS, 74, 121 & 124-126.

Muench, R.D. and A.L. Gordon (1995) Circulation and Transport of Water Along the Western Weddell Sea Margin. J. Geophs. Res. 100: 18,503-18,515.

Sea Ice Growth in Antarctic Leads: Top Freezing vs. Bottom Melting

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Ocean heat flux values, as observed in many regions of the Southern Ocean, often exceed 25 W/m^2 and will melt ice, from below at a rate of 1 cm/day at this level. Models of the ice-ocean processes (e.g. Martinson, 1990) have estimated a leads fraction, or open water percentage, of 5% or greater is necessary to provide adequate ventilation for this level of ocean heat to the atmosphere, otherwise the ice cover may be destroyed prematurely from below. Ice growth in leads (covered with thin ice) is typically treated as a one-dimensional heat transfer problem, with the energy balance at the bottom ice surface balanced between three terms: conduction of heat upward through the overlying ice (F_c), upward ocean heat flux (F_w) and the latent heat of the phase change from water to ice at the ice bottom ($\rho_i LdH/dt$).

Observations, however, show a radically different behavior for ice growth in Antarctic sea ice leads than is currently used in models. During the winter Antarctic Zone Flux Experiment (AnzFlux), we installed thermistor strings and ice thickness gauges into leads and sea ice at the beginning of two drift experiments (Ackley, et al., 1995). The sites were measured at 15 minute intervals for temperature, twice daily for ice thickness changes and periodically for ice structure during the experiment. For a narrow (3-5 m width) lead, we observed bottom ice accretion (16 cm) for the first 1.5 days during a calm cold period. During the following two days, however, a storm caused two effects. One was a strong increase in oceanic heat flux as vertical mixing was enhanced (McPhee, et al., 1996), which resulted in bottom melting of several cm of the newly accreted sea ice at this site. The second storm effect, caused by surface winds in excess of 20 m/s, was to deposit drifting snow on the originally bare ice surface to a depth of 20 cm. Flooding of the full depth of the snow by sea water then took place through pores in the ice. The surface slush subsequently froze as sea ice from the top snow surface downward. At the end of five days, the original lead was covered with 20 cm of sea ice, all of it converted from the flooding of the snow cover, while the original sea ice that had formed had been ablated from below by the high ocean heat flux.

The ice thickness measurements from the other sites, located on sea ice up to 0.8 m thickness, showed bottom ablation rates (>1 cm/day) commensurate with the lead site and also in agreement with turbulent heat flux measurements in the ocean mixed layer (McPhee, et al., 1996). Two other regional observations showed that the formation of snow ice on the surface by flooding and refreezing were common occurrences. First, we found the ice structure was dominated by granular ice (>80%) of primarily snow ice origin, in the ice cores that were taken throughout the region. Second, ice thickness, snow depth and surface elevation measurement profiles taken concurrently with the ice cores showed widespread areas where the ice surface was below sea level, and approximately one-third of the measured profiles were flooded at the snow cover base at the time of measurement.

Results from a one-dimensional thermodynamic model (e.g. Maykut, 1986), showed however, that in the absence of a snow slush freezing mechanism, that ice less than 40 cm thickness (the mean thickness observed) would be melted prematurely for this region.

Two dilemmas therefore summarize the conflict of the observations with some models: 1) the direct melting of sea ice by the ocean heat flux is observed rather than ventilation through leads and, 2) ice of observed mean thickness or thinner is predicted to melt prematurely when typical heat flux models are used.

These are resolved however by the additional observation of widespread and relatively continuous freezing of surface snow slush onto the ice top surface. The sea ice cover acts as a *vertical conveyor belt*, with ice added on the top surface by snow slush freezing, at a similar rate that it is melted from below by the high ocean heat flux A continuous lead fraction is therefore not necessary to ventilate the ocean heat flux, and the ice cover may therefore be sustained by this process, freezing from above while melting from below for the period of its observed lifetime of several months rather than melting prematurely.

References

Ackley, S.F., V.I. Lytle, K.M. Golden, M.N. Darling, G.A. Kuehn, 1995, Sea Ice Measurements during AnzFlux, Ant. Jl. of the U.S.

McPhee, M., S.F. Ackley, P. Guest, B.A. Huber, D.G. Martinson, J.H. Morison, R.D. Meunch, L. Padman, T.P. Stanton, 1996, The Antarctic Zone Flux Experiment, Bull. of the AMS, v. 77, p. 1221-1232.

Martinson, D.G., 1990, Evolution of the Southern Ocean winter mixed layer and sea ice: open ocean deepwater formation and ventilation, Jl. of Geophys. Res., 95(C7), p. 11641-54.

Maykut, G.A., 1986, The Surface Heat and Mass Balance, in the Geophysics of Sea Ice (N. Untersteiner, ed.), NATO ASI Series v. 146, Plenum Press, New York.

Modeling Sea Ice Behavior

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Modern Beginning

A brief history of sea ice dynamics modeling is presented. It leans heavily toward studies in which I was involved. The story begins in the early 1970s with the Aidjex elastic plastic constitutive law [*Coon, et al.*, 1974]. *Thorndike, et al.* [1975] described ice condition by its thickness distribution. Equating the power dissipated by stress during plastic stretching to the rate of work done by changing gravitational potential energy and sliding friction provided an estimate of the compressive strength [*Rothrock*, 1975]. This strength estimate was too low.

Idealized problems and simulations using ideal plasticity showed that isotropic compressive strength must be of order 100 kN/m [*Pritchard*, 1976] for typical Beaufort and Chukchi Sea ice conditions. The energy dissipated by shear ridging was added to rate of work done by small scale sinks, and parameters were adjusted to increase strength [*Pritchard*, 1981]. Unconfined compressive strength of order 100 kN/m for typical Chukchi Sea winter ice conditions is necessary to support arching across the Bering Strait. By comparing model motions with buoy motions, the model was found to have errors of order 3 km/day for a wide range of conditions [*Kollé and Pritchard*, 1983].

Hibler [1979] introduced a viscous plastic constitutive law. The geophysics community warmly embraced this model, and it has been widely used for large scale simulations. Scientists have made hundreds of simulations, mostly using versions of Hibler model with two-component ice description. It is the ice model used in the PIPS system developed by the Navy and used by the Joint Ice Center. This two-component description of ice conditions, while quick and easy to implement because it uses only the fraction of open water and the mean thickness, cannot accurately describe strength because the amount and thickness of the thinnest ice controls strength. Recently, *Flato and Hibler* [1995] improved this model by returning to a complete thickness distribution, with separate categories for ridged and undeformed ice.

Ice dynamics models were coupled to ocean dynamics models in the early 1980s [*e.g., Hibler and Bryan*, 1987; *Pritchard, et al.*, 1990, and many more recent studies], so that currents, thermal and salt fluxes become part of the solution. These models have developed into sophisticated climate dynamics tools [*e.g., Maslovski*, 1997], but most retain the viscous plastic ice model with a two-component description of ice conditions.

Coon and Pritchard [1979] introduced the mechanical energy balance of the ice cover as a simple diagnostic tool for understanding the essential processes that control ice behavior. These scalar fields clearly described the transfer of mechanical energy from the atmosphere, through the ice, and into the ocean. A simulation of Beaufort Sea ice behavior showed that the rate of dissipation of energy as measured by the product of stress and plastic stretching, is an order of magnitude larger in the nearshore region where extensive ridging occurs [*Thomas and Pritchard*, 1980]. The energy balance equation is a natural extension of the Aidjex model because we define the strength in terms of small scale energy sinks that we equate to this rate of dissipation of energy.

Pritchard [1984] developed a model to simulate and forecast under-ice ambient noise. The noise at any location is assumed to be generated at all locations in the ice cover by different processes. Four different processes were considered: pressure and shear ridging, microcracking, and mixed layer shearing [*Pritchard*, 1990]. Each source propagates outward, and propagation loss is estimated. We assume that the source level related to variables that appear in the ice dynamics model. For example, ridging noise is assumed to be proportional to the energy dissipated in ridging. This model attempts to use basic acoustic principles wherever possible. The acoustic intensities of the different source processes are summed, rather than the logarithmic magnitudes that are more common in the acoustics community. Therefore, it is natural to assume that each noise source is proportional to an energy measure, rather than to the force [*Makris and Dyer*, 1986] or deformation [*Lewis and Denner*, 1988] measures used by other investigators.

Present

During the 1990s, an anisotropic elastic plastic constitutive law was introduced to describe lead formation and evolution directly [*Coon, et al.*, 1992]. We are still developing it. *Coon, et al.*, [1998a] describe the physical basis for introducing an anisotropic elastic plastic constitutive law. Small scale processes that affect leading, rafting, and ridging are taken into account directly. The idea is that the large-scale stress state must lie within all of the yield surfaces that describe failure of individual ice features. Coordinate rotations provide the technique for bringing together the differently oriented surfaces and their flow rules. The new anisotropic model allows our research attention to focus on the individual small scale processes that contribute to leading, rafting and ridging.

In the new anisotropic plasticity model, *Coon, et al.*[1998b] describe ice conditions in terms of a thickness distribution for each lead and ridge system. A system here may mean an individual or a set of parallel leads or ridges. *Pritchard* [1998] describes ice conditions using a three-dimensional thickness distribution, which is the fraction of area covered by ice having each thickness and each orientation. Isotropic ice conditions resulting from equal fractions of ice having all orientations.

Much of the mathematical formalism of the plasticity model follows from the Aidjex numerical model, with several crucial exceptions [*Pritchard*, 1996, 1998]. First, the stress state in the isotropic Aidjex model had its principal directions aligned with principal directions of stretching, but in the new anisotropic model they are not necessarily aligned. Thus, we must obtain solutions for three stress components ($\sigma_{xx}, \sigma_{yy}, \sigma_{xy}$) in a general coordinate system, rather than the stress invariants. Second, the yield surface of the isotropic model was constructed from one tensile cutoff cone and a compression cap with strength dependent on the ice thickness distribution. The anisotropic yield surface is defined by the region in stress component space lying within the isotropic surface plus additional yield surfaces for each lead or ridge system. The numerical integration will be more complex because of the piecewise definition of this combined yield surface.

Assume that a set of *m* features exist. These features might include new deforming leads, ridges that have formed from older leads, or velocity discontinuities that have been generated along a mathematical characteristic but have not yet opened. The stress state cannot violate the yield criterion of any feature $\phi_j(\sigma,\kappa_j) \le 0$, where σ is the stress tensor, κ_j represents variables such as strength of the feature that depends on its thickness distribution, and *j* ranges from 1 to *m*, where *m* is the number of branches undergoing plastic deformation. For a normal flow rule the plastic stretching is orthogonal to the yield surface

$$\mathbf{D}_p = \sum_{j=1}^{m} \lambda_j \mathbf{n}_j$$

where

$$\mathbf{n}_j = \frac{\partial \phi_j}{\partial \sigma}$$

is orthogonal to the yield surface ϕ_j, and the multiplier λ_j must be nonnegative. We also define $\mathbf{D}_j = \lambda_j \mathbf{n}_j$ as the plastic stretching of each lead system. The plasticity model shows that deformations from multiple active leads combine by addition.

For an elastic plastic material, the stress rate satisfies a linear elastic law

$$\dot{\sigma} = \mathbf{M}\,\dot{\mathbf{e}}$$

where **M** is the elastic modulus tensor and **e** is the elastic strain. The kinematic expression relates the elastic strain rate and plastic stretching [*Pritchard*, 1975]

$$\dot{\mathbf{e}} - \mathbf{We} + \mathbf{eW} = \mathbf{D} - \mathbf{D}_p$$

where **D** is stretching and **W** is spin, which are the symmetric and antisymmetric parts of the velocity gradient **L**, respectively

$$\mathbf{L} = \frac{\partial \mathbf{v}}{\partial \mathbf{x}}.$$

Here **v** is ice velocity and **x** is position.

The anisotropic plasticity model is better. It can identify lead formation and evolution directly. Leads are oriented, and their strength along the lead direction may be large. The older isotropic models averaged the strengths along and across the leads by assuming that a range of ice thicknesses affected the strength. We expect that the more accurate description of a lead system will allow for more accurate estimates of open water fractions. This last variable is essential for determining the effect of sea ice on climate dynamics.

We expect that the anisotropic plasticity model can resolve behavior of individual lead systems, which might be as small as a few kilometers.

Future

The new anisotropic plasticity model is not yet tested. We have devised a numerical method to integrate the constitutive equations. The method has been implemented into a computer program [*Pritchard*, 1996], but the material model has not yet been incorporated into a finite element or finite difference code to allow simulations. Output from this model will include motion, deformation, stress, lead size and orientation. The last two variables will be observable in satellite images, and allow direct testing of model performance.

The Sea Ice Mechanics Initiative (SIMI) had a goal of including micro mechanical physical behavior such as fracture and damage modeling in the large scale constitutive laws. The basic question remains: How do these processes affect the large scale behavior where leading, rafting, and ridging dominate the essential processes? It appears now that these smaller scale effects are small compared with the uncertainty in large scale parameters. We now assume that tensile strength is zero. Perhaps fracture affects the initiation of large scale processes.

Models should combine the best statistical and the best deterministic components. Some method of blending observations (historical and local) with statistical relationships and physics-based models is desirable. There are random components to behavior that deterministic models alone cannot describe. However, we now have only a poor idea how large are these random components. We are still trying to understand the errors in deterministic modeling of ice motions and open water fractions. We have only begun to compare the deformations or ice conditions.

The stream of high resolution SAR imagery that now exists could be used to initialize and correct calculated fields of ice motion and ice condition data. This will require that sophisticated data assimilation techniques be available for these systems. Future simulations and forecasts should use these satellite data more actively.

Ice forecasting techniques are still not very reliable. Errors often exceed the 3 km/day found during extensive simulations with careful tuning. Ice models provide little information on ice conditions or stresses.

Shipping offers an operational need for understanding sea ice behavior and its forecasting. However, this must move far from our research approach into a practical industrial approach. Satellite imagery is now available to ship masters, and they are far more comfortable with accurate pictures of the present than they are with uncertain forecasts of the future. The new anisotropic model might help here because it provides a measure of lead formation and evolution, which is one of the ice condition measures needed specifically for navigation.

Something is wrong with the large scale models. I showed that compressive strengths (both isotropic and unconfined) must be greater than 100 kN/m to avoid movement under certain conditions. Yet large scale models use strengths of order 10 kN/m, and simulations show their best comparisons with this lower strength. I do not know what the problem is. It could be that isotropic plasticity is not adequate. It could be that we do not characterize strength formulations adequately in terms of thickness distribution. Specifically, strengths must vary more rapidly with changes in ice condition. It could be that we must characterize ice condition differently, although similar low strengths are needed by both Hibler 2-level models and a 6-level model [*e.g., Polyakov, et al.*, 1997]. We must understand this contradiction.

We must identify known sea ice properties and avoid redoing the same calculations. For example, we know that a yield surface cannot have an arbitrary shape because nonzero unconfined compressive strength implies that the tensile cutoff cone must lie within or on the yield surface. Yet present-day studies ignore this fact while attempting to learn the effects of varying the yield surface shape. I believe that these properties should be fixed, and our limited funding should address other essential questions.

High resolution coupled ice-ocean models now use the best ocean models at ever smaller resolution, but they use simplified ice models (*e.g.*, two component ice conditions). These global climate models must begin to use the best ice models if they are to ensure accurate estimates of open water fractions and heat transfer rates.

We do know the essential physical processes that affect ice behavior on scales of 1-100 km. They are leading, rafting, and ridging. We can describe some smaller scale processes that contribute to rafting and ridging forces: gravitational potential energy changes and sliding friction. These small scale processes control the forces needed to continue the large scale processes after they begin. We know little about the loads needed to initiate these large scale processes, however. Some guidance might come from the micro mechanics community, including fracture mechanics.

Except for questions about climate dynamics, the study of Arctic sea ice is fading away. The U. S. Navy has reduced interest because it no longer perceives an enemy across the Arctic Ocean. The petroleum companies have all but quit the Alaskan Arctic for cheaper international finds. This includes the Russian Arctic, where Russian scientists have difficulty finding work. Arctic acoustics, which was once an essential field of study to the military, is now far less important. We can use our acoustic knowledge as a tool for acoustic oceanography, and we can use acoustic techniques to identify and measure sea ice deformations. Thus for the near term future, interest in sea ice must arise from its basic scientific interest, from its ability to provide insight into other scientific areas such as material science, or from a need to study climate dynamics.

REFERENCES

Coon, M.D., and Pritchard, R. S. (1979) "Mechanical Energy Considerations in Sea Ice Dynamics," *J. Glaciol.*, 24(90), 377-389.

Coon, M.D., Maykut, G. A., Pritchard, R. S., Rothrock, D. A., and Thorndike, A. S., (1974) Modeling the Pack Ice as an Elastic-Plastic Material, Aidjex Bulletin No. 25, University of Washington, Seattle, WA, pp. 1-105.

Coon, M.D., Echert, D. C., and Knoke, G. S. (1992) "Pack Ice Anisotropic Constitutive Law," in *IAHR 92, Proceedings of the 11th International Symposium on Ice*, Banff, Alberta.

Coon, M.D., Knoke, G. S., and Echert, D. C., and Pritchard, R. S. (1997a) "An Oriented Thickness Distribution for Sea Ice," *J. Geophys. Res.*, to be submitted.

Coon, M.D., Knoke, G. S., and Echert, D. C., and Pritchard, R. S. (1997) "The Architecture of a New Sea Ice Mechanics Model," *J. Geophys. Res.*, to be submitted.

Flato, G.M., and Hibler, W. D., III. (1995) "Ridging and strength in modeling the thickness distribution of Arctic sea ice," *J. Geophys. Res.*, 100(C9), 18,611-18,626.

Hibler, W.D., III. (1979) "A dynamic thermodynamic sea ice model," *J. Phys. Oceanogr.*, 9, pp. 817-846.

Hibler, W.D., III, and Bryan, K. (1987) "A diagnostic ice-ocean model," *J. Phys. Oceanogr.*, 17, pp. 987-1015.

Kollé, J. J., and Pritchard, R. S. (1983) "A Comparison of Two Sea Ice Trajectory Models with AIDJEX Observations," *J. Energy Res. Tech*, 105(3), pp. 346-351.

Lewis, J.K. and Denner, W. W. (1988) "Arctic Ambient Noise in the Beaufort Sea: Seasonal Relationships to Seasonal Kinematics," *J. Acoust. Soc. Am.*, 83, pp. 549-565.

Makris, N.C. and Dyer, I. (1986) "Environmental Correlates of Pack Ice Noise," *J. Acoust. Soc. Am.*, 79, pp. 1434-1440.

Maslowski, W. (1997) "Advanced Modeling of the Arctic Ocean and Sea Ice in Support of Global Climate Studies," *Bull. Meteorol. Soc.*, in press.

Polyakov, I.V., Kulakov, I. Yu., Kolesov, S. E., Dmitriev, N. Eu., Pritchard, R. S., Driver, D., and Naumov, A. K. (1997) "A coupled Sea Ice-Ocean Dynamical Thermodynamical Model of the Arctic Ocean," *J. Offshore Mech. and Arctic Engrg.*, submitted.

Pritchard, R.S. (1975) "An Elastic-Plastic Constitutive Law for Sea Ice," *J. Appl. Mech.*, 42(E2): pp. 379-384.

Pritchard, R.S. (1976) "An Estimate of the Strength of Arctic Pack Ice," AIDJEX Bulletin No. 34, University of Washington, Seattle, WA, pp. 94-113.

Pritchard, R.S. (1981) "Mechanical Behavior of Pack Ice," In A.P.S. Selvadurai, Ed. *Mechanics of Structured Media*, Part A, pp. 371-405. Elsevier, Amsterdam.

Pritchard, R.S., (1984) "Arctic Ocean Background Noise Caused by Ridging of Sea Ice," *J. Acoust. Soc. Am.*, 75(2), 419-427.

Pritchard, R.S. (1990) "Sea Ice Noise-Generating Processes," *J. Acoust. Soc. Am.*, 88(6), 2830-2842.

Pritchard, R.S. (1996) "Sea Ice as a Pathway for the Transport of Radionuclides," IceCasting, Inc., Seattle, WA.

Pritchard, R.S., Mueller, A. C., Hanzlick, D. J., and Yang, Y.- S. (1990) "Forecasting Ice Edge Motion in the Bering Sea," *J. Geophys. Res.*, 95(1), pp. 775-788.

Rothrock, D.A. (1975) "The Energetics of the Plastic Deformation of Pack Ice by Ridging," *J. Geophys. Res.*, 80(33), 4514-4519.

Thomas, D.R., and Pritchard, R. S. (1980) "Beaufort Sea Ice Mechanical Energy Budget 1975-76," Flow Research Company, Kent, WA.

Thorndike, A.S., Rothrock, D. A., Maykut, G. A., and Colony, R. (1975) "The Thickness Distribution of Sea Ice," *J. Geophys. Res.*, 80(33), 4501-4513.

Sea Ice Thickness Distribution as a State Variable

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Statistical representations of the sea ice pack are used in climate models, the most common representation being a distribution function for ice thickness. This practice can be defended using two arguments. First, observed ice thickness distributions, from different regions, different seasons, and different years, have enough similarity — and enough variation — to suggest that the thickness distribution can serve as a state variable. The idea is that bulk properties of the ice pack, such as its strength, might be expressed in terms of the thickness distribution. If a local property, p, depends on ice thickness, then there is a corresponding bulk property, P, constructed as a weighted average of p, weighted by the thickness distribution, g(h).

The thickness distribution therefore provides a way to model bulk properties of the ice pack. Because observations show variation in g(h), it is likely that there are variations in bulk ice properties. Successful models of the ice pack will probably need to account for these variations.

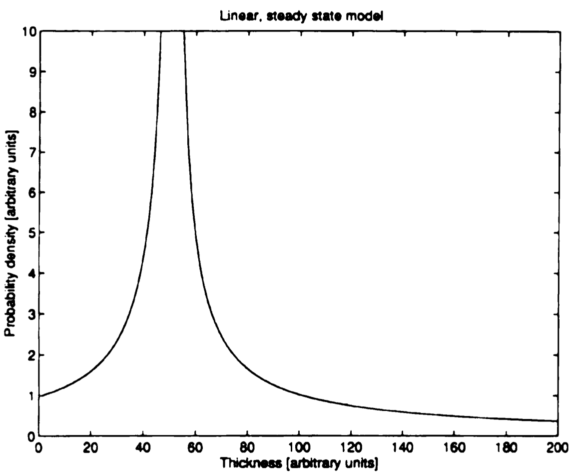
The second reason why thickness distributions appear in models is that theory exists for how the thickness distribution adjusts to other climate variables. Thus it is possible, in models, to study interactions between the statistical ice pack and the modeled climate.

At the same time, the practice can be challenged on two grounds. First, we do not know enough about the present spatial and temporal variations in thickness distribution to evaluate the theory. Second, the theory involves free parameters that represent certain thermal and mechanical processes. It is not likely that these parameters can be determined uniquely from observations.

Ongoing measurement programs using moored upward looking sonar and submarines and data from the Surface Heat Balance experiment will address these challenges. Within a few years we will have improved our documentation of the current ice state. We should also be able to say how much of the observed space and time variation in thickness distribution is explained by variation in the thermal and mechanical forcing, while holding the free model parameters constant.

Figure 1

Results of a linear, steady state thickness distribution model. The singularity at the equilibrium thickness diverges as |h-H| raised to the power DH/f(0)-1. The area of ice thicker than equilibrium is E/kD. The value of g at h=0 is (D+E)/f(0).



It is important to know the magnitude of the unexplained variance, because this sets a threshold for detection of climate change.

While a prodigious quantity of data is accumulating, it is important not to underestimate the difficulty involved in assembling a useful data set from it. Take as one goal, for example, maps of the climatological mean and variance of thickness at the times of minimum and maximum ice extent. The interannual departures from climatology are equally important. The existing data seem to justify a careful effort to estimate these fields. Until this is done, it won't be possible to make more than a qualitative assessment of the ability of the thickness distribution theory to simulate the ice climate.

Another way to test the theory is to attempt to simulate the actual space and time variations in the thickness distribution, rather than the climatology. Work on this problem, by Rothrock and Zhang, uses the observed time varying forcing fields, since 1979, to determine the thickness distribution at all subsequent times and locations. From these calculations they extract distributions for comparison with distributions observed along submarine tracks or at fixed locations. It is too early to tell if the calculations explain any of the variance in the observations.

There has been no challenge to the 1975 theory, partly because the data demands for testing the theory are so formidable, and also because the theory itself depends on several free or poorly constrained parameterizations. First, there is the growth rate function dh/dt = f(h,x,y,t). Second is the redistribution process $\psi(h)$. It is tempting to think that the theory would be exact, if we knew these functions, but this is not true. The theory supposes that these functions exist, whereas, in fact, even in a particular location and time, dh/dt may depend on other variables than thickness (snow thickness, for example). So there is room for an examination of the theory. In particular, someone should look into the effect of random fluctuations in f and ψ. It is also interesting to ask whether a simpler theory might yield insights into the behavior of the natural system, insights that are hard to extract from the full theory.

This latter possibility motivated my attempt to examine steady state solutions. Similar features of the thickness distribution appear in all observations: a strong maximum between 2 and 4 meters, and a thick end that drops off exponentially. The thin end shows more variation since it is more sensitive to the recent thermal and mechanical history. A linear, steady state argument helps to explain these features. Taking D as the mean divergence, E as the rms shear strain rate, k as the ridging multiplier (h-->kh), H as the equilibrium thickness, and f(h) as the annual growth function, one finds that g(h) depends on two dimensionless numbers: DH/f(0) and E/kD. Solutions have the form in the sketch, provided D is not too small.

There are a few conclusions to be drawn from this argument. First, a plausible thickness distribution has been produced based only on a statistical representation of the deformation, and annual average thermodynamics. Second, the importance of the slope of the growth function f(0)/H, is highlighted. Third, the failure of this approximation to the theory at small D should be examined carefully. How can we recast the theory in some simple way that remains valid when D=0?

Much work remains to be done. We have an idea that has been useful in developing a conceptual model of the ice pack. But it is not yet known how successful this idea is in ccounting for the natural phenomenon, or whether simpler ideas might be just as successful. There is reason to expect progress on these issues during the next few years.

Project SPINNAKER; ICESHELF 1988 -1996 and Beyond

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1. Introduction

Project SPINNAKER was an ambitious technology demonstration project combining long range fiber optic cables, Autonomous Underwater Vehicle (AUV) operations under the ice, low power, lightweight array technology and real time data processing and recording. Significant engineering and environmental challenges were resolved during a series of field experiments called ICESHELF. In addition, the project was been able to assemble an important set of environmental and oceanographic observations from the sparsely measured Lincoln Sea.

As SPINNAKER was essentially completed this year it seems an appropriate time to review the project, highlight some of its major accomplishments and present some of the significant oceanographic contributions of the project.

2. Brief Overview of Project SPINNAKER

SPINNAKER is a joint United States/Canadian program whose objective was to install a large, bottom-mounted, multi-aperture array of acoustic and engineering sensors under the ice on the continental shelf break of the Lincoln Sea. The array system would be cabled to shore for data processing and recording.

The project focused on an area of the Lincoln Sea continental slope about 170 km north of Ellesmere Island, NWT, Canada in water depths of 500 to 700 m. The field work and array installation was staged and supported logistically from the Canadian forces station at Alert.

Joint field work for SPINNAKER started in 1988. A memorandum of understanding was signed between the US and Canada in 1992. While most of the work was joint, the US focused on acoustic array technology and deployment, and the Canadians had primary responsibility for the development and testing of the large AUV which would lay the fiber optic cable to the shore.

3. ICESHELF Objectives and Accomplishments

ICESHELF experiments were conducted annually during the springtime to collect information to support the final installation. These field efforts tested aspects of the array technology and the developed and practiced array deployment techniques.

A critical part of the ICESHELF experiments were the navigation tests and Arctic trials of the Theseus AUV. Theseus, developed by International Submarine Engineering of Vancouver, Canada, had the formidable task of laying the fiber optic cable from Alert to the array site. Theseus is about 11 m (35 ft) in length, 1.3 m (50 in) in diameter and displaces about 8900 kgs (10 tons, 19,500 lbs). The cargo bay (2.4 m x 1.1 m, 96 in x 44 in) was modified to hold 220 km of 1.8 mm (0.07 in) fiber optic cable. The vehicle is capable of about 4 knots and was batteried (silver-zinc) for a minimum of a 50 hour mission. Navigation was accomplished by a combination of an inertial navigation unit for heading, a Doppler sonar for velocity, with a provision for position updates at transponders along the route.

4. SPINNAKER 1996 Deployment

The deployment of the SPINNAKER array required a rather large ice floe, about 4 km across, which, of course had to be conveniently located in the desired area. Because a shear zone between moving ice to the north and more stationary ice near land exists in the ice cover along the shelfbreak, this can be a difficult requirement. After an icecamp was established, a series of large holes were melted, tents set up, and the deployment equipment was installed.

Lines were run under the ice between the deployment holes using a small AUV developed and operated by the Applied Physics Laboratory/University of Washington. This vehicle has a nominal range of about 1 km and strings a light (80 lb test) line between the holes. Using the light line, a series of stronger working lines were then passed under the ice for array deployment. The array was lowered and held under the ice off of the ocean bottom, just in case the ice decided to start to move.

Theseus then began the deployment of the small fiber optic trunk cable from Alert to the camp. When Theseus was about half way on its 24 hour journey, the array was lowered to the seafloor and tensioned so that the horizontal part of the array was straight. The Theseus AUV successfully completed the deployment of the 180 km fiber optic data link from shore by passing through a triangular saddle with 200 m sides at the camp. This was quite a feat; the overall cross track error in navigation was less than 0.05% of the distance traveled. The fiber optic cable was recovered, fusion spliced to the array and released. Good data immediately appeared on the shore processing and recording system.

In its final deployed configuration the primary SPINNAKER array consists of a long horizontal bottom array (2400 m), a short, perpendicular horizontal bottom array (213 m) and two vertical arrays (468 m). 120 acoustic and 39 engineering sensors are distributed in the array.

The SPINNAKER array is batteried for a lifetime of 3 to 5 years. The acoustic sensors have a design spacing of 30.2 m (50 Hz wavelength spacing) in both the horizontal and vertical arrays. The system has a design frequency range from below 2 Hz to just above 60 Hz. Engineering sensors include a variety of test signals and the receivers/controllers necessary to navigate the vertical arrays.

Each acoustic sensor is sampled at 256 Hz. Engineering and test sensors are sampled at various, usually slower rates. Analog signals are converted to digital in the array Node and output with synch and status words into a serial bit stream. Data is transmitted optically through the non-repeatered trunk cable to the shore processing site.

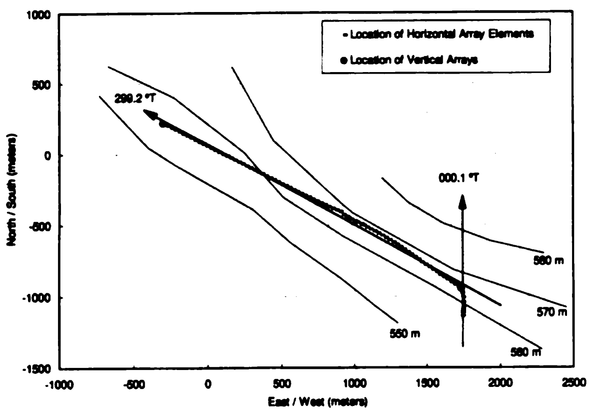
5. Preliminary Acoustic Results

Acoustic and engineering data was continuously collected for 8 weeks. A problem with the array electronics or the fiber optic data link terminated data collection.

On a positive note the two month data record seems quite good. Several groups including ARL, University of Texas, Naval Research Laboratory, APL, University of Washington, Institute of Ocean Sciences in Victoria, and the Scripps Institution of Oceanography have started analysis. I would like to briefly show some of the physical characteristics of the installation and examples of the data.

Figure 1 is a view looking down on the array. A north/south east/west grid in meters is superimposed and the local bathymetric contours are shown. Each element of the horizontal array, shown as the - symbols, was located acoustically by popping lightbulbs at several locations around the array. These locations were referenced to a careful theodolite survey of the camp and high accuracy GPS position recordings. The acoustic elements are located with a relative accuracy of 1 to 2 m. On a geographic scale the location of the array is known to about 10 to 20 m. The long horizontal array is oriented at 119/299 Deg T, roughly along the bathymetric contours; the short horizontal array lays almost ex-

Figure 1
Orientation of the Spinnaker array.



actly north/south. Because the vertical arrays are very light-weight they move significant distances with the currents and must be navigated using a set of transponders on the ocean floor and receivers on the array.

6. Environmental Measurements

Environmental measurements collected during the ICESHELF included: Conductivity and Temperature versus Depth (CTD) profiles, current profiles, winter-over moorings, ice drift, meteorological information, geoacoustic studies, bottom samples, bottom photographs.

CTD sections were obtained by helicopter in 1991, 1992, and 1993. Year long current meter moorings were deployed in 1992-93 and 1993-94. Oceanographic moorings with CTDs and current meters were set out in 1994 in

Figure 2
Simplified view of geostrophic current structure over the continental slope of the Lincoln Sea.

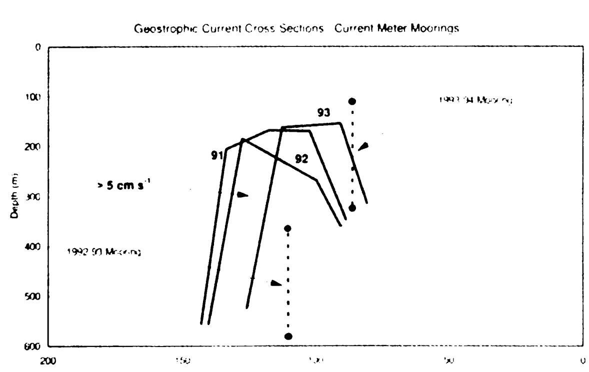
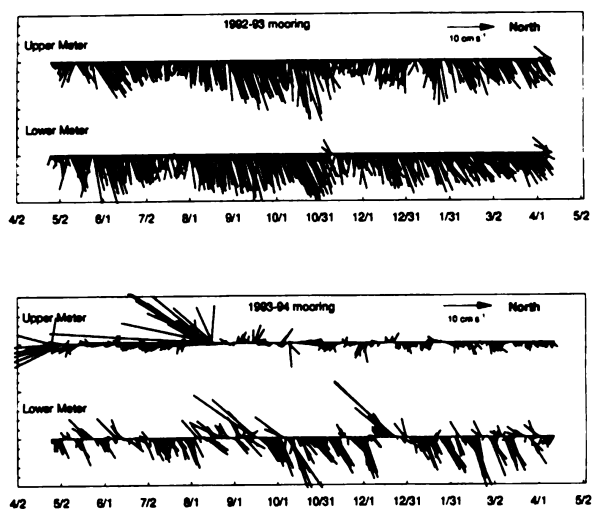


Figure 3
Daily average currents from winter-over current moorings on the continental slope.



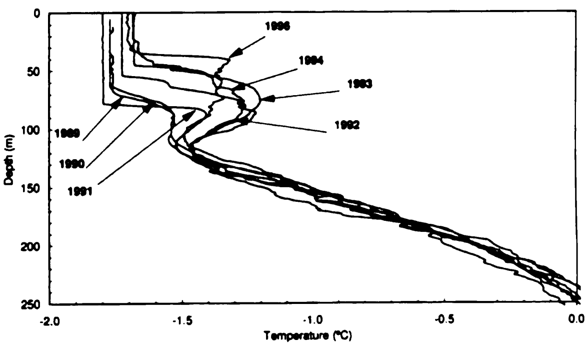
cooperation with Dr. Knut Aagaard of APL, University of Washington. All moorings were recovered with good data with the exception of one of the 1994 moorings.

A paper discussing the major results from the 1988 through 1994 experiments has been accepted by JGR Oceans. These results are presented adding some CTD data from the 1996 experiment. Two oceanographic features of the Lincoln Sea are of particular importance. First is the presence of a boundary undercurrent along the slope; the second is the inter annual changes in the temperature and salinity structure of the upper 200 m.

Geostrophic currents were computed from the three CTD cross sections using the ocean surface as the level of no motion. Measured currents suggest motion at the surface is less than at depth in this area. Each section displayed an under current directed toward the east along continental slope. Figure 2 is a simplified view of the geostrophic current structure over the slope. The 5 cm s^{-1} iso tach and shaded region is the area of relative high geostrophic currents of 5 to 9 cm s^{-1}. The shaded region defines a persistent current core, along the slope, which is interpreted as a boundary undercurrent. Outside the shaded region currents were less than 5 cm s^{-1} and usually less than 2 cm s^{-1}. The positions of the recording current meters from the 1992-3 and 1993-4 moorings are shown.

Daily averages from the current moorings are shown in Figure 3. To better display the vectors, north is to the right rather than up. In the core of the under current, currents are persistently directed toward the east. The mean currents are easterly at 5 to 6 cm s^{-1} at both meters in the current core. Above the current, core currents are variable in direction and except for a couple of events are relatively

Figure 4
Temperature variations over the Lincoln Sea continental slope from 1989 through 1996.



low with a mean value near zero. Near the southern edge of the current, currents are typically directed toward the east but there are a fair number of reversals. Here the mean current was about 2 cm s^{-1} toward the east.

The year long current measurements confirm the presence of an easterly flow at depth along the slope suggested by the geostrophic calculations. Similar under currents in the Beaufort Sea and the Barents Sea are described by Aagaard in several papers. In the Lincoln Sea the under current has a width of about 50 km and mean speeds of 5-8 cm s^{-1} and daily average speeds up to 20 cm s^{-1}. Transport would be about 2 Sverdrups.

The waters within the undercurrent evidenced temperature-salinity (TS) characteristics similar to Canadian Basin waters, suggesting a boundary current system, which is continuous along the continental slope north of Alaska and Canada.

Temperature and salinity profiles over the slope during 1989 through 1994 reflected significant inter-annual variations which may be related to variations in the large scale circulation of the Arctic. In 1989 and 1990 the upper pycnocline waters over the slope did not indicate a significant contribution of waters with Bering Sea characteristics. Starting in 1991 and continuing through the most recent measurements in 1994 the TS correlation evidenced a relative temperature maximum overlying a relative temperature minimum in the upper part of the pycnocline. The TS characteristics of these features were similar to waters attributed to Bering Sea origin typically found in the Canadian Basin.

7. Summary

The Spinnaker project successful deployed a large acoustic array on the continental slope of the Lincoln Sea. The array is cabled to shore via a long (180 km) non-repeatered fiber optic cable. The system collected a valuable set of acoustic data which is being used to study ambient noise and seismic events such as earthquakes. Oceanographic data collected by the project defined a boundary undercurrent along the continental slope and quantified significant inter annual temperature changes in the upper 200 m.

Interdisciplinary Interaction in Arctic Research

H. J. Niebauer, School of Fisheries and Ocean Science, University of Alaska, Fairbanks, AK

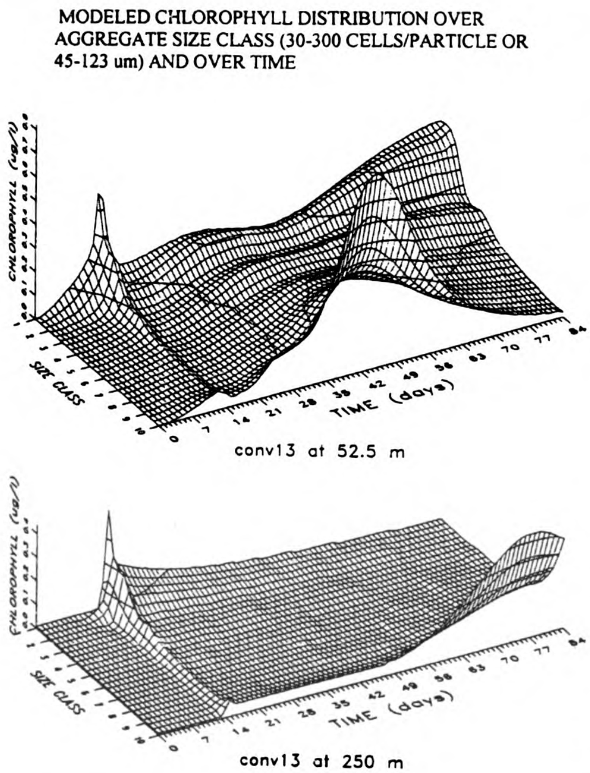
I started out my career as a physical scientist; a physical oceanographer. However, a thread that has woven its way throughout my career is interdisciplinary interactive research with biological and chemical oceanographers and other physical scientists such as meteorologists and computer modelers. In particular, I have concentrated on Arctic air-ice-ocean interaction at marginal ice edge zones (MIZ) where melting ice lays down stratification leading to intense phytoplankton blooms. This work involves both oceanographic cruises into the ice as well as constructing numerical models of these phenomena. This has led into the topic of vertical flux of carbon out of the photic zone into the deep ocean. In order to make progress in understanding these phenomena it became necessary to interact with scientists outside my discipline.

The Arctic Chair/ONR experience came along for me at just the right time. My tenure in the Arctic Chair in 1985 crossed for about 2 weeks with the only Biological Oceanographer, Professor Walker O. Smith, Jr., to occupy the Arctic Chair. It was a very productive time in which we sat and discussed bio-physical-nutrient interactions in the MIZ. This lead to collaborative biophysical numerical modeling and field work in the Greenland Sea supported by ONR. The modeling was supported primarily by ONR (Initially through Dr. Leonard Johnson and then by Drs. Thomas Curtin and Lou Codispoti). This work had its genesis in joining a physical ocean circulation model with an ice model and with a nutrient-phytoplankton-zooplankton (N-P-Z) model applied to the MIZ in both Arctic and Antarctic. We are continuing this work and have recently we added particle aggregation in studying the 'biological pump' and particle scavenging (through the Arctic Nuclear Waste Assessment Program, ANWAP) and flux of carbon to the deeper ocean as shown in Figures 1 and 2.

Figure 1 is model output showing modeled chlorophyll distribution over time and over aggregate size class (30-300 cells/particle or 45-123 μm diameter), and through 2 depths (52 m and 250 m). This model is for conditions similar to

Figure 1

Modeled chlorophyll distribution over aggregate size class (30-300 cells/particle or 45-123 μm diameter) and over time.



spring in the Greenland Sea. Maximum surface primary productivity is about 1000 mg C m^{-2} day^{-1}. The sharp increase in chlorophyll at about 14 days is penetrative convection of ~0.08 ms^{-1} (~7000 m day^{-1}) with vertical transort of about 600 mg C m^{-2} day^{-1}, or about 60% of the surface productivity.

This convection is caused by first preconditioning the surface water through upwelling (by cyclonic eddy and cyclonic wind) warmer but saltier water from deeper in the water column. At the beginning of the second week, the wind and eddy are turned off and the cooling turned on. The cooling not only cools the surface water but generates ice which generates cold salty brine which aids in the convection. Even then, the advective penetrative convection will not occur without including Coriolis effects and without making density a function not only of temperature and salinity, but also pressure.

The other mode of transport of carbon is through the slower sinking of the aggregating material from the bloom. This is seen first in the smaller particles at about 35 days at 52 m, and then in progressively larger particles which reach a peak at about 50 days at 52 m and about 80 days at 250 m. The vertical flux associated with the sinking bloom (note, this is not sinking water) is about 150 mg C m^{-2} day^{-1}, or about 15% of the surface productivity and 25% of the convective flux.

Figure 2 shows the mean winter sea level pressure patterns over the Greenland Sea for 1994-1996. Recent observations (Dr. Kim Van Scoy, pers. comm.) suggested that there was little deep convection around the Odin region of the Greenland Sea in winters of 1993-94 and 1994-95, but that there seemed to be much more deep convection in winter 1995-96. Figure 2 shows that the winter of 1994-95 (also the previous winter 1993-94, not shown) was a period of deeper than normal Icelandic low (992 mb). This cyclonic flow is conducive to wet, windy, warmer conditions with upwelling to bring warmer salty water closer to the surface (i.e., preconditioning) .

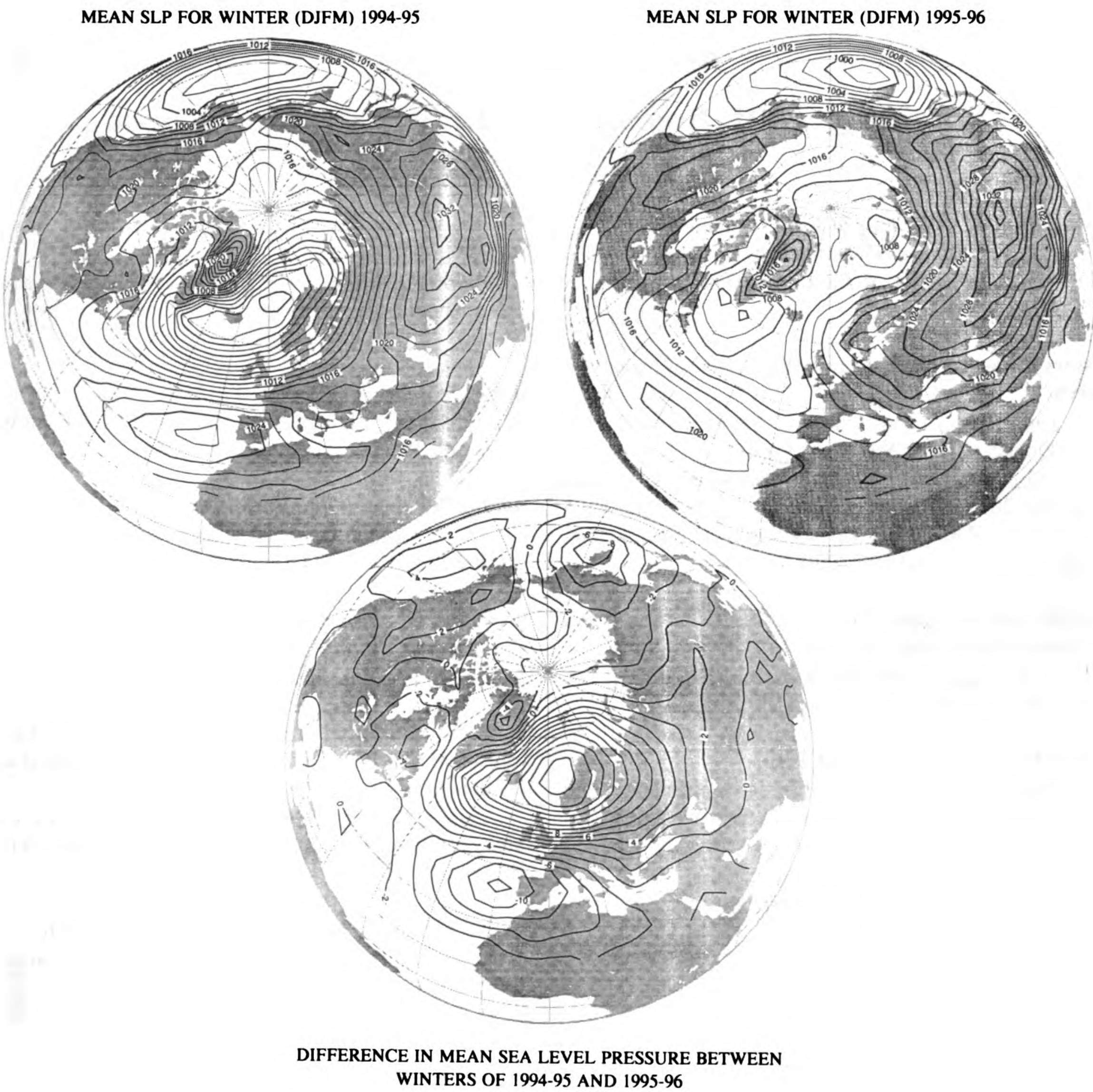
The next panel shows that during the next winter, 1995-96, the Icelandic low does not occupy the Greenland Sea. Instead, the Asian high has reached all across Europe out over the Greenland Sea (~1012 mb). These high pressure conditions tend to be clear and cold and conducive to deep convection by producing cold, salty water from the previous "preconditioned" warm salty water. The third panel shows the difference between the two winters with a rise of 22 mb within one year.

Two points here

1. Obviously, it takes true interdisciplinary interaction to solve these problems. It appears that quite a lot science and science funding is going in that direction now (e.g., Global Ocean Ecosystems Dynamics, or GLOBEC) and I certainly see interdisciplinary science as continuing and increasing.

2. A somewhat peripheral point is that the availability and accessibility of large, high quality, collated data sets is greatly increasing. This is especially true for the internet (e.g., the Northern Hemisphere sea level pressure data for Figure 2). I expect to see this trend continue and expand into biological, chemical, geological, physical oceanographic etc. realms. I think that the availability of these data sets combined with better numerical models on better and faster computer systems will allow greatly increased understanding of these complicated interdisciplinary ecosystem problems such as e.g., global ecosystem change.

Figure 2
Mean winter sea level pressure patterns over the Greenland Sea for 1994-1996.



FALL MEETING AMERICAN GEOPHYSICAL UNION
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20TH ANNIVERSARY SESSION
DECEMBER 16, 1996
Presiding: R. H. Bourke, Naval Postgraduate School

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Robert H. Bourke (Department of Oceanography, Naval Postgraduate School, Monterey, CA 93943: ph. 408-656-2373).

History of the Arctic Program at the Office of Naval Research
Thomas B. Curtin (Office of Naval Research, 800 North Quincy Street, Arlington, VA 22217: ph. 703-696-4119). G. Leonard Johnson (7708 Lake Glen Drive, Glen Dale, MD 20769: ph. 301-464-6724). Michael VanWoert (Office of Naval Research, 800 North Quincy Street, Arlington, VA 22217: ph. 703-696-4720).

Two Decades of Upper Ocean Physics from Sea Ice: a Tribute to ONR Arctic Sciences
M. G. McPhee (McPhee Research Co., Nachea WA 98937: ph. 509-658-2575).

Sounds from the Ice: Past and Future
Warren W. Denner (EOS Research Associates,200 Camino Aguajito #202, Monterey, CA 93940: ph. 408-373-1567).

A Summary of Progress in Understanding Low Frequency Arctic Ambient Noise
James H. Wilson (Neptune Sciences, Inc., 4711 Viewridge Ave. # 150, San Diego, CA 92123; ph. 619-167-1146).

Interdisciplinary Interaction in Arctic Research
Henry J. Niebauer (Institute of Marine Science, University of Alaska, Fairbanks, AK 99775-7220; ph. 907-174-7832).

Project SPINNAKER: Iceshelf 1988-1996 and Beyond
John L. Newton (Polar Associates, Inc., 100 Burns Place, Goleta, CA 93117; ph. 619-553-3007).

On Modeling Sea Ice Dynamics in Numerical Investigations of Climate
W. D. Hibler III (Dartmouth College, Hanover, NH 03755; ph. 603-646-3172).

Satellite Passive Microwave Remote Sensing of Sea Ice in the Laptev Sea
L. W. Brigham (ONR Arctic Chair, Department of Oceanography, Naval Postgraduate School, Monterey, CA 93943-5122; ph. 408-656-2226).

Modeling Sea Ice Behavior
R. S. Prichard (IceCasting Inc., 11042 Sand Point Way NE, Seattle WA 98125; ph. 206-363-3394).

Weddel Sea Plumes and Bottom Water
A. L. Gordon (Lamont-Doherty Earth Observatory, Palisades, NY 10964-8000).

Arctic Sea Ice: Properties and Processes
Stephen F. Ackley (CRREL-SI, 72 Lyme Road, Hanover NH 03755; ph. 803-464-4258).

Spatial Variability in the Arctic Ocean Measured at Large Scales and Small by Underwater Vehicles, Manned and Unmanned
James M. Morison (Polar Science Center, APL University of Washington, 1013 NE 40th St. Seattle, WA 98105; ph. 206-543-1394).

Sea Ice Thickness Distribution as a State Variable
Alan S. Thorndike (University of Puget Sound, Tacoma, WA 98105; ph. 206-756-3817).

Recent Climate Change in the Arctic
John E. Walsh (University of Illinois, Urbana, IL 61801; ph. 217-333-7521).

Biological Oceanography in the Arctic: Past Experiments and Future Challenges
Walker O. Smith (University of Tennessee, Knoxville, TN 37996; ph. 615-974-3065).

Sea Ice Mechanics Initiative (SIMI)
Ice Camp in 1992