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Thinning of the Arctic Sea-Ice Cover

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Abstract. Comparison of sea-ice draft data acquired on submarine cruises between 1993 and 1997 with similar data acquired between 1958 and 1976 indicates that the mean ice draft at the end of the melt season has decreased by about 1.3 m in most of the deep water portion of the Arctic Ocean, from 3.1 m in 1958–1976 to 1.8 m in the 1990s. The decrease is greater in the central and eastern Arctic than in the Beaufort and Chukchi seas. Preliminary evidence is that the ice cover has continued to become thinner in some regions during the 1990s.

Introduction

There is substantial evidence that the Arctic climate is warming [e.g., *Dickson*, 1999]. In addition, the sea-ice cover shows signs of diminished extent and seasonal duration in (1) the Northern Hemisphere over the period 1978–1995 [*Johannessen et al.,* 1996,], (2) the eastern Arctic Ocean and Kara and Barents seas over the period 1979–1986 [*Parkinson*, 1992], and (3) the East Siberian and Laptev seas over the period 1979–1995 [*Maslanik et al.*, 1996]. In this paper we use submarine data to examine whether sea-ice thickness, or actually draft, in the Arctic Ocean is also changing.

Several investigators have explored ice draft changes. *McLaren* [1989] studied a thousand-kilometer transect in two summer cruises 12 years apart (1958 and 1970) and found a draft reduction of 0.2 m in the Transpolar Drift Stream and the Eurasian Basin, and of 0.7 m in the Canada Basin. *Wadhams* [1990, 1992] reported a thinning from 1976 to 1987 of 0.8 m between Fram Strait and the pole and of 2.2 m north of Greenland. *McLaren et al.* [1994], however, found no trend in data from 12 cruises at the North Pole over a 34-year period. *Wadhams* [1994] summarized several earlier data sets and reported a reduction between the 1970s and the 1980s of 0.6 m in the region bounded by Fram Strait, Greenland, and the North Pole. Re-examining the later portion of the McLaren's North Pole data, *Shy and Walsh* [1996] also found no trend and explained some of the variance in draft by ice dynamical processes. The differing time periods and regions studied make it hard to see a comprehensive picture, although the aggregate of these studies points to a widely thinning ice cover over the last few decades.

In the 1990s many ice draft data have been acquired by the Scientific Ice Expeditions (SCICEX) program, which provided the opportunity to use U.S. Navy submarines for Arctic research [*Gossett*, 1996]. The 1990s data used here (Figure 1) are from September 1993 (USS *Pargo*), September–October 1996 (USS *Pogy*), and September 1997 (USS *Archerfish*). Data from the first two of these cruises are publicly available through the National Snow and Ice Data Center, Boulder, Colorado. Because data from these cruises cover most of the deep Arctic Ocean basin, they invite a more comprehensive analysis of interannual ice draft variations than was previously possible.

Ice draft data from these three SCICEX cruises show a perennial ice cover with mean drafts of between 1 and 3 m, considerably thinner than previous estimates of mean draft [*Bourke and McLaren*, 1992]. Of the historical data used in previous studies, few are publicly available. The historical data to which we found access are published by *LeSchack* [1980] and *McLaren* [1986]. To obtain broad spatial samples, we pool together in one group all data from these early cruises (1958–1976) and in a second group all data from the 1990s SCICEX cruises. Because the SCICEX data are from the end of summer, we limit our comparison to summer and autumn data from the earlier cruises, whose tracks are shown in Figure 1. The early cruises used here are from August 1958 (USS *Nautilus*), August 1960 (USS *Seadragon*), July 1962 (USS *Seadragon* and USS *Skate*), August 1970 (USS *Queenfish*), and October 1976 (HMS *Sovereign*). The USS *Nautilus* and USS *Queenfish* data come from *McLaren* [1986] and the rest from *LeSchack* [1980]. All data are from narrowbeam sonars except for *Nautilus* and *Sovereign* whose widebeam data we corrected to the narrowbeam equivalent by multiplying by 0.84 [*Wadhams*, 1983]. There are a few data from the intervening years (between 1976 and 1993), but these do not provide wide spatial coverage, and we have not tried to incorporate them.

Analysis and Results

To quantify the differences between SCICEX data and historical data, we compare mean drafts from crossing or nearly overlapping segments of tracks from the two data sets. The quantity we examine is the mean draft $\bar{D}$, defined as the average over a section of track of length L (including portions of track with open water).

$$\bar{D} = \frac{1}{\bar{L}} \int_0^L D(x)dx \qquad (1)$$

To compare drafts observed in the 1990s with those of earlier years, we identified 29 locations (numbered in Figure 1) at which the earlier submarine tracks either cross, or are closely parallel to, the 1990s cruise tracks. The historical (pre-1990s) data are available only as mean drafts (and open water fraction) averaged over distances of roughly 50 km for LeShack's data and about 100–500 km for McLaren's data, as indicated by red dots in the figure. Selecting the crossings is subjective. Where an early and a recent track cross somewhat perpendicularly (e.g., crossing #5), we take samples of about 150 km centered on the crossing. Where an early and a recent track run parallel and no more than 50 km apart (e.g., #10), we take longer segments of about 200

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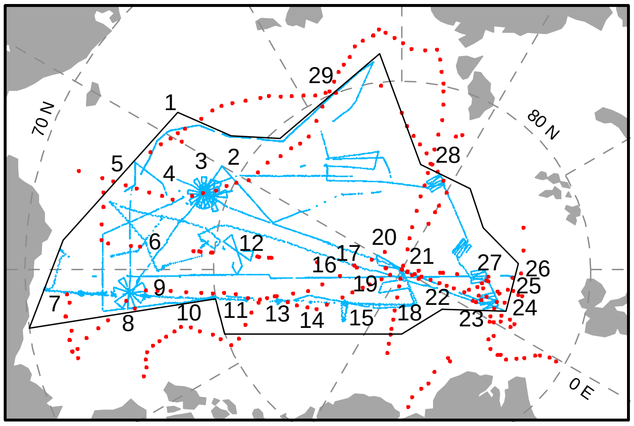

Figure 1. Submarine cruise tracks and comparison locations, indicated by location number. Tracks in the early cruises (1958–1976) are indicated by dotted red lines, and those in the 1990s by solid blue lines. The area from which SCICEX data could be released is the interior of the solid black polygon.

km. In general, we use for each period records from fifty to several hundred kilometers long, and the average sample length at crossings is about 160 km.

During SCICEX'96 we oversampled a patch of ice 160 km in diameter to determine spatial sampling error. The mean draft on ten different diameters of the region had a standard deviation of 0.13 m over a diameter length of 50 km, of 0.14 m over 100 km, and of 0.11 m over 160 km. So for the present comparison we assign a spatial sampling error of about 0.13 m to the estimate of mean draft at each crossing. Others have estimated the overall sampling and measurement errors to be 0.06 to 0.15 m in mean draft over a 50-km segment [*Bourke and McLaren*, 1992]; we believe that, conservatively, the overall errors are probably less than 0.3 m.

To reveal interannual change it seems crucial to remove the seasonal cycle, even though just how to do so is far from clear. We seasonally adjust all mean drafts downward by the change in draft from the observation date to the minimum on September 15 in the modeled annual cycle shown in Figure 2. This cycle was derived from an ice-ocean model with a 12-category ice thickness distribution [*Zhang et al.*, 1998]. The model was forced with 40 years of winds and temperatures from the NCEP (National Center for Environmental Prediction) reanalysis, and thickness was averaged over those 40 years, over the SCICEX data release area in Figure 1, and over the thickness distribution (including open water). (An ice slab has a smaller annual thickness range of

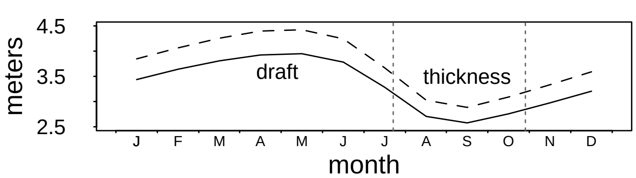

Figure 2. Modeled seasonal cycle of ice thickness and draft used to correct observations to 15 September. Draft is computed as modeled thickness divided by 1.12. The observations all lie between late July and late October, as shown by the dotted vertical lines.

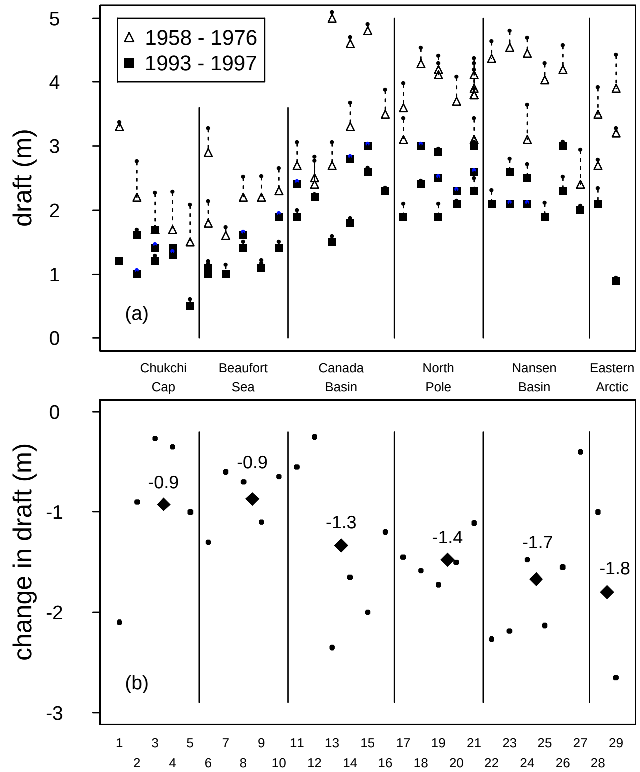

Figure 3. (a) Mean ice drafts at crossings of early cruises with cruises in the 1990s. Early data (1958–1976) are shown by open triangles and those from the 1990s by solid squares, both seasonally adjusted to September 15. The small dots show the original data before the seasonal adjustment. The crossings are grouped into six regions separated by the solid lines and named appropriately. (b) Changes in mean draft at cruise crossings (dots) from the early data to the 1990s. The change in the mean draft for all crossings in each region is shown by a large diamond. The abscissa gives the number of each crossing from Figure 1.

roughly 0.5 m, but models that include a thickness distribution show an annual cycle of over a meter.) This adjustment reduces all observations, none by more than 0.6 m; because

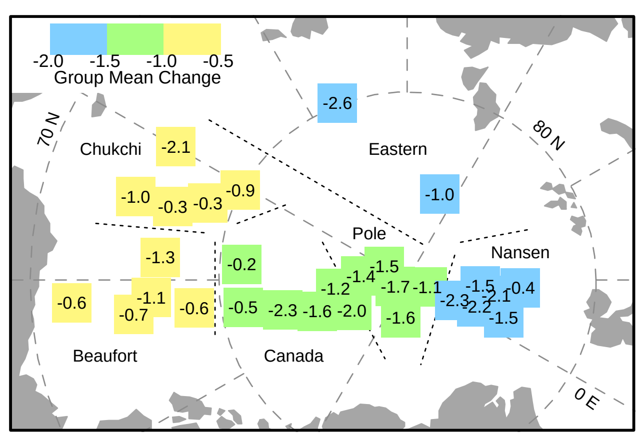

Figure 4. Changes in mean draft from the early period to the 1990s. The change at each crossing is shown numerically. The crossings within each regional group (Figure 3) are given the same shading equivalent to their group mean. Each square covers about 150 km, the typical sample size.

the dates of the early data lie further from the September minimum than those of the SCICEX data, the adjustment reduces the early data the most.

The draft data are shown in Figure 3a, and the changes in draft from the earlier cruises to the SCICEX cruises are shown in Figure 3b. The changes are striking both in the uniformity of their sign and in their magnitudes. The regional groupings are intended to represent roughly equal areas of the Arctic Ocean; the groupings are somewhat arbitrary and do not affect the main conclusions. Note that without the seasonal adjustments the older ice would appear thicker and the decrease to the 1990s even greater. The data show a thinning of about 1.7 m in the Nansen Basin and the eastern Arctic. The thinning in the Beaufort Sea and Chukchi Cap is less, a meter or so. The North Pole and northern Canada Basin fall in between. The mean draft within each regional grouping is given in Table 1. Overall, the mean draft has decreased 1.3 m, or some 40%, from the earlier period. In Figure 4 the pattern clearly emerges that it is in the central and eastern portions of the Arctic Ocean that draft has decreased the most. Within the limitation that the early data are available only as mean draft and open water fraction, the thinning appears to be due minimally to changes in the open water fraction and mostly to changes in draft itself.

A similar analysis of ice draft at crossings among the 1990s cruise tracks makes a modest case that the ice cover continued to thin somewhat during that 4-year span (1993–1997). Table 2 shows the mean drafts and the trend over the 4-year period in six regions. These trends are not well defined by only three cruises, but they are significant at the 80 to 90% level overall and in four of the six regions, and they are negative in three of those four.

Discussion and Conclusions

What changes in arctic heat fluxes would cause the observed change in ice thickness? This question can be explored using sensitivity equations that relate change in equilibrium ice thickness h_{eq} to changes in components of the arctic heat budget. From *Thorndike* [1992, Eq. 32] we calculate that the observed decrease of 1.4 m in thickness (1.3 m in draft) could arise from any of the following flux increases:

- a 4 W m^{-2} increase in ocean heat flux F_w from a nominal value of 2 to 4 W m^{-2},
- a 13 W m^{-2} increase in poleward atmospheric heat transport D from a nominal value of about 100 W m^{-2} (about half of which reaches the surface as longwave radiation), and
- a 23 W m^{-2} increase in downwelling shortwave radiation F_{SW} from a nominal value of about 200 W m^{-2} for about half the year.

Although these changes are significant compared to the flux components, they are at the threshold of our observational capability, and it may prove difficult to isolate the cause of a thinner ice cover by direct flux measurements. Alternatively, the reduction in ice could be related to changes in precipitation and snow cover or to advective processes such as increased ice export that accompanied the elevated North Atlantic Oscillation index in the late 1980s and early 1990s [*Kwok and Rothrock*, 1999].

In summary, ice draft in the 1990s is over a meter thinner than two to four decades earlier. The mean draft has decreased from over 3 m to under 2 m, and volume is down by some 40%. The thinning is remarkable in that it has occurred in a major portion of the perennially ice-covered Arctic Ocean. This is not a case of thicker ice appearing in one region simultaneously with thinner ice appearing in another, induced perhaps by a change in surface winds and ice advection. *Parkinson's* [1992] study of the duration of the ice season, for instance, does show a pattern of compensating regional trends: a shortened season in eastern longitudes, focused in the Barents, Kara and Okhotsk seas, and a lengthened season in western longitudes, more diffusely spread over the Labrador, Beaufort, and Bering seas and Hudson Bay. The present analysis, by contrast, shows a widespread decrease in ice draft within the central Arctic Ocean, with the strongest decrease occurring in the eastern Arctic. Not only is the ice cover thinner in the 1990s than earlier, it appears to be continuing to decline in some regions through four years of SCICEX cruises at a rate of about 0.1 m yr^{-1}.

Whether ice volume has reached a minimum in a multidecadal cycle or will continue the observed decline, this large thinning of the ice cover is a major climatic signal that needs to be accounted for in a successful theory of climate variability. There is not yet a good temporal record of ice draft over the Arctic Ocean; what we have constructed here is better thought of as two climatologies, one for 1958–1976 and another for 1993–1997. A larger pool of publicly archived data

Table 1. Mean ice draft, in meters, in various regions of the Arctic Ocean during the early submarine cruises of 1958 to 1976 and during the cruises in the 1990s, along with the change in meters and percent. The number of crossings in each region is given in parentheses.

Region	'58–'76	1990s	Change m	Change %
Chukchi Cap (5)	2.1	1.2	−0.9	−43
Beaufort Sea (5)	2.1	1.2	−0.9	−43
Canada Basin (6)	3.5	2.2	−1.3	−37
North Pole (5)	3.8	2.4	−1.4	−37
Nansen Basin (6)	3.9	2.2	−1.7	−43
Eastern Arctic (2)	3.3	1.5	−1.8	−55
All regions (29)	3.1	1.8	−1.3	−42

Table 2. Mean drafts, in meters, for regional groups of crossings among SCICEX cruises. The number of crossings in each region is given in parentheses. Each trend (in m yr^{-1}) including that for "all regions" is estimated by a regression through the three (or two) data points in the table.

Region	1993	1996	1997	Trend
Chukchi Cap (7)	1.1	1.2	1.1	0.01
Beaufort Sea (5)	1.8	1.0	1.4	−0.14
Canada Basin (5)	2.6	1.7	2.0	−0.17
North Pole (4)	2.6	2.2	2.8	0.01
Nansen Basin (1)	2.1	2.6	n/a	0.17
Eastern Arctic (2)	2.1	1.7	0.8	−0.28
All regions (24)	2.0	1.7	1.6	−0.10

of ice draft profiles acquired by submarines over the last 40 years would be of immense help in refining this climatic signal.

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