Direct observations of Arctic sea ice thickness variability on seasonal to decadal time scales

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ABSTRACT
Variability in ice thickness observed by moored sonars in the Transpolar Drift in Fram Strait during 1990-2011 is described and quantified. Over the 22 year long period the modal ice thickness decreased by 20% per decade, relative to its long-term average. The mean ice thickness remained relatively constant during 1990-2005, after which it dropped from its prevailing level around 3 m down to 2 m. There are indications of a 6-8 year cycle in modal ice thickness. The cycle's crest to trough difference in thickness is 0.73 m. The cycle is less pronounced in the mean ice thickness, which hints towards thermodynamically controlled processes in explaining the origin of the cycle. The peak-to–peak amplitude of the modal ice thickness seasonal cycle is 0.54 m. The corresponding peak-to-peak amplitude for the mean ice thickness is 1.14 m. The seasonal maximum modal ice thickness in April occurs two months before the corresponding maximum in mean ice thickness in June. The seasonal minimum modal ice thickness in August occurs one month before the minimum in mean ice thickness in September. Combined, this illustrates how different processes control the modal (thermodynamics) and mean (dynamics + thermodynamics/ocean heat) ice thickness.

INTRODUCTION
Arctic sea ice has seen widespread change over the past decades (Meier et al., 2014). A younger and thinner Arctic sea ice cover (Maslanik et al., 2011; Kwok and Rothrock, 2009) remains preconditioned for recent record low sea ice extent minima, such as those in 2007 and 2012 (Parkinson and Comiso, 2013).

It is not straightforward to establish a link between the observed thinning and the drivers of this process. The spatial and temporal resolution of Arctic sea ice thickness data sets available to document long term thinning does not allow a detailed dissection of the ice thickness distribution to be carried out. Often the mean ice thickness is the only summary statistic at hand to document thickness change. The ice thickness distribution is typically bimodal and heavy-tailed, a reflection of how different processes operate differently in different segments over the range of ice thicknesses and ice types. With only the mean ice thickness available to document thinning, it is difficult to conclude on which ice type has changed, and why. Moreover, such long term data sets fail to resolve the seasonal cycle. This complicates the quantification of long term variability.

Here we present time series (1990-2011) of monthly ice thickness distributions obtained by moored sonars in the Transpolar Drift in Fram Strait (Hansen et al., 2013). The spatial and temporal resolution of the data allows us to 1) resolve the full thickness distribution, and 2) resolve the seasonal variability. Here we separate between variability in the thickness of old level ice and that of the rest of the ice. The variability is quantified for the modal (old ice) and mean ice thickness as deduced from the monthly ice thickness distributions.

The Fram Strait data set was presented by Hansen et al. (2013). The present contribution takes this previous study one step further by identifying and quantifying variability on three time scales; seasonal, interannual and decadal or longer.

DATA AND METHODS

The data set comprises 22 years (1990-2011) of continuous draft observations by moored upward looking sonars in the Transpolar Drift at 79° N 5° W in Fram Strait (Figure 1, and Hansen et al. 2013). During 1990-2006 the observations were made with CMR ES300 sonars operating with a sampling rate of 4 min. The instrumentation was replaced by ASL IPS sonars in 2006, operating with a sampling rate of 2 s. Installed at a depth of 50 m, the nominal footprint of the sonars is approximately 1.8 m. The full data set was processed and quality controlled by ASL Environmental Sciences following the methodology of Melling et al. (1995). Further details about the data set and its processing are found in Hansen et al. (2013).

The draft values were converted to ice thickness by multiplying with the factor 1.136 (empirically derived by Vinje and Finnekåsa, 1986). This simplified conversion is only made to facilitate a direct comparison with ice thickness data sets. The conversion is linear, the original draft value may be obtained by dividing with this factor. Monthly normalized ice thickness distributions were constructed by binning, counting, and normalizing the thickness observations month by month. The accuracy of summary statistics like the modal and mean ice thickness is within the bin width of the monthly thickness distributions of 10 cm (Vinje et al. 1998; Hansen et al. 2013).

The thickness series used to construct the monthly ice thickness distributions are time referenced (the quality of concurrent ice drift velocity observations is too poor to carry out a conversion to spatially referenced thickness series). In practice this means that the sampling distance is varying with time, and that the statistics derived for each month are based on segments of ice of different distances. However, subsampling with different subsampling periods shows little effect on the monthly statistics (Hansen et al., 2013). Statistical modelling of the effect of time varying ice drift demonstrates the same insensitivity in the monthly summary statistics to the drift (Uteng et al., in prep.).

The observation site in Fram Strait is illustrated in Figure 1. The figure also shows the backward trajectories of ice exported through Fram Strait for each month of the observation period (Hansen et al., 2013). This illustrates the source regions of the ice observed in Fram Strait. In investigating variability in this dynamic region, it is imperative that variability due to advection is separated from that of any other causes. Hansen et al. (2013) found little relation between thickness variability and advection patterns on any time scale.

The objective of this study is to identify and quantify variability in ice thickness over the timescales seasonal, interannual and decadal or longer. The term seasonal variability is used to address the variability over each year (the seasonal cycle). Interannual variability is referring to variability in thickness on timescales 1-9 years. When using the term decadal or longer variability we are referring to variability with periods over scales longer than 10 years.

The seasonal variability of the thickness of sea ice drifting through Fram Strait is quantified by averaging the modal and mean ice thickness over all available calendar months into an average seasonal cycle. Due to the longer scale variability, the cycle is calculated around the average modal and mean ice thickness for each year, respectively. The interannual variability is highlighted by filtering out the seasonal cycle. The filter is a three-step centred simple moving average with a window of 13 months in the first step, then 9 and 7 in the two subsequent steps. The time series contains individual months with missing data. A total of 52 months are missing in the 252 months long time series. In order to enable the filtering to be performed, the gaps were filled by using the average value of the same month the preceding and succeeding year to fill the gap for each missing month. This approach ensures that any cyclicity in the time series is maintained.

We apply two other methods of smoothing to ensure that the gap filling technique does not introduce artefacts: First we reproduce the annual averages presented by Hansen et al. (2013), where years with missing months were represented by the average of the remaining months. Secondly, we do the smoothing on the segments of data between the missing months with a centred simple moving average with a 13 month window. The combination of these two methods supplements the method of filling the gaps.

Finally an indication of long term variability (or change) is indicated by a linear fit through the data points. The fit start in August 1990, and ends in August 2011. In a time series featuring cyclicity, such a fit is sensitive to the location of the start and end points. Ideally any cyclicity should be removed from the time series prior to the fit. However, our time series is not long enough to precisely identify the period of any cyclicity on longer time scales. The fit is therefore crudely made across the entire time series, as an indication of the variability or change over the entire 22 years long observation period.

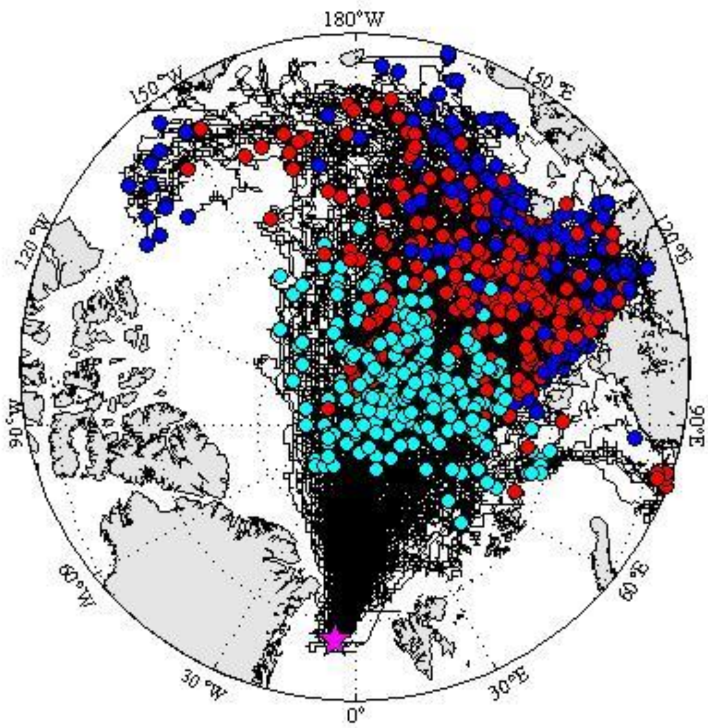

Figure 1. The location of the observation site in Fram Strait (magenta star). The black lines show the ice trajectories, calculated backward from the observation site from the month of observation up to 3 years earlier. The bullets indicate the position of the ice 1 (cyan), 2 (red) and 3 (blue) years prior to the observation of its thickness in Fram Strait (adapted from Hansen et al., 2013).

RESULTS

Long term trend: Variability on decadal or longer time scales

The time series of modal ice thickness is presented in Figure 2. It is too short to provide detailed information about the different modes of variability in the Arctic occurring om time scales from decadal and longer (e.g., Venegas and Mysak, 2000; Hilmer and Lemke, 2000; Polyakov and Johnson, 2000). However, even a trend derived from a plain linear regression may provide information about the scale of variability or change over the observation period. For that purpose we use the time series where the occasional gaps in monthly values are filled.

The linear trend of the modal ice thickness, bluntly taken across seasonal and interannual variability, is estimated to be negative at -0.51 m per decade (Figure 2 a). This corresponds to -20% per decade, relative to the long term average modal thickness.

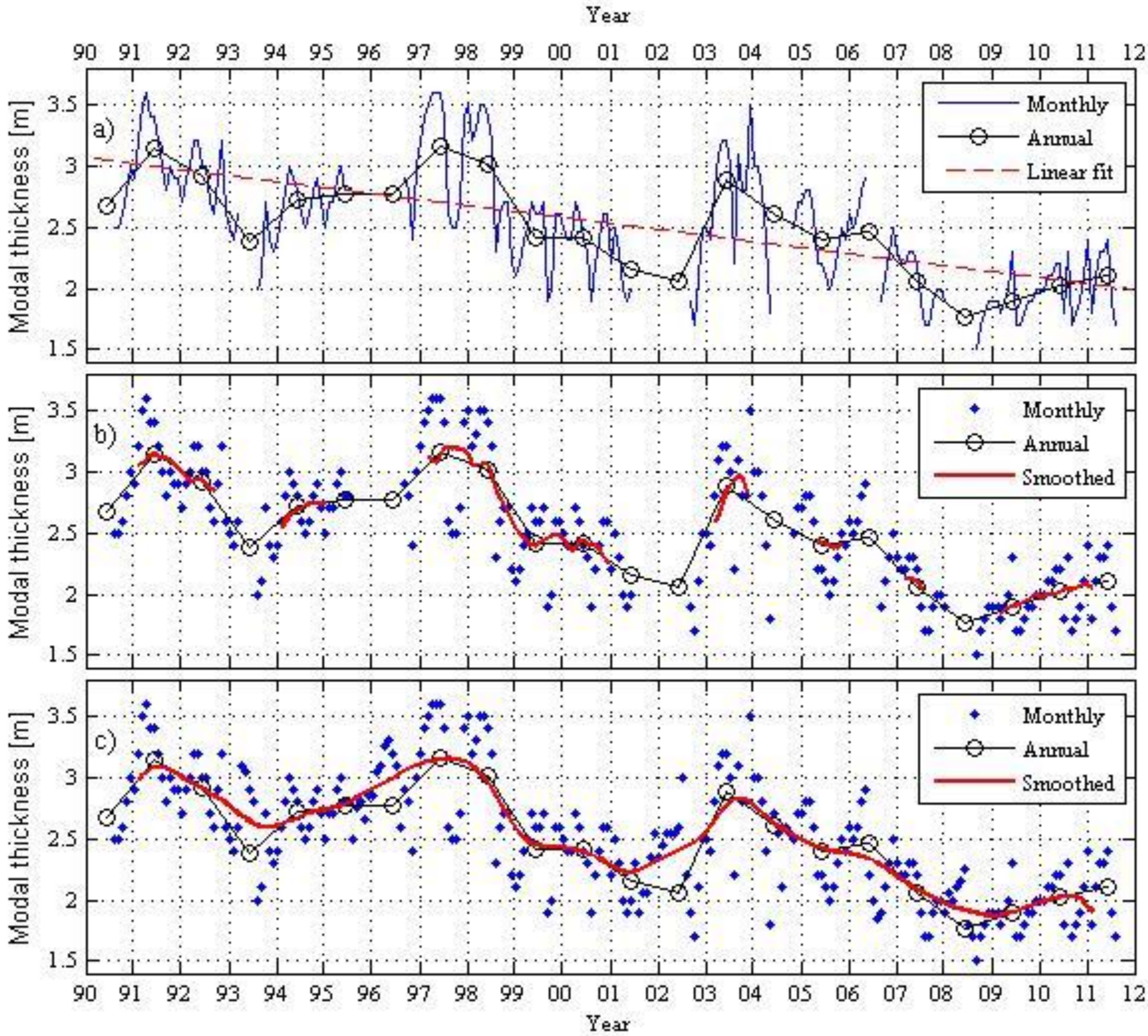

Figure 2. Time series of modal (old ice) thickness observed in Fram Strait during 1990-2011. To ensure readability the same data is presented over three panels, highlighting different approaches to address the variability. The upper panel (a) shows the monthly and annually averaged data, along with a linear fit to the monthly data. The middle panel (b) shows the monthly values, along with a smoothed version (13 month simple centred running average) of the data segments between missing data. The lower panel (c) shows the monthly time series with filled gaps. It also shows its smoothed version (triple running mean, centred, 13 month window).

The time series of mean ice thickness is shown in Figure 3. A linear regression analysis across the whole time series yields a negative trend at -0.36 m per decade (Figure 3 a). This corresponds to –12% per decade, relative to the long term average of the mean ice thickness. However, in this case the linear model appears less representative for the change over the 22 year long period. Considering the smoothed curves in Figure 3 b) and c) where the seasonal variability is filtered out, the mean ice thickness appears to remain around 3 m from 1990 to 2006. It then plummets down to approximately 2 m over only 4-5 years.

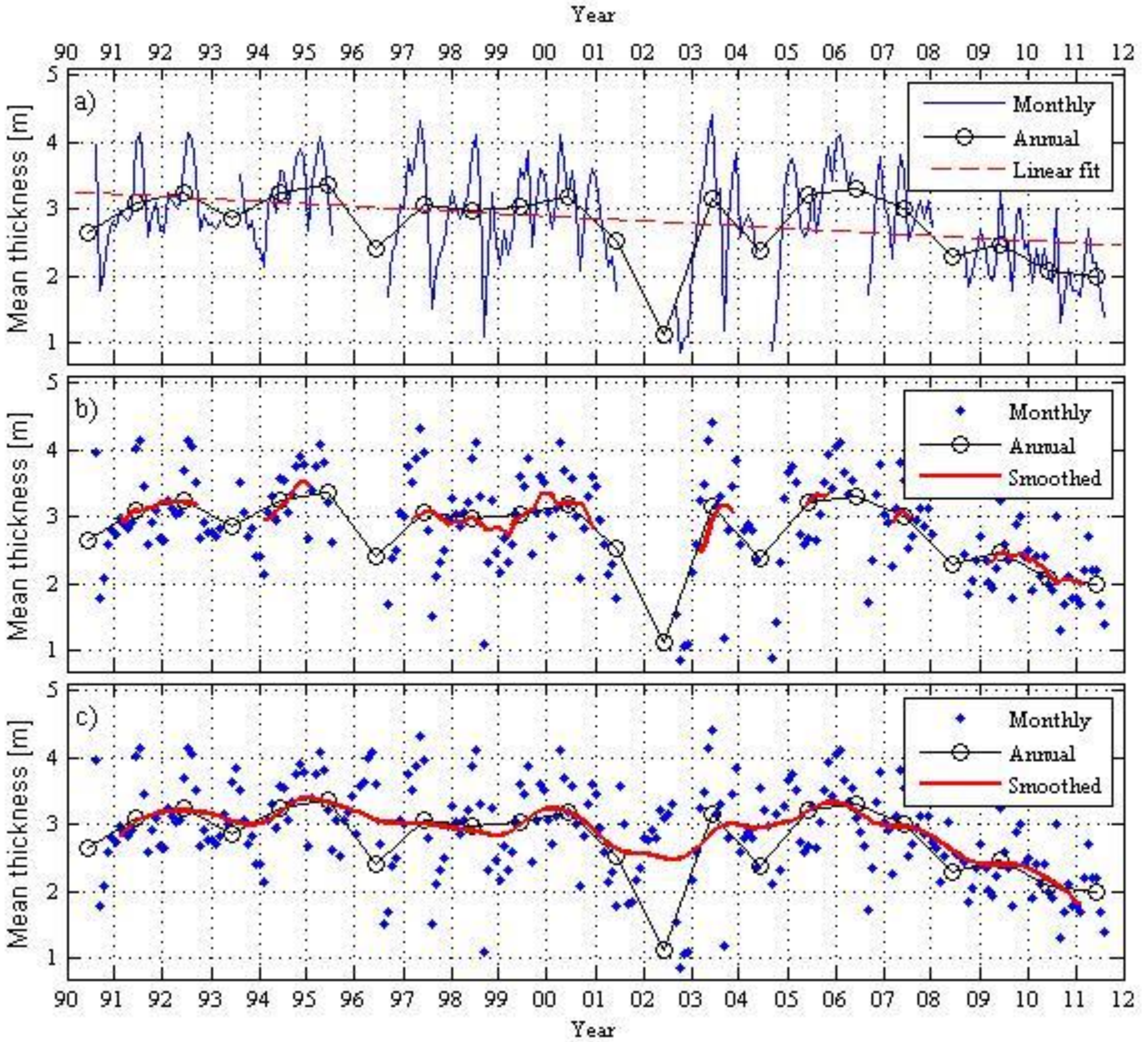

Figure 3. Time series of mean ice thickness observed in Fram Strait during 1990-2011. The content of panels a), b) and c) follows the structure as outlined in the caption of Figure 2.

Interannual variability

The seasonal cycle of the modal ice thickness should be filtered out to highlight variability on timescales longer than seasonal. Due to occasional gaps in the time series, we must either do the filtering on the data segments between the gaps, or fill the gaps. The first approach may result in loss of information, while the latter may introduce artefacts. Here we have done both, in addition to adding the annual averages of Hansen et al. (2013) (where the average of years with missing months were represented by the average of the remaining months). This reduces the risk of misinterpretation of the smoothed curves.

The result for the modal thickness is presented in Figure 2 b) and c). The two versions of the smoothed curves are seen to behave in a similar pattern. The annual averages are also seen to follow the smoothed curves, except for the years containing data gaps where there are deviations. Based on the three approaches combined, we conclude that superimposed on the downward trend there is interannual thickness variability on time scales of 6-8 years. The apparent crests at the start and end of the times series in 1991 and 2010/11 is excluded from these considerations, due to the risk of artefacts from the smoothing process. Crests in 1997 and 2003, combined with troughs in 1993, 2001 and 2008/09, nevertheless indicate the potential existence of a periodic cycle.

For the purpose of identifying the amplitude of this apparently periodic cycle in modal thickness, we detrend the curve of monthly modal ice thicknesses by subtracting the linear fit. The result is seen in Figure 4. Counting from the start in 1990, there are three troughs. Their amplitudes are -0.30 m, -0.29 m and -0.25 m. Correspondingly there are two crests, with amplitudes 0.45 m and 0.44 m. This provides four peak-to-peak amplitudes; 0.75 m (1993-1997), 0.74 m (1997-2001), 0.73 m (2001-2003) and 0.70 m (2003-2008).

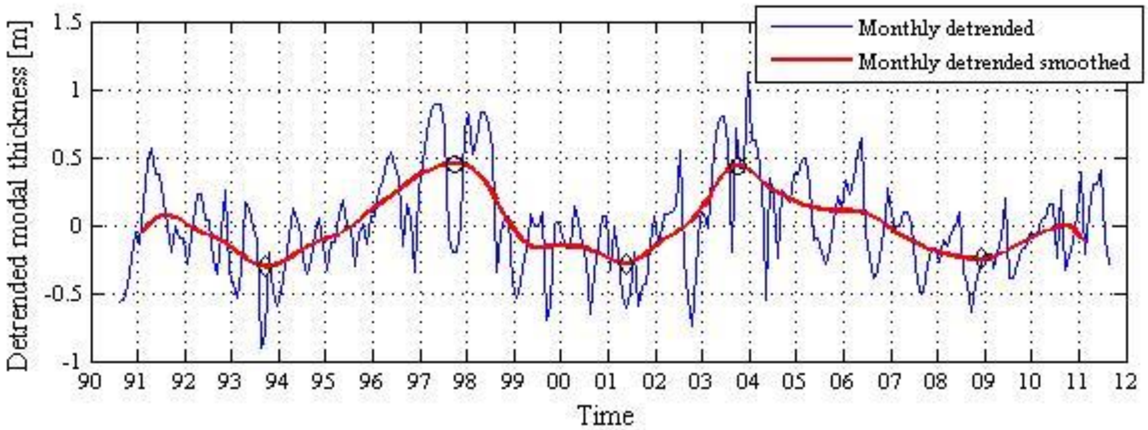

Figure 4. The detrended modal ice thickness from Fram Strait. The detrending is carried out on the monthly time series with filled gaps, by subtracting the linear fit from the monthly values. The time series is smoothed to highlight interannual and decadal variability. Troughs are indicated with a diamond, while crests are indicated by a circle.

Figure 3 b) and c) shows the smoothed mean ice thickness. There are indications of variability on the same 6-8 year time scale time as for the modal thickness, but for the mean ice thickness this is much less pronounced. There is variability though, with the smoothed mean ice thickness varying from 3.2 m to 2.5 m over just 2-3 years (2000-2003). The most pronounced feature of variability (or change) is the drop in mean ice thickness starting in 2006 (from 3.2 to 2 m over 5 years).

Seasonal variability

The average seasonal cycle in modal thickness (the thickness of old level ice) over the 1990-2011 period is shown in Figure 5. On average, the maximum thickness is reached in April, when the ice is 0.23 m thicker than the annual average. The minimum modal thickness is reached in August; the ice is then -0.31 m thinner than the annually averaged thickness. This yields a seasonal peak-to-peak amplitude of 0.54 m around the average thickness over the year. This is the work of thermodynamical processes during freeze and melt. Clearly the magnitude of thickness gain or loss during the seasons varies with the factors controlling the seasonal freezing and melting. In addition to the thermodynamic factors, the age of the ice is a major factor in controlling the level of the thickness which the seasonality cycles around. Hence advection also plays a role in the sense that ice that is not exported to lower latitudes may survive the melt season to form older ice. The average seasonal cycle observed in Figure *5* is reflecting the work of the average thermodynamic factors and the prevailing age of the ice during this period.

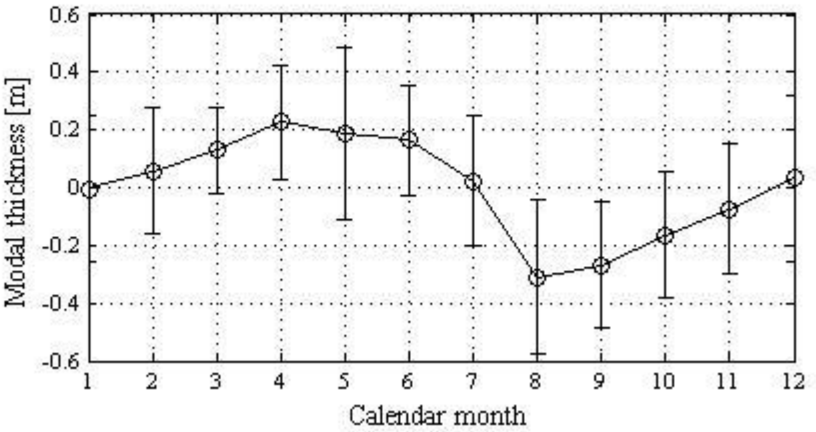

Figure 5. The average seasonal cycle of the modal ice thickness observed in Fram Strait during the period 1990-2011. The error bars show the standard deviation of each monthly average.

The average seasonal cycle of the mean ice thickness in Fram Strait over the 1990-2011 period is shown in Figure 6. The monthly mean ice thickness is calculated as the arithmetic mean of all thickness observations during each month since the onset of the observations in 1990. Unlike the modal thickness, which is reflecting the thickness of old level ice and where the variability reflects variability in thermodynamic processes, the mean ice thickness is influenced by all available ice types. Moreover, variability in the mean ice thickness generally reflects variability in both thermodynamic and dynamic processes acting on the ice to change its thickness. Clearly the mean ice thickness it is not a summary statistic which is well suited to describe ice thickness change or to point to likely causes for the change. However, it is much used to describe the thickness of the ice cover in reports from large scale ice models or large scale ice thickness observations, or in reports based on ice thickness data sets where the temporal and spatial coverage does not allow more details than the mean thickness to be deduced.

During 1990-2011 the maximum seasonal mean ice thickness is reached in June, when it peaks to 0.43 m above the annual average. The seasonal minimum is reached in September at -0.70 m. The average seasonal peak-to-peak amplitude of the mean ice thickness is therefore 1.14 m around the annually averaged mean thickness. In addition to the thermodynamic processes and ice age which controls the thickness of level ice, the mean ice thickness is also controlled by dynamic processes (rafting, ridging and rubble building). The mean ice thickness is dominated by dynamically deformed ice, due to the generally great thicknesses of this ice type. On average 66% of the mean ice thickness is due to deformed ice in this region (Hansen et al., 2014). However, it is not straightforward to separate between the role of dynamic and thermodynamic processes in controlling the seasonal thickness change.

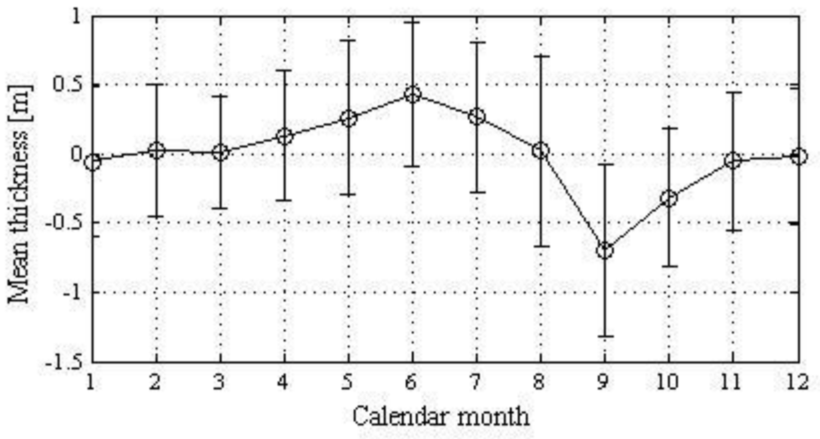

Figure 6. The average seasonal cycle of the mean ice thickness in Fram Strait during the period 1990-2011. The error bars show the standard deviation of each monthly average.

DISCUSSION

The variability in modal and mean ice thickness is observed to behave differently on all timescales. This illustrates how the physics controlling the modal and mean ice thickness differ. The first parameter is largely controlled by thermodynamic processes. The latter is dominated by ridged ice (Hansen et al., 2014), hence dynamic processes are dominating in increasing the value of this parameter. On the other hand thermodynamics play a major role in taking the mean ice thickness down, since ridged ice is particularly vulnerable to ocean heat (Amundrud et al., 2006). Since the sensitivity to ocean heat is much larger for ridged ice than for level ice, the difference in variability between modal and mean ice thickness should be expected.

In the seasonal cycle the difference in controlling processes is reflected in the timing of seasonal maxima and minima. The seasonal maximum in modal ice thickness is reached in April, the last month where freezing dominates the freeze/melt balance. For the mean ice thickness the seasonal maximum is reached two months later in June. A possible explanation is that the ridging process continues to operate on the surviving thin ice until this month, even after surface melt has started to occur. Correspondingly the seasonal minimum in modal thickness is reached in August, one month prior to the minimum in mean ice thickness. A likely contributing factor, is that ocean heat accumulated during summer is available to melt and disintegrate the deep and porous ridges, while the less ocean heat sensitive level ice floats in a fresher and more rapidly cooling surface layer.

The difference in timing of seasonal maximum and minimum is also likely to be affected by the fact that melt/freeze may change the modal and mean ice thickness in different directions. At onset of melt during spring, thin ice and old level ice becomes thinner. The modal thickness is decreasing. However, the removal of thin ice from the distribution acts to increase the mean ice thickness of the surviving ice. (Statistically speaking, the false conclusion that melting ice becomes thicker is an example of the effect of a survivorship bias. It is, therefore, also an example of how one should be careful when using the mean ice thickness to interpret the effect of processes in play). Likewise, at the onset of freeze during fall, new and thin ice is added while the modal thickness is increasing. However, the addition of thin ice in the distribution may act to reduce the mean ice thickness.

The drop in mean ice thickness from 3 m to 2 m during 2006-2011 is not reflected in the modal ice thickness in the same way. This decrease in mean ice thickness occurred during a period where both the number and average depth of ridges decreased (Ekeberg et al., 2014). The reason for this loss of ridged ice in the Transpolar Drift in Fram Strait remains unresolved; it might be connected to changes in both ridge formation and/or ridge degradation processes. However, the fact that this loss of ridged ice occurred concurrent with a shift towards younger ice (Hansen et al. 2013; Maslanik et al., 2011) points to a contributing factor: Younger ice contains larger fractions of young ridges, which are more prone to disintegration than their older consolidated counterparts. When facing increased ocean heat storage in the upper ocean (Stroeve et al., 2014) it is expected that such young ridges are effectively eroded, thereby taking the mean ice thickness drastically down.

The apparent 6-8 year cycle in modal thickness is intriguing. Comiso (2012) saw indications of an 8-9 year cycle in his time series (1978-2010) of area covered by multiyear ice. Such variability in age composition is likely to affect the modal thickness. Another possible source of the cycle is thickness anomalies formed in the Siberian shelf seas and in the Chukchi Sea, which propagate across the Arctic Ocean to Fram Strait and contribute to thickness anomalies with timescales of about 9 years (Koenigk et al., 2006). However, our time series is too short to conclude on the long-term consistency, origin and significance of the cycle observed in the modal ice thickness. It is therefore important to continue the observations of ice thickness in Fram Strait.

CONCLUSIONS

Variability on seasonal, interannual and decadal or longer time scales in monthly values of modal and mean ice thickness observed in the Transpolar Drift in Fram Strait is described. The time series were obtained by moored upward looking sonars during the period 1990-2011.

The peak-to–peak amplitude of the modal ice thickness seasonal cycle is 0.54 m. The corresponding peak-to-peak amplitude for the mean ice thickness is 1.14 m. The seasonal maximum modal ice thickness in April occurs two months before the corresponding maximum in mean ice thickness in June. The seasonal minimum modal ice thickness in August occurs one month before the minimum in mean ice thickness in September. This difference in timing illustrates how different processes control the two parameters.

There are indications of a 6-8 year cycle in modal ice thickness. The cycle’s crest to trough difference in thickness is 0.73 m. The cycle is less pronounced in the mean ice thickness, which hints towards thermodynamically controlled processes in explaining the origin of the cycle. However, our time series is too short to conclude on the long-term consistency, origin and significance of the cycle.

Variability (or change) on decadal or longer time scales was quantified by the linear trend through the data. The linear trend of the modal ice thickness was estimated to be negative at -0.51 m per decade. This corresponds to -20% per decade, relative to the long term average modal ice thickness. The linear trend in the mean ice thickness was found to be negative at -0.36 m per decade (12% relative to the long term average mean ice thickness). However, a pronounced decrease from 3.2 m to 2 m over the period 2006-2011 is the most pronounced long term feature of the mean ice thickness time series.

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