Estimates of sea ice thickness: Remote Sensing

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November 16-17, 2016
Sea Ice Thickness Workshop
NCAR, Mesa Lab
Boulder, CO
Questions posed

- What is the state of the art in remote sensing in terms of sea ice thickness?
- What are the uncertainties around sea ice thickness?
- What capabilities/advances would help reduce these uncertainties?
- What does sea ice thickness mean to you in terms of how it is observed and/or modelled?
The average winter sea ice thickness within the Arctic Basin decreased between 1980 and 2008 (high confidence). The average decrease was likely between 1.3 and 2.3 m. High confidence in this assessment is based on observations from multiple sources: submarine, electro-magnetic (EM) probes, and satellite altimetry, and is consistent with the decline in multi-year and perennial ice extent. Satellite measurements made in the period 2010–2012 show a decrease in sea ice volume compared to those made over the period 2003–2008 (medium confidence).

(see also Lindsay and Schweiger, 2015)
Topics

• Focus on sea ice thickness from freeboard (Methodologies/Uncertainties)
  • Spaceborne (radar, lidar) - ICESat, CryoSat
  • Airborne (lidar) - Operation IceBridge
• Electromagnetic Sounding
  • Airborne

• Improvements/Future Capabilities
  • Scope: Arctic-only, not a survey
Ice thickness from sea ice freeboard

- Freeboard (ice)
- Freeboard (ice + snow)
- Range

Provided by N. Untersteiner
Freeboard retrieval and thickness estimation

- **Surface finding**
- **Ice/Water discrimination**
- **Freeboard determination**
- **Thickness estimation**

Profile of the surface from radar or lidar altimetry

Use surface reflectance

\[ h_o \text{ – surface height} \]
\[ h_w \text{ – sea surface height} \]

\[ h_f \text{ or } h_{fi} = h_o - h_w \]

\[ h_i = \left( \frac{\rho_w}{\rho_w - \rho_i} \right) h_f - \left( \frac{\rho_w - \rho_s}{\rho_w - \rho_i} \right) h_{fs} \]  (lidar)

\[ h_i = \left( \frac{\rho_w}{\rho_w - \rho_i} \right) h_{fi} + \left( \frac{\rho_s}{\rho_w - \rho_i} \right) h_{fs} \]  (radar)

Snow depth \( h_{fs} \)
ICESat track over near-coincident RADARSAT image

*Reference thickness estimated using ice age from RGPS

Kwok et al., 2004
Width of leads in the Arctic (to provide sea surface reference)

CS-2 has a synthesized footprint of ~250-300 m. But specular surfaces within the footprint dominate the returns.

Kwok and Cunningham, 2006
Freeboard, Snow depth, Ice Draft and Thickness

Isostatic Equilibrium

\[ h_i = \left( \frac{\rho_w}{\rho_w - \rho_i} \right) h_{fi} + \left( \frac{\rho_s}{\rho_w - \rho_i} \right) h_{fs} \] (lidar)

\[ h_i = \left( \frac{\rho_w}{\rho_w - \rho_i} \right) h_{fi} + \left( \frac{\rho_s}{\rho_w - \rho_i} \right) h_{fs} \] (radar)

Snow depth \( h_{fs} \)

Freeboard (ice + snow) \( h_f \)

Freeboard (ice) \( h_{fi} \)

Thickness \( h_i \)

Sea surface

Sea water

Air

\( \rho_w \)

\( \rho_s \)

\( \rho_i \)
Sea ice bulk density and ice type

\[ \rho_i^{FY} = 917 \rho_i^{MY} = 882 \]

Kwok and Cunningham, 2015

**Figure 2.** Dependence of \( \rho_i^{MY}/(\rho_i - \rho_i) \) in equation (3.1) on the ice thickness using ice densities from Ackley et al. [30], Kovacs [29] and Alexandrov et al. [31].

\[ \rho_i(f_{FY}) = \rho_i^{MY}(1 - f_{FY}) + \rho_i^{FY} f_{FY} \]

Accounting for density differences between FY and MY ice

Figure 7. Arctic sea ice volume from ICESat and CS-2. Arctic sea ice volume is computed within the boundaries in figure 4. One-density (filled symbols) and two-density (open symbols) volume estimates and their trends are shown. See §5e for remarks on uncertainty in volume estimates.

Kwok and Cunningham, 2015
Snow depth distribution and snow density

Climatology over sea ice: Seasonal Cycle (1951-91)

Warren et al., 1999
Advection of accumulated snowfall from beginning of growth season

Kwok and Cunningham, 2006

November 16-17, 2016 - Sea Ice Thickness Workshop
Thickness estimates from ICESat

Feb-Mar 06

Mar-Apr 07

Feb-Mar 08

MY: 3.5 m
FY: 2.0

MY: 3.6 m
FY: 2.2

MY: 3.1 m
FY: 1.9

(Kwok, 2008)
Data quality/uncertainties

- Error propagation methodology
  - potential biases/variability of competing ice parameters used in the retrievals (e.g. snow depth, snow and ice density, etc.) have not been sufficiently quantified
  - Space-time dependence of these parameters
- Assessments (comparison with other measurements – field/airborne)
  - Resolution
  - Time-space coincidence (ice motion)
  - Uncertainties in estimates from other instruments

\[ \hat{e}_h(x, y, t) \]
\[
\sigma_h^2 = \sigma_f^2 \left( \frac{\partial h_i}{\partial h_f} \right)^2 + \sigma_{h_0}^2 \left( \frac{\partial h_i}{\partial h_0} \right)^2
+ \sigma_{\rho_i}^2 \left( \frac{\partial h_i}{\partial \rho_i} \right)^2 + \sigma_{\rho_w}^2 \left( \frac{\partial h_i}{\partial \rho_w} \right)^2,
\]

where

\[
\begin{align*}
\frac{\partial h_i}{\partial h_f} &= \frac{\rho_w - \rho_i}{\rho_f - \rho_i}, \\
\frac{\partial h_i}{\partial h_0} &= \frac{\rho_w - \rho_i}{\rho_0 - \rho_i}, \\
\frac{\partial h_i}{\partial \rho_i} &= \frac{\rho_w - \rho_i}{h_f - h_i}, \\
\frac{\partial h_i}{\partial \rho_w} &= \frac{\rho_w - \rho_i}{(\rho_w - \rho_i)^2}.
\end{align*}
\]

Table 1. Sensitivity of Thickness Estimates $h_i$ to Uncertainties in the Parameters Used in Equation (4)*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$h_f$ (m)</th>
<th>$h_0$ (m)</th>
<th>$\frac{\partial h_i}{\partial x}$</th>
<th>$\sigma_x$ (%var)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_f$-total freeboard</td>
<td>0.05</td>
<td>0.05</td>
<td>0.0025</td>
<td>0.25, 29-32</td>
</tr>
<tr>
<td>$h_0$-snow depth (m)</td>
<td>0.43</td>
<td>0.19</td>
<td>0.0010</td>
<td>0.10, 2</td>
</tr>
<tr>
<td>$\rho_i$-snow density (kg/m$^3$)</td>
<td>0.19</td>
<td>0.19</td>
<td>0.0036</td>
<td>0.10, 2</td>
</tr>
<tr>
<td>$\rho_i$-ice density (kg/m$^3$)</td>
<td>10.0</td>
<td>0.30</td>
<td>0.0019</td>
<td>0.10, 2</td>
</tr>
<tr>
<td>$\rho_w$-seawater density (kg/m$^3$)</td>
<td>0.43</td>
<td>0.030</td>
<td>0.0150</td>
<td>0.10, 2</td>
</tr>
<tr>
<td>$\sigma_{h_i}$</td>
<td>0.65</td>
<td>0.62</td>
<td>0.0140</td>
<td>0.01, 0</td>
</tr>
</tbody>
</table>

*Uncertainties are given in units of percentage of the mean value.

**Bulk densities: \( \rho_i = 300 \text{ kg/m}^3 \), \( \rho_w = 920 \text{ kg/m}^3 \), \( \rho_f = 1024 \text{ kg/m}^3 \).

**ON05 multiyear ice \( h_f = 0.45 \text{ m}, h_0 = 0.26 \text{ m} \) from Figure 4.

**ON06 first-year ice \( h_f = 0.19 \text{ m}, h_0 = 0.10 \text{ m} \).

**ON05 multiyear ice \( h_f = 0.54 \text{ m}, h_0 = 0.37 \text{ m} \).

**ON06 first-year ice \( h_f = 0.30 \text{ m}, h_0 = 0.20 \text{ m} \).
Observations used for assessments
- IceBridge freeboard/thickness/snow depth
- Airborne EM thickness estimates
- Submarine ice draft
- Mooring ice draft
- Field ice thickness
Sea Ice Thickness: Interannual Variability

March/April 2009-2015

Central Arctic:
- Predominantly multi-year
- Stable mean and modal ice thickness
- Mean: 3.2 m, mode: 2.5 m

Beaufort/Chukchi seas:
- More seasonal in nature
- Mix of multiyear (~25 %) and first-year ice (~75 %)
- Ice thickness distribution more variable
- Mean: 2.1 m, mode 1.8 m
- Inter-annual variability primarily related to the presence and location of a band of multi-year sea ice in the southern Beaufort Sea

Richter-Menge and Farrell (2013) GRL, updated
Sea ice thickness: Crosscheck

*NASA IceBridge and ESA CryoSat-2*

Strong gradient to thinner, seasonal ice in the Canada Basin and the eastern Arctic Ocean, where ice is between 1 m and 2 m thick.

Oldest ice north of Greenland and the Canadian Arctic Archipelago remains thicker than 3 m.

Good consistency between independent estimates of sea ice thickness.
EM thickness sounding

\[ Z_i = d_{EM} - d_{Laser} \text{ (snow + ice)} \]

Provided by C. Haas
AEM - Unique, high-resolution data of complete Ice Thickness Distribution

- Required to improve modeling and prediction of ice deformation, ridging, and extreme ice features

Provided by C. Haas
Arctic thickness snapshot, April 2009

Provided by C. Haas

Haas et al., GRL 2010
Assessments
Kwok et al., 2009

SCICEX - NSIDC

BGEP (Proshutinsky) and AIM (Melling) moorings

Relative contributions of errors?
Assessment of CryoSat-2 retrievals
(2011-2015)

LAXON ET AL.: CRYOSAT-2 SEA ICE THICKNESS AND VOLUME

Kwok and Cunningham, 2015

(c) 

BGEP moorings

(d) 

IceBridge

(e) 

AEM

(f) 

IceBridge
Assessment of intersatellite Biases
(time series of mooring/submarine ice draft)

Kwok et al., 2009
Laxon et al., 2003
Kwok and Cunningham, 2015
Snow depth
IceBridge snow radar vs Warren climatology

**OIB snow depth** vs **Warren**

- **2014**
  - OIB: MY 36.67 ± 10.15 cm, FY 24.27 ± 5.53 cm
  - Warren: MY 34.73 ± 2.28 cm, FY 27.86 ± 3.52 cm

- **2015**
  - OIB: MY 36.05 ± 9.15 cm, FY 23.96 ± 6.13 cm
  - Warren: MY 35.25 ± 3.28 cm, FY 27.29 ± 2.57 cm

Snow Depth (cm)
IceBridge snow radar vs Modeled field (w/ERA-interim)

OIB snow depth

- MY: 36.67±10.15 cm
- FY: 24.27±5.53 cm

2014

Modeled field

- MY: 30.40±6.90 cm
- FY: 24.32±7.49 cm

- MY: 5.76±7.83 cm
- FY: 0.01±5.89 cm

Snow Depth (cm)

15  55
Current working group (STOSIWG) on intercomparison of snow depth retrievals approaches (Operation IceBridge): assessment with field measurements, climatology, and precipitation
Partitioning of freeboard into Snow and ice components

**Question:** What is the snow depth at footprint scale given large scale mean?

\[ h_{\text{snow}} = f(\overline{H}_{\text{snow}}, h_{fb}, \sigma_s, f_{FYi}) \]

(Kwok et al., 2011, Kwok and Maksym, 2014)

(Kwok, 2015)
• Snow (highest priority)
  • Time-variable snow depth
  • Partition into smaller length scales based on surface roughness and redistribution
  • Snow density
  • Condition of surface (wet snow, bare ice etc.)
  • Need: field/airborne measurements of snow depth for validation/understanding snow distribution

• Ice thickness
  • High quality and high density of measurements of comparable length-scale for assessment of ice thickness measurements
  • Field/airborne measurements
Some recent results
Trends in Arctic Sea Ice Volume

End-of-winter

ICESat

CryoSat-2

ICESat

CryoSat-2

Winter

Summer

Kwok and Cunningham (2015)
Combined Submarine, ICESat, and CS-2 records

Kwok and Cunningham (2015)
At selected locations

updated Kwok and Rothrock [2009]
On-going and future missions

- NASA
  - ICESat-2 (mid-2018)
  - IceBridge Campaigns (2009 - 2019)
  - SWOT (2020-2023)
- ESA
  - CryoSat-2 (2010-)
  - Sentinel-3
  - Airborne campaigns (validation)
- Airborne EM
  - AWI, York, and others
NASA ICESat-2 Altimetry Mission (launch date: Oct 2016)

- 6 beams
- 14 m spots
- 0.7 m separation
Multibeam Photon Counting Altimetry

Profile

Launch: mid-2018

- 3 beam pairs
- 15 m spots
- Spacing: 70 cm (10 kHz)
Coverage of the Greenland Sea
(nominally ICESat-2 has a 91-day repeat orbit)
ICESat-2 coverage for Barrow area
(each line represents a pair of beams)
July-29

Fig. 9. Lead density, freeboard (10-km averages) and associated freeboard distribution along the MABEL flightline on July 29, 2014. N is the number of 10-km segments and quantities are mean and standard deviation of calculated freeboard.
# ICESat-2 Data Products

<table>
<thead>
<tr>
<th>ATBD</th>
<th>Lead</th>
<th>Affiliation</th>
<th>ATLAS Science Data Products</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precision Pointing Determination (PPD)</td>
<td>Bob Schutz</td>
<td>UTCSR</td>
<td>ancillary data</td>
<td>Precise laser pointing solutions input to all level 2 and higher level products</td>
</tr>
<tr>
<td>Precision Orbit Determination (POD)</td>
<td>Scott Luthcke</td>
<td>GSFC</td>
<td>ancillary data</td>
<td>Precise orbit solutions input to all level 2 and higher level products</td>
</tr>
<tr>
<td>Level 1A</td>
<td>John DiMarzio</td>
<td>SGT/GSFC</td>
<td>ATL01</td>
<td>Conversion and reformating of Level 0 data</td>
</tr>
<tr>
<td>Level 1B</td>
<td>Phil Dabney</td>
<td>GSFC</td>
<td>ATL02</td>
<td>Apply necessary corrections from housekeeping data, e.g. calibrated ranges</td>
</tr>
<tr>
<td>Level 2A</td>
<td>Thorsten Markus/ Tom Neumann</td>
<td>GSFC</td>
<td>ATL03</td>
<td>combine elevation corrections, geolocation information, laser spot location (which requires preliminary surface finding) with L1B product; also will produce histograms</td>
</tr>
<tr>
<td>Ice Sheet</td>
<td>Ben Smith</td>
<td>UW</td>
<td>ATL06, 11, 14, 15</td>
<td>Define ice sheet products and parameters</td>
</tr>
<tr>
<td>Sea Ice</td>
<td>Ron Kwok</td>
<td>JPL</td>
<td>ATL07, 10, 20, 21</td>
<td>Define sea ice products and parameters</td>
</tr>
<tr>
<td>Land</td>
<td>Amy Neuenschwander</td>
<td>UTCSR</td>
<td>ATL08</td>
<td>Define land and vegetation products and parameters</td>
</tr>
<tr>
<td>Ocean</td>
<td>James Morison</td>
<td>UW</td>
<td>ATL12, 19</td>
<td>Define ocean products and parameters</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>Steve Palm</td>
<td>SSAI/GSFC</td>
<td>ATL04, 09, 16, 17</td>
<td>Define atmosphere products and parameters and the calibrated backscatter</td>
</tr>
<tr>
<td>Inland Water and Snow</td>
<td>Mike Jasinski</td>
<td>GSFC</td>
<td>ATL13</td>
<td>Significant interaction with the veg. file ATL08 with possible water-specific algorithm</td>
</tr>
</tbody>
</table>
Simultaneous Observations Of Thickness and Kinematics

Sea Ice Motion and Deformation

Ice Thickness distribution

Sea Ice Thickness

Sea Ice Motion

- Circulation changes, export and regional redistribution of sea ice
- Small-scale motion for quantifying deformation-relation thickness changes
- Volume storage associated with ridging

~10^2 km

~10^2 m
Ice thickness distribution

Ridging and rafting
Add to seasonal ice growth
Richness and beauty!

Thank you!