Decline in Arctic sea ice thickness from submarine and ICESat records: 1958–2008

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[1] The decline of sea ice thickness in the Arctic Ocean from ICESat (2003–2008) is placed in the context of estimates from 42 years of submarine records (1958–2000) described by Rothrock et al. (1999, 2008). While the earlier 1999 work provides a longer historical record of the regional changes, the latter offers a more refined analysis, over a sizable portion of the Arctic Ocean supported by a much stronger and richer data set. Within the data release area (DRA) of declassified submarine sonar measurements (covering ~38% of the Arctic Ocean), the overall mean winter thickness of 3.64 m in 1980 can be compared to a 1.89 m mean during the last winter of the ICESat record—an astonishing decrease of 1.75 m in thickness. Between 1975 and 2000, the steepest rate of decrease is −0.08 m/yr in 1990 compared to a slightly higher winter/summer rate of −0.10/−0.20 m/yr in the five-year ICESat record (2003–2008). Prior to 1997, ice extent in the DRA was >90% during the summer minimum. This can be contrasted to the gradual decrease in the early 2000s followed by an abrupt drop to <55% during the record setting minimum in 2007. This combined analysis shows a long-term trend of sea ice thinning over submarine and ICESat records that span five decades. **Citation:** Kwok, R., and D. A. Rothrock (2009), Decline in Arctic sea ice thickness from submarine and ICESat records: 1958–2008, *Geophys. Res. Lett.*, *36*, L15501, doi:10.1029/2009GL039035.

1. Introduction

[2] Since 1958, submarine ice draft data sets from upward-looking sonars have allowed assessments of the ice thickness changes in various regions of the Arctic Ocean. These assessments by a number of investigators are listed and discussed by *Rothrock et al.* [2008]. Two such studies are *Rothrock et al.* [1999, 2008] (hereinafter referred to as RYM99 and RPW08, respectively). RYM99 provide evidence of significant thinning by comparing available ice drafts during two periods (1958–1976 and 1993–1997) separated by roughly 28 years, while RPW08 estimated the rates of ice draft decline over a 25-year period between 1975 and 2000. However, in contrast to the concerted SCICEX efforts of the 1990s, since the turn of the century rather few submarine cruises have provided ice draft data for assessing more recent changes.

[3] Recent work has demonstrated the feasibility of retrieving sea ice freeboard and thickness from space by a laser altimeter on ICESat (Ice, Cloud, and land Elevation Satellite). In particular, *Kwok et al.* [2009] (hereinafter referred to as K09) use ice freeboard of the Arctic Ocean to produce basin-scale ice thickness estimates from ten ICESat campaigns that span a period of five years (2003–2008), and assess the relative consistency and quality of these estimates with ice draft data from submarine and moored profiling systems. The basin-wide decline in ice thickness during this five-year period is large (−0.17 m/yr). In this note, we compare the ICESat estimates with the changes and trends in ice thickness reported by RYM99 and RPW08. Our aim is to place the recent thickness changes as depicted by ICESat in context with the submarine results that span over 40 years. Section 2 describes the data sets used, and Sections 3 and 4 compare the ICESat estimates with the results from RYM99 and RPW08. Section 5 summarizes this paper.

2. Data Description

2.1. Ice Thickness From U. S. Navy Submarines

[4] We use the analyzed ice draft results from RYM99 and RPW08. The length of the data record, including gaps in coverage, spans 42 years from 1958 to 2000. Very few ice draft data are available from submarine cruises since 2000. The ice draft data that are declassified and released for public use are within a DRA [*National Snow and Ice Data Center*, 2006], an irregular polygon that lies within the Arctic Ocean and outside the 'exclusive economic zones' of foreign countries (Figures 1a and 2a). This polygon encloses an area of 2.7×10^6 km^2, about 38% of the Arctic Ocean. In all the figures and where appropriate in the text, submarine ice draft estimates are converted to thicknesses by first subtracting a bias (0.29 m), and then multiplying by the average thickness to draft ratio of 1.075 (RPW08). The draft estimates are biased with respect to actual draft, due to the first return nature of sonar measurements [*Rothrock and Wensnahan*, 2007]. The differences between the records and sampling of the two data sets of RYM99 and RPW08 are discussed where relevant.

2.2. Ice Thickness From ICESat

[5] These basin-scale estimates are derived from ten ICESat campaigns that span a period of five years (2003–2008) (K09). These campaigns are selected to provide representative samplings of the fall and winter Arctic sea ice cover. Each fall and winter ICESat campaign covers a ~33-day period from roughly mid-October to mid-November (2003–2007), and from late February to late March (2004–2008). The variance of the difference between ICESat draft and submarine draft is (0.42 m)^2 (see K09). This can be

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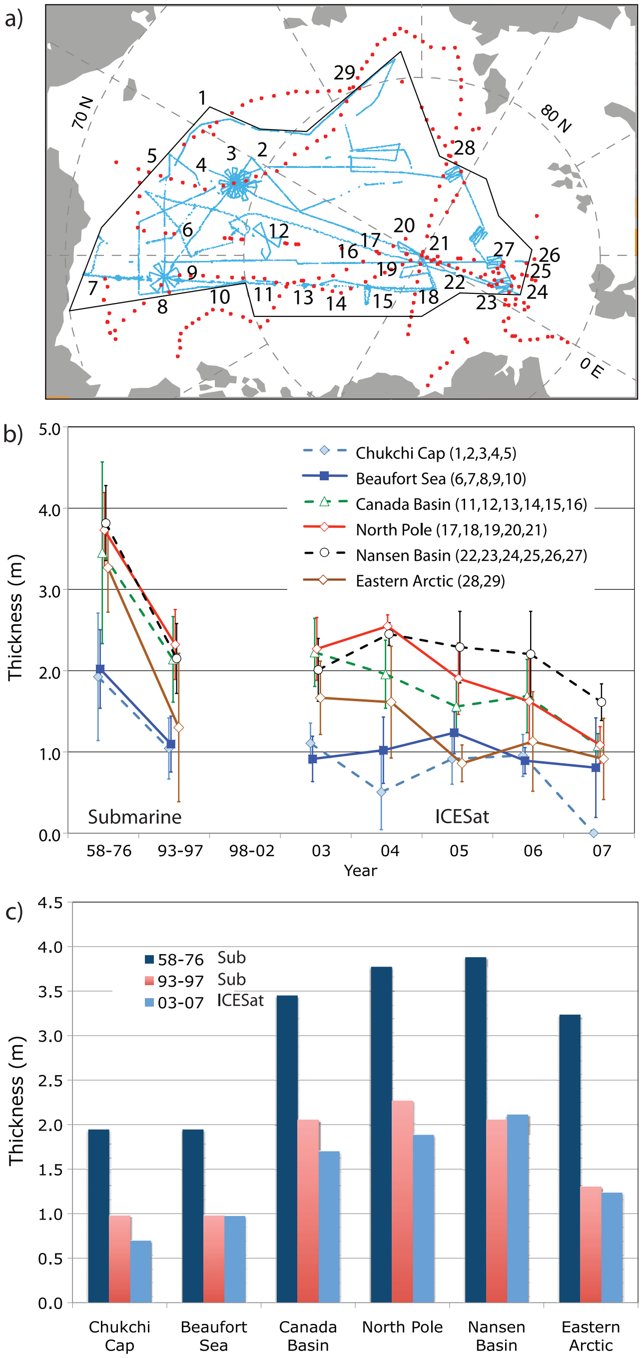

Figure 1. (a) Submarine cruise tracks and comparison locations, indicated by location number. Tracks in the early cruises (1958–1976) are indicated by dotted red lines, and those in the 1990s by solid blue lines. The area from which SCICEX data could be released is the interior of the solid black polygon [after *Rothrock et al.*, 1999]. (b) Regional comparisons of the submarine data ((1958–1976, and 1993–1997) and five years (2003–2007) of ICESat thickness data. The locations used to compute the regional averages are given in parentheses. Vertical bars show the variability within each region. (c) Bar chart shows the mean thicknesses of the six regions for the three periods (1958–1976, 1993–1997, 2003–2007). Thicknesses have been seasonally adjusted to September 15.

partitioned into the variance of observational errors in the submarine data (0.25 m)^2 [from *Rothrock and Wensnahan*, 2007], and the variance in the ICESat data themselves (0.34 m)^2. We take the value, 0.34 m (0.37 m), to be the standard deviation of the uncertainty in ICESat estimates of draft (thickness) if they could be compared to perfect measurements.

2.3. Ice Concentration

[6] Changes in thickness are viewed in light of the bootstrap ice concentration estimates from SMMR and SSM/I observations available at the National Snow and Ice Data Center [*Meier et al.*, 2008]. These 25-km gridded fields span the period from 1979 to 2008.

3. Three Periods (1958–1976, 1993–1997, 2003–2008)

[7] RYM99 compared nine submarine cruises between 1993 and 1997 with similar data acquired between 1958 and 1976. These earlier data (1958–1976) were manually digitized from paper charts and are likely of lower quality than the post-1990 data, which are from digitally processed paper charts and digitally recorded data. RYM99 identified 29 locations (numbered in Figure 1a) at which the earlier submarine tracks either cross, or are closely parallel to, the 1990s cruise tracks. The pre-1990s ice draft data (indicated by red dots in Figure 1a) are available only as mean drafts (and open water fraction) averaged over distances of roughly between 50 km and 500 km. Overall, the average sample length at the crossings is ~160 km. The estimated error due to spatial variability is 0.13 m about the mean draft at each crossing, and the total error (including measurement errors) is 0.3 m. All ice drafts are then seasonally adjusted to September 15 using the modeled annual cycle from an ice-ocean model. The crossings are grouped to represent the changes in six regions: Chukchi Cap, Beaufort Sea, Canada Basin, North Pole, Nansen Basin, and Eastern Arctic. Figure 1b shows the numbered locations that were used to create the averages for each region.

[8] To compare the ICESat data with these submarine data, we replicate a similar sampling procedure. At the 29 locations, average thicknesses are extracted from the 25-km gridded ICESat fields. The thickness at each grid cell represents the average of all 25-km ICESat segments that fall within that grid cell. The thickness from the five fall-ICESat campaigns are seasonally adjusted to September 15 using the same modeled annual cycle as RYM99. Since each fall ICESat campaign covers a ~33-day period from mid-Oct to mid-Nov and no more than 2 months from September 15, the adjustment reduces all ICESat thicknesses by less than 0.2 m. So within Section 3, "fall" is at the end-of-melt minimum.

[9] The changes in ice thickness are shown in two ways: Figure 1b is a line plot that shows the regional variability and changes with the five ICESat years resolved, and the bar chart in Figure 1c depicts the regional averages over the three periods (1958–1976, 1993–1997, 2003–2008). Vertical bars in Figure 1b show the standard deviation of the thickness estimates at the numbered locations within each region. In addition, Table 1 shows the mean thickness of

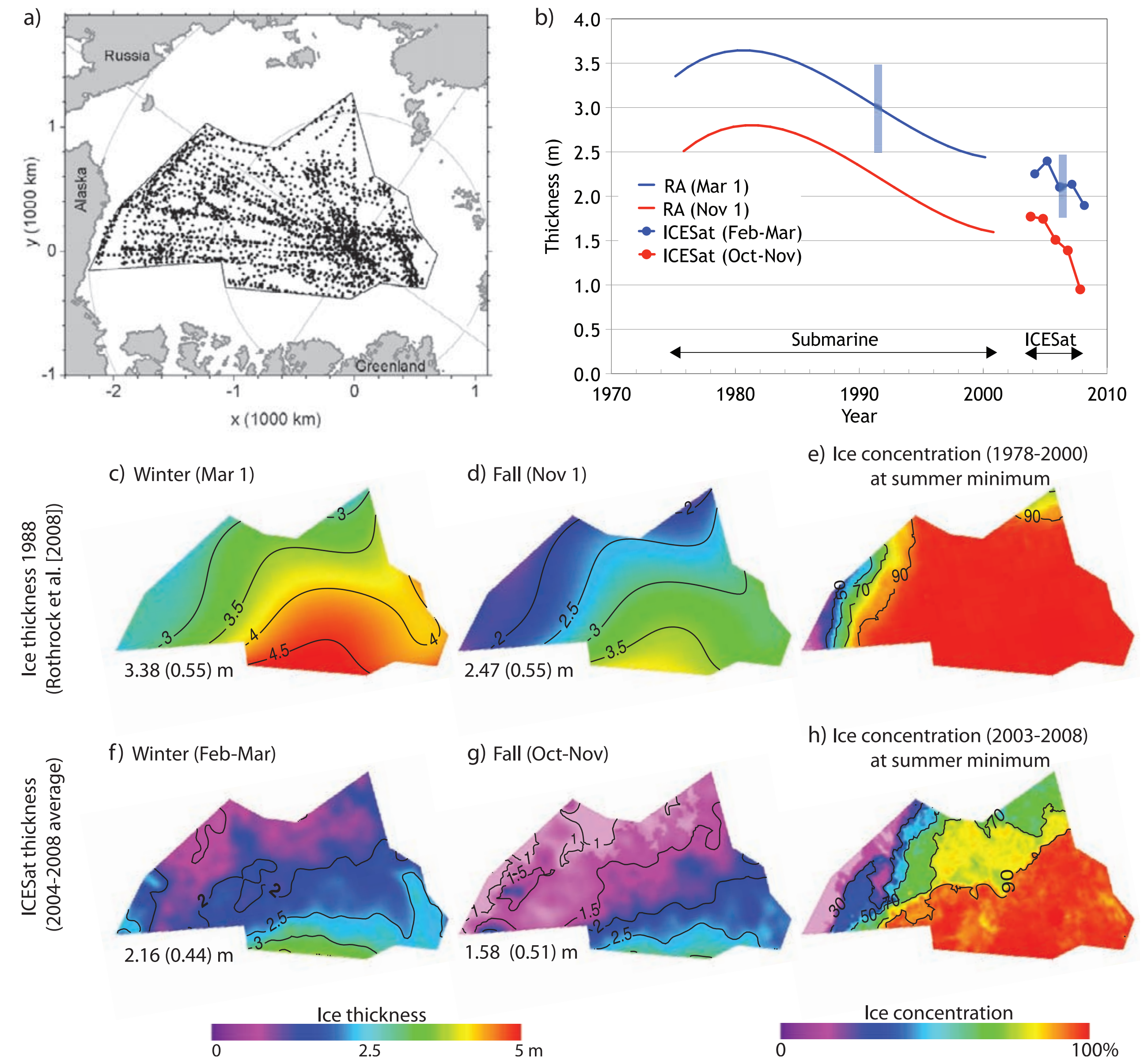

Figure 2. (a) Data points from U.S. Navy cruises used by RPW08, and the data release area (irregular polygon). (b) Interannual changes in winter and summer ice thickness from RPW08 and K09 centered on the ICESat campaigns. Blue error bars show residuals in the regression and quality of ICESat data. (c, d) Spatial patterns of ice thickness in winter (Feb–Mar) and fall (Oct–Dec) of 1988. (e) Mean sea ice concentration at summer minimum (1978–2000). (f, g) Spatial patterns of mean winter (Feb–Mar) and fall (Oct–Dec) ice thickness from ICESat (2003–2008). (h) Mean sea ice concentration at summer minimum (2003–2008). Quantities in Figures 2c, 2d, 2f, and 2g are mean and standard deviation of ice thickness within the DRA.

Table 1. Mean Ice Thickness at the End of Melt Season in the Six Regions of the Arctic Ocean From Submarine Cruises in 1958–1976, 1993–1997, and ICESat Acquisitions in 2003–2007[a]

	Period			Change					
				(2)–(1)		(3)–(1)		(3)–(2)	
Region	Period 1, 58–76	Period 2, 93–97	Period 3, 03–07	Thickness	Percent	Thickness	Percent	Thickness	Percent
Chukchi Cap	1.95	0.98	0.70	−0.97	−50	−1.25	−64	−0.28	−29
Beaufort Sea	1.95	0.98	0.97	−0.97	−50	−0.97	−50	0.00	0
Canada Basin	3.45	2.05	1.70	−1.40	−40	−1.75	−51	−0.35	−17
North Pole	3.77	2.27	1.89	−1.51	−40	−1.89	−50	−0.38	−17
Nansen Basin	3.88	2.05	2.11	−1.83	−47	−1.77	−46	0.06	3
Eastern Arctic	3.24	1.30	1.24	−1.94	−60	−2.00	−62	−0.06	−5
All Regions	3.02	1.62	1.43	−1.40	−46	−1.59	−53	−0.19	−12

[a]Mean ice thickness is shown in meters, and changes in thickness are shown in meters and percent.

Table 2. Trends in Mean Ice Thickness for the Regional Groups of Crossings for the SCICEX Period (1993–1997) and ICESat period (2003–2007) at the End of the Melt Season

Region	Trend (m/yr) 1993–1997	Trend (m/yr) 2003–2007
Chukchi Cap	0.01	−0.18
Beaufort Sea	−0.15	−0.03
Canada Basin	−0.20	−0.26
North Pole	0.01	−0.33
Nansen Basin	0.18	−0.10
Eastern Arctic	−0.30	−0.20
All Regions	−0.11	−0.18

each region during the three periods and their relative changes (in thickness and percent) while Table 2 shows the regional trends for the two later periods.

[10] Briefly, the results of RYM99 indicate that the mean ice thickness at the end of the melt season decreased by 1.4 m in most of the deepwater portion of the Arctic Ocean, from 3.0 m in 1958–1976 to 1.6 m in 1993–1997. The decrease is greater in the central Arctic (which includes the Canada Basin, North Pole and Nansen Basin) and eastern Arctic than in the Beaufort and Chukchi seas. Over the mean separation of 28 years between these two periods, the mean thickness has decreased by 1.4 m or 46%.

[11] The ICESat data show further decreases in the thickness, albeit rather smaller, in the ten years between 1993–1997 and the 2003–2007 (Table 1). Between the second and third periods, the mean thickness decreased by another 0.2 m or 12% of the thickness. Relative to the first period, over about four decades, the average thickness decreased by 1.6 m or some 53% of the thickness.

[12] There are negative trends in ice thickness in all regions during the ICESat period (Table 2). The Chukchi Cap is actually ice-free at the end of the melt season in 2007 (Figure 1b). The largest trends are at the North Pole and in the Canada Basin. Due to the large retreat of the multiyear ice cover during the ICESat period, the ice edge during the summer minimum has moved closer to the North Pole. By 2007 some of the locations in the Canada Basin and Nansen Basin are covered by thinner seasonal ice.

4. Comparison of Submarine (1975–2000) and ICESat (2003–2008) Ice Thicknesses

[13] While the RYM99 analysis extends back to the late 1950s, its assessment of thinning is restricted to select locations and regions. The RPW08 analysis uses a much stronger and richer data set from 34 submarine cruises that provide 2203 samples of 50-km mean draft within the DRA (Figure 2a). These cruises are equally distributed in spring and fall over a 25-year period from 1975 to 2000. Values of 50-km mean ice draft range from 0 to 6 m with a standard deviation of 0.99 m. Multiple regression is employed to separate the interannual change, the annual cycle, and the spatial field of draft, D, viz:

$$D(t,\tau,x,y) = C + I(t-1988) + A(\tau) + S(x,y) + \varepsilon(t,\tau,x,y)$$

where C is a constant, $I(t - 1988)$ describes the interannual change centered around 1988, $A(\tau)$ describes the annual cycle, and $S(x, y)$ is the spatial field. The unmodeled residuals are represented by ε. The solution gives the space-time dependence of ice draft (D) over the 25-year period. Regression coefficients for the terms in the above equation can be found in the work by RPW08. The residuals of the regression have a standard deviation of 0.46 m, slightly more than the expected observational error standard deviation of 0.38 m. The overall mean of the solution is 2.68 m (2.88 m in thickness using the conversion factors in Section 2). Annual mean ice draft declined from a peak of 3.13 m in 1980 to a minimum of 2.0 m in 2000, a decrease of 1.13 m (1.21 m in thickness). The steepest rate of decrease is −0.08 m/yr in 1990. The rate slows to −0.007 m/yr at the end of the record.

[14] Here, the results from the regression analysis (RA) are combined with the ICESat thickness fields from ten campaigns to extend the length of the thickness record from 1975 to 2008. Since the equation provides the space-time dependence of ice draft (or thickness), we elect to compare the ICESat data with the solution at the center of the fall and winter ICESat campaigns (November 1 and March 1) with minimal affect (<0.1 m) on the amplitude of the annual cycle.

[15] Figure 2b shows the combined record of mean thickness in winter and summer within the DRA from the RA (RPW08) and the ICESat estimates (K09). The values of the five winter/summer ICESat data points (in blue/red) represent the mean of the thickness distribution within the DRA. From the peak winter thickness in 1980 of 3.64 m (RPW08) to the 1.89 during the last winter (2008) of the ICESat record (K09), there is a net decrease of 1.75 m in thickness. The summer thickness declines from 2.80 m in 1980 to 1.15 m in 2007 of the ICESat record, a decrease of 1.65 m. This adds another 0.55/0.44 m of winter/summer decline to the 1975–2000 analysis. These are large and significant decreases considering the residuals of 0.5 m in the RA, and the uncertainty of the ICESat thickness data of 0.37 m (see Section 2). These values are shown as error bars in Figure 2b. The winter/summer trend in thickness over the 5-year ICESat record of −0.10/−0.20 m/yr is steeper than the steepest decline of −0.08 m/yr in 1990 (RPW08). The (blue) curve from the RA and the ICESat data points suggest a slowing in the downward trend from the late 1990s and within the data gap, before it picks up again in the ICESat period.

[16] Next, we compare the thickness fields from RPW08 with the ICESat estimates. The spatially varying component of D ($S(x, y)$, a 5th-order polynomial) represents the spatial dependence of the mean draft, averaged over an annual cycle and over the 26 years of the data record 1975–2000. The spatial fields from the winter and fall of 1988 (near the mid-point of the RA) in Figures 2c and 2d are everywhere thicker than the mean ICESat fields from 2003–2008 (Figures 2f and 2g). In the 18 years between the mid-points of the submarine and ICESat periods, the winter ice thickness averaged over the DRA decreases by 1.22 m, and the fall thickness by 0.89 m.

[17] The difference between the winter and fall thickness fields from the two records provides a measure of the annual cycle amplitude. Within the DRA and for the dates chosen, the seasonal difference of 0.91 m from the RA is 36% higher than the 0.58 m from the ICESat estimates. The larger annual thickness cycle from the RA of 1.12 m (peak-

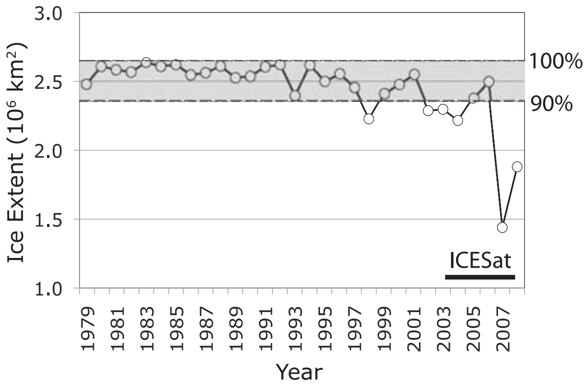

Figure 3. Sea ice extent (area with ice concentration >15%) during summer minimum within the data release area (DRA) from 1978–2008. Gray band shows the range from 90% to 100% ice extent.

to-trough) is compared to the 0.5 m on a mature ice slab of 3 m; a credible reason for this difference is the inclusion of the larger annual cycles of thinner ice and of the thicker, ridged ice (RWP08). Barring any systematic biases, possible reasons for the more moderate differences in the ICESat data could be the muting of the annual cycle during the 2003–2008 period due to the warmer winters and shorter growth seasons, or the fastest growth rate in the early fall unaccounted for by the ICESat periods. These hypotheses could be examined in numerical ice-ocean model simulations driven by recent forcings.

[18] The resemblance in the structure of the spatial fields from the two records is striking. The thickest ice in the DRA is found just northwest of Ellesmere Island, and thickness decreases towards the Siberian coast. The fields from the RA also resemble the mean ice concentration fields at summer minimum (Figure 2e) that provide an indication of the likely location of thin seasonal ice in the DRA. The significant retreat of the multiyear ice edge during the ICESat period, compared to earlier years (1978–2000), is reflected in the large gradients in the summer ice concentration fields.

[19] Figure 3 shows the time series of ice extent (areas where ice concentration >15%) in the DRA during summer minimum. Prior to 1997, the ice extent during the summer minimum stayed above 90% of the DRA. The steady decline in extent after 1997 is clearly visible and the dramatic decline during the record retreat in 2007 stands out.

5. Conclusions

[20] In this note, we consider recent ICESat thickness estimates of K09 for the ICESat period (2003–2008) in the light of thickness estimates of RYM99 and RPW08 from submarine cruises spanning the years 1958–2000.

[21] Relative to the submarine data used by RYM99 for the years 1958–1976, the ICESat data show that the average thickness at the end of the melt season has decreased by 1.6 m or some 53% of the thickness in over 40 years. In the shorter ten years between the periods 1993–1997 and 2003–2008, the decrease in thickness of 0.2 m is smaller. In the ICESat period, ice thickness trends are negative in all regions.

[22] The peak winter thickness of 3.64 m in 1980 (in the submarine data, RPW08) decreased to 1.89 m by the winter of 2008 (in the ICESat record, K09), a net decrease of 1.75 m or 48% in thickness. This represents an additional decrease of 0.55/0.44 m in the winter/summer after the end of the 1975–2000 analysis. The steepest downward trend in the submarine data is −0.08 m/yr in 1990 (RPW08). There then seems to have been a period from the late 1990s through the data gap (2000–2004), of a lower rate, followed in the five-year ICESat record (2003–2008) by another strong winter/summer decline, −0.10/−0.20 m/yr.

[23] In the earlier years, the thinning is remarkable in that it has occurred in a major portion of the perennially ice-covered Arctic Ocean. During the ICESat record, the significantly increased coverage of thinner seasonal ice in the DRA, linked to the record summer retreats in 2005 and 2007, has certainly contributed to the dramatic overall decline in ice thickness. This can be seen in the near-zero replenishment of the multiyear ice cover [*Kwok*, 2007] and the increasing coverage of younger multiyear ice within the Arctic Ocean [*Maslanik et al.*, 2007].

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