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# Arctic sea ice thickness loss determined using subsurface, aircraft, and satellite observations

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## Abstract

Sea ice thickness is a fundamental climate state variable that provides an integrated measure of changes in the high-latitude energy balance. However, observations of ice thickness have been sparse in time and space making the construction of observation-based time series difficult. Moreover, different groups use a variety of methods and processing procedures to measure ice thickness and each observational source likely has different and poorly characterized measurement and sampling biases. Observational sources include upward looking sonars mounted on submarines or moorings, electromagnetic sensors on helicopters or aircraft, and lidar or radar altimeters on airplanes or satellites. Here we use a curve-fitting approach to evaluate the systematic differences between eight different observation systems in the Arctic Basin. The approach determines the large-scale spatial and temporal variability of the ice thickness as well as the mean differences between the observation systems using over 3000 estimates of the ice thickness. The thickness estimates are measured over spatial scales of approximately 50 km or time scales of 1 month and the primary time period analyzed is 2000–2013 when the modern mix of observations is available. Good agreement is found between five of the systems, within 0.15 m, while systematic differences of up to 0.5 m are found for three others compared to the five. The trend in annual mean ice thickness over the Arctic Basin is $-0.58 \pm 0.07$ m decade$^{-1}$ over the period 2000–2013, while the annual mean ice thickness for the central Arctic Basin alone (the SCICEX Box) has decreased from 3.45 m in 1975 to 1.11 m in 2013, a 68 % reduction. This is nearly double the 36 % decline reported by an earlier study. These results provide additional direct observational confirmation of substantial sea ice losses found in model analyses.





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## 1 Introduction

In recent years great interest has developed in the changes seen in Arctic sea ice as ice extent and volume have markedly decreased. While ice extent is reasonably well observed by satellites, observations of ice thickness have been, until recently, sparse. Sea ice model reanalyses (e.g. Schweiger at al., 2011) provide useful estimates of thickness and volume loss but so far do not directly incorporate observations of ice thickness so that an observational record that does not depend on a sea ice model remains of substantial interest. In the last ten years or so a number of different observations of sea ice thickness have been made available by different groups using a variety of different methods. The longest historical record is from sporadic observations from submarines using upward looking sonar (ULS) to measure ice draft (Rothrock et al., 1999, 2008). These measurements are currently available starting in 1975 and ending in 2005 and include data from 34 cruises. They have broad but incomplete spatial coverage and limited sampling of the seasonal variations. ULS measurements from anchored moorings have been made by a number of different groups (e.g. Vinje et al., 1998; Melling et al., 2005; Krishfield et al., 2014; Hansen et al., 2013). Each has excellent temporal sampling with record lengths of up to 10 years, but only for a single location. More recently airborne and satellite-based observations have become available. Operation IceBridge uses lidar and radar technology on a fixed-wing aircraft beginning in 2009 (Kurtz et al., 2012) and electromagnetic methods from helicopters have been used to measure the snow plus ice thickness since 2001 (Pfaffling et al., 2007; Haas et al., 2009). Satellite-based lidar techniques began with IceSat during the years 2003–2008 (Kwok et al., 2008; Yi and Zwally, 2009) and radar altimeter techniques are used on CryoSat-2 beginning in 2010 (Laxon et al., 2013; Kurtz et al., 2014) (CryoSat-2 estimates are not included in the current study because there are few publicly available ice thickness data).

Can these observations, despite their sparseness, be used to collectively characterize the changes seen in sea ice thickness? Observations from submarine ULS





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instruments have previously been used to establish the time and space variation of sea ice thickness for a limited area of the Arctic Basin (Rothrock et al., 2008). Here we extend this approach by including more recent observations from multiple sources and expand the area to the entire Arctic Basin. In addition, we examine if there are systematic differences between individual data sources. This is important because the data sources differ markedly in their methodologies and sampling characteristics which may result in systematic biases that can affect the spatial and temporal characteristics of the ice thickness time series.

### Approach

All available ice thickness observations are fit with a multiple regression least-squares solution of an expression that is a function of time and space. The expression includes non-linear terms that characterize the spatial and temporal variability as well as terms that indicate which observation system is associated with each observation. The observations can be restricted to particular observation systems, geographic regions, or time periods to refine the analysis with the trade-off of the results being less general. We begin the analysis with a basin-wide selection of all available observations for the time period 2000–2013, then focus on specific observation systems or regions. The trend in the mean ice thickness determined by the regression expression is compared to model-based estimates and other observational studies. We then expand this analysis to include data back to 1975 to compare with and update the results of Rothrock et al. (2008) and provide an assessment of the 40 year change in ice thickness from the observational record.

## 2 Data

The Unified Sea Ice Thickness Climate Data Record (Sea Ice CDR) is a collection of Arctic sea-ice draft, freeboard, and thickness observations from many different sources. It includes data from moored and submarine-based upward looking sonar (ULS) instruments, airborne electromagnetic (EM) induction instruments, satellite laser altimeters (ICESat), and airborne laser altimeters (IceBridge). The point observations have been averaged spatially for roughly 50 km and temporally for one month. The mean measurements and the probability distributions for all of the sources are collected in a single data set with uniform formatting, allowing the scientific community to better utilize what is now a considerable body of observations. The Sea Ice CDR data are available at the National Snow and Ice Data Center (Lindsay, 2013; also at http://psc.apl.washington.edu/sea_ice_cdr). The data sets used in this study are listed in Table 1 and maps of the data locations and times of the observations from the various systems are shown in Fig. 1. A short description of the eight different data sets follows.

– *Submarines:* ULS instruments have been deployed on US Navy submarines using either digital or analog methods of recording. (Polar Science Center, University of Washington; US Navy Arctic Submarine Laboratory; Cold Regions Research and Engineering Laboratory; NSIDC, 1998; Rothrock and Wensnahan, 2007; Wensnahan and Rothrock, 2005; Tucker et al. 2001). The point data are archived at NSIDC. While there are 34 cruises archived for the years 1975–2005, only three are from after 2000, our period of primary interest: one in 2000 and two in 2005. The draft measured by the ULS instruments is based on the first-return echo. This introduces a positive mean bias in the measured draft that is estimated by Rothrock and Wensnahan (2007, RW07 hereinafter) for multiyear ice and for typical US submarine depths and beam widths as $0.44 \pm 0.09$ m, based on work by Vinje et al. (1998). RW07 also identify an open water detection bias of $-0.15 \pm 0.08$ m. Combined, the draft measurements reported for the submarines have a likely bias of $0.29 \pm 0.25$ m. The error range includes the error contributions from other unbiased sources of error (RW07). We have subtracted this bias from the US submarine draft data but not from any of the other ice draft measurements, as the bias for these measurement types is unknown and will be accounted for in the multiple regression procedure.

- *Air-EM, Airborne electromagnetic induction:* the Air-EM measurements include an electromagnetic induction instrument that determines the distance to the ice–water interface and a lidar to measure the distance to the top snow surface; consequently the measurements are of the ice + snow thickness. The method is based on measurements of the amplitude and phase of a secondary EM field induced in the water by a primary field transmitted from the EM instrument. In order to obtain an estimate of the ice thickness alone, the snow depth must be subtracted. The snow depth used here is the mean snow depth estimated from the PIOMAS ice–ocean model which estimates snow accumulation from the NCEP Reanalysis (Zhang and Rothrock, 2003). Haas et al. (2009) report on the configuration of the EM instruments and give an accuracy of 0.1 m for the ice + snow thickness over level ice. The footprint of the Air-EM system is 40–50 m at common operational altitudes and as a consequence the thickness of pressure ridges are smoothed and underestimated by as much as 50 % (Haas and Jochmann, 2003; Pfaffling and Reid, 2009). Pfaffling et al. (2007) report mean errors compared to drill holes of the ice + snow thickness of $-0.04 \pm 0.09$ m over approximately 200 m of level ice in Antarctica. Haas et al. (2010) report that the thickness distributions obtained from the instruments are most accurate with respect to their modal thickness and less so for the mean thickness. Ice+snow thickness samples used here are obtained from various locations around the Artic Basin. (Alfred Wegener Institute for Polar and Marine Research and York University; Haas et al., 2009; Pfaffling et al., 2007).

- *BGEP, Beaufort Gyre Exploration Project:* this data set is comprised of a set of three or four (depending on the year) bottom-anchored moorings with top-mounted ULS instruments located in the Beaufort Sea (Woods Hole Oceanographic Institute; Krishfield et al., 2014). These installations use the ASL acoustic



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Ice Profiler moored at a depth of approximately 50 m below the surface. There are a total of 28 station years of data from 2003 to 2012. The data processing procedures are outlined in Krishfield and Proshutinsky (2006) and the point data are available at www.whoi.edu/page.do?pid=66566.

- *IceBridge, NASA Operation IceBridge:* scanning lidar altimeter, snow radar, and cameras aboard NASA aircraft are used to determine the surface freeboard and snow depth from an altitude of approximately 300 m. These data are then used to determine the ice thickness distribution (Goddard Space Flight Center; Kurtz et al., 2013, 2012; Richter-Menge and Farrell, 2013). The IceBridge mission was initialized after the end of operations of the ICESat-1 satellite in order to partially continue the time series of sea ice and ice sheet observations until the launch of ICESat-2. The data are provided along the aircraft track at a spacing of 40 m. An estimate of the error is provided for each point and is primarily a function of the distance to a lead where the ocean water level needed to compute freeboard can be determined. The data for each spring campaign are clustered into 50 km samples, combining data from different flights if they are in close proximity. Points with a thickness uncertainty greater than $1.0 + 0.25h$ or 2.0 m, where $h$ is the ice thickness, are excluded.

- *IOS-CHK, Institute of Ocean Sciences Chukchi Sea:* these are bottom-anchored moorings with ULS instruments located in the Chukchi Sea (Institute of Ocean Sciences; Melling and Ridel, 2008). These moorings also use the ASL acoustic Ice Profiler. Just two station years are available, starting in 2003.

- *IOS-EBS, Institute of Ocean Sciences, Eastern Beaufort Sea:* this collection includes data from bottom-anchored moorings with ULS instruments located near the coast at nine different locations in the eastern Beaufort Sea near the Mackenzie River delta and Banks Island (Institute of Ocean Sciences; Melling and Ridel, 2008; Melling, 2002; Melling et al., 2005). We use data from 1990 to 2003. The moorings use various models the ASL acoustic Ice Profiler.





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- *ICESat-G, ICESat measurements processed by NASA Goddard Space Flight Center:* satellite laser altimeter measurements of freeboard are used to compute ice thickness (Yi and Zwally, 2009; Zwally et al., 2008). Snow depth is from climatology (Warren et al., 1999). Fifteen 1 month measurement campaigns are included in this data set. The track data of position and ice thickness have a resolution of about 170 m in the along-track direction. All track data from each campaign are clustered to form 50 km samples. 900 randomly selected samples from the Arctic Basin from all campaigns are used in order to account for the high spatial autocorrelation of these data and to make the ICESat data have roughly the same number of points as the submarine data in order to not bias the fit of the multiple regression procedure to the satellite data. There are no published estimates of the expected ice thickness errors for this system.

- *ICESat-J, ICESat measurements processed by the Jet Propulsion Laboratory:* these data use different processing methods from ICESat-G and cover just ten measurement campaigns. In particular the methods of determining the freeboard and the snow depths are different (Kwok and Cunningham, 2008). Snow depth was estimated from daily snow accumulation data from the ECMWF Reanalysis. The data gap at the pole due to the orbital configuration and areas of missing data are filled by interpolation. Kwok and Cunningham (2008) find the overall uncertainty in the ice thickness estimates within 25 km ICESat track segments is $\sim 0.7$ m but varies with the relative thickness of the total freeboard and the snow depth. In a second study, Kwok et al. (2009) find their ICESat estimates of ice draft are $0.1 \pm 0.42$ m thinner than those from a submarine cruise in 2005. This data set gives the thickness of ice not including open water, so in some locations it overestimates the mean ice thickness if open water were included, which is the norm for the other data sets. A weighting by passive microwave derived ice concentration to address this is sometimes applied to this data set (e.g. Kwok and Cuningham, 2008; Schweiger et al., 2011; Laxon et al., 2013) but this adjustment is not made here. Weighting by ice concentration reduces the 2003–2008 average





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ICESat thickness by 0.18 m in October/November and 0.07 m in February/March (computed from Table 1 in Laxon et al., 2013). The data are provided on a 25 km grid but they have been clustered to a 50 km grid so as to be compatible with the other data sets. Similar to the ICESat-G data, a subsample of 600 randomly selected points (proportional to the number of measurement campaigns) from all campaigns are included in order to account for the high spatial autocorrelation of these data. This data set is not in the Sea Ice CDR but may be obtained from JPL (http://rkwok.jpl.nasa.gov/icesat/index.html).

The submarine and mooring observations of ice draft are converted to ice thickness following Rothrock et al. (2008) using a density of water = 1027 kg $m^{-3}$ and a density of ice = 0.928 kg $m^{-3}$ (a factor of 1.107) and the weight of the snow. The ice thickness $T$ is then related to the ice draft $D$ by

$$T = 1.107D - f(m) \quad (1)$$

where $f(m)$ is the monthly mean ice equivalent of the snow on the surface. We use the monthly values of $f(m)$ determined by Rothrock et al. (2008, RPW08 hereafter) who found $f(m)$ ranges up to 0.12 m in May based on the snow climatology of Warren et al. (1999).

We have little information on the absolute accuracy of the averaged samples because we do not know the degree to which the reported measurement errors are uncorrelated. Clearly if the errors are uncorrelated, the many thousands of point observations that typically comprise a sample would result in very small sample errors (Kwok et al., 2008). However this assumption is unrealistic since the sea ice characteristics that affect these errors (e.g. thickness variability, snow cover, ridging) likely have spatial autocorrelations substantially larger than the distance between samples (Zygmontovska et al., 2014). There may also be significant over-all mean differences between the measurement systems related to the methodology or sampling.





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## 3 Methodology

Following RPW08, who developed a regression model to fit ice draft observations from US submarine data for a sub-area of the Arctic Basin, a smooth function of space and time is fit to all of the selected observations, $h(x,y,t)$, simultaneously using a least-squares multiple linear regression procedure. We refer to this as the Ice Thickness Regression Procedure, or ITRP. This function can be evaluated at all locations and times to yield a time-and-space-complete record of Arctic Basin ice thickness. However an additional complication, the fact that different observation systems may have unknown biases relative to each other, needs to be accounted for. In order to do this, an indicator variable $I$ which can take values 0 or 1 is included for each observation system in the multiple regression procedure, except for a reference system. The regression equation becomes ill posed if all systems have an associated indicator so one of the observations systems needs to be excluded and therefore implicitly becomes the reference system. We typically chose the ICESat-G data as a reference data set in this study because of their extensive spatial and temporal coverage, but we emphasize that this does not mean it is assumed to be more accurate than the other systems. The choice of the reference does not change the form or goodness of fit of the regression equation or the relative magnitudes of the indicator variable coefficients. The regression equation for the ice thickness is

$$h(x,y,t) = a_0 + \Sigma a_i T_i(x,y,t) + \Sigma b_j I_j + \text{error} \quad (2)$$

where $T_i(x,y,t)$ are the spatial and temporal terms of the regression equation, the $I_j$ are the indicator variables for each of the observation systems (excluding the reference), and error is the residual of the fit. Positive coefficients $b_j$ for the indicator variables $I_j$ of a particular observation system indicate that the error in the regression is reduced if a constant value (the coefficient $b_j$) is added to the expression for all observations from that system, so positive coefficients indicate that measurements from the system are systematically thicker relative to the reference measurements.

The choice of terms in the regression follows the methods of RPW08. The spatial coordinate system $x, y$ is based on a Cartesian grid in units of 1000 km and the time coordinate $t$ is in years relative to 2000. Spatial and temporal terms are included in sequence in a forward selection procedure, starting with the one that is most correlated with the observed thickness. Additional terms are then added one-by-one and at each step the variable that is most correlated with the residuals is added to the list of terms. Terms considered for the expression are up to 3rd order in space and time, including mixed terms involving both space and time. The seasonal cycle of the thickness is estimated by including COS = cos(2$\pi$Year-fraction) and SIN = sin(2$\pi$Year-fraction) as the first harmonic of the annual period. The second and third harmonics (COS2, SIN2, COS3, and SIN3) are also included. The linear time variable is introduced before the quadratic and all sine and cosine seasonal terms are always included. The partial $p$ values of all coefficients are assessed at each step and any terms with a value less than 0.90 are dropped unless they are one of the indicator functions or SIN or COS. The procedure is stopped when a new coefficient has a partial $p$ value of less than 0.90. The multiple regression procedure provides an estimate of the standard error of each of the coefficients, $\sigma_i$ for the space and time terms or $\sigma_j$ for the indicator terms. For the reference source we say the coefficient is zero and the standard error is taken as the standard error of the mean for that source.

## Fit for the Arctic Basin

For the entire Arctic Basin, 2000–2013, the ITRP outlined above selected 21 terms: 7 for indicator variables, and 14 for time and space variability of the ice thickness. Table 2 shows all of the terms and coefficients for this fit. The multiple regression coefficient is $R_{\text{mul}} = 0.84$ ($R^2 = 0.70$) and the RMS error of the fit is 0.62 m. A summary of the data locations and times, the values of the fit predictions at the time and location of the observations, and the residuals are depicted in Fig. 2. The spatial coverage from the ICESat data sets is good while the other data sets are much more localized and the temporal coverage from individual data sets is sporadic except for the moorings. The scatter in the temporal plot for the predictions is due to the spatial distribution of the observations. This mixture of time and space variability is also seen in the map. The residuals have little temporal or spatial structure, as we would expect because the terms have been selected to largely account for those.

## 4 Results

### 4.1 Systematic differences between the ice thickness estimates

As a step of generating a time series of sea ice thickness from observations alone, we need to determine what, if any, are the mean differences between the ice thickness estimates from the different measurement systems. The ITRP provides a method to do this even when the observations are not coincident. However the uncertainty of such a comparison depends very much on the nature of the samples available for each data set. If they are far removed from each other in space or time, the true variability of the ice thickness may contaminate the difference estimates. For example a bias between the observations could be partially resolved by the regression procedure with a spatial term if there is no spatial overlap. In addition, the differences between measurement systems may not be constant. One way of addressing these uncertainties is to examine subsets of the data to see if differences observed between the systems are more or less robust. We look at five different regions, all for the period 2000–2013: (1) the entire Arctic Basin and using all measurement systems (the fit mentioned above), (2) the so-called SCICEX Box in a broad region of the central basin that includes all submarine observations, (3) a 500 km radius circle centered on the BGEP moorings in the Beaufort Sea, (4) a 500 km circle centered on the North Pole, where a variety of observations are concentrated, and (5) a 300 km circle in the Lincoln Sea to evaluate Air-EM and IceBridge observations. Table 3 lists the summary information for each fit and Fig. 3 shows their locations.





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The coefficients of the indicator variables provide an estimate of the mean difference between each set of observations and the reference set in the sense that the RMS error of the fit is minimized if this difference is accounted for. Table 4 lists the values of the indicator coefficients for each fit and Fig. 3 shows the relative magnitudes of the coefficients for easy intercomparison of the bias terms determined for the different regions.

*Entire basin:* in this analysis the observation sources with indicator coefficients not significantly different from zero are Air-EM, BGEP, IOS-CHK, ICESat-G, and the Submarines, indicating that these sources are all consistent in the mean with each other over the region and period analyzed (see Table 4). There is just a 0.11 m spread in the mean between the five systems. Ice thickness data from the three submarine cruises agree in the mean with the ICESat-G data very closely, with a bias coefficient of $-0.05 \pm 0.06$ m (error brackets are one standard deviation). Three indicator coefficients are significantly different from zero at the $p = 0.95$ level: ICESAT-J, IOS-EBS, and IceBridge, meaning they are significantly larger or smaller than the reference data set, and, in this case, from the cluster of five observation sets that agree with each other.

The ICESat-J coefficient, $0.42 \pm 0.03$, indicates that on average the JPL thickness product is 0.42 m thicker than the Goddard product. A small portion of this difference is due to the lack of inclusion of open water in the ice thickness estimates. In contrast, Kwok et al. (2009) found that the ICESat track estimates of ice draft were $0.1 \pm 0.4$ m thinner than the 2005 submarine ice draft data. If we just concentrate on these two data sets in 2005 and only use observations with values within 100 km of each other, the ITRP indicates that the ICESat-J ice thickness is $0.13 \pm 0.05$ m thicker than the submarine-based ice thickness. However this value is within the standard deviation of the Kwok et al. (2009) value relative to the submarine observations. While the two bias estimates are thus consistent, they are of different sign.

The IceBridge data is also significantly thicker than the reference data, in this case by $0.59 \pm 0.06$ m, hence also thicker than the submarine, BGEP, IOS-CHK, and Air-EM



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data. We will examine the IceBridge and Air-EM data sets below to see if this difference is robust. The IOS-EBS data are 0.20 ± 0.10 m thinner than the reference. However we have less confidence in this result since the IOS-EBS moorings are near the coast in the extreme southeast corner of the Beaufort Sea and may not be well represented by the spatial terms of the regression model. Without the indicator variables, the RMS error of the fit for this region increases slightly from 0.62 to 0.64 m and the RMS difference in the fit values at the data locations is 0.20 m, indicating that these variables play a minor role in determining the shape of the regression function while at the same time providing an estimate of the relative bias of the different observational data sets.

*SCICEX Box:* data from US submarines are available mostly from a data release area defined by the US Navy (RPW08), the so-called "SCICEX Box" (taken from the project name Scientific Ice Expeditions). Of the 34 submarine cruises available since 1975, there are only three cruises after 2000. However the box is a convenient way to restrict the geographic extent of the data considered to a broad region in the central basin and to also compare our results to those of RPW08. For the 2000–2013 period the submarine data are still in good agreement with the reference, 0.14 ± 0.05 m, however the coefficients for Air-EM (0.81 ± 0.08 m) and IceBridge (0.98 ± 0.07 m) are both notably thicker than the reference and submarines when compared to the full-basin fit. These changes illustrate the fact that the differences between observation systems are not constant and may depend on the region and time periods included in the analysis.

*Beaufort Sea:* in the Beaufort Sea the four BGEP moorings provide abundant data for the entire annual cycle and this is a good location to further assess the mean differences between the data sets while restricting the amount of spatial variability that is encountered. Within a 500 km circle of the center of the mooring array there are Air-EM and IceBridge observations as well as the satellite-based estimates. Compared to the reference, ICESat-J estimates are 0.54 ± 0.07 m thicker and IceBridge estimates are 0.77 ± 0.10 m thicker, similar to what we found for the full basin (Table 4). The Air-EM and BGEP coefficients are both substantially larger than for the full basin, 0.87 ± 0.11 m and 0.31 ± 0.07 m respectively. The difference between the two, 0.46 m, is much larger than the difference between them for the fit for the basin, 0.10 m, and is likely due to regional changes in the bias of the Air-EM data. This again illustrates that comparisons between data sets can be highly sensitive to the particular ice conditions encountered and that caution is recommended in assuming that intercomparisons and validation results for one area are applicable elsewhere.

*North Pole:* abundant observations from submarines, IceBridge, Air-EM, and ICESat are available in the vicinity of the North Pole. ICESat-G has no observations closer than 400 km because of the nadir viewing of the satellite lidar while the ICESat-J data set has estimates within this circle based on interpolation from adjacent data points. A 500 km circle centered on the pole includes observations from both data sets. Note that data from a mooring at the pole, part of the North Pole Environmental Observatory, is still being processed and is not included. Within this circle 508 observations are used for the fit. In this region the IceBridge estimates are 1.13 m thicker than the submarine estimates and 0.59 m thicker than the Air-EM estimates. ICESat-J estimates are 0.28 m thicker than the ICESat-G estimates. The coefficients from this fit are in general consistent with those for the entire basin (Fig. 3 and Table 4).

*Lincoln Sea:* is the large thickness bias in the IceBridge observations seen in the previous analyses robust? IceBridge observations have a coefficient larger than that of any of the other measurement systems in each of the fits except for the Beaufort Sea, where it is smaller than the Air-EM coefficient. Perhaps the IceBridge data is not well represented in the regression equation because it is concentrated in thick ice near the Canadian coast. We can partially address the IceBridge bias by examining only IceBridge and Air-EM measurements in a limited region in the Lincoln Sea, where there are 50 Air-EM and 76 IceBridge measurements within 100 km and one month of each other during the springs of 2009, 2011, and 2012. The ITRP shows that for this sample the IceBridge data are 0.75 ± 0.13 m thicker than the Air-EM data. This is larger than the difference computed for the entire basin where the difference between the two is 0.59–0.06 = 0.53 m (Table 4). It is also larger than for the ITRP fits for the SCICEX Box and for the Beaufort Sea where the differences between the two are smaller, 0.17 and





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−0.10 m respectively. While we cannot be confident of the exact magnitude of the bias, indeed as we have seen it changes considerably from place to place, it is likely that the IceBridge estimates are systematically thicker than any of the other measurements by up to 1.0 m (Table 4).

## 4.2 Evaluation of ice thickness trends

*Arctic Basin for 2000–2013:* the ITRP expression for the whole basin can be used to evaluate the spatial and temporal patterns of ice thickness change. To do this, the expression was evaluated at every location within the basin on a 40 km grid. The mean ice thickness for the 2000–2013 period is shown in Fig. 4. The map shows a maximum along the Canadian coast and a minimum in the vicinity of the New Siberian Islands. The ITRP annual mean basin-average ice thickness has declined from 2.12 to 1.37 m, 35 %, a linear trend of $-0.58 \pm 0.07$ m decade$^{-1}$. A quadratic time term in the fit, $xT^2$ (Table 2), creates a slight curvature in the basin-wide mean thickness seen in Fig. 4. The September thickness has declined from 1.41 to 0.67 m, 52 %. This observationally-based trend can be compared to that of an ice–ocean model commonly used for ice volume estimates. The PIOMAS ice–ocean model (Version 2.1, Zhang and Rothrock, 2003) has a trend of $-0.60 \pm 0.04$ m decade$^{-1}$ for the same area and time period, thus its trend is quite consistent with that of the observations. In another observational study, Laxon et al. (2013) computed the ice volume in the Arctic Basin from CryoSat-2 data for two years, 2010 and 2011 and computed volume trends by concatenating the ICESAT-J estimates to compute a trend from 2003–2011. They find a thickness trend for fall and spring of 0.75 m decade$^{-1}$. Another recent observational study of ice thickness measurements in Fram Strait using both surface-based and helicopter-based EM methods Renner et al. (2014) also finds a steep decline in the mean ice thickness. They found a steep decrease of 2.0 m decade$^{-1}$ in late summer for the period 2003–2012, a decline of over 50 %.

*SCICEX Box for 1975–2013:* the regression analysis of RPW08 concentrated on submarine ice draft data from 1975 to 2000 within the SCICEX Box. They determined





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that the best fit included terms up to fifth order in space and up to third order in time. They found a maximum in 1980 followed by a steep decline and then a leveling off at the end of the period. Kwok and Rothrock (2009) used five years of ICESat data to analyze the fall and winter changes in the ice draft for an additional five years, to 2008, but their regression procedure did not take advantage of the spatial information in the ICESat data but simply concatenated submarine and satellite records. They found the ICESat data showed an additional modest thinning. In order to estimate the temporal variation of ice thickness from 1975 to 2013 and to compare our results to those of RPW08 the ITRP is extended back to 1975 in this region. The fit procedure was performed using all of the data available from all sources that fall within the box, 3017 observations in all. Figure 5 shows the third-order fit from this study and the third-order curve from RPW08 that is computed for the years 1975–2001. The fit includes indicator variables as before and 12 additional terms: $T$, $T^3$, $X^3$, $Y$, COS, SIN, COS2, SIN2, COS3, SIN3, $X \times$ SIN, and T*SIN2. It explains 80 % of the variance and the RMS error is 0.49 m while the fit in RPW08 study explained 79 % of the variance and has an RMS error of 0.49 m as well, so the two are very similar in the fit properties. With an additional 13 years of data it is apparent that the annual mean ice thickness in the central Arctic Basin has continued to decline at an approximately linear rate and the short leveling off at the end of the RPW08 and Kwok and Rothrock (2009) time periods did not persist. We find that the annual mean ice thickness for the SCICEX Box has declined from 3.45 m in 1975 to 1.11 m in 2013, a 68 % decline. This is nearly double the decline reported by RPW08, 36 %, for the period ending in 2000. In September the mean ice thickness has declined from 2.90 to 0.45 m, an 84 % decline. The linear trend of the annual average thickness over this period is $-0.69 \pm 0.03$ m decade$^{-1}$. This is double the rate of ice thickness loss computed from PIOMAS for the same area for the period 1979–2013, $-0.34$ m decade$^{-1}$, showing that for the central Arctic Basin and for the longer time period, and consistent with our prior assessment that the PIOMAS trend in ice volume is too conservative (Schweiger et al., 2011). This is in contrast to the good match for the trend with that found from the observations when averaged over the whole basin for just the most recent 14 years.

The difference in the trends between the observations and the model may possibly be due in part to the time-varying bias of the submarine observations. The early part of the record has much thicker ice in this region than the later part. The thicker ice has much larger variability in the ice draft and hence the bias related to the first return correction may be much larger for the earlier thick ice. If this is the case the early ice thickness is overestimated by the draft measurements and the magnitude of the ice thickness trend be smaller than estimated here.

## 5 Error assessment

Percival et al. (2008) find that the spatial autocorrelation of 1 km ice draft measurements from submarines exhibits what is known as a long-memory process in which the spatial autocorrelation does not drop off as quickly as for an autoregressive process at length scales up to 80 km. This means that the sampling error drops off with the track length $L$ as $L^{-0.49}$ rather than $L^{-1}$. However RPW08 found that accounting for this long-memory correlation has only a small effect on the multiple regression coefficients determined from submarine ice draft data. Hence we have not accounted for this process in our analysis.

As mentioned above, the submarine ice draft data have all been corrected with a constant −0.29 m to account for the first-return and open-water-detection errors of ULS draft measurements as done by Rothrock and Wensnahan (2007). This first-return bias is a function of the roughness of the underside of the sea ice and of the footprint width of the region insonified by the sonar beam (Vinje et al., 1998). For the submarines the spatial sampling is typically 2 m and the footprint size is 2 to 5 m (Rothrock and Wensnahan, 2007), which according to the analysis of Vinje et al. (1998), corresponds to a first-return correction of −0.44 m for multiyear ice. However it is likely an over simplification to assume this correction is constant. It increases as the roughness or the



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footprint size increases (Vinje et al.,1998; Moritz and Ivakin, 2012). In addition, our analysis shows a strong positive correlation for all data sources between the mean thickness and the standard deviation within the samples determined from the point values. Similarly, Moritz and Ivakin (2012) show a strong correlation ($R = 0.81$) between the within-footprint roughness for a set of ULS observations and the standard deviation of the sample thickness values for 256 profiles of length 50 to 150 m. Future research may show it is possible to determine a correction for first return that is based on the sample standard deviation; clearly for smooth ice for which there is no variation in the bottom topography it should be zero. Not accounting for this dependence on bottom roughness may create an artificial thin bias for thin ice and a thick bias for thick ice as was mentioned above in regards to the thickness trend.

*Sampling error:* as we have alluded to above, sampling error can be a significant and serious source of uncertainty in comparing different ice thickness observations. All of the samples are from different times and/or places, so there are real differences in the nature of the ice sampled by the different measurements. The method used here depends on obtaining a large number of observations from a broad range of ice conditions so that comparisons in the mean can be made while accounting for large-scale variations in the mean ice thickness. The error in the fit includes random measurement errors, systematic measurement errors, sampling errors, and errors related to the inadequacy of the expression for representing the thickness variability.

Are the magnitudes of the coefficients sensitive to the data selected for the fit? Are the errors due to sampling large? One way to address the robustness of the results is to withhold some of the data and repeat the fits to see if the coefficients change significantly. A set of 100 fits were computed for the entire Arctic Basin, 2000–2013, for each of which only half of the data, randomly selected from each system, was used. The mean of the resulting indicator coefficients is very similar to that found using all of the data and the variability of the coefficients from this ensemble is comparable to the standard error, $\sigma_j$, of the coefficients computed as part of the fit procedure. This exercise shows that the error bars in Fig. 3 are good indicators for determining if the difference between systems is significant for the data analyzed. For example, we can conclude that the IceBridge data for the full Arctic Basin is significantly thicker than Air-EM, BGEP, ICESat-G, IOS-EBS, and the submarines, but perhaps not thicker than ICESat-J.

The importance of the individual data sources for computing the bias coefficients can be explored by repeating the analysis while leaving out one of the sources, each in turn. Do the bias coefficients change significantly? Figure 6 shows a bar chart of the indicator coefficients when just one data source is left out. The coefficients for most of the sources are quite similar for all of the ITRP fits. The largest variability is seen for the coefficients for IOS-EBS, which is not surprising given the isolated location of these measurements. The IOS-EBS coefficient is particularly sensitive to the exclusion of the BGEP or Submarine data. There is also a fair amount of variability for the IceBridge coefficients, but in all cases the coefficients are still large. However if both ICESat data sets are excluded and the submarines are used as a reference we find very large changes in the relative magnitudes all of the remaining coefficients. This indicates the great importance of the satellite data in establishing the spatial structure of the ice thickness fields when performing broad analyses of observing system differences.

## 6 Conclusions

There is no gold standard for the estimation of the mean thickness of sea ice. All of the existing measurement techniques have one or more large sources of uncertainty. The submarine ULS measurements depend of the first-return echo to determine the ice draft, which is a potential source of unknown bias that may be a function of the bottom roughness. The moorings may also be subject to this same source of error. Both have potential errors in determining the open water level. The satellite and airborne lidar observation depend on reliable detection of the surface height of nearby leads to accurately determine the height of the ocean surface and hence the freeboard. The Air-EM measurements require an independent estimate of the snow depth, as does the satellite lidar measurements and the ULS draft measurements. All of the measurements struggle with obtaining an accurate mean value when the thickness is highly variable within the sensor footprint due to ridging. And finally, none of the measurements have been verified against other observations over regions that encompass the full thickness distribution of the area.

This study has determined some broad measures of the relative bias of the different systems. The ITRP method is dependent on having a large number of independent observations from each system so that a function can be fit to the thickness observations to account for the large-scale variability of the ice thickness. In addition to the nonlinear space and time variables, a bias term is included for each system that can contribute to the minimization of the error of the fit by adding or subtracting a constant value to all observations from a given system. This bias term can only be interpreted in a relative sense: how much thicker or thinner, in the mean, is one system compared to another? While we have typically used the ICESat-G system as a reference here, that does not mean it is a priori considered to be more accurate than the others. Indeed nothing in the study speaks to the absolute accuracy of the measurements.

When ordered by relative magnitude of the coefficient of each system (Table 2), we see that the coefficient for IOS-EBS has the largest negative value. However because these measurements are in a small corner of the southeastern Beaufort Sea we have little confidence that this result is a good indicator of the bias of the ULS measurements in this location compared to the other measurements. Of the others, ICESAT-G, Submarines, IOS-CHK, BGEP, and Air-EM are all in broad agreement and in the mean are within 0.11 m of each other. ICESat-J is 0.42 m thicker than ICESat-G and slightly more so than the submarines. Finally, the IceBridge measurements average 0.59 m thicker than ICESat-G measurements and 0.47 m thicker than the submarine measurements.

It is beyond the scope of this study to determine why some of the observation systems appear to have biases, sometimes very significant, compared to the others. Possible sources of these discrepancies are the interpretation of ULS echo data, assumptions about snow depth or snow water equivalent, and methods of determination of





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the ocean water level for the lidars. While it is possible that there are systematic errors in determining the measurement differences introduced by the different times and locations of the observations, so called sampling errors, all of the systems, with the possible exception of IOS-EBS, have sufficient observations spread over large spatial or temporal ranges to make this unlikely. Figure 3 shows the range of the coefficients determined with various spatial subsets of the data. For the entire basin the experiment in which only a random half of the data from each systems was used in a large set of fits gives very similar results to that of using the full data set. The leave-one-out experiment showed that the satellite measurements had a greater impact on the bias coefficients than the other systems.

The ITRP annual mean basin-average ice thickness over the period 2000–2013 has declined 35 %, a trend of $-0.58 \pm 0.07\,\mathrm{m\,decade^{-1}}$ while the September thickness has declined from by 52 %. Finally, all of the observations in the central Arctic Basin within the SCICEX Box for the period 1975–2013 indicate that the annual mean ice thickness in this region has decreased from 3.45 to 1.11 m, a 68 % decline. In September the mean ice thickness has declined from 2.90 to 0.45 m, an 84 % decline.

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**Table 1.** Observational data sets.

| Short Name | Long Name | Years | Location | Parameter/instrument |
|---|---|---|---|---|
| Submarines | US Navy Submarines | 1975–2011 | Arctic Basin | Draft/submarine ULS |
| BGEP | Beaufort Gyre Exploration Project | 2003–2012 | Beaufort Sea | Draft/moored ULS |
| IOS-EBS | Institute of Ocean Sciences | 1990–2003 | Eastern Beaufort Sea | Draft/moored ULS |
| IOS-CHK | Institute of Ocean Sciences | 2003–2005 | Chukchi Sea | Draft/moored ULS |
| Air-EM | Airborne EM | 2001–2009 | Arctic Basin | Ice+Snow thick/airborne EM |
| ICESat-G | NASA ICESat–Goddard | 2005–2008 | Arctic Basin | Ice thickness/satellite lidar |
| ICESat-J | NASA ICESat–JPL | 2003–2008 | Arctic Basin | Ice thickness/satellite lidar |
| IceBridge | NASA Operation IceBridge | 2009–2012 | Western Arctic Basin | Ice thickness/airborne lidar |





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**Table 2.** ITRP coefficients for the Arctic Basin for all observational sources, 2000–2013. Sigma is the standard error of the coefficient and the $p$ value is the probability of being nonzero. The $X$ and $Y$ spatial coordinates are oriented as in the map in Fig. 4 and are in units of 1000 km. The time $T$ is in years relative to 2000. The indicator coefficients are ordered by the magnitude of the coefficients.

| Term | Coefficient | Sigma | $p$ value |
|---|---|---|---|
| Indicator variables | | | |
| IOS-EBS | −0.204 | 0.103 | 0.000 |
| BGEP | −0.045 | 0.058 | 0.000 |
| Submarine | −0.049 | 0.061 | 0.000 |
| IOS-CHK | −0.007 | 0.130 | 0.000 |
| ICESat-G | 0.000 | 0.066 | 0.000 |
| Air-EM | 0.063 | 0.061 | 0.000 |
| IceBridge | 0.590 | 0.057 | 1.000 |
| ICESat-J | 0.420 | 0.034 | 1.000 |
| Time and space variables | | | |
| $T$ | −0.079 | 0.007 | 1.000 |
| COS | −0.233 | 0.032 | 1.000 |
| SIN | 0.296 | 0.024 | 1.000 |
| COS2 | 0.162 | 0.028 | 0.953 |
| SIN2 | −0.226 | 0.021 | 1.000 |
| COS3 | −0.140 | 0.030 | 0.582 |
| SIN3 | 0.015 | 0.025 | 0.000 |
| $Y$ | −1.767 | 0.038 | 1.000 |
| $X^2$ | −0.329 | 0.017 | 1.000 |
| $XY^2$ | 0.253 | 0.040 | 0.991 |
| $X$SIN | −0.199 | 0.019 | 1.000 |
| $Y^2$ | 0.674 | 0.037 | 1.000 |
| $X^2Y$ | 0.398 | 0.024 | 1.000 |
| $XT^2$ | −0.002 | 0.000 | 1.000 |





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**Table 3.** The region, the time period, the number of observations used, the number of terms, the multiple regression coefficient, and the RMS error (m) for each ITRP fit.

| Region | Years | $N_{obs}$ | $N_{terms}$ | $R_{mul}$ | RMSERR |
|---|---|---|---|---|---|
| Arctic Basin | 2000.0–2012.6 | 3070 | 21 | 0.84 | 0.62 |
| SCICEX Box | 2000.8–2012.6 | 1440 | 16 | 0.80 | 0.49 |
| Beaufort Sea | 2000.8–2012.6 | 725 | 15 | 0.76 | 0.49 |
| North Pole | 2000.8–2012.3 | 508 | 10 | 0.75 | 0.56 |
| Lincoln Sea | 2009.3–2012.3 | 127 | 3 | 0.62 | 0.69 |
| SCICEX Box | 1975.3–2012.6 | 3017 | 18 | 0.89 | 0.49 |

**Table 4.** Number of observations, coefficients, and $\sigma$ values of the indicator variables for all fits for the period 2000–2013.

| Region | Air-EM | BGEP | ICESat-G | ICESat-J | IOS-CHK | IOS-EBS | IceBridge | Submarines | |
|---|---|---|---|---|---|---|---|---|---|
| Arctic Basin | 354 | 334 | 900 | 600 | 26 | 107 | 588 | 161 | $N_{obs}$ |
| | 0.06 | −0.04 | 0.00 | 0.42 | −0.01 | −0.20 | 0.59 | −0.05 | Coefficients |
| | 0.06 | 0.06 | 0.02 | 0.03 | 0.13 | 0.10 | 0.06 | 0.06 | $\sigma$ |
| SCICEX Box | 131 | 334 | 371 | 247 | 26 | 0 | 170 | 161 | |
| | 0.81 | 0.24 | 0.00 | 0.45 | 0.27 | | 0.98 | 0.14 | |
| | 0.08 | 0.05 | 0.03 | 0.04 | 0.11 | | 0.07 | 0.05 | |
| Beaufort Sea | 48 | 334 | 150 | 100 | 0 | 0 | 64 | 29 | |
| | 0.87 | 0.31 | 0.00 | 0.54 | | | 0.77 | −0.28 | |
| | 0.11 | 0.07 | 0.04 | 0.07 | | | 0.10 | 0.11 | |
| North Pole | 66 | 0 | 150 | 100 | 0 | 0 | 139 | 53 | |
| | 0.37 | | 0.00 | 0.28 | | | 0.96 | −0.17 | |
| | 0.13 | | 0.05 | 0.07 | | | 0.14 | 0.11 | |
| Lincoln Sea | 51 | 0 | 0 | 0 | 0 | 0 | 76 | 0 | |
| | 0.00 | | | | | | 0.75 | | |
| | 0.09 | | | | | | 0.13 | | |



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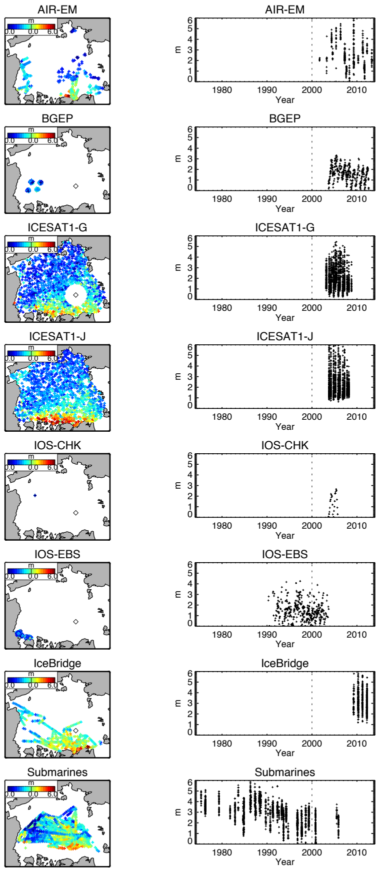


**Figure 1.** Observational data sources. The locations are plotted on the left with the colors indicating the ice thickness (0 to 6 m) and the observation times are on the right. The primary focus is in the years after 2000 (dotted line).

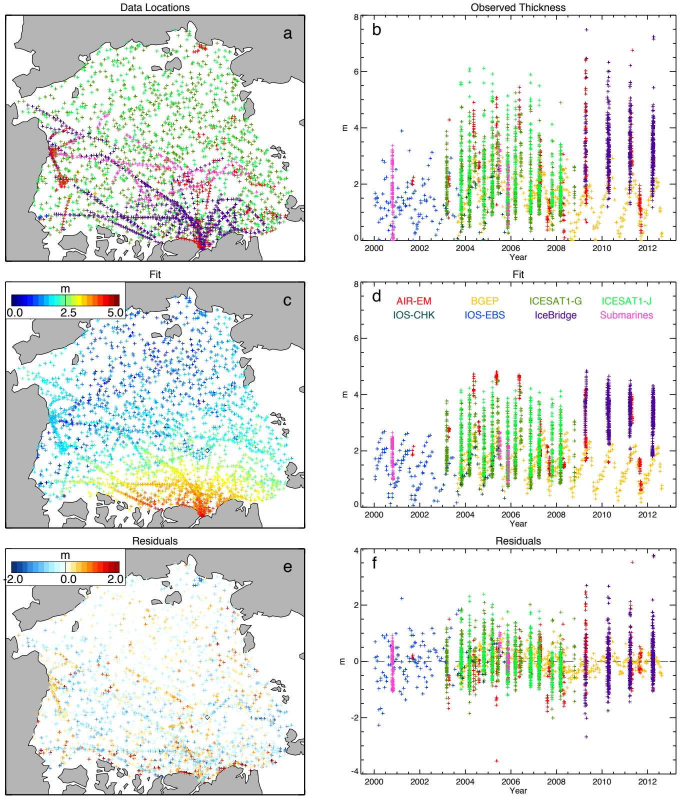


**Figure 2.** Fit to data from the Arctic Basin for 2000–2013. **(a)** Data locations color coded by system (see **d**), **(b)** data times, **(c)** map of ice thickness of the fit predictions at the data locations, **(d)** the fit predictions at the data times, **(e)** map of the residuals, **(f)** residuals as a function of time.

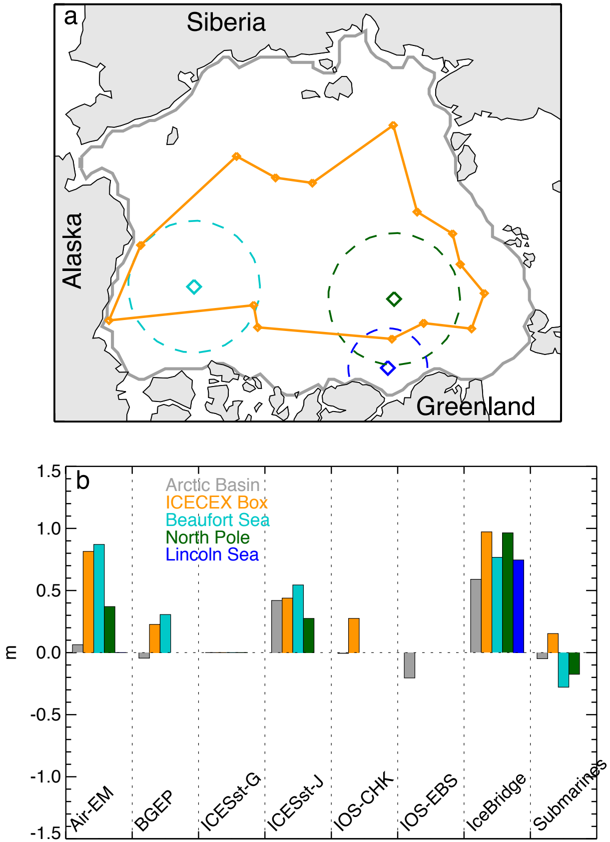


**Figure 3.** Relative magnitudes of the ITRP indicator coefficients **(b)** for fits at the five different locations shown in **(a)**. In each case the time period is 2000–2013 and only observations from within the regions shown are included. In **(b)** the magnitudes of the coefficients are grouped by observation type and color coded by the region. Grey depicts the coefficients for the fit for the entire basin.





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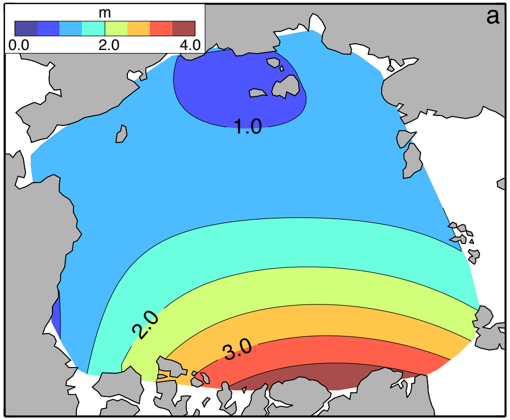


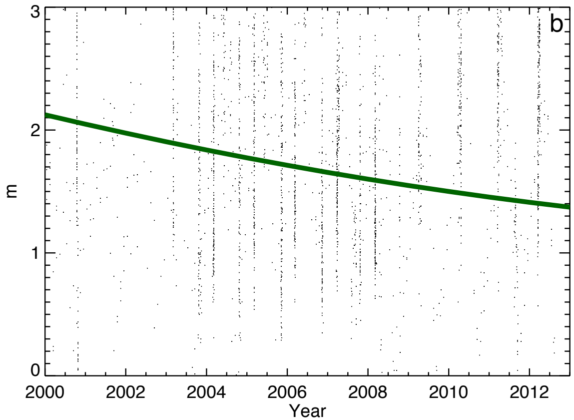


**Figure 4. (a)** Mean annual ice thickness from the regression function for the period 2000–2013. **(b)** Mean annual ice thickness for the Arctic Basin (green) and all observations adjusted for the bias of each.





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Arctic sea ice thickness loss

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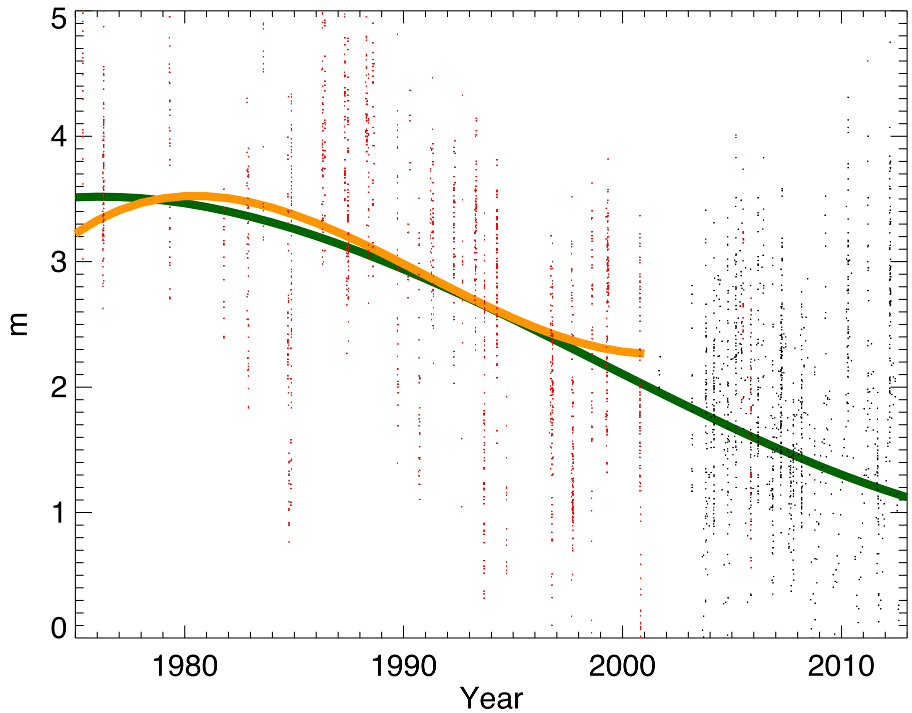


**Figure 5.** Annual mean ice thickness in the SCICEX Box. The dots show the observations, red are from the submarines. The orange line is the third-order polynomial from RPW08 for which the draft was converted to thickness with a factor of 1.107. The green line is a third-order polynomial from this study.





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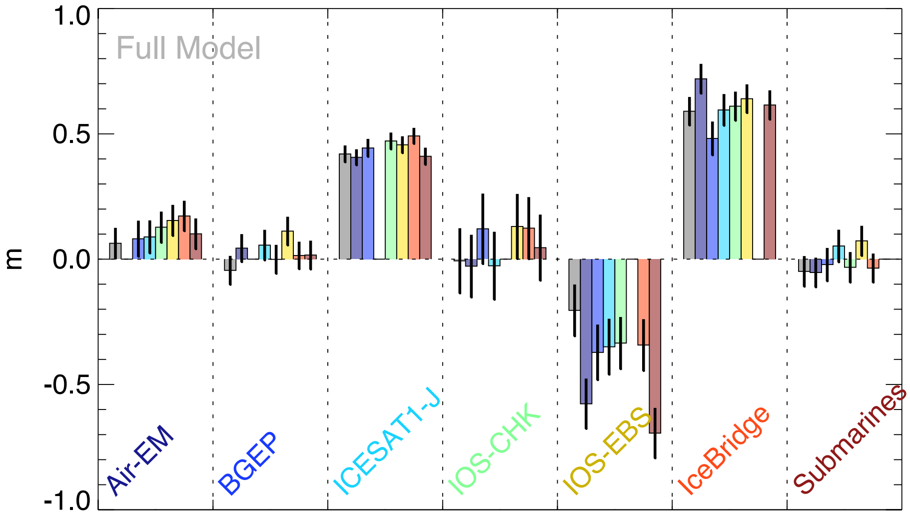


**Figure 6.** Coefficients of the ITRP indicator variables for a fit for the Arctic Ocean for 2000–2013. Grey bars show the coefficients for a fit that includes all of the observations. Bars in other colors indicate which source has been left out in fits that leave one data source out at a time. The legend for the bar colors is given by the color of the diagonal labels. ICESat-G is always the reference.





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