Reduced ice thickness in Arctic Transpolar Drift favors rapid ice retreat

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Abstract

Helicopter-borne electromagnetic sea ice thickness measurements were performed over the Transpolar Drift in late summers of 2001, 2004, and 2007, continuing ground-based measurements since 1991. These show an ongoing reduction of modal and mean ice thicknesses in the region of the North Pole of up to 53 and 44%, respectively, since 2001. A buoy derived ice age model showed that the thinning was mainly due to a regime shift from predominantly multi- and second-year ice in earlier years to first-year ice in 2007, which had modal and mean summer thicknesses of 0.9 and 1.27 m. Measurements of second-year ice which still persisted at the North Pole in April 2007 indicate a reduction of late-summer second-year modal and mean ice thicknesses since 2001 of 20 and 25% to

1.65 and 1.81 m, respectively. The regime shift to younger and thinner ice could soon result in an ice free North Pole during summer.

Introduction

The summer of 2007 saw another record low sea-ice coverage of the Arctic Ocean, with a minimum monthly ice extent of 4.28 x 10^6 km^2, 23% less than during the previous minimum in 2005 (Stroeve et al., 2008). Questions arise weather this drastic reduction of ice extent is just the result of natural variability superimposed on a generally declining trend, or if the Arctic sea ice cover has transitioned into a different climatic state where completely ice-free summers would soon become normal (Lindsay and Zhang, 2005; Holland et al., 2006). The rapidity of the Arctic summer sea ice decline is also surprising as it is much faster than predicted by any of the Intergovernmental Panel of Climate Change model scenarios (Stroeve et al., 2007). A better representation of sea ice in these models is complicated by the variety of different processes contributing to the presence of sea ice. For example, anomalous wind patterns, air temperatures, and radiation regimes have all been considered as causes for the minimum ice coverage in 2007 (Stroeve et al., 2008). It is unclear how much the warming of the Atlantic layer contributes to increases in ocean heat flux and therefore ice reduction (Polyakov et al., 2007). These factors all overlay a general, continued reduction of the fraction of older ice in the Arctic Ocean, as shown by drifting buoys and satellite radar maps (Nghiem et al., 2007). The latter also implies an overall shrinkage of ice volume, as the thickness of sea ice generally increases with age (Thorndike et al., 1975).

However, due to methodological and logistical constraints, little is known about recent changes of ice thickness. The ice thickness distribution includes important information about both, thermodynamic and dynamic boundary conditions of ice formation and development (Thorndike et al., 1975). The mode of the thickness distribution, or modal thickness, represents level ice thickness, which is a result of winter accretion and summer ablation. Mean ice thickness is dominated by the tail of the thickness distribution which represents the thickness and amount of deformed ice as a result of ice convergence and shear.

Electromagnetic-inductive (EM) measurements by Haas (2004) showed that between the summers (August/September) of 1991 and 2001 the modal (and mean) thickness of large numbers of individual ice floes in the region of the North Pole had decreased from 2.50 m (3.11 m) to 1.95 m (2.41 m), or by 22% (22.5%). Here, we update those findings with more recent measurements performed by means of helicopter-borne EM sounding in the same geographical region in 2001, 2004 and 2007. These show a continued thinning of the ice of the Transpolar Drift. However, as results were obtained in the same geographical region, i.e. in an Eulerian reference system, changes of ice regime and age (Nghiem et al., 2007) have to be considered in their interpretation. Therefore, we include information about the age of the surveyed ice obtained from a buoy-based Drift-Age Model (DM; Rigor and Wallace, 2004). In 2007, some measurements were also performed during April, i.e. at the end of the freezing season. These will be compared with the summer measurements taking into account and revealing the magnitude of the seasonal thickness cycle.

Data

Extensive helicopter-borne EM ice thickness surveys have been performed during cruises of the German icebreaker RV Polarstern in August and September of 2001, 2004 and 2007, representing the minimum ice thickness at the end of the ablation season. In total, 280, 540, and 3140 km of profile data were obtained during 5, 6, and 21 flights in 2001, 2004, and 2007. Each flight was typically performed along a triangular track with a side length of 40 to 80 km, including measurements over thin and thick ice and open water. Figure 1 shows the center location of each flight. Data from the marginal ice zone were excluded from the analysis to limit bias due to low ice concentration which would have enhanced bottom melt (Perovich et al., 2008). Thickness distributions for each year were derived by averaging over normalized distributions of individual flights, to prevent bias due to different profile lengths. Figure 1 also includes the track of one 350 km long flight performed in April 2007 between the North Pole and 87ºN, 58ºW, as well as the locations of individual floes profiled by ground-based EM sounding in 1991, 1996, 1998, and 2001 (same as in Haas, 2004).

EM sounding is a classical geophysical method to detect the distance between an EM instrument and the boundary between the resistive sea ice and the conductive sea water. With ground-based measurements, an EM instrument is placed onto the snow or ice surface, and the measured distance to the ice-water interface corresponds to the ice-plus-snow thickness (Haas and Eicken, 2001). These measurements can only be performed on ice which is accessible to walking, i.e. not on very thin or heavily rubbled ice. With helicopter-borne EM (HEM) measurements, the EM instrument is operated at an altitude of 15 to 20 m above the snow or ice surface, and its altitude is measured with a laser altimeter. Ice-plus-snow thickness (hereafter referred to as ice thickness) results from the difference between the altitude above the ice/water-interface and above the snow or ice surface (Haas et al., 2008). Note that almost all surveys were performed in the summer when the ice was snow-free. Point-spacing of all ground-based and helicopter-borne measurements ranged between 3 and 5 m.

The accuracy of EM measurements is better than ±0.1 m over level ice (Haas and Eicken, 2001; Pfaffling et al., 2007). However, the maximum thickness of pressure ridges is generally underestimated due to their porosity and the lateral extent of electromagnetically induced eddy currents of up to 3.7 times the instrument altitude (Reid et al., 2006). Measured ridge thickness can deviate by as much as 50% from the “true” thickness. Therefore, obtained thickness distributions are most accurate with respect to their modal thickness, while mean ice thickness can still be used for relative comparisons between regions and campaigns.

In April 2007, in addition to the airborne survey, a 1.78 km long ground-based EM and snow thickness profile was obtained with a point spacing of 8 m. Snow thickness was measured with a meter stick. Results from the snow thickness measurements will be used for comparisons between the April 2007 data and all other summer measurements.

An estimate of the Arctic sea ice age distribution was obtained from the DM (Rigor and Wallace, 2004). It tracks a grid of points (ice parcels) as they move about the Arctic Ocean. This model defines new, first year sea ice in areas of open water in September (the month of the climatological annual minimum in sea ice extent), and advects these ice parcels using the monthly gridded fields of ice motion based on buoy and ice-camp data. If these drifting parcels lie within the limit of the ice edge in September of the following year, they are said to have survived the summer melt, and these parcels are marked as one year older. The process is repeated for each year since 1955. Because of the limited number of buoys, variations in sea ice motion may not be adequately captured in some regions, resulting in uncertainties in the final results.

Results

Figure 1 shows that all measurements between 1991 and April 2007 have been performed over ice older than one year. The disagreement in 1996 points to some uncertainty of the ice age maps in the region of the previous summers ice edge, which had been taken as the 90% ice concentration isoline. For an ice concentration threshold of 50% the areas of the 1996 measurements would also be estimated to be older than 1 year. Results presented by Eicken et al. (1995), Haas and Eicken (2001), and Haas (2004) showed that ice thicknesses over each study region was remarkably uniform, although the age of the older ice might have been variable, as suggested by Figure 1. This has justified their summary into a single thickness distribution for each observational campaign. In August/September 2007 however, measurements over the generally same geographical region including the North Pole were performed mainly over first-year ice (FYI), as a result of the fundamental regime shift due to the replacement of second-year and older ice by FYI (Nghiem et al., 2007).

Figure 2 summarizes the measurements performed in April 2007. Mean and modal thicknesses along the 350 km long HEM profile were 3.31 ± 1.51 m (mean ± 1 standard deviation) and 2.35 m, respectively. There was only a very small thickness gradient of 0.19 m/° Latitude towards Ellesmere Island in the South, confirming the result of Figure 1 that the flight was exclusively performed over ice of the same, second-year age. Although not measured over the same ice fields nor in the same season, and neglecting interannual variations, Figure 2 compares this thickness distribution with an individual HEM profile obtained on September 8, 2001, close to the North Pole as well (cf. Fig. 1), to contrast typical summer and winter ice thickness distributions in a certain region. Modal thickness was only 2.05 m in 2001, in agreement with ground-EM results of Haas (2004). Mean ice thickness amounted to 2.21 ± 1.12 m, including 8 % open water. In contrast, there was only 0.3 % of open water in April 2004. The comparison nicely demonstrates different characteristics of seasonal ice thickness distributions, with large amounts of open water during summer, and much more deformed ice during winter (Thorndike et al., 1975).

When comparing modal thicknesses observed in August/September of 2001 with the one from April 2007, the seasonal thickness cycle and the winter snow thickness have to be taken into account. Figure 2 shows a snow thickness distribution obtained on an individual ice floe close to the North Pole in April 2007. Mean snow thickness was 0.32 ± 0.21 m. There were two modes of 0.05 and 0.3 m, representing snow on FYI and second-year ice (SYI). This corresponded to the ground-based ice thickness distribution, which was also bimodal with modes of 1.65 and 2.35 m for the FYI and SYI, respectively, and a mean thickness of 2.56 ± 0.80 m. The modal thickness of 1.65 m is in good agreement with ice thickness results from a freezing-degree-day (FDD) model (Lebedev, 1938). The model was forced with air temperature observations from surrounding drifting buoys of the International Arctic Buoy Programme between September 2006 and March 2007. Note that the good agreement between modeled and observed thickness is partially due to the thin FYI snow, because it hardly acted as an insulating layer. The large fraction of first-year ice was a local phenomenon, as part of the profiled ice floe had been selected as a landing strip for large supply aircrafts. Otherwise, FYI was hardly present along the HEM profile (Fig. 2). However, the modal SYI thicknesses of ground-based and HEM measurements are in very good agreement.

Subtraction of the modal SYI snow thickness of 0.3 m from the modal (total) SYI HEM thickness results in an ice-only modal thickness of 2.05 m, which is very similar to the modal thickness observed in September 2001. Observations of Perovich et al. (2008) show that summer surface and bottom ablation amount to 0.3 to 0.5 m in the region of the North Pole. Therefore, our observations suggest that modal SYI thicknesses in our study region would have reduced to 1.75 to 1.55 m in the summer of 2007, i.e. approximately 0.4 m or 20% less than in 2001. If we assume an Arctic seasonal mean thickness cycle of 1.5 m between April and September (Rothrock et al., 1999), mean ice thickness would have reduced to 1.81 m, i.e. 0.59 m or 25% less than the ice-only mean thickness in the summer of 2001.

Figure 3 shows a comparison of all thickness distributions obtained in the Transpolar Drift since 1991. Since 2001, airborne measurements were performed, and the excellent agreement of the 2001 ground-based (Haas, 2004) and HEM thickness distributions show how well both methods are comparable.

Table 1 summarizes the results of all HEM thickness measurements, and compares them with the earlier results of Haas (2004). In contrast to the ground-based measurements, the HEM data also include information about the thickness and fraction of thin ice and open water. Here, all measurements less than 0.15 m thick have been defined as open water, and the open water fraction and ice-only thicknesses are listed separately.

In 2001, overall modal thickness was 1.90 m, and mean thicknesses amounted to 2.20 ± 1.05 m including 5% of open water. In 2004 modal and mean ice thicknesses amounted to 2.20 and 2.59 ± 1.27 m including 1% open water. This was slightly thicker than in 2001, probably as a result of the more downstream location of the study region along the Transpolar Drift and the older age of the ice (Fig. 1). Therefore, the 2004 data is not discussed in more detail. In Figure 3, the April 2007 SYI thickness distribution has been shifted by 0.7 m towards thinner ice, corresponding to the seasonal adjustment for snow ablation (0.3 m) and summer ice thinning (0.4 m) outlined above.

Figure 3 also includes the thickness distribution obtained from all flights in August/September 2007 over vast regions of predominantly FYI (cf. Fig. 1). As in previous years and despite the partial contribution of SYI according to Figure 1, ice thicknesses of all profiles were remarkably similar, with modal and mean thicknesses of individual flights ranging between 0.65 and 0.95 m, and 1.01 and 1.48 m respectively. Overall, modal and mean ice thicknesses amounted to 0.90 m and 1.27 ± 0.77 m (1.30 ± 0.76 m) including (excluding) measurements over the 2% coverage of open water. This is a drastic thinning of 53% and 44% modal and mean (ice only) thickness of the ice in the region of the North Pole between 2001 and 2007. However, it is largely due to the replacement of predominantly second-year and older ice by FYI in the study region. Therefore, the August/September 2007 results can best be compared with ground-based thickness measurements over FYI performed further south in the Laptev Sea in the summer of 1995, which marked a previous ice thickness and extent minimum with a similar atmospheric pressure pattern as in the summer of 2007 (Haas and Eicken, 2001;

Stroeve et al., 2008). In 1995 the ice had modal and mean thicknesses of 1.25 m and 1.80 ± 1.10 m, respectively, i.e. 28% and 30% thicker than in 2007.

The modal FYI thickness of 1.65 m in April 2007 in Figure 2 and its good agreement with the FDD-model can be considered as some maximum thickness of ice grown between the fall of 2006 and April 2007. If compared with the modal thickness of 0.9 m measured in August/September 2007, the difference of 0.75 m could be considered as a measure of the seasonal thinning during the summer.

Discussion and Conclusions

Our ice thickness data set is very heterogeneous as it has been obtained during sporadic expeditions to varying but overlapping regions of the Transpolar Drift. However, the uniformity of the derived thickness distributions and the inclusions of ice age information in our interpretations justify the conclusion of a rapidly thinning ice cover. Both, modal and mean SYI and FYI thicknesses have decreased in the region of the North Pole. The reduction of modal thicknesses is a result of increased atmospheric and ocean heat fluxes to the ice. Unfortunately, we are not able to distinguish between the individual processes. However, the good agreement with the FDD model suggests an important role of increased air temperature, while increases in ocean heat flux might have played a minor role in the present thinning. Ice concentration was remarkably high in our study region in 2004 and 2007, limiting the deposition of heat in the mixed layer (Perovich et al., 2008). The presented results provide valuable information for the validation and improvement of numerical sea ice models.

Ice concentration in the summers of 2004 and 2007 was also significantly higher than in 2001. In contrast, there were large open areas in the region of the North Pole in 2001, and overall Arctic ice extent assumed a local small temporal maximum. In 2007, high ice concentrations could have been a result of ice compression in the study region by the general atmospheric circulation over the Arctic, which was also responsible for the strong northward retreat and advection of the ice edge and resulting minimum ice extent (Stroeve et al., 2008; Kwok, 2008). One can speculate that this intensification of ice drift and the displacement of SYI towards North America have increased ice thickness north of the coasts of Greenland and Canada. Future surveys should be extended over that region to allow better observations of the overall ice mass balance.

Clearly, the thinner ice cover favors a stronger areal retreat of the ice during summer. The uniformity of the observed thickness distribution points to the possibility of further rapid reductions once that vast uniform region has thinned further below certain tresholds, e.g. due to the amplitude of the average or melt-pond related seasonal summer thinning. Unfortunately, we cannot demonstrate any causal relation between ice thickness and ice drift, but it is likely that the thinner and weaker ice cover also facilitates a faster ice drift, which resulted in the occurrence of FYI at the North Pole in the summer of 2007, and is still ongoing as of this writing (July 2008).

Our measurements mark a technological milestone with the onset of regional HEM surveying. Now, observations of the fractions and thicknesses of thin ice and open water are included in the results, in contrast to the earlier ground-based measurements (Haas and Eicken, 2001; Haas, 2004). With this, the measurements are also better comparable with other thickness estimates, e.g. from upward-looking sonars (ULS) or satellite altimetry. We hope that we will soon be able to perform more systematic surveys, e.g. by employing the EM method from fixed-wing aircraft, airships, or hovercrafts.

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References

Eicken, H., M. Lensu, M. Leppäranta, W. B. Tucker, A. J. Gow, and O. Salmela (1995), Thickness, structure and properties of level summer multi-year ice in the Eurasian Sector of the Arctic Ocean, *J. Geophys. Res.*, *100*(C11), 22,697-22,710.

Haas, C., and H. Eicken (2001), Interannual variability of summer sea ice thickness in the siberian and central Arctic under different atmospheric circulation regimes, *J. Geophys. Res., 106(C3)*, 4449-4462.

Haas, C. (2004) Late-summer sea ice thickness variability in the Arctic Transpolar Drift 1991-2001 derived from ground-based electromagnetic sounding, *Geophys. Res. Lett., 31*, L09402, doi:10.1029/2003GL019394.

Haas, C., J. Lobach, S. Hendricks, L. Rabenstein, and A. Pfaffling (2008), Helicopter-borne measurements of sea ice thickness, using a small and lightweight, digital EM system, *J. Appl. Geophys*., doi:10.1016/j.jappgeo.2008.05.005.

Holland, M. M., C. M. Bitz, and B. Tremblay (2006), Future abrupt reductions in the summer Arctic sea ice, *Geophys. Res. Lett.*, *33*, L23503, doi:10.1029/2006GL028024.

Kwok, R. (2008), Summer sea ice motion from the 18 GHz channel of AMSR-E and the exchange of sea ice between the Pacific and Atlantic sectors, *Geophys. Res. Lett.*, 35, L03504, doi:10.1029/2007GL032692.

Lebedev, V.V. (1938), Rost l'da v arkticheskikh rekakh i moriakh v zavisimosti ot otritsatel'nykh temperatur vozdukha, *Problemy Arktiki 5*, 9-25.

Lindsay, R.W., and J. Zhang (2005), The thinning of arctic sea ice, 1988-2003: have we passed a tipping point?, *J. Climate*, *18*, 4879–4894.

Nghiem, S.V., I.G. Rigor, D.K. Perovich, P. Clemente-Colon, J.W. Weatherly, and G. Neumann (2007), Rapid reduction of Arctic perennial sea ice, *Geophys. Res. Lett.*, *34*, L19504, doi:10.1029/2007GL031138.

Perovich, D. K., J. A. Richter-Menge, K. F. Jones, and B. Light (2008), Sunlight, water, and ice: Extreme Arctic sea ice melt during the summer of 2007, *Geophys. Res. Lett.*, 35, L11501, doi:10.1029/2008GL034007.

Pfaffling, A., Haas, C., Reid, J.E. (2007), A direct helicopter EM sea ice thickness inversion, assessed with synthetic and field data, *Geophysics*, *72*, F127-F137.

Polyakov, I., et al. (2007), Observational Program Tracks Arctic Ocean Transition to a Warmer State, *Eos Trans. AGU*, *88(40)*, 398.

Reid, J., Pfaffling, A., Vrbancich, J. (2006), Airborne electromagnetic footprints in one-dimensional earths, *Geophysics, 71(2),* G63-G72, doi: 10.1190/1.2187756.

Rigor, I.G. and J.M. Wallace (2004), Variations in the Age of Sea Ice and Summer Sea Ice Extent, *Geophys. Res. Lett.*, *31*, doi:10.1029/2004GL019492.

Rothrock, D. A., Y. Yu, and G. A. Maykut (1999), Thinning of the Arctic sea-ice cover, *Geophys. Res. Lett.*, *26*, 3469-3472.

Stroeve, J., M. M. Holland, W. Meier, T. Scambos, and M. Serreze (2007), Arctic sea ice decline: Faster than forecast, *Geophys. Res. Lett.*, *34*, L09501, doi:10.1029/2007GL029703.

Stroeve, J. ., M. Serreze, S. Drobot, S. Gearheard, M. Holland, J. Maslanik, W. Meier, and T. Scambos (2008), Arctic Sea Ice Extent Plummets in 2007, *Eos Trans. AGU*, *89(2)*, 13.

Thorndike, A. S., D. A. Rothrock, G. A. Maykut, and R. Colony (1975), The thickness distribution of sea ice, *J. Geophys. Res.*, *80*, 4501-4513.

Table 1: Summary of late summer ice thicknesses in the Transpolar Drift shown in Figure 3

Year	Mean thickness incl. water (m) [b]	Open water fraction (%)	Mean thickness, ice only (m) [b]	Modal thickness (m)
1991[a]	N/A	N/A	3.11±1.03	2.50
1996[a]	N/A	N/A	3.11±1.12	2.45
1998[a]	N/A	N/A	2.88±1.49	2.10
2001[a]	N/A	N/A	2.41±0.98	1.95
2001	2.20±1.05	5	2.31±0.95	1.90
2004	2.59±1.27	1	2.63±1.24	2.20
2007 (April)[c]	1.81[c] (3.31±1.51)	0.3	1.82[c] (3.32±1.35)	1.65[c] (2.35)
2007	1.27±0.77	2	1.30±0.76	0.90

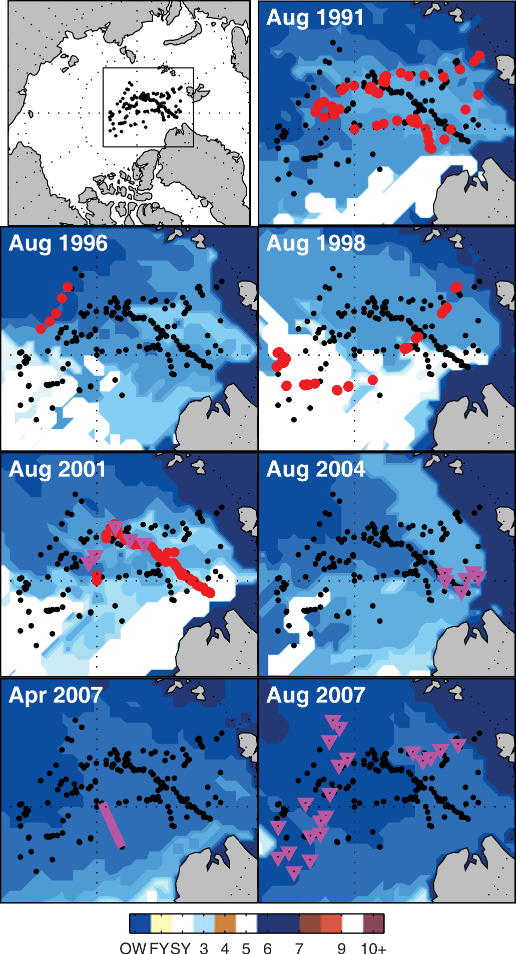
[a] from Haas (2004)
[b] Mean ± 1 standard deviation
[c] Values are seasonally adjusted. Brackets show original April thickness.
N/A: Not applicable.

Figure Captions

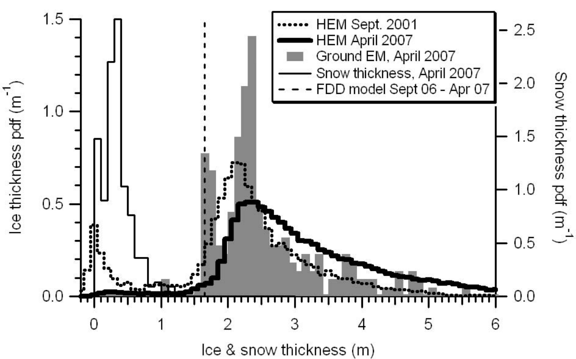
Figure 1: Maps of locations of ground-based (red circles) and helicopter-borne (magenta triangles / line) ice thickness surveys and buoy-derived ice age (color scale) during the measurement campaigns. Black dots show the location of all measurements for comparison.

Figure 2: Thickness distributions (probability density functions, pdf; bin width 0.1 m) of ice and snow obtained from HEM sounding in September 2001 and April 2007 in the same region of the Transpolar Drift (cf. Fig. 1), and ground EM and snow stake measurements on an individual ice floe at the North Pole in April 2007. Stippled vertical line shows ice thickness of 1.65 m derived from a FDD model.

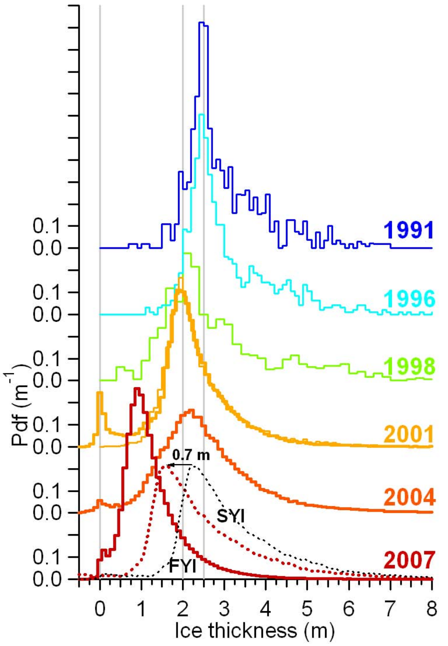
Figure 3: Late summer ice thickness pdfs of the Transpolar Drift, between 1991 and 2007, obtained by means of ground-based (thin lines) and HEM sounding (thick lines), see Figure 1 for measurement locations. The 2007 SYI thickness distribution has been obtained in April 2007 (stippled black line) and was seasonally adjusted by 0.7 m (stippled red line; see text). Vertical grey lines mark ice thicknesses of 2.0 and 2.5 m for reference.



Aug 1991
Aug 1996
Aug 1998
Aug 2001
Aug 2004
Apr 2007
Aug 2007
OW FY SY 3 4 5 6 7 9 10+



HEM Sept. 2001
HEM April 2007
Ground EM, April 2007
Snow thickness, April 2007
FDD model Sept 06 - Apr 07
Ice thickness pdf (m^{-1})
Snow thickness pdf (m^{-1})
Ice & snow thickness (m)
0.0
0.5
1.0
1.5
2.0
2.5
0
1
2
3
4
5
6



1991
1996
1998
2001
2004
2007
0.7 m
SYI
FYI
0.1
0.0
Pdf (m^{-1})
-0 1 2 3 4 5 6 7 8
Ice thickness (m)