How thick is the ice?

What scale?
How thick is the ice?

April – pre-melt

May – pre-melt

June – melt

July – melt

August – melt

September – freezeup

What time?
How thick is the ice?

New ice

First year ice

Young ice

Multiyear ice

What age?
How thick is the ice?

What kind?
What does ice thickness mean to you?

The great integrator

The key parameter (even bigger than albedo)

$g(h) -$ the thickness distribution

An insulator

Ice strength

A barrier to heat, moisture, momentum

Storage of fresh water

Mass balance

Ice deformation

Light transmission

The distance from the top of the ice to the bottom
In situ observations of ice thickness

Jackie Richter-Menge, Don Perovich

High resolution over small scales
Drilling holes

- Direct measurement
- Accurate
- Snow, ice, freeboard
- Simple equipment

- Hard work
- Slow, limited coverage

Point measurement of:
- Snow depth = 30 cm
- Freeboard = 40 cm
- Ice thickness = 400 cm

Uncertainty of 1 cm

Most direct, most accurate, most information
Melt pond survey

Important for
- Mass balance
- Mechanical properties
- Salinity balance
- Light transmittance

- Mechanical drilling
- 150 m long line
- Every 2 m
- 1.5 hour

Pond morphology matters
Ridge surveys

- Mechanical drilling
- 100 m long line
- Every 5 m
- Mean thickness = 410 cm
- Range from 160 cm to 760 cm
- Took 2.5 days
Ridges and rubble fields

Rubble fields are worse. Want to borrow my drill?
Hot water drilling

- Direct measurement
- Accurate
- Snow, ice, freeboard
- More coverage

- Complicated, heavy equipment
- Major setup effort
- Jackie hates it...a lot

- 100 m x 100 m grid
- Every 10 m
- Mean thickness = 300 cm
- Range from 180 cm to 651 cm
- Took 2 days

Two dimensional look at heterogeneity
Sea ice mass balance

- Simple concept
  - ice growth
  - surface melt
  - bottom melt
- Equipment
  - ablation stakes and thickness gauges
  - autonomous buoys

Simple, but powerful observation – attributes change
An array of mass balance sites

In this case all ice thinned over annual cycle
Sea ice mass balance buoys

- Position
- Air temperature
- Barometric pressure
- Ice temperatures
- Upper ocean temperatures
- Snow accumulation and ablation
- Ice growth
- Surface and bottom ice melt

Autonomous measurements of thickness and mass balance
Electromagnetic induction

- Easy to operate
- Lightweight, portable
- More coverage (km)

- In situ remote sensing
- Calibration needed
- 6 m maximum thickness
- Footprint 1.35 x distance

Cover more area, with less resolution
In situ ice thickness surveys

Add a magnaprobe!

Snow depth and ice thickness over kilometers
Transarctic ice thickness observations

Sampling across the Arctic

26 August

17 September
Spatial surveys EM-31

83 17.9 N, 171 53.3 W
26 Aug 2005

First year ice near the end of the melt season
Spatial surveys EM-31

87 28.3 N, 57 35.3 E
17 Sep 2005

Snow depth (cm)

Ice thickness (cm)

Distance From Sea Level (cm)

Distance (m)

Snow

Ice

Count 368 362
Average 15 164
Median 15 150
Std dev 4.9 58.9
Minimum 1 93
Maximum 32 463
% > 6m 1.6%

Multiyear at the beginning of freezeup
Transarctic thickness surveys

August – September 2005

8% of sample was ridges more than 6 m thick
Ship-based ice watch

- Many variables
- Standardized format
- Software widely available
- Many ships including tourism
- Excellent Antarctic dataset

😊
- Very rough estimate
- Limited by season
- Sampling is biased

Rough estimate, but multiple ships
Ship-based ice watch

- In transit ice description
- Thickness plus concentration, ridges, ponds, ice type, etc

Large in situ areal coverage
In situ thickness and remote sensing

Connecting the scales
• Measure surface elevation of snow, ice and open water
• Derive sea ice freeboard
• Assume equilibrium of floating ice cover
• Infer ice thickness, a function of:
  – Snow, ice and water density
  – Snow depth
  – Ice freeboard
• Ice thickness uncertainty primarily influenced by errors snow depth
Sea Ice Thickness: Airborne and Satellite Altimetry

An inferred measurement

- Measure surface elevation of snow, ice and open water
- Derive sea ice freeboard
- Assume equilibrium of floating ice cover
- Infer ice thickness, a function of:
  - Snow, ice and water density
  - Snow depth
  - Ice freeboard

Ice thickness uncertainty primarily influenced by errors snow depth measurements

Photo Credit: Andrew Roberts, SEDNA 2007
Snow depth

**Magnaprobe** (Sturm et al.)
- Snow depth
- Point measurement
- GPS
- Automatically logs obs
- Easy to use
- Quick
- cm accuracy

**Snow pit**
- Detailed snow characterization
- Point measurement
- Density, grain size, salinity, layers
- Tedious
ICEX 2011: US Navy Ice Exercise
Supporting Arctic Submarine Operations

March 2011, Alaskan Beaufort Sea
ICEX2011: Coordinated Measurement Campaign

Snow depth and ice thickness

Ground-based

Drill holes

NRL Twin Otter

IceBridge NASA P3

Region of highly deformed ice

US Navy Submarine
ICEX2011: Coordinated around a 9-km-long survey line

- North End
- Calibration drill hole
- Widely varying ice
- Reflector site
- Devil’s Cauldron
- South End

Region of highly deformed ice

Drill Hole
Stake
Radar
Reflector
Locator
Beacon
NASA P3 Over Flight of ICEX2011 Survey Line
The Adventure Ends...

...The Analysis Begins
Improving in situ observations for cal/val

Snow depth: In situ versus radar

Surface roughness impacts snow radar return signal

Newman et al., 2014, JGR
Improving in situ observations for cal/val

**THE GRID: Provides 2D footprint of snow depth**

Undeformed ice: 12 ± 5 cm

Rubble: 30 ± 16 cm

March 2014: Barrow offshore
March Madness 2014

Rich resource of in situ, airborne and satellite observations
ECCC Operation IceBridge 2016 Campaign Snow on Sea Ice Survey

Stephen Howell\textsuperscript{1}, Joshua King\textsuperscript{1}, Peter Toose\textsuperscript{1}, Arvids Silis\textsuperscript{1}, Chris Derksen\textsuperscript{1}, Jack Landy\textsuperscript{2}, and Thomas Newman\textsuperscript{3}

\textsuperscript{1}Environment and Climate Change Canada
\textsuperscript{2}University of Manitoba, Centre for Earth Observation Science
\textsuperscript{3}Laboratory for Satellite Altimetry / Sea Ice Research Group, NOAA Center for Weather and Climate Prediction
Eureka Sound

Ideal site: no drift, variable conditions, accessible
Smooth first year ice

Snow Depths:
n=8361
avg = 15.3 cm
STDV = 7.3 cm

Intensive Observation Site
ECCC 2016 Eureka Campaign

By the numbers

- 8 intensive survey sites measured
  - 2 on multi-year ice; 6 on first-year ice
- 54,287 GPS-tagged snow depths measured
- 22 snow pits providing detailed characterization
- 21 manually augured ice thickness measurements
- 260+km of GPS-tagged EM31 ice thickness measurements
- 255+ million LiDAR measurements of snow on sea ice surface roughness

https://github.com/kingjml/ECCC-Eureka-2014-Snow-on-Sea-Ice-Campaign
In situ: **Good news and bad news**

We can examine in detail

But we have to be there

We can cover meters to kilometers

But not hundreds of kilometers

We can measure undeformed ice easily

But ridges are problematic

We have a wealth of data

But it has to be accessible

We can answer many questions

But we need a network

**What is the evolution of the ice thickness distribution?**
Arctic sea ice thickness archive

- Develop a climatological record of sea ice thickness based on *in situ surface-based* observations of the Arctic Ocean
  55,000 points from 1894 to present

- Highly accurate and long-term records (Nansen/Fram -> present)
- Broader regional sampling than submarines (later discussion)
- Field Experiments: Position, date, ice thickness, snow depth, ice type, transects, grids

*Ben Holt (JPL) is building this archive*
Summary: *in situ* thickness

- Always measure every hole
- Drilling holes is most accurate
  - Snow depth, freeboard, ice thickness
- *In situ* autonomous for thickness changes
- Electromagnetic surveys provide coverage
  - Snow depth, ice thickness
  - Price is increased “fuzziness”
- Need to organize and archive data

Many detailed observations, but not everywhere, always
Questions?
Remote Ice Thickness Observations

Submarines

SCICEX cruise tracks, 1993-2003

From Rothrock and Wensnahan (2007):
  • Bias in ice draft obs: + 29 cm
  • STD: ± 25 cm
Remote Ice Thickness Observations

Submarines

- Changes: 1950s-1970s to 1990s
- Early evidence of thinning Arctic sea ice cover

Rothrock et al., 1999

- Extends satellite-derived record of sea ice thickness

Kwok and Cunningham, 2015
Remote Ice Thickness Observations

Submarines

New data:
- 6 traverses
- Alaska → North Pole
- More to come
- 65+ year record!

Register for data alerts: https://nsidc.org/scicex