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World Climate Research Programme

ARCTIC CLIMATE SYSTEM STUDY
CLIMATE AND CRYOSPHERE

RECENT VARIATIONS IN ARCTIC SEA-ICE THICKNESS

(Seymour Laxon[1], Peter Wadhams[2], Chad Dick[3] and Konrad Steffen[4])

Report to the Arctic Ocean Sciences Board
by
ACSYS/CliC Observation Products Panel

Tromsø, Norway
April 2002

IACPO Informal Report No. 7

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By: Seymour Laxon[1], Peter Wadhams[2], Chad Dick[3] and Konrad Steffen[4]

[1]Center for Polar Observation and Modelling
University College London
London WC1E 6BT
United Kingdom

[2]Scott Polar Research Institute
Lensfield Road
Cambridge CB2 1ER
United Kingdom

[3]International ACSYS/CliC Poject Office
Norwegian Polar Institute
The Polar Environmental Centre
NO-9296 Tromsø, Norway

[4]CIRES
University of Colorado
Campus Box 216
Boulder, CO 80303

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Table of Contents

Summary and Recommendations

Measurements of Arctic sea-ice thickness made since the 1950s seem to show that ice thickness in the central Arctic during the summer season has decreased by approximately 40% during the last two decades. There is still uncertainty about the magnitude of this decrease, but it appears to have been accompanied by a decrease in the fraction of multiyear ice present in the Arctic and a sharp decrease in the number of deep pressure ridges. This last observation suggests that there has been a change in the dynamics controlling sea-ice thickness distribution, in addition to any possible changes in thermodynamics. There are also some indications that winter sea-ice thickness may have decreased, but this is less certain, and the magnitude of any change is likely to be less than that of the summer decrease. There are also large areas of the Arctic for which there are no data, and the magnitude of any changes in these areas is unknown. Numerical simulations of Arctic sea-ice thickness suggest that a thinning may have occurred, but that rather than the approximately 40% decrease of thickness, there is a more modest decrease of about 4% per decade over the last 40 years. Some models also suggest that rather than an overall thinning for the entire Arctic, there has been a redistribution of sea ice.

The overall conclusion is that the thinning observed may be explained as the result of the large uncertainties introduced by sparse data coverage and large interannual variability of sea-ice thickness. The available data are not yet sufficient to provide a full understanding of any recent changes in Arctic sea-ice thickness.

Data on Arctic sea-ice thickness have been collected over many years, using a number of techniques. Each of these techniques has limitations, either in spatial or temporal coverage or in accuracy.

The most useful techniques for measuring ice thickness have employed ice-profiling sonars (IPS) (also known as upward looking sonars (ULS)). Moored sonars do not have wide spatial coverage, but, because they can be left collecting data in one place for periods of up to two years, and are then often directly replaced, they have the potential to provide long-term records for determining trends and cycles in the sea-ice thickness spectrum. However, the data collected are difficult to process, and lack of resources to carry out this task has meant that little of the collected data have so far been made available to the scientific community.

> Recommendation 1
> A well coordinated effort should be established to process and publish, all useable data so far collected by moored ice-profiling sonar (IPS) instruments in the Arctic and marginal seas.

IPS instruments can also be mounted on submarines, and such instruments have made measurements in the Arctic for many years. Even so, data coverage is still sparse and sporadic. The main purpose of most cruises was military/strategic, and for this reason there has been no systematic repetition of measurements in a scientifically controlled manner. Comparisons of early and recent data have been made, but the scarcity of data makes this difficult and contentious. Increasing the amount of data available to the scientific community should greatly enhance the ability to discern climatically significant variations in sea-ice thickness. Data from some, but not all, British and US cruises has now been made available and are being processed, but access to Soviet cruise data is still very limited.

Recommendation 2
Efforts should be made through appropriate channels to obtain the release to the scientific community of scientifically-useable, submarine ice-profiling sonar (IPS) data currently held in Russia, the UK and the USA. Regions not covered by previous data releases should have priority.

None of the techniques currently used for measuring sea-ice thickness has yet been able to demonstrate that it can, on its own, provide the broad spatial and temporal coverage needed for developing and understanding a climatology of Arctic sea-ice thickness. The promise shown by some satellite and modelling techniques (see below) has not yet been fully realised. Therefore, for the immediate future, measurements will need to continue with a variety of techniques in an attempt to gain adequate coverage of the ice thickness variability over the entire region. In particular, extension of measurements with ice-profiling sonars, both moored and mounted on submarines and autonomous underwater vehicles (AUVs)) will be needed.

Recommendation 3
Data collection with a variety of measurement techniques, and in particular with ice-profiling sonars, should continue for the immediate future as the best current way of providing broad spatial and temporal coverage of ice thickness over the Arctic basin.

The latest techniques used to gain an understanding of Arctic sea-ice thickness employ satellite measurements and computer models. Because all other techniques give limited spatial or temporal coverage, it is only through satellite measurements that we can hope to obtain the long-term, basin-wide observations of sea-ice thickness needed to develop a climatology of Arctic sea ice. In conjunction with models and developing data assimilation techniques, these will be the tools that will allow assessment and understanding of ice thickness trends. However, these techniques are not yet well developed and calibration and validation using other methods is vital to making full use of satellite observations.

Recommendation 4.
Because satellite and modelling techniques are the only viable methods for gaining basin-wide coverage of Arctic sea-ice thickness, high priority should be given to:
a) efforts to calibrate and validate observations from the new satellites that are to be launched over the next few years, and
b) development of data assimilation techniques that will improve sea-ice models and their ability to predict trends in Arctic sea-ice thickness.

Introduction

Sea-ice thickness is a critical climate parameter. As sea ice thickens, cold dense brine is released and sinks, leading to deeper mixing within the upper layers of the ocean. In contrast, the release of fresh water from melting ice leads to increased stratification and less mixing in the upper layers. Sea-ice thickness also plays a role in thermal insulation. Where ice is thin, heat can be transferred from the warm ocean water to the cold atmosphere above, but where it is thicker heat transfer is very limited and occurs only through leads and cracks in the ice. Similarly, sea ice restricts the transfer of water vapour from the ocean to the atmosphere.

Another important climatic feature of sea ice is its ability to support snow. The albedo of sea ice may not be substantially different from that of seawater, but the albedo of snow is generally much higher. Hence snow on sea ice plays an important role in the radiative balance of polar regions. Snow also plays a further role in insulation between the ocean and atmosphere, being a better insulator than the ice itself. The thickness of sea ice affects the amount of snow that can be supported before the weight of snow pushes the ice down and allows flooding of the snow itself. Snow can also affect the measurement of ice thickness, especially when this is done remotely. Without changing the ice thickness, more snow will decrease the ice freeboard and increase its draft *(Figure 1)*. The thickness of snow may therefore be important both from the point of view of ice thickness measurements, and for an understanding of the interactions between sea-ice thickness and climate.

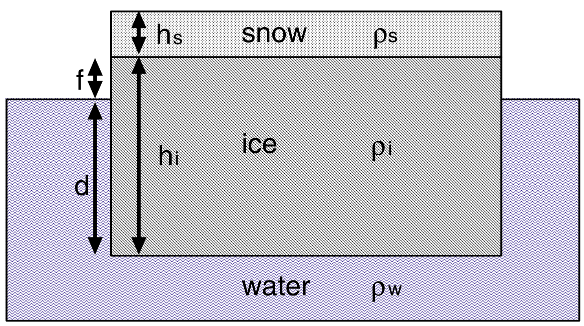

Figure 1. Sea-ice thickness (h_i) is not a simple parameter to measure. Remote techniques usually measure either draft (d) or freeboard (f), and this must then be converted to thickness. The precise relation between draft and freeboard depends on the density of the sea ice (ρ_i) and the density of the water (ρ_w). It can also be affected by the thickness (h_s) and density (ρ_s) of snow on the sea ice. Snow lying on the sea ice decreases the freeboard and increases the draft, as well as increasing the insulation between the ocean and the atmosphere, and contributing additional freshwater to the surface layer during melting.

Attention has been focussed on the issue of sea-ice thickness in the Arctic by recent papers examining both observational data and model output. Computer models suggest that with changing climate, sea-ice thickness will change more rapidly in the nearly land-locked Arctic than will sea-ice extent. Some observations have suggested a dramatic thinning of Arctic sea ice over a wide geographical region during the past two decades [*Rothrock et al.*, 1999; *Wadhams and Davis,* 2000]. Other observations [*Shy and Walsh,* 1996] and some models [*Polyakov and Johnson*, 2000; *Hilmer and*

Lemke, 2000] have suggested either a much smaller decrease of ice thickness or virtually no change over the same period.

It was against this background that the Arctic Ocean Science Board requested the Observation Products Panel (OPP) of the WCRP's Arctic Climate System Study (ACSYS) and Climate and Cryosphere (CliC) projects to review the current state of scientific knowledge on Arctic sea-ice thickness. This report provides a summary of the current state of knowledge of Arctic sea-ice thickness from recent literature, and discusses the weaknesses in what is known of the subject. It also reviews what is being done using currently available data, measurement techniques and models, and assesses possible new techniques for the future. This report also provides recommendations based on the review of this subject.

State of knowledge

At present, submarine sonar (see 'Current sea-ice thickness measurement techniques' below) datasets provide the best method for examining trends in Arctic sea-ice thickness over large areas. A number of papers have recently compared data from early submarine cruises with more recent data from the 'SCICEX' series of cruises during the 1990s.

Mean ice draft measured by 6 submarine cruises between 1958-1976 were compared by Rothrock et al. [1999] with 3 submarine cruises in 1993, 1994 and 1997. After using a model to convert the data to equivalent thicknesses for the month of September, the data show an average 42% reduction in Arctic ice draft *(Figure 2)*. What was perhaps most remarkable about the findings of these authors was that the thinning, which on average represented a greater than 1m decrease between the earlier set of measurements and the later cruises, occurred in all areas where measurements were available, with no corresponding areas of increased thickness. From the three most recent cruises, these authors also suggested a continuing decline of 0.1 m yr^{-1} during the 1990s. A further comparison of two UK cruises in the Eurasian Basin shows a 43% decline in ice draft between 1976 and 1996 [*Wadhams and Davis*, 2000], extending the geographical area affected and adding weight to the result. The latter datasets also showed a radical decline in the incidence of deep pressure ridges in the Eurasian Basin, to only 27% of their former concentration, indicating a major change in the nature of the ice dynamics [*Wadhams and Davis,* 2001]. This observation has not yet been fully explained. The physics of ridging and rafting and the structure of ridges are still relatively poorly known.

Not all measurements yield exactly the same picture. From analysis of ice draft measurements gathered during 12 cruises near the North Pole between 1977 and 1992, Shy and Walsh [1996] reported that they had found no significant trends in thickness. Similarly, from six cruises in the Beaufort Sea to North Pole region between 1991 and 1997, Winsor [2001] reported no significant trends. A further analysis of data from 1976 to 1994 shows a significant decrease in the Western Arctic but no trend at the North Pole [*Tucker et al.*, 2001]. These results suggest that any thinning that has occurred is much less dramatic than the > 40% decrease suggested by Rothrock et al., [1999] and Wadhams and Davis [2000].

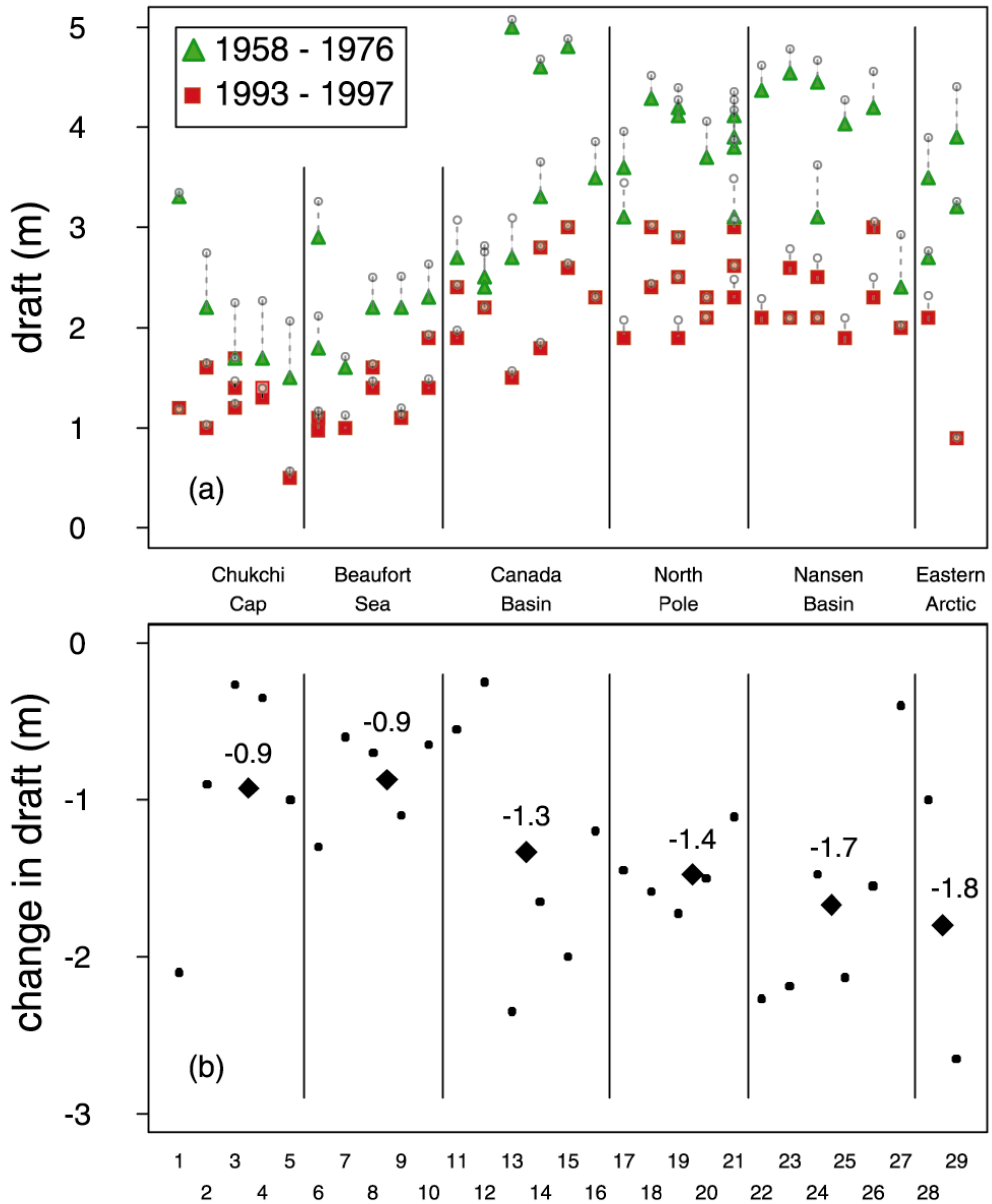

Figure 2. (a) Mean ice drafts at locations where measurements were made by both early submarine cruises and SCICEX (1990s) cruises, with all original data (small dots) adjusted to 15 September (large symbols). Data are grouped into six regions as shown. (b) Changes in mean draft between early and 1990s measurements. The large diamond and number show the mean change for each region. (Adapted from Rothrock et al., [1999].)

However, there are some difficulties with these latter analyses. Rothrock et al. [1999] and Wadhams and Davis [2000] made efforts to compare values representative of the summer season in all cases, using models were applicable to convert all data to one season. In contrast, Shy and Walsh [2001], Winsor [2001], and Tucker et al. [2001] compared data from different seasons, making their findings more difficult to interpret. The apparent discrepancies between these different analyses of submarine derived ice thickness are almost certainly a result of using data from different seasons, and processing the data in different ways. In addition, each group of authors has used a different subset of the submarine record.

Overall, these results suggest that a large relative loss of ice thickness has occurred in summer, while losses at other seasons remain to be accurately assessed, but are probably more modest.

The results also betray the fact that the effect of the natural regional, seasonal and inter-annual variability of ice thickness on trends derived from limited subsets of data is poorly understood. In particular the lack of submarine data in the Eastern Arctic and over the Canadian shelves has led to suggestions that the observed thinning was peculiar to the regions analysed and that thickening of ice may have occurred elsewhere.

Numerical simulations of Arctic sea ice from the 1950s to the 1990s attribute some or all of the 42% decrease suggested by [*Rothrock et al.*, 1999] to the location and timing of the submarine cruises. Two studies reproduce the trends in the regions observed but, for the Arctic as a whole, show either no significant decrease in thickness [*Polyakov and Johnson*, 2000], or a more modest decrease of 16% (4% per decade) [*Hilmer and Lemke*, 2000].

In a further study, Holloway and Sou [2001] considered the results of Rothrock et al. [1999] in detail, sending 'virtual submarines' to the locations in their model where thinning had been found. The particular locations were nearly all in the 'central' Arctic, and were in areas where the model also showed substantial thinning. However, in the model this thinning was partially compensated by thickening of the ice in the area north of the Canadian Archipelago, leading to an overall suggested decrease in ice volume of only 12% *(Figure 3)*. Much of the ice had not disappeared, but had been redistributed. Furthermore, Holloway and Sou [2001] assessed the inter-annual variability of sea-ice thickness in their model, and noted that by moving each of the early measurements to one year earlier and each of the recent measurements one year later, the differences would disappear and in fact no thinning would be found (Figure 4). The different patterns of sea-ice distribution were explained by differences in the wind patterns over the Arctic between the years of the early cruises and the later. In the later years, the wind over the months preceding the virtual measurements moved relatively more ice out of the central Arctic and pushed it into the Canadian sector.

However, there are many uncertainties in the model representations of the physical processes that control ice thickness. Changing the model physics can significantly change the response to variable forcing [*Chapman et al.*, 1994]. The key to assessing the validity of the numerical simulations is data on ice thickness and such data do not yet exist in sufficient quantity and adequate quality [*Battisti,* 1997; *McLaren et al.,* 1992; *Steele and Flato*, 2000].

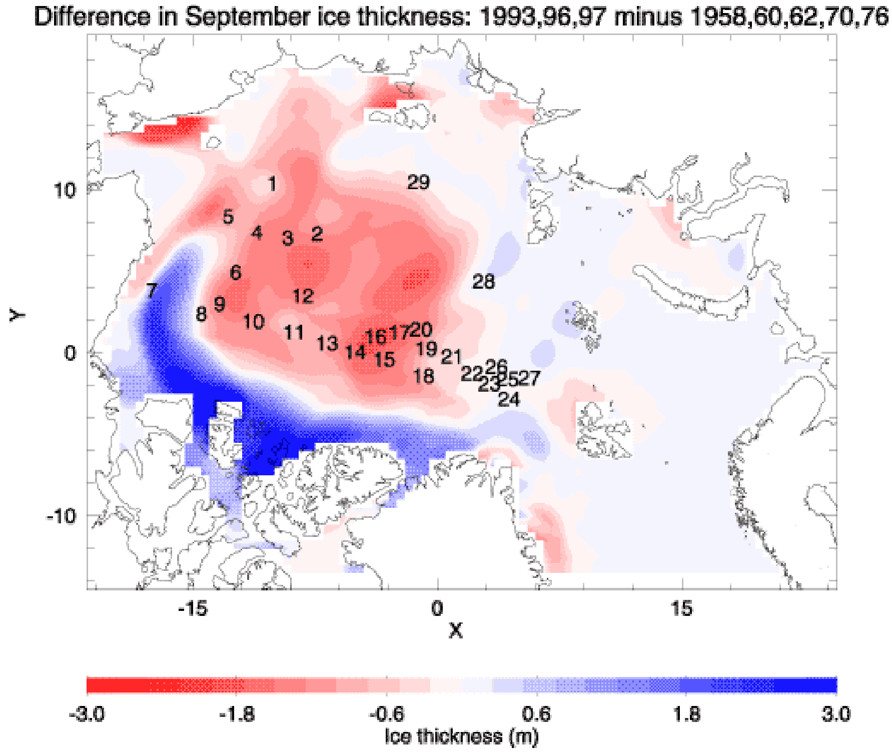

Figure 3. Changed ice thickness, SCICEX (1990s) cruises minus earlier submarine periods. The numbers show the 29 locations where Rothrock et al. [1999] were able to compare data, and to which Holloway and Sou [2001] sent their 'virtual submarines'. (From Holloway and Sou [2001].)

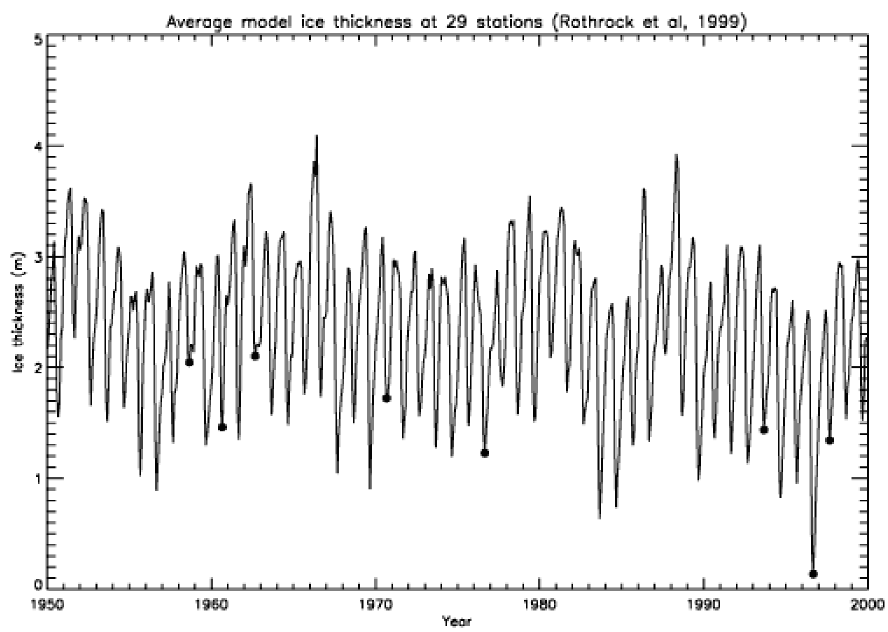

Figure 4. Time series of model ice thickness averaged over the 29 submarine measurement locations. Moving early measurements to one year earlier would generally lead to the measured ice being thinner, while moving the later measurements to one year later would yield a greater average ice thickness. There would then have been no difference in average thickness, according to the model. (From Holloway and Sou [2001].)

The limited sampling by submarines and the questionable validity of numerical simulations therefore leaves the question of the extent of recently observed thinning, and its cause somewhat open. Efforts to validate model thickness with submarine data are underway but if anything these are highlighting the limitations of models in capturing natural variability and the need for more comprehensive data on ice thickness [*Shy et al.*, 2000]. In particular a large amount of submarine data on ice thickness gathered over the last 40 years, including some that have been used for published trends analysis, is still not available in the public domain. Another serious concern is the fact that valuable time-series of data gathered from moored ice-profiling sonars in the last 10-15 years remains unpublished and unavailable [*Melling and Riedel*, 1995]. Some data from the Norsk Polar Institute has been released and published [*Vinje et al.*, 1998] but there are still concerns about the accuracy of some draft estimates in the record. There is a pressing need for all available historical ice thickness data to be provided in a consolidated and quality controlled manner to the ice modelling community.

Recommendation 1
A well coordinated effort should be established to process and publish, all useable data so far collected by moored ice-profiling sonar (IPS) instruments in the Arctic and marginal seas.
Recommendation 2
Efforts should be made through appropriate channels to obtain the release to the scientific community of scientifically-useable, submarine ice-profiling sonar (IPS) data currently held in Russia, the UK and the USA. In particular regions not covered by previous data releases should have priority.

Current sea-ice thickness measurement techniques

A number of techniques have been used to measure sea-ice thickness, but unfortunately all of them have their limitations.

Direct measurement by drilling through the ice is the most accurate method of measurement, with typical errors of approximately 1 cm. However, the labourious and occasionally dangerous nature of the technique means that it is impractical for giving broad coverage of the Arctic basin, particularly during ice formation and break-up. In addition, there can be significant variations over even short distances of seemingly uniform ice.

Visual observations from ships provide a reasonably effective method of estimating undeformed ice thickness, especially when carried out by experienced observers. As ice floes are turned on edge at the ship's bow, thickness can be compared with a visual reference of known dimensions, yielding fairly accurate estimates. However, these visual observations are less accurate for estimating the thickness of ridged ice. In addition, access to all areas is again a problem, as is the bias produced when ships are deliberately steered towards areas of thinner and more broken ice.

Electromagnetic-inductive sounding, exploiting the different electrical conductivity of sea ice and seawater, can yield useful results. Deployment from helicopters means that measurements can be made over 10's of kilometres, but again there are operational constraints, which limit both the spatial and seasonal coverage. Measurements tend to be close to ship tracks or manned stations, and are limited by winter darkness in polar regions.

Using a dual radar/laser system, aircraft can be used to give measurements ranging over 1000's of kilometres. Operational constraints still limit basin-wide and seasonal coverage, and uncertainties in snow depth place limits on accuracy, but aircraft have performed an extremely useful role in operational sea-ice charting for many years, particularly close to major shipping routes.

Ice-profiling sonars can be either moored to the seabed or mounted on submarines. These provide estimates of ice draft and hence thickness. Moored sonars have been given Doppler capability to allow estimation of ice velocity, and can therefore be used to estimate ice export from the Arctic basin, as has been done for Fram Strait [for example, *Vinje,* 2001]. However, expense and deployment/recovery difficulties mean that they have not been used to cover large areas of the Arctic. Submarines have the mobility to cover large areas, but cannot provide the time series that moored instruments can. In addition, there have been problems of access to data from submarines, whose primary function during the Cold War was to collect strategic information. The end of the Cold War has not helped much in this regard, as the number of cruises has dropped as military requirements in the region are reduced. However, these data are now becoming available to climate scientists with help from military authorities.

Upward or multibeam ice-profiling sonar fitted to autonomous underwater vehicles (AUVs) are now beginning to yield data on sea-ice thickness, and in principle could supplant or replace similar sonars on military submarines, especially as they can be deployed over a planned grid rather than a transit of opportunity. These AUVs have a range of a few hundred kilometres, and are a step towards basin wide coverage using a surface-deployed technique.

Since none of these techniques provides wide coverage on its own, the best picture of current sea-ice thickness can only be obtained by using data from all these methods. Until satellite techniques are more fully validated and models are improved, a combination of these different methods will continue to be needed.

Recommendation 3
Data collection with a variety of measurement techniques, and in particular with ice-profiling sonars, should continue for the immediate future as the best current way of providing broad spatial and temporal coverage of ice thickness over the Arctic basin.

Future techniques: Satellites and models

Satellite data will ultimately help to fill the gaps left by other techniques, giving broad coverage of the Arctic at frequent intervals. Four techniques in particular, each at a different stage of development, are showing promise.

1) Radar altimeters deployed on satellites can provide a direct measurement. The technique has been developed over a period of years, and uses the time taken for a

radar pulse to return to the satellite from the snow/ice interface. This yields a measure of the freeboard (*Figure 1*) from which the ice thickness can be estimated. The technique has a number of uncertainties that yield an overall uncertainty of approximately 0.5 m for a single radar pulse. For example, snow lying on the sea ice will depress the snow/ice interface, making the ice appear thinner. An estimate of snow depth and density must therefore be made and lack of data on snow depth leads to increased uncertainty. In addition, the radar pulse has a footprint of approximately 1 km, and more information is therefore collected from floes of this size or greater. If the thickness distribution of floes is different for this size of floe compared to the general thickness distribution then this will bias the results obtained by this method. The uncertainty resulting from this footprint effect requires that further calibration and validation work be carried out to improve the understanding of satellite radar altimeter data. Additional uncertainty comes when ice is thin and there is difficulty distinguishing between reflections from thin sea ice and open water. Hence the technique works better for thicker sea ice. Despite these problems, data from ERS-1 and ERS-2 have been used to construct a record of Arctic sea-ice thickness over the past decade, and further data from ENVISAT and CryoSat are now expected to extend and improve this record.

2) Laser altimeters provide another method of ice thickness measurement using the return from the surface of a pulsed signal. With a smaller footprint, this technique provides greater precision for a single pulse. However, there are still problems with this method and overall accuracy may not be any greater than with radar altimetry. For example, in this case, the return is from the snow surface, and increasing snow depth will make the ice appear thicker. Once again the technique works better over thick sea ice, where the difference between open water and sea ice is more distinct. Laser altimetry has been used successfully from aircraft and the launch of ICESAT in 2002 should see coverage extended in both time and space.

3) The Radarsat Geophysical Processing System combines 3-day repeat satellite observations with models of ice growth and deformation to estimate ice thickness. At the start of the winter season, a grid is produced to cover the Arctic Basin. Deformation of this grid is tracked with each repeat image of an area, and changes within each grid box are used to calculate ice thickness. Where a box has grown, sea ice is assumed to have formed in the leads created by this divergence. Where the area of a grid box has shrunk, the thinnest ice is assumed to have deformed and thickened according to the model physics. This method has been used to produce a four-year record of sea-ice motion, age and thickness for the Arctic and has proved to be particularly useful in areas of thin ice. However, the system has difficulties in areas of high deformation, such as near the ice edge and near land, where tracking of ice features becomes increasingly difficult.

4) One further satellite method detects thin ice in winter via its greater emission of infrared radiation caused by higher surface temperature [*Lindsay and Rothrock,* 1995]. Once again there can be a variety of confounding factors, including insulation by snow lying on the sea ice preventing the loss of heat from the ocean below.

It should be noted that, while these methods have met with some success, they are all still in the development stage, and it may well be some years before adequate climatological coverage is available. In order to achieve this, satellite techniques require detailed calibration and validation by surface methods to ensure adequate precision and accuracy.

The only other method by which basin-wide coverage of sea-ice thickness can be obtained is through modelling. At present models are able to represent some features of Arctic sea-ice cover with reasonable accuracy, but all current models have some limitations. Models are primarily used for climate research purposes and very little use has been attempted for forecasting of sea-ice conditions; a task still based almost entirely on empirical observations of sea ice. In a move that should parallel the development of numerical weather prediction models some 20 to 30 years ago, there is now a need for models and data assimilation techniques to be developed for sea-ice forecasting in order to improve both sea-ice prediction and sea-ice modelling methods.

Recommendation 4.
Because satellite and modelling techniques are the only viable methods for gaining basin-wide coverage of Arctic sea-ice thickness, high priority should be given to:
a) efforts to calibrate and validate observations from the new satellites that are to be launched over the next few years, and
b) development of data assimilation techniques that will improve sea-ice models and their ability to predict trends in Arctic sea-ice thickness.

Conclusions

There now seems to be a growing consensus that there has been a decrease in the thickness of summer sea ice in the Arctic over the past two decades. There seem to be sufficient measurements in the central Arctic region to show that this is the case. There may also be decrease in thickness during other seasons, but this is less certain, and if it has occurred, the thinning is by a smaller amount.

A number of questions about this thinning still remain to be answered.

- There are insufficient data to accurately quantify the decrease in thickness, especially in the light of the major inter-annual variations in thickness that have been observed. New measurements and recovery of old data are both required to reduce the uncertainties in the magnitude of change.
- The reasons why the major thinning seems to be restricted to the summer season are also not yet clear. It could be an artefact of the analyses of the limited amount of data available, or a real physical effect that is yet to be fully understood.
- The observation of decreases in the number of pressure ridges in the Eurasian Basin, and the changed dynamics that this implies, also require explanation. The physics of ridge formation and the resulting structure of ridges are yet to be fully understood, and since ridges are thought to make up a high fraction of the total sea-ice volume in the Arctic this is a topic requiring further research.
- If the thinning observed in the central Arctic is a result of ice redistribution by wind, then there is a need to gain a better understanding of the changed pattern of atmospheric motion. This in itself could be part of a trend, a cycle or merely

a result of similar large inter-annual variability. Ice thickness changes cannot be properly understood in isolation.

Current surface-based observational techniques are unable to provide basin-wide measurements of ice thickness for the Arctic. Newer satellite observations are showing promise and it will be these methods that in future give the broad coverage needed to follow changes in Arctic sea-ice thickness. However, these techniques are not yet fully proven, and calibration and validation of satellite sensors is still of vital importance. For radar altimeter measurements in particular, there is a need to understand the relationship between floe size distribution and floe thickness. Depth and density of snow cover are also critical parameters that need to be better defined. Ultimately, it is unlikely that one type of satellite measurement proves ideal for all situations, and the best results will come from combined use of several different methods.

Models of Arctic sea ice continue to be developed and improved. However, their main purpose remains climate research, while operational ice forecasting is carried out using empirical observation methods. In the same way that climate models have benefitted from progress with numerical weather prediction models, a move to attempt ice forecasting using sea-ice models and data assimilation techniques would be likely to benefit both communities. There is no doubt that improved models will be required if predictions of future Arctic ice conditions are to be made with confidence.

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Appendix 1

List of Participants

Howard Cattle
Hadley Centre for Climate
Prediction and Research
Room 245, Meteorological Office
London Road
Bracknell, Berkshire, RG12 2SZ
United Kingdom

Jens H. Christensen
Danish Meteorological Institute
Lyngbyvej 100
DK-2100 Copenhagen O, Denmark

Roger Colony
IARC/Frontier Research Program
University of Alaska, Fairbanks
P.O. Box 757335
Fairbanks, AK 99775-7335, USA

Josefino C. Comiso
NASA Goddard Space Flight Center
Laboratory for Hydrospheric Processes
Code 971
Greenbelt, MD 20771, USA

Chad Dick
International ACSYS/CliC Project Office
The Polar Environmental Centre
NO-9296 Tromsø, Norway

Hugues Goossee
Unversitè catholique de Louvain
Institut d'astronomie et de
gèophysique G. Lemaître
2 chemin de Cyclonotron
B-1348 Louvain-la Neuve, Belgium

Seymour Laxon
Center for Polar Observation and Modelling
University College London
London WC1E 6BT
United Kingdom

Christoph Oelke
National Snow and Ice Data Center (NSIDC)
CIRES/University of Colorado
Campus Box 449
Boulder, CO 80309, USA

Victor Savtchenko
Joint Planning Staff for the World Climate
Research Programme
WMO Secretariat
7bis, Avenue de la Paix, CP2300
Geneva 2, CH-1211, Switzerland

Vladimir Smirnov
Arctic and Antarctic Research Institute
38 Bering St.
199397 St. Petersburg, Russia

Koni Steffen
CIRES
University of Colorado
Campus Box 216
Boulder, CO 80303, USA

Jinro Ukita
NASA-Goddard Space Flight Center
Code 971
Greenbelt, MD 20771, USA

Tordis Villinger
International ACSYS/CliC Project Office
The Polar Environmental Centre
NO-9296 Tromsø, Norway

Peter Wadhams
SPRI
Lensfield Road
Cambridge CB2 1ER
United Kingdom

Anthony Worby
Australian Antarctic Division and
Antarctic CRC
P.O. Box 252-80
Hobart, Tasmania 7001
Australia