GEOPHYSICAL INSTITUTE

DIV. A. PHYSICAL OCEANOGRAPHY

ARCTIC OCEAN MODELLING MEETING*

CAMBRIDGE, JUNE 21-25, 1982

REPORT FROM

SCOR WORKING GROUP 58

REPORT NO. 57 JUNE 1983

UNIVERSITY OF BERGEN
BERGEN, NORWAY

I N S T I T U T E   O F   G E O P H Y S I C S

DEPARTMENT OF PHYSICAL OCEANOGRAPHY

ARCTIC OCEAN MODELLING MEETING*

CAMBRIDGE, JUNE 21-25, 1982

REPORT FROM

SCOR WORKING GROUP 58

REPORT NO. 57 JUNE 1983

*THIS MEETING WAS SPONSORED BY
COMITÉ ARCTIC INTERNATIONAL

UNIVERSITY OF BERGEN

BERGEN, NORWAY

Preface

This document is a report of the Arctic Ocean Modelling meeting held in Cambridge on June 21-25, 1982. Nearly thirty scientists took part in the meeting, with talks given by sixteen, and a laboratory demonstration of some Arctic flow simulations. Half the talks related to theory, half to observations. A list of those attending, and the talks given, is in Appendix A and B.

This report is in two sections. The first gives an overview of modelling studies related to the Arctic Ocean and updates the review of SCOR WG58 (1979). The second is an attempt to connect the problems raised by observationalists with the unsolved theoretical problems, in order to focus attention on what were perceived as the fundamental areas for study.

This meeting was originally proposed by the Scientific Committee on Oceanic Research Working Group 58 (The Arctic Ocean Heat Budget) and funded by the Comité Artique International. This document has been prepared by P.D. Killworth and E.C. Carmack, with major help from D. Rothrock, and contributions from K. Aagaard, R. Bourke, K. Hunkins, E.L. Lewis, P.F. Linden, B. Rudels, A. Semtner and V. Squire, although these contributors may not recognise the final form of their contributions. Mrs. N. Coyle provided efficient secretarial help on all occasions.

I. A Review of Arctic Ocean Modelling

1. The Physical Situation

Fig.1 shows a simplified polar projection of the Arctic Basin and Greenland Sea, and demonstrates how like a Mediterranean basin the Arctic really is. Its sole deep connection with the world ocean is through Fram Strait, between Spitsbergen and Greenland. Fig.2 shows a modeller's schematic of the Arctic, with indications of many of the processes known or believed to be taking place. Predominant is the strong in- and outflow at the Strait; these two currents are known as the West Spitzbergen and East Greenland currents respectively (cf. Fig.3).

The water masses of the Arctic have been well delineated in the literature (Nansen, 1902; Coachman and Barnes, 1961, 1962, 1963; Nikiforov, Belysheva and Blinov, 1966; Coachman and Aagaard, 1974; Treshnikov, 1977; Aagaard, Foldvik and Rudels, 1981). Fig.4 shows the classical cross-basin vertical section, revealing temperatures and salinities surprisingly uniform in the horizontal, save near-surface, where salinities are strongly affected by river runoff, and in the deep ocean, where there are changes between the two basins separated by the Lomonosov ridge. The many complexities involved in Arctic sea ice have been reviewed by Vowinckel and Orvig (1970).

Figure 2 indicated many processes which may occur in the Arctic (e.g. slope currents, fronts, eddying, fine-structure, etc.). Observations have been made of many of these processes, especially by large-scale projects such as the Arctic Ocean Dynamics Joint Experiment (AIDJEX): Neshyba, Neal and Denner (1971); Paquette and Bourke (1981); Hunkins (1974;

Newton, Aagaard and Coachman (1974); McPhee (1980a); Kinder, Coachman and Galt (1975); Gade, Lake, Lewis and Walker (1974); and many contributors to this meeting. An extremely detailed reference list and review on ice-covered oceans in general has been produced by Carmack (1982).

It is fair to say that the modelling effort in the Arctic has not kept up with the observational programs. This is mainly due to manpower restrictions, and also because large-scale programs in the 70's were mostly aimed at comprehending some of the equatorial and midlatitude features. However, now that climatic programs like the World Climate Research Program (WCRP), the World Ocean Circulation Experiment (WOCE), and industry, are all showing renewed interests in polar regions, more theorists may be steered toward the many interesting and unique problems in the Arctic.

2. Ocean Modelling

Only three large-scale models have been created for the Arctic. Galt (1973) proposed a barotropic model; the concept was extended by Creegan (1976) to include a two-layer ocean. In both cases the effects of bottom topography seemed unrealistically large. As a result, Semtner (1976a) adapted the Princeton three-dimensional ocean model for polar use, and drove the Arctic with specified surface fluxes (i.e. finessing any ice effects) and inflows/outflows at Fram Strait. The results over most of the depth range were good (even to such details as the cross-Lomonosov ridge temperature and salinity differences), but the pycnocline and near-surface details were poorly represented in the model. The only other large-scale models were primarily aimed at the Antarctic (Killworth, 1973, 1974) although possessing some relevance to the Arctic.

The main thrust of Arctic Ocean modelling has been, and continues to be, process-oriented. On the mesoscale, the effect of sinking near oceanic boundaries and plumes has been of interest to several workers (Smith, 1975; Killworth, 1977; Melling and Lewis, 1982). Eddying motions on scales of the internal radius of deformation, which are of course observed throughout the world ocean, have been studied in polar contexts by Gascard (1973); Hunkins (1974); Killworth(1976); Hart and Killworth (1976); Killworth (1978); Martinson, Killworth and Gordon (1981); Wadhams and Squire (1980); and Wright (1981). These studies adopt two differing positions: one generated primarily from instability considerations, and one from the idea of driving by surface convection. With the discovery of isolated lenses like "meddies" (McDowell and Rossby, 1978), theorists are beginning to consider the motion of such lenses, and their formation (Gill, Smith, Cleaver, Hide and Jonas, 1979; Gill, 1981; Nof, 1981; Killworth, 1983). Fronts, and the transfer of properties across them have been primarily studies in midlatitude contexts, but see Gill (1973), Coachman and Walsh (1981), and Niebauer (1982). Interleaving of water masses, involved in the above, has been partially studied by Carmack and Killworth (1978), and Melling and Lewis (1982). However, work on mixing processes on the mesoscale is only just beginning; experiments like the Deep Ocean Tracer Release Experiment (DOTREX) will aid our understanding of these problems.

On the small scale, boundary-layer processes have received study (McPhee, 1979, for example). Models of the Arctic mixed layer have been produced by Solomon (1973) and Stigebrandt (1981).

(1981). Thermohaline and double-diffusive processes have been discussed for the Arctic by Foster (1968, 1969, 1971, 1972), Schauss and Galt (1973), and Katsaros (1973); a larger-scale "thought" model is given by Welander (1977).

3. Ice Modelling

Ice models incorporate a momentum equation, some treatment of the mass balance and a specified or modelled surface heat balance. The momentum balance is dominated by air stress and water stress, which are fairly well known relative to geostrophic surface wind and current (Banke, Smith and Anderson, 1976; Brown, 1981; McPhee, 1980b; Thorndike and Colony, 1982). Internal ice stress is also significant, especially within one or two hundred kilometers of shore (Pritchard, 1976; Thorndike and Colony, in press). The consensus is that a plastic stress model is most desirable, although strong observational confirmation is lacking (Rothrock, 1975; Pritchard, Coon and McPhee, 1977; Hibler, 1980; Rothrock, Colony and Thorndike, 1980).

The surface heat balance has been modelling in one dimensional (vertical) heat flux models for a sheet of sea ice (Maykut and Untersteiner, 1971; Semtner, 1976b). Because heat flux and ice growth are strong functions of ice thickness (Maykut, 1978) and because ice cover deformation continually produces open water and ridges thin ice into thick ice, the mass balance is sensitive to the ice thickness distribution (Thorndike et al., 1975).

Models of the entire Arctic ice cover, including an internally determined ice edge, have been constructed by Washington, Semtner, Parkinson and Morrison (1976), Parkinson and Washington (1979), and Hibler (1979, 1980). Mesoscale ice and oceanic phenomena in the marginal ice zone have received considerable attention (Clarke, 1978; Røed and O'Brien 1981; Neshyba and Badan-Dangon, 1974; Wadhams, 1981; Wadhams and Squire, 1982). Statistical descriptions of ice extent variability have been presented by Lemke, Trinkl and Hasselmann (1980) and Walsh and Johnson (1979). McPhee (1978, 1980) has modelled inertial oscillations of the summer ice cover.

4. Climate Modelling

The climatic effect of the polar regions is understudied. Large-scale atmospheric modelling (e.g. Gates, 1976) tends to treat the underlying ice and sea in a passive, pre-specified manner or to reduce the complexity of the coupled problem by parameterising most effects (Sergin, 1979). Apart from historical surveys (e.g. Malmberg, 1969), studies have been speculative, concentrating on such questions as the effect of Russian river diversions on Arctic ice cover (e.g. Aagaard and Coachman, 1975; Nikiforov, Belysheva and Blinov, 1966; Micklin, 1981). More recently, work reported at the NATO Air-Sea-Ice meeting is beginning to extend climatic studies (cf. Herman, 1982).

II. Problems for study by Arctic modellers

As the preceding section suggested, the substantive questions requiring urgent attention in the Arctic, as identified by the meeting, involve coordinated efforts between many different branches of modelling. An attempt to discuss each question in terms of what modelling efforts would be needed would become repetitive. To avoid such overlap, the questions will merely be stated here, and then a more discursive discussion on modelling efforts given. The questions identified are:

(a) How are the dynamics of the upper ocean affected by interaction with sea-ice?

(b) How are ice-cover and atmospheric conditions affected by the unique character of the upper layer of the Arctic Ocean?

(c) What controls the exchange of mass, heat, salt and ice through Fram Strait?

(d) What mechanisms are important regarding exchange of properties between the wide Arctic shelves and the open sea?

The various modelling studies possible will now be discussed in the light of these questions. A schematic of these is given in Fig.5.

1. Ocean processes and scales of motion

The first obvious area in which modelling will be useful is oceanic processes and scales of motion. It will be important to use models to give dynamical parameters as a guide for experimental design; and, conversely, to feed hydrographic data back into the models. Many processes which occur in the Arctic and adjacent regions are, however, very difficult to study using analytic or numerical techniques. Almost all mixing processes (turbulent entrainment, double diffusion, intrusions) are poorly understood, and much of the available information on these processes has come from laboratory experiments. In some cases — for example turbulent entrainment into a convective plume — this information has been successfully used in analytic and numerical models. In the majority of situations, though, present knowledge is fragmentary and cannot be used with great confidence, particularly in the extreme oceanic conditions found in the Arctic. Laboratory experiments can provide useful guides as to which processes will operate in given conditions, and how they relate to the large-scale fields. For example, a laboratory model of the exchange through Fram Strait would help to identify which of the many possible processes are dynamically significant in controlling the exchange. On an even larger scale, the formation of eddies in the main ocean basin and the circulation of the deep water are related to earlier laboratory experiments, and much more could be done in this area.

Laboratory experiments also help oceanographers know what to look for. For example, frontal eddies observed at the ice edge on the East Greenland Current by satellite (Vinje), and recently surveyed in detail by Wadhams and Squire (1982) have been found to have many features in common (and some differences!) with those observed by Griffiths and Linden in the laboratory.

This last example shows how the interaction of experimentalists and observationalists can lead to some relatively clear-cut results. There is a need to increase this kind of collaboration to help plan sensible laboratory work related to the Arctic Ocean; it is significant that there were no talks at the meeting discussing laboratory work. It is hoped that this report will encourage more work of this kind.

At the opposite end of the theoretical spectrum lie oceanic general circulation models (OGCM), i.e. numerical models for the prediction of the three-dimensional structure of velocity, density, and other variables in an ocean basin. OCGM's use the observed atmospheric and sea-ice state at the surface, as well as prescribed oceanic exchanges at open lateral boundaries. The effects of instabilities of strong ocean currents can be explicitly calculated if grid spacing is approximately equal to the Rossby radius; otherwise such effects can be crudely included through the diffusive terms in the governing equations, although a grid size smaller than 80km may still be needed to keep these terms realistically small. Other important processes that affect near-surface conditions or deep water mass formation can be included as components of the OGCM when parameterisations become available from process studies.

OGCM's are extremely demanding of computer time, but constitute the only means of assimilating so many diverse physical processes with strong nonlinearities and complex feedbacks, in order to make comparison with the observed three-dimensional ocean circulation, as well as to understand dynamical balances and make predictions of future states. The Arctic Ocean and its marginal seas are more tractable regions of the world ocean from the point of view of numerical modelling than other regions, because they are relatively small and have narrow open boundaries with known fluxes. Because a relatively complete set of physical processes are at work, the Arctic region provides an ideal area for significantly improving both oceanic modelling and physical understanding, if subjected to concentrated study.

A number of important questions about the Arctic can be examined by the use of OCGM's in conjunction with observations. What are the heat and salt budgets of the Arctic Ocean, and how might they change with environmental changes? What controls exchange through the Fram Strait? Is the amount of sea ice regulated by Siberian river runoff or by dynamical constraints on heat transport? These equations are of specific importance to the Arctic region. Other more general questions about the interaction of diverse processes occurring on continental shelves in deep stratified oceans, and in regions of deep convection, can also be treated, but smaller individual process models may well be more efficient for this purpose.

Finally, the joint interactions of the ocean with the atmosphere and with sea ice can be understood by the addition of models for those physical systems.

The problem of the seasonal variation within the Arctic, and its response to variability in the West Spitsbergen current entering through Fram Strait, will probably have to be attacked by an OGCM, although coastal wave studies (see below) may prove useful here. Variability on seasonal or interannual time scales is a very difficult problem for modellers and observationalists at midlatitudes, and much work needs to be done. This can be viewed as part of the larger problem of sensitivity studies, which are an important tool to determine the correct dynamics dominant in an area. (The term 'sensitivity' here relates both to internal sensitivity, i.e. the dependence on model assumptions parameters, and external sensitivity, i.e. the dependence on forcing functions and inputs.)

As an example, consider the question of the controlling processes at work in Fram Strait. Using an OGCM or a simplified model of the Arctic, a series of experiments could be conducted to isolate each potential driving mechanism in turn. The large-scale wind fields, for instance, may be important. One calculation might relax the anticyclonic circulation over the Arctic Ocean; another could relax the mainly cyclonic circulation over the Norwegian and Greenland Seas; another might adjust the seasonal signal between these circulations. Again, thermohaline effects may be important. By modifying the mixing terms in a model, one could create a more or less dense upper layer in the Arctic and produce a quasi-estuarine circulation through Fram Strait; or modification of the deep and bottom water formation in the

Greenland Sea (however this is formed) may drive deep water into the Arctic Basin, and the resulting increased upwelling could severely modify the circulation. The problem of why the "thermal wind" balance does not seem to hold in the upper 200m of Fram Strait (Killworth, this meeting) could be usefully attacked.

Sensitivity studies should also be made to discover whether the heat flux from the Arctic is dominated by atmospheric or oceanic conditions; one such study could remove the sea ice entirely (as an aside, could an ice-free Arctic still generate a Mediterranean-style circulation through Fram Strait?); another could require a modification of the upper layer of water to modify drag coefficients or the parameterisation of heat, salt and momentum mixing as affected by stratification; another could remove the river runoff to model Soviet diversion proposals; and another could examine the sensitivity of flow in the Arctic to variations of deep water inflow from the Greenland Sea.

2. Hydrographic state studies

The problem of deep-water formation is probably not of direct importance to near-surface events on times scales of a few years; nonetheless, there are many problems associated with deep water which are not understood. This identifiable gap in knowledge must be filled so that the circulation of the Arctic may be understood. For example, in at least two sites in the Arctic the salinity is higher than in any of the surrounding regions, and the causes are unknown. The deep Eurasian basin is anomalously salty (Aagaard, 1981); modelling studies may suggest where some form of deep convection is required to maintain this salinity. The Arctic pycnocline is also anomalous: it cannot be created by vertical mixing (cf. Fig.6; Aagaard, Coachman and Carmack, 1981; Melling and Lewis, 1982). The dynamics suggested by observations involved the sinking of cold salty water off the wide continental shelves and subsequent lateral spreading within the pycnocline. Yet quantitative calculations using this idea (Killworth, this meeting) find that vertical advection is more efficient at redistributing heat and salt than the lateral advection; Semtner's (1976a) model also failed to reproduce the upper pycnocline correctly. Östlund (1982), examining upper-layer Arctic tritium, also finds difficulty in explaining his data by these dynamical ideas. There is also no totally satisfactory model of production of Greenland Sea bottom water.

Transformation of water masses is under-studied by modellers; it is only recently, with the advent of programs such as WOCE, that modellers are returning to the concept of water masses used by observationalists in the 1930's. Yet understanding of how the warm Atlantic water loses its heat within the Arctic is a key to the dynamics of the whole basin. Are the mixing processes relatively large scale (e.g. barotropic instability, although barotropic currents are difficult to measure; baroclinic instability, known to be present in Fram Strait on parts of the continental shelves, and possibly north of Alaska) or mesoscale (carried out by small eddies or lenses of fluid, or by shelf convection) or small scale (fine structure, internal waves, double diffusion, etc.)? What are the time scales involved? Are these synoptic, seasonal or interannual, or a mixture of all three?

Participants felt strongly that modelling, or even discussion of water masses would be facilitated if uniform pycnocline is also anomalous: it cannot be created by vertical mixing (cf. Fig.6; Aagaard, Coachman and Carmack, 1981; Melling and Lewis, 1982). The dynamics suggested by observations involved the sinking of cold salty water off the wide continental shelves and subsequent lateral spreading within the pycnocline. Yet quantitative calculations using this idea (Killworth, this meeting) find that vertical advection is more efficient at redistributing heat and salt than the lateral advection; Semtner's (1976a) model also failed to reproduce the upper pycnocline correctly. Östlund (1982), examining upper-layer Arctic tritium, also finds difficulty in explaining his data by these dynamical ideas. There is also no totally satisfactory model of production of Greenland Sea bottom water.

Transformation of water masses is under-studied by modellers; it is only recently, with the advent of programs such as WOCE, that modellers are returning to the concept of water masses used by observationalists in the 1930's. Yet understanding of how the warm Atlantic water loses its heat within the Arctic is a key to the dynamics of the whole basin. Are the mixing processes relatively large scale (e.g. barotropic instability, although barotropic currents are difficult to measure; baroclinic instability, known to be present in Fram Strait on parts of the continental shelves, and possibly north of Alaska) or mesoscale (carried out by small eddies or lenses of fluid, or by shelf convection) or small scale (fine structure, internal waves, double diffusion, etc.)? What are the time scales involved? Are these synoptic, seasonal or interannual, or a mixture of all three?

Participants felt strongly that modelling, or even discussion of water masses would be facilitated if uniform

nomenclature (e.g. the Swift and Aagaard, 1981 terminology)
could be adopted.

3. Regional exchanges

The meeting has identified coastal and shelf processes as of major importance. A variety of process models will be required for the complex exchanges which Lewis described at the meeting. A two-dimensional model of the mixed layer beneath sea ice would be required at a minimum (i.e. one which allowed for lateral variation as well as vertical structure). Lemke's (1982) model is an obvious starting point. This would enable study of the effects of non-uniform buoyancy flux, and the interaction of the surface mixed layer with river runoff. It would also provide a feedback mechanism at the surface of various shelf wave models, which will be necessary to examine wave propagation around the Arctic (limited because of the low beta effect except at coasts). Can events in Fram Strait influence, say, the North Canadian coastline by anticlockwise propagation of Kelvin or shelf waves? Do seasonal variations remain in situ or can they propagate along the coast also? The mixed layer model would also be needed to study convection over a sloping bottom (for which some laboratory studies already exist), and as an upper boundary to upwelling simulations at the shelf edge.

The problem of water exchange between shelf and deep ocean also needs study. Traditionally, shelf models have tended to treat the main ocean as a passive recipient of water from the shelf; there are only a few models which consider shelf processes driven by events in the main ocean, for example. Arctic shelf models will have to be fully interactive with the main ocean, as well as permitting nonlinear events (e.g. frontal formation) to occur. An important feature to model will be the case of upwelling at some locations and downwelling at others, to account for some of the observations. Double-diffusive effects could well be important between the cold saline shelf waters and the warmer, fresher ocean waters; how would these effects be included in a mesoscale model?

Exchange processes also need modelling between basins. What drives the flow across the Lomonosov ridge between the deep waters of the Canadian and Eurasian basins, and, given such a flow, why do the basins continue to possess different temperature-salinity characteristics? Why does so much water flow through Fram Strait, which, although wide in terms of the baroclinic deformation radius, must still present a considerable barrier to barotropic flow? Is the mass exchange sensitive to the width of Fram Strait, and would the problem become one of sill flow if the strait became sufficiently narrow?

4. Sea-Ice and Marginal Ice-Zone (MIZ) Modelling

For the purpose of understanding the Arctic Ocean heat budget, sea-ice models need to describe ice extent, ice motion or the ice-water stress, the rates of ice production and brine rejection, and the surface heat balance. Present ice modelling work addresses the annual cycle of some long-term mean state, testing model performance with any piece of data that can be found. A useful new direction for ice-modelling work would be the simulation of specific time periods with the goal of testing a particular aspect of model performance. The most useful results would be those which pinpoint weaknesses in model performance and the reason for these weaknesses.

For instance, ice extent is a variable of considerable importance, presently modelled rather poorly. The probable villain is a very simple treatment of the upper ocean which makes no allowance for advection or upwelling of warm water. Data sets exist which bear on this issue (Paquette and Bourke's work in the Chukchi and Greenland Seas; also Norwegian Remote Sensing Experiment (NORSEX) transect through the ice edge). Much could be learned from case studies of frontal regions and the ice edge, particularly if the advective and thermodynamic changes in the position of the edge can be estimated (e.g. the forthcoming Marginal Ice Zone Experiment (MIZEX)).

The position of the ice edge could also be studied with rather theoretical models. How closely is the ice edge tied to the surface position of the polar front? Is ice continually swept across a front to melt in warm water, or can the ice edge be maintained with little or no melting? To what extent can the frontal dynamics be studied separately from the dynamics of the ice edge?

On-ice winds act to compact the ice-edge region, whereas off-ice winds tend to disperse it, and hence to cause motion with little resistance. An internal ice stress is usually introduced to reduce further convergence after the ice has been sufficiently compacted. Such behaviour may be effectively characterised by the plastic rheology often assumed in Arctic Basin models. In the MIZ however, compactness may not be adequate to fully represent the phenomenological nature of the ice cover because of the presence of open water. It may therefore be necessary to think in terms of floe size distribution or areal coverage in particular zones within the ice-edge region.

Ocean waves offer three major contributions to the marginal ice-zone region. First they compact and consolidate the edge by exerting a significant radiation stress along its length. Secondly, they randomly jostle, bump and rotate ice floes within the region. And thirdly, they act to break up floes and help to sort the region into a particular floe size distribution. Only the second of these effects has been included in models to date (Røed and O'Brien, 1981), and this has been shown to affect significantly the processes which occur in the ocean beneath. Unfortunately, this contribution, which is represented in the momentum equations as an additional pressure term, is particularly difficult to characterise in any quantitative sense. Radiation stress is as effective as the wind stress in controlling ice-edge dynamics, yet it has not been included in the momentum equations of existing models. It is a relatively simple matter to include this contribution since ocean wave data are available for most MIZ regions, and simulation studies for ice floes are underway (Squire, 1982). The final contribution, that of altering the character of the ice cover by wave-induced fracture and sorting, is significant since it will determine the state of the ice concentration and distribution at any particular time. This is clearly of importance since the nature of the ice cover will determine atmospheric-ocean coupling.

Finally, some parameterisation of surface and under-ice roughness is essential if reliable ice edge models are to be devised. The thickness distribution of many MIZ regions is unknown, and more work is required to describe the statistical character of these regions more fully. Thickness is important in determining surface fluxes, and ridge keels can increase mixing in the upper layer.

Any modelling of oceanic processes occurring in the MIZ will benefit considerably from data collected during the forthcoming MIZEX programme due to take place in the Bering and Greenland Seas. At present there is a singular lack of data in this regard. MIZEX will collect a large dataset of both oceanic and ice-edge processes which must be utilised if effective and accurate modelling of the marginal ice zone region is to be contemplated.

Estimates of ice production, salt rejection and surface heat fluxes are required as oceanic boundary conditions. Over the central Arctic Ocean, they help determine the structure of the upper ocean; on the shelf regions and in the Greenland Sea, their magnitude determines the structure of deep water, (See the sections of shelf processes and general circulation.) The most direct observations from which to provide flux estimates are of ice-thickness distribution, especially the concentrations of ice thinner than one metre, but these are not generally available (although submarine sonar profiles have been analysed to yield ice thickness distributions; Wadhams and Horne, 1980; Wadhams, 1981b). The next most direct estimate can be made from observations of ice motion and surface air temperature, using a model of thickness distribution. These observations are available from the Arctic Buoy Program continuously from 1979 to present (1982), for the central Arctic, but not for the Siberian shelves and Greenland Sea. In these latter regions, one requires the even less direct approach of estimating ice motion from wind.

The notion that ice deformation involves gradients of a continuous horizontal velocity field does not square with observations that the ice moves as a set of rigid pieces - some as large as 100 km (Hall and Rothrock, 1981). Models of ice production driven by ice deformation should be improved by a more realistic treatment of the piece-like velocity field.

References

Aagaard, K. (1981) On the deep circulation in the Arctic Ocean. Deep-Sea Res. 28, 251-268.

Aagaard, K. and L.K. Coachman (1975) Toward an ice-free Arctic Ocean. EOS 56, 484-486.

Aagaard, K,, Coachman, L.K. and Carmack, E.C. (1981) On the halocline of the Arctic Ocean. Deep-Sea Res. 28, .

Aagaard, K., Foldvik, A. and Rudels, B. (1981) Fysisk oceanografi. Ymer 101, 110-121.

Banke, E.G., Smith, S.D. and Anderson, R.J. (1976) Recent measurements of wind stress on arctic sea ice, J. Fish. Res. Board Can., 33, 2307-2317.

Brown, R.A. (1981) Modelling the geostrophic drag coefficient for AIDJEX. J. Geophys. Res., 86, 1989-1994.

Campbell, W.J. (1969) The wind-driven circulation of ice and water in a polar ocean. J. Geophys. Res. 70, 3279-3301.

Carmack, E.C. (1982) Circulation and mixing in ice-covered waters. In: Air-sea-ice interaction (eds. N.J. Untersteiner et al.) Proceedings of NATO Advanced Study Institute, Maratea, Italy 1981.

Carmack, E.C. and Killworth, P.D. (1978) Formation and interleaving of abyssal masses off Wilkes Land, Antarctica. Deep-Sea Res. 25, 357-369.

Clarke, A.J. (1978) On wind-driven quasi-geostrophic water movement at fast ice edges. Deep-Sea REs. 25, 41-51.

Coachman, L.K. and Aagaard, K. (1974) Physical oceanography of arctic and subarctic seas. In: Marine geology and oceanography of the Arctic seas. Springer-Verlag, New York, pp.1-72.

Coachman, L.K. and Barnes, C.A.(1961) The contribution of Bering Sea Water to the Arctic Ocean. Arctic 14, 147-161.

Coachman, L.K. and Barnes, C.A. (1962) Surface water in the Eurasian basin of the Arctic Ocean. Arctic 15, 251-277.

Coachman, L.K. and Barnes, C.A. (1963) The movement of Atlantic water in the Arctic Ocean. Arctic 16, 8-167.

Coachman, L.K. and Walsh, J.J. (1981) A diffusion model of cross-shelf exchange of nutrients in the southeastern Bering Sea. Deep-Sea Res. 28, 819-846.

Creegan, A. (1976) A numerical investigation of the circulation in the Norwegian Sea. Tellus 28, 451-459.

Doake, C.S.M. (1976) Thermodynamics of the interaction between ice shelves and the sea. Polar Record 18, 37-41.

Foster,, T.D. (1968) Haline convection induced by freezing of sea water. J. Geophys. Res. 73, 1933-1938.

Foster, T.D. (1969) Experiments on haline convection induced by freezing of sea water. J. Geophys. Res. 74, 6967-6974.

Foster, T.D. (1971) Intermittent convection. Geophysical Fluid Dynamics 2, 201-217.

Foster, T.D. (1972) An analysis of cabbeling instability in sea water. J. Phys. Oceanogr. 2, 2941301.

Gade, H.G. (1979) Melting of ice in sea water. A primitive model with applications to the Antarctic ice shelf and icebergs. J. Phys. Oceanogr. 9, 189-198.

Gade, H.G., Lake, R.A., Lewis, E.L. and Walker, E.R. (1974) Oceanography of an Arctic Bay. Deep-Sea Res. 21, 547-571.

Galt, J.A. (1973) A numerical investigation of Arctic Ocean dynamics. J. Phys, Oceanogr. 3, 379-396.

Gascard, J.C. (1973) Vertical motion in a region of deep water formation. Deep-Sea Res. 20, 1011-1028.

Gates, W.L. (1976) The numerical simulation of ice-age climate with a general circulation model. J. Atmos. Sci. 33, 1844-1873.

Gill, A.E. (1973)Circulation and bottom water production in the Weddell Sea. Deep-Sea Res. 20, 111-140.

Gill, A.E. (1981) Homogeneous intrusions in a rotating stratified fluid. J. Fluid Mech. 103, 275-297.

Gill, A.E., Smith, J.M., Cleaver, R.P., Hide, R., Jonas, P.R. (198). The vortex created by mass transfer between layers of rotating fluid. Geophys. Astrophys. Fluid Dyn.12, 195-220.

Hart, J.E. & Killworth, P.D. (1976) On open ocean baroclinic instability in the Arctic. Deep-Sea Res. 23, 637-645.

Herman, G. (1982) (paper in Air-sea-ice interaction (eds.Untersteiner et al).Proc. NATO Adv.Study Inst. Maratea, Italy, 1981.

Hibler, W.D. (1979) A dynamic thermodynamic sea-ice model. J. Phys. Oceanogr. 9, 815-846.

Hibler, W.D. (1980) Modeling a variable thickness sea ice cover. Mon. Wea. Rev. 108, 1043-1973.

Hunkins,, K.L. (1974) Subsurface eddies in the Arctic Ocean. Deep-Sea Res. 21, 1017-1033.

Huppert,H.E. and Turner, J.S. (1980) Ice blocks melting into a salinity gradient. J. Fluid Mech. 100, 367-384.

Katsaros, K.B. (1973) Supercooling at the surface of an Arctic Lead. J. Phys. Oceanogr. 3, 482-486.

Killworth, P.D. (1973) A two-dimensional model for the formation of Antarctic bottom water. Deep-Sea Res. 20, 941-971.

Killworth, P.D. (1974) A baroclinic model of motions on Antarctic continental shelves. Deep-Sea Res. 21, 815-839.

Killworth, P.D. (1976) The mixing and spreading phases of MEDOC. I. Progress in Oceanogr. 7, 59-90.

Killworth, P.D. (1977) Mixing on the Weddell Sea continental slope Deep-Sea Res. 24, 427-448.

Killworth, P.D. (1979) On 'chimney' formations in the ocean. J. Phys. Oceanog. 9, 531-554.

Killworth, P.D. (1983) On the motion of isolated lenses on a beta-plane. J. Phys. Oceanogr, 13, 368-376.

Kinder, T.H., Coachman, L.K. and Galt, J.A. (1975) The Bering Slope Current System. J. Phys. Oceanogr. 5, 231-244.

Lemke, P., Trinkl, E.W. and Hasselmann, K. (1980) Stochastic dynamic analysis of polar sea ice variability. J. Phys. Oceanogr. 10, 2100-2120.

McDowell, S.E. and Rossby H.T. (1978) Mediterranean water: an intense mesoscale eddy off the Bahamas. Science 202, 1985-1087.

McPhee, M.G. (1978) A simulation of inertial oscillation in drifting pack ice. Dyn. Atmos. and Ocans, 2, 107-122.

McPhee, M.G. (1979) The effect of the oceanic boundary layer on the mean drift of pack ice: application of a simple model. J. Phys. Oceanogr. 9, 2331400.

McPhee, M.G. (1980a) A study of oceanic boundary-layer characteristics including inertial oscillations at three drifting stations in the Arctic Ocean. J. Phys. Oceanogr. 10, 870-884.

McPhee, M.G. (1980b) An analysis of pack ice drift in summer. In Sea Ice Processes and Models, R.S. Pritchard, ed., Univ. of Wash. Press, 62-75.

Malmberg, S.A. (1969) Hydrographic changes in the waters between Iceland and Jan Mayen in the last decade. Johull 19, 30-43.

Martin, S. and Kauffman, P. (1977) An experimental and theoretical study of the turbulent and laminar convection under a horizontal ice sheet floating on warm salty water. J. Phys. Oceanogr. 7, 272-283.

Maykut, G.A. (1978) Energy exchange over young sea ice in the central Arctic, J. Geophys. Res., 83, 3646-3658.

Maykut, A.G. and Untersteiner, N. (1971) Some results from a time-dependent thermodynamic model of sea ice. J. Geophys. Res. 76, 1550-1575.

Melling, H. and Lewis, E.L. (1982) Shelf drainage flows in the Beauford Sea and their effect of the Arctic Ocean pycnocline. Deep-Sea Res., 29, 967-986.

Micklin , P.P. (1981) A preliminary system analysis of impacts of proposed Soviet river diversion on Arctic sea ice. EOS 62, 489-493.

Nansen, F. (1902) Oceanography of the North Polar Basin. The Norwegian North Polar Expedition, 1893-1896, Scientific Results 3 (9) 427 pp.

Neshyba, S. and Badan-Dangon, A. (1974) On ocean current induced by a prograding ice pack. Geophys. Res. Lett. 1, 351-354.

Neshyba, S. and Josberger, E.G. (1980) On the estimation of Antarctic iceberg melt rate. J. Phys. Oceanogr. 10, 1681-1685.

Neshyba, S., Neal, V.T. and Denner, W. (1971) Temperature and conductivity measurements under ice island T-3. J. Geophys. Res. 76,8107-8120.

Newton, J.L., Aagaard, K. and Coachman, L.K. (1974) Baroclinic eddies in the Arctic Ocean. Deep-Sea Res. 20, 707-719.

Niebauer, H.J. (1982) Wind and melt-driven ocean circulation in a marginal sea ice edge frontal system. A numerical model. Submitted.

Nikiforov, Y.G., Belysheva, Y.V. and Blinov, N.I. (1966) The structure of water masses in the eastern part of the Arctic Basic. Oceanology 6, 58-64.

Nof, D. (1981) On the beta-induced movement of isolated baroclinic eddies. J. Phys. Oceanog. 11, 1662-1672.

Östlund, H.G. (1982) The residence time of the freshwater component in the Arctic Ocean. J. Geophys. Res., 87, 2035-2044.

Paquette, R.G. and Bourke, R.H. (1974) Observations on the coastal current of Arctic Alaska. J. Mar. Res. 32, 195-207.

Parkinson, C.L. and Washington, W.M. (1979) A large-scale numerical model of sea ice. J. Geophys. Res., 84, 311-337.

Pritchard, R.S. (1976) An estimate of the strength of arctic pack ice. AIDJEX Bulletin No. 34, University of Washington, Seattle.

Pritchard, R.S., Coon, M.D. and McPhee, M.G. (1977) Simulation of sea ice dynamics during AIDJEX, J. Press. Vessel Tech., 99J, 491-497.

Rothrock, D.A. (1975) The energetics of the plastic deformation of pack ice by ridging. J. Geophys. Res., 80, 4514-4519.

Rothrock, D.A. and Thorndike, A.S. (1980) Geometric properties of the underside of sea ice. J. Geophys. Res. 85, 3955-3963.

Rothrock, D.A., Colony, R. and Throndike, A.S. (1980) Testing pack ice constitutive laws with stress divergence measurements. In Sea Ice Processes and Models, R.S. Pritchard, ed. Univ. of Washin. Press. 102-112.

Schaus, R.H. and Galt, J.A. (1973) A thermodynamic model of an arctic lead. Arctic 26, 208-221.

Semtner, A.J. (1976a) Numerical simulation of the Arctic Ocean circulation. J. Phys. Oceanog. 6, 409-425.

Semtner, A.J. (1976b) A model for the thermodynamic grwoth of sea ice in numerical investigations of climate. J. Phys. Oceanog. 6, 379-389.

Sergin, V. Ya. (1979) Numerical modeling of the glaciers-ocean-atmosphere global system. J. Geophys. Res. 84, 3191-3204.

Smith, P.C. (1975) A streamtube model for the bottom boundary currents in the ocean. Deep-Sea Res. 22, 853-874.

Solomon, H. (1973) Wintertime surface layer convection in the Arctic Ocean. Deep-Sea Res. 20, 269-283.

Squire, V.A. (1982) Numerical modelling of realistic ice floes in ocean waves. Paper presented at Applied Glaciology Symposium, Hanover, New Hampshire.

Stigebrandt, A. (1981) A model for the thickness and salinity of the upper layer in the Arctic Ocean and the relationship between the ice-thickness and some external parameters. J. Phys. Oceanog. 11, 1407-1422.

Swift, J.H. and Aagaard, K. (1981) Water mass formation in the Iceland and Greenland Seas. Deep-Sea Res., 28, 1107-1130.

Thorndike, A.S., Rothrock, D.A. Maykut, G.A. and Colony, R. (1975) The thickness distribution of sea ice. J. Geophys. Res., 80, 4501-4513.

Thorndike, A.S. and Colony, R. (1982) Sea ice motion in response to geostrophic winds. J.Geophys. Res., 87, 5845-5852.

Treshnikov, A.F. (1977) Water masses of the Arctic Basin. In: Polar Oceans. M. Dunbar, Ed. Arctic Inst. of North America Calgary, 17-31.

Vowinckel, E. and Orvig, S. (1970) The climate of the North Polar basin. In: World survey of climatology, 14, Climates of Polar regions. S. Orvig, Editor, Elsevier, 370 pp.

Wadhams, P. and Squire, V.(1982a) An ice-water vortex at the edge of the East Greenland current, J. Geophys. Res. 88, 2770-2780.

Wadhams, P. (1981b) Sea-ice topography of the Arctic Ocean in the region 70^{o}W to 25^{o}E. Phil. Trans. Roy. Soc. A, 302, 45-85.

Wadhams, P. and Horne, R.J. (1980) An analysis of ice profiles obtained from submarine sonar in the Beaufort Sea. J. Glaciol. 25, 401-424.

Walsh, J.E. and Johnson, C.H. (1979) An analysis of Arctic sea ice fluctuations 1953-1977. J. Phys. Oceanogr. 9, 580-591.

Washington, W.M., Semtner, A.J., Parkinson, C. and Morrison, K. (1976) on the development of a seasonal change sea-ice model. J. Phys. Oceanogr. 6, 679-685.

Weber, J.E. (1977) Heat and salt transfer associated with formation of sea ice. Tellus 29, 151-160.

Welander, P. (1977) Thermal osciallations in a fluid heated from below cooled to freezing from above. Dyn. Atmos. Oceans 1, 215-223.

Wright, D.G. (1981) Baroclinic instability in Drake Passage. J. Phys. Oceanogr. 11, 231-246.

Appendix A

Talks Given

P.D. Killworth (DAMTP) A flawed model of the Arctic pycnocline

W.D. Hibler (USA Cold Region Res.) On modelling seasonal and interannual fluctiations of Arctic Sea ice.

J.J. O'Brien (Tallahassee) Long-term plans for modelling the marginal ice zone and adjacent ocean.

L.P. Røed (Inst. of Geofysikk, Oslo) Ice-edge upwelling.

K. Hunkins (Lamont-Doherty) The polar front in Fram Strait observed by helicopter CTD surveys in springtime.

T. Vinje (Norsk Polar-Institutt, Oslo) Special features in the Fram Strait area of importance to modellers

R.Bourke (Naval Postgrad School, Monterey) Early winter observations of the polar front

V. Squire (SPRL) Modelling of ice floe-motions due to ocean waves.

A. Semtner (NCAR) Modelling the water masses of the Arctic Ocean and their relation to climate.

J.-C Gascard (L d'HN, Paris) Deep convection problems in general circulation models.

D. Rothrock (Polar Science Center, Seattle) Ice motion and the atmospheric pressure - basic data for studying air-sea-ice interactions.

B. Rudels (Bergen) Some implications of the YMER observations at 79°N.

E.L. Lewis (FSRG, Sidney) Observations north of Spitzbergen, 1981.

P. Wadhams (SPRI) Statistical properties of sea ice thickness distribution

E.C. Carmack (CCIW, Vancouver) Discussion of modelling problems in the Arctic.

* * * * *

Arctic Modelling Conference - Address List

June 21-25, DAMTP, Cambridge, CB3 9EW, UK

Dr. K. AAGAARD, Department of Oceanography, WB-10,
University of Washington, Seattle, WA 98195, USA

Prof. G.E. BIRCHFIELD, Geological Sciences Department,
Northwestern University, Evanston, IL 60201, USA

Dr. R. BOURKE, Department of Oceanography,
Naval Postgraduate Institute, Monterey, CA 98940, USA

Mr. Ian BRATCHIE, Scott Polar Research Institute,
Cambridge, UK.
Dr. E.C. CARMACK, Canada Centre for Inland Waters,
4160 Marine Drive, W. Vancouver, BC V7V 1N6.

Dr. M.K. DAVEY, Dept. of Applied Mathematics and Theoretical Physics
Silver Street, Cambridge CB3 9EW, UK

Dr. A. FOLDVIK, Geofysisk Institutt, Universitetet i Bergen,
Bergen, Norway.

Dr. J.-C. GASCARD, Laboratoire d'Océanographie Physique,
Museum d'Histoire Naturelle, 42 Rue Cuvier, Paris Cedex 05.

Dr. A.E. GILL, DAMTP, Silver Street, Cambridge CB3 9EW.

Dr. P. GUDMANSEN, Technical University of Denmark,
Electromagnetic Institute, Building 348,
DK-2800 Lyngby, Denmark.

Dr. G. HERMAN, Department of Atmospheric Physics,
Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK.

Dr. W. HIBLER III, Snow and Ice Branch
USA Cold Region Research & Engineering, Hanover,
NH 03755, USA

M. HOUSSAIS, Laboratoire d'Océanographie Physique,
Museum d'Histoire Naturelle, 42 Rue Cuvier, Paris Cedex 05

Dr. K.L. HUNKINS, Lamont-Doherty Geological Observatory of
Columbia University, Palisades, NY 10964, USA

Dr. P.D. KILLWORTH, DAMTP, Silver Street, Cambridge CB3 9EW, UK

B. KING, DAMTP, Silver Street, Cambridge CB3 9EW, UK

M. KRISTENSEN, Scott Polar Research Institute, Cambridge, UK

Dr. E.L. LEWIS, Frozen Sea Research Group, PO Box 6000,
9860 W. Saanich Road, Sidney, BC, Canada V8L 4B2

Dr. P. LINDEN, DAMTP, Silver Street, Cambridge CB3 9EW, UK

Dr. J.J. O'BRIEN, Department of Meteorology,
Florida State University, Tallahassee, FL 32306, USA

Dr. L.P. RØED, Institue for Geophysics, University of Oslo,
BP 1022, Blindern, Oslo 3,Norway.

Dr. R.G. RODENHUIS, Danish Hydraulic Institute,
Agern Alle 4, Horshold, DK 2970, Denmark.

Dr. D. ROTHROCK, Polar Science Center, Universtiy of Washington,
4059 Roosevelt Way, NE, Seattle, WE 98105, USA

Dr. B. RUDELS, Geofysikk Institutt, Bergen, Norway

Prof. V. SCHYTT, Stockholm Universitet, Box 6801, S-113 86 Stockholm,
Sweden

Dr. C. SEAR, Climate Research Unit, University of East Anglia
Norwich NR4 7TJ, UK

Dr. A. SEMTNER, NCAR, PO Box 3000, Boulder, CO 80307, USA

Dr. V. SQUIRE, Scott Polar Research Institute, Cambridge, UK

Dr. T. VINJE, Norsk Polarinstitutt, Oslo, Norway

Dr. P. WADHAMS, Scott Polar Research Institutel Cambridge, UK

R. WAJSOWICZ, DAMTP, Silver Street, Cambridge, UK.


0°
SCANDINAVIA
GREENLAND
SEA
BARENTS
SEA
SPITSBERGEN
GREENLAND
BAFFIN BAY
2000
EURASIAN
BASIN
KARA SEA
90°
90°
2000
CANADIAN
BASIN
LAPTEV SEA
EAST SIBERIAN SEA
USSR
CHUKCHI SEA
ALASKA
180°

FIG. 1

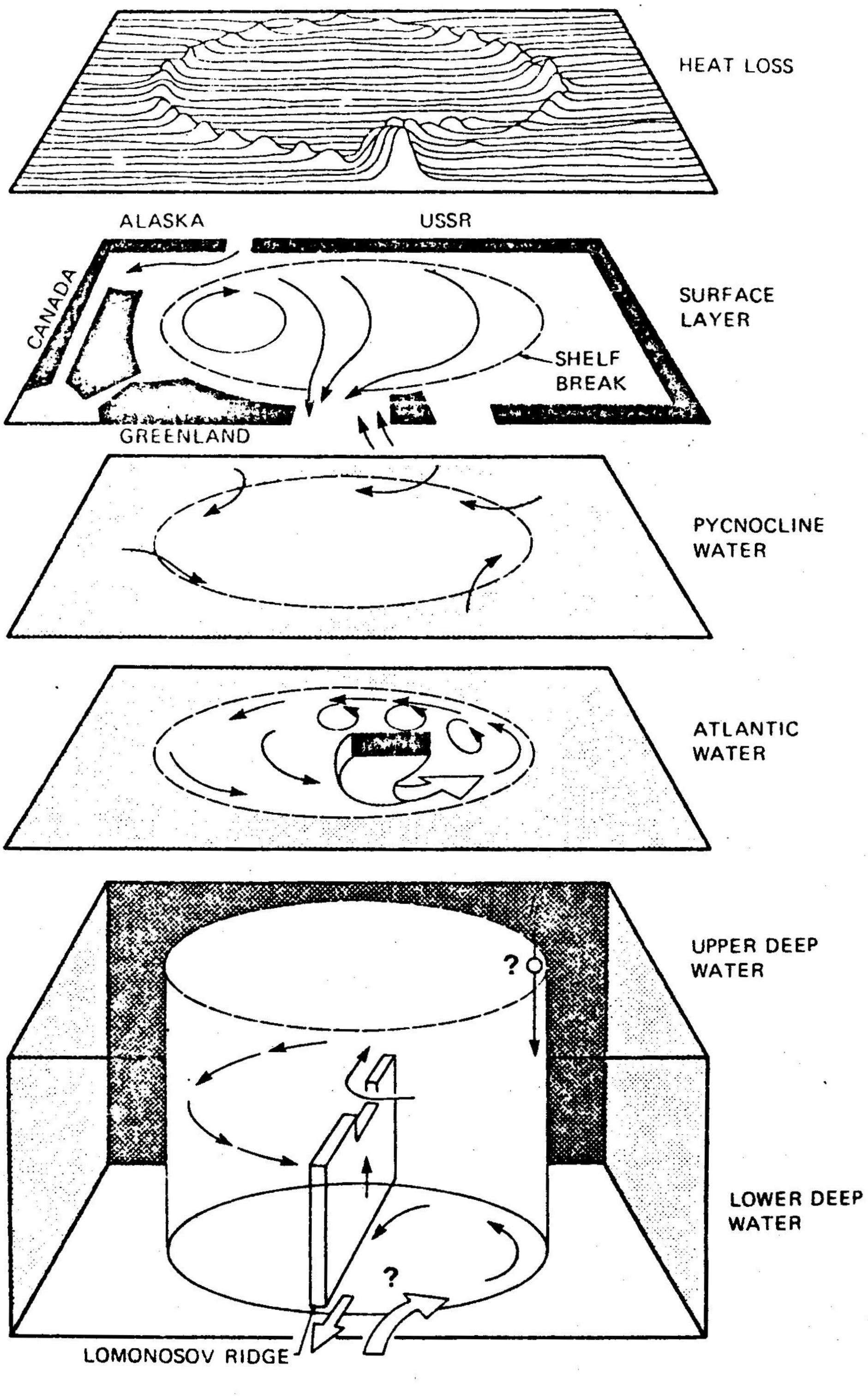

HEAT LOSS
ALASKA
USSR
CANADA
SURFACE
LAYER
SHELF
BREAK
GREENLAND
PYCNOCLINE
WATER
ATLANTIC
WATER
UPPER DEEP
WATER
?
LOWER DEEP
WATER
?
LOMONOSOV RIDGE

FIG. 2

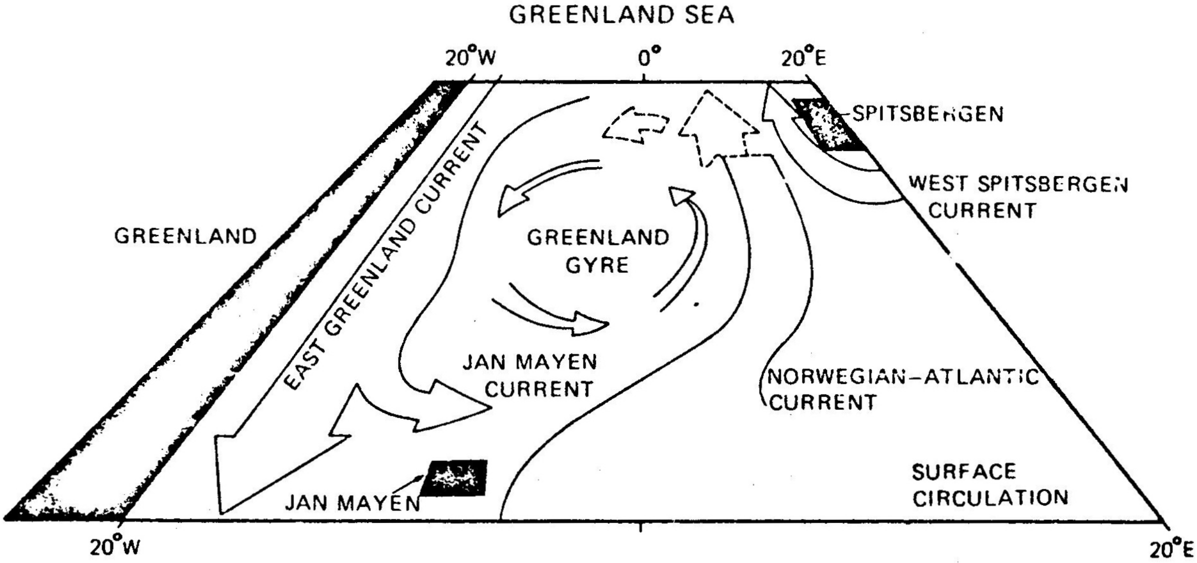

GREENLAND SEA
20°W
0°
20°E
SPITSBERGEN
WEST SPITSBERGEN CURRENT
GREENLAND
EAST GREENLAND CURRENT
GREENLAND GYRE
JAN MAYEN CURRENT
NORWEGIAN-ATLANTIC CURRENT
SURFACE CIRCULATION
JAN MAYEN
20°W
20°E

FIG. 3

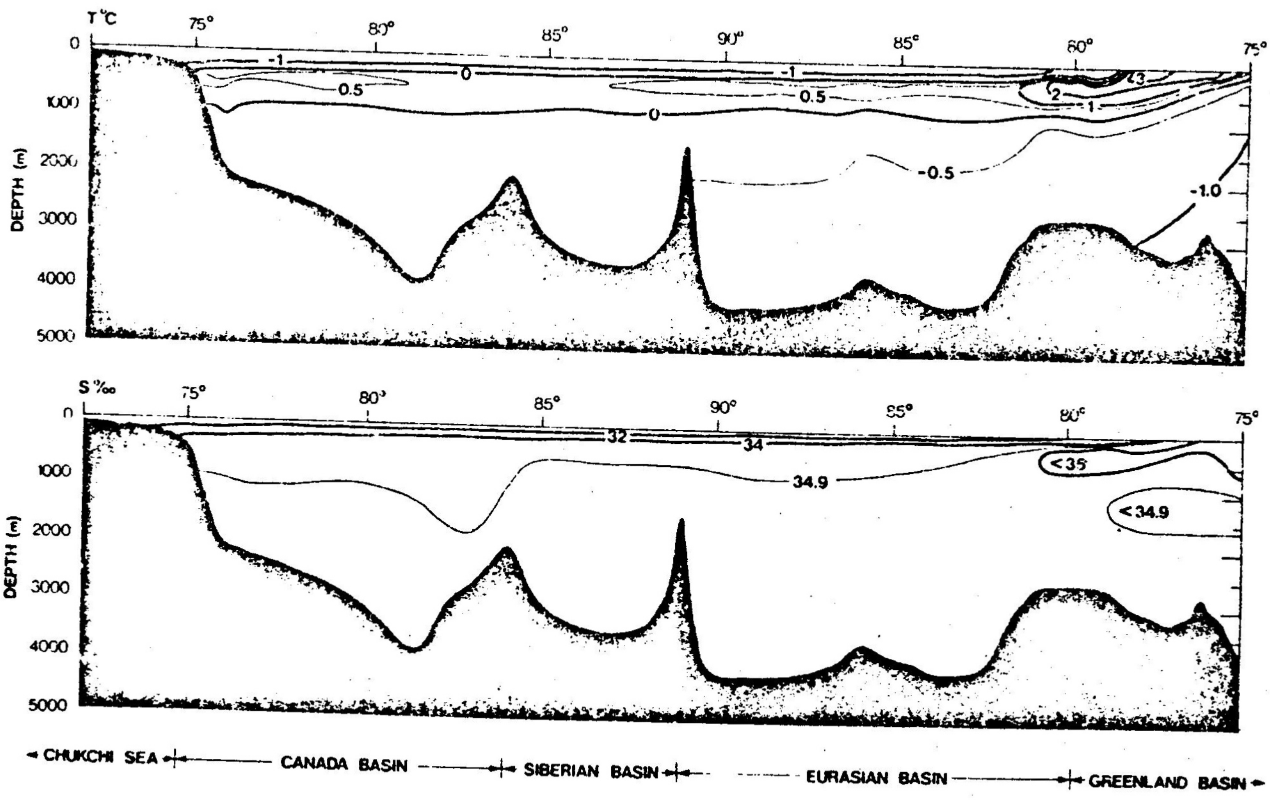
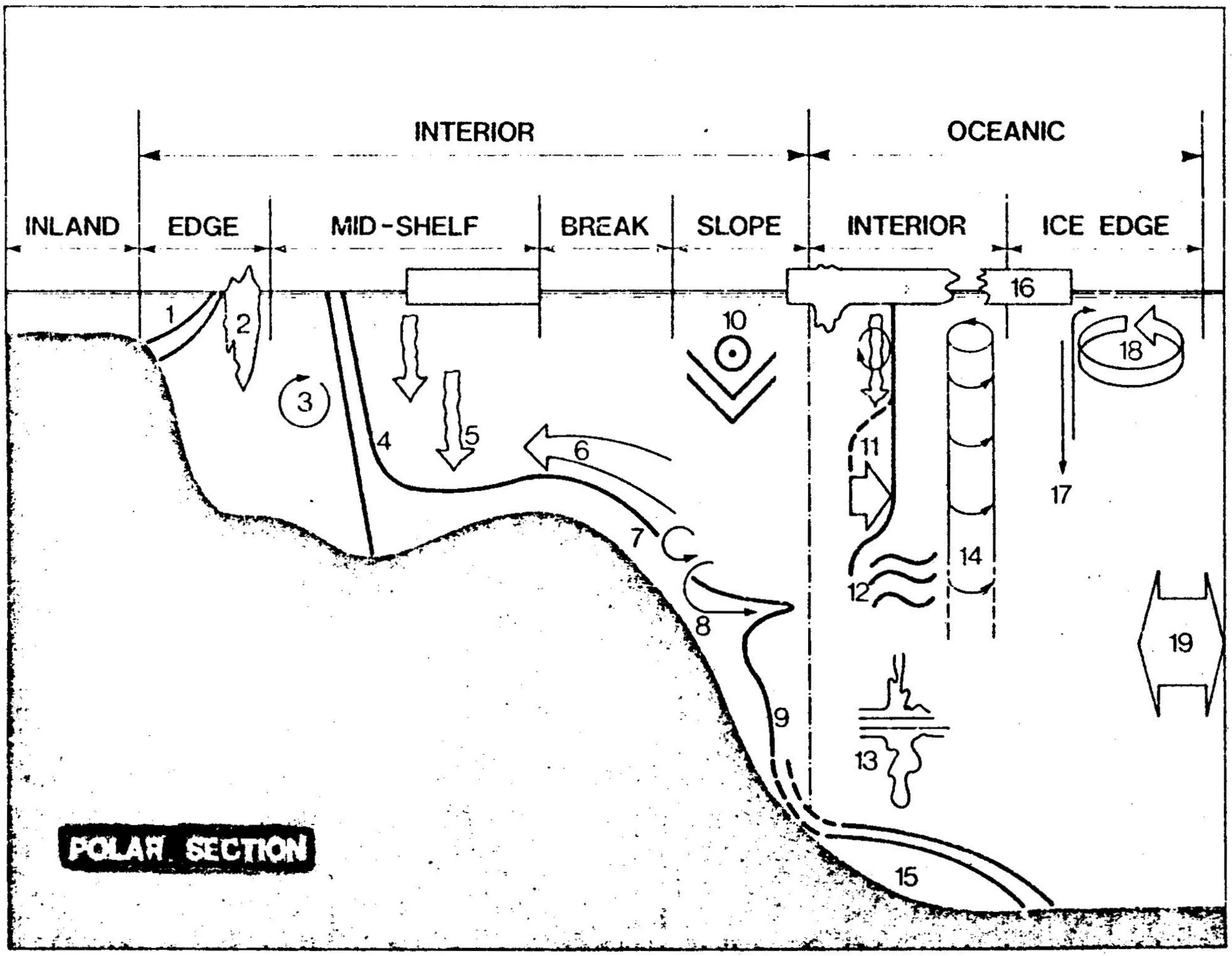

T °C
75°
80°
85°
90°
85°
80°
75°
0
1000
2000
3000
4000
5000
DEPTH (m)
-1
0
0.5
-1
0.5
0
2
3
1
-0.5
-1.0
S ‰
75°
80°
85°
90°
85°
80°
75°
32
34
34.9
<35
<34.9
CHUKCHI SEA
CANADA BASIN
SIBERIAN BASIN
EURASIAN BASIN
GREENLAND BASIN

FIG. 4



INTERIOR
OCEANIC
INLAND
EDGE
MID-SHELF
BREAK
SLOPE
INTERIOR
ICE EDGE
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
POLAR SECTION

FIG. 5

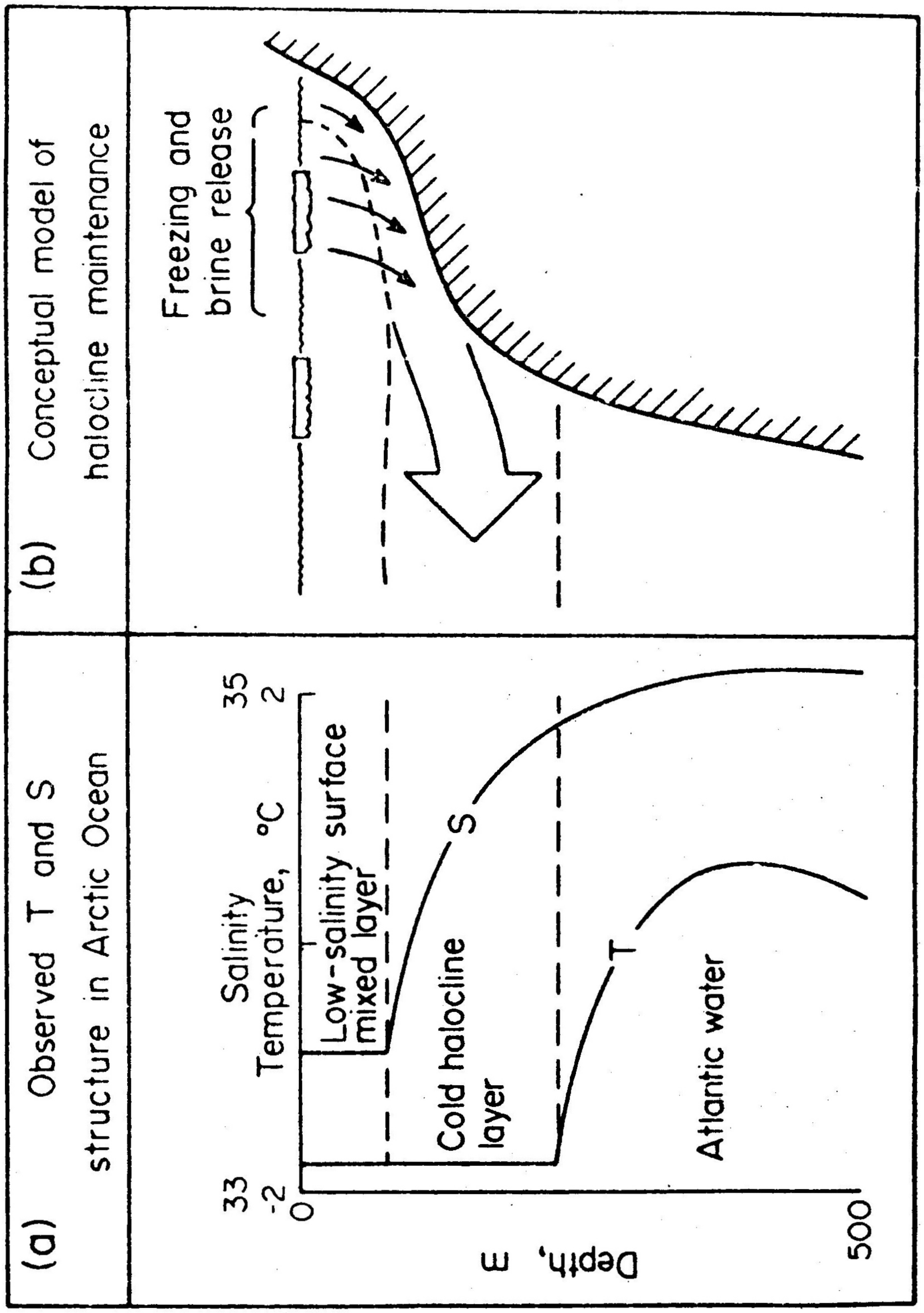

(a) Observed T and S structure in Arctic Ocean
(b) Conceptual model of halocline maintenance
Salinity
Temperature, °C
33
35
-2
2
Depth, m
0
500
Low-salinity surface mixed layer
Cold halocline layer
Atlantic water
S
T
Freezing and brine release

FIG. 6