

# Monitoring Ice Thickness in Arctic Seas

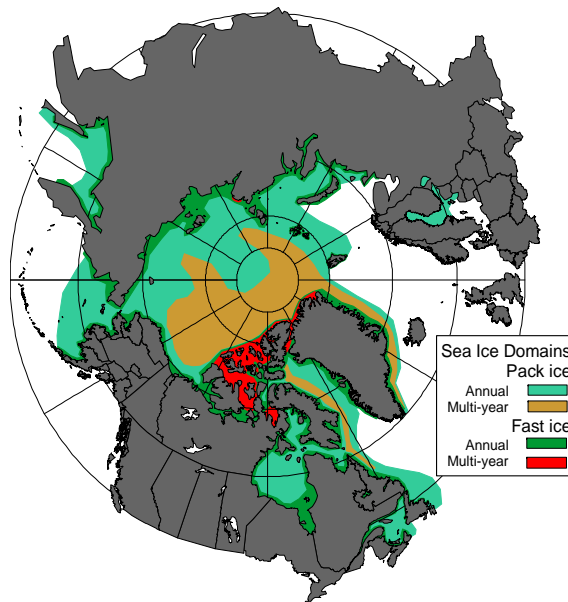
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## 1: Domains of Arctic Sea Ice

There are two principal sea-ice types in the Arctic (first-year, multi-year), each of which may exist as either pack ice or fast ice [see map below].

Because the energy balance and dynamics are different in each domain, the impacts of changing climate are likely different too. A network for monitoring variability and change must span all four domains.

Multi-year fast ice has special significance for Canada: the Earth's largest accumulation is in the Canadian Archipelago, blocking the North West Passage.



## 2: Sea Ice Thickness

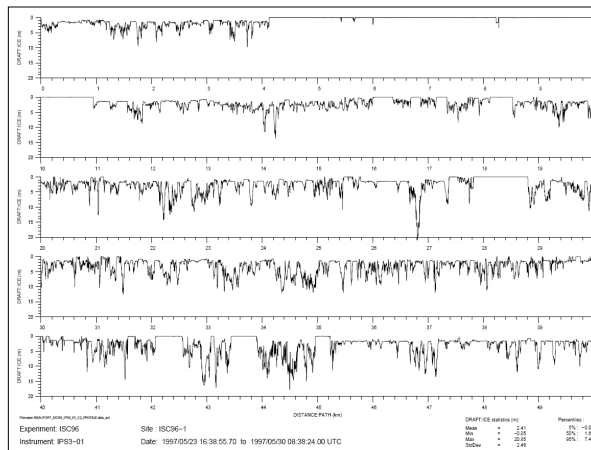
Measurements at a fixed point in the ice cover are poorly representative of thickness

Sea ice is very rough and a local diversity of ice forms is typical [see topographic profile below]. The distance of relevance for a single measurement is generally less than 25 m, except perhaps in the first-year fast ice domain.

The period of relevance for a single survey may also be short

Ice movements and fracturing to form leads and build ridges during storms can dramatically transform an icescape. Ablation during July and August causes rapid deterioration and thinning of sea ice.

Surveys based on manned platforms (e.g. aircraft or submarines) are necessarily infrequent for reasons of remoteness, environmental challenge and cost.



## 3: Measuring the Thickness of Sea Ice

Present capability to map the extent of sea ice is impressive, a product of effective sensors that operate from Earth satellites.

Capability to map the thickness of sea-ice lags behind because accurate high-resolution space-based measurement is proving very challenging.

There are presently two established techniques for determining sea-ice thickness: 1) Direct measurement after drilling a hole, 2) Calculation from draft measured remotely by sub-sea sonar.

There are a number of promising contenders – surface-based or airborne electromagnetic induction sounder, satellite-based laser altimeter, satellite-based microwave altimeter.

Among these techniques, only sub-sea sonar and the emerging satellite technologies can provide the continuous year-round observations generally associated with monitoring [see table below].

### Methods Available for Sea Ice Thickness Monitoring

Field of view	Characteristics of the Technique						Logistics			
	0.1 m	1 m	0.3 to 3 m	0.1 to 100 m	3,000 to 10,000 m	30 to 100 m				
Warm season operability	Difficult	No	Yes	Yes	Poor	?				
Confidence in derivation of ice thickness	Excellent	Excellent	Good	Moderate to poor	Good to poor	Excellent to poor				
Scope		Technique				Logistics				
Temporal	Spatial	Drill <sup>1</sup>	Thermistor chain <sup>4</sup>	Sonar <sup>5</sup>	Lidar <sup>6</sup>	Radar <sup>7</sup>	Electromagnetic induction <sup>8</sup>	Platform	Logistic implications	Site or survey cost
Continuous	0.01 km 100 km	■	■	■				On ice	Nearby settlement	\$10k-\$100k/year
								Sub-sea mooring	Ship, or aircraft with shore base	\$30k-\$100k/year
								Submarine	Limited access	Very high
Episodic (surveys)	3,000 km 0.3 to 1 km 100 to 300 km	■		■			■	On ice	Ship, or aircraft with shore base	\$10k-\$30k/survey
								Helicopter	Aircraft with shore base	\$10k-\$100k/survey
								Earth satellite	Purpose built space platform & ground segment	Very high

<sup>1</sup> Large differences in ice thickness typically occur over distances of order 10 m  
<sup>2</sup> Thickness is not congruent to ice mass per unit area. The latter may best be determined by drilling or EMI, which are sensitive to voids in ice  
<sup>3</sup> Simultaneous measurement of snow depth is a bonus  
<sup>4</sup> Simultaneous measurement of snow depth is a bonus  
<sup>5</sup> Requires upper ocean sound speed (or surrogate) & surface atmospheric pressure. Thickness = 1.1 x Draft  
<sup>6</sup> Requires sea-surface height & snow depth. Thickness = 10 x Draft. Required accuracy = 1 cm is challenging  
<sup>7</sup> Requires sea-surface height & knowledge of source of scattering from ice. Thickness = 10 x Draft. Required accuracy = 1 cm is challenging  
<sup>8</sup> Provides snow depth with concurrent use of lidar & radar

## 4: Mapping Sea-Ice Draft using Sonar on Submarines

Upward-looking sonar provides the depth of submergence (viz. draft) of sea ice. Pack-ice thickness is 10-15% larger.

The best geographic coverage has been provided by sonar operating on patrolling US and UK submarines starting in the late 1950's. Tracks of US Navy submarines to the mid 1980's are shown on the map [below right] from Lyon (1984).

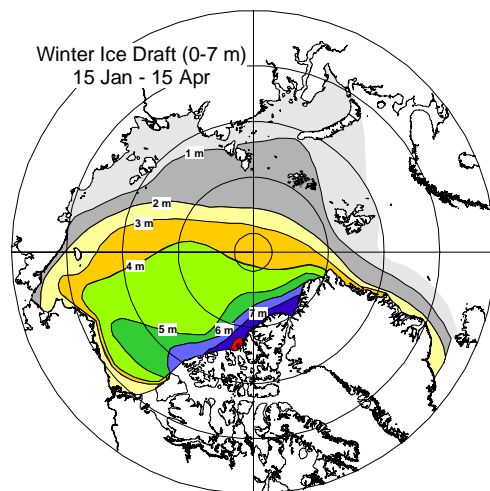
Coverage has typically been restricted to the deep basins of the central Arctic, an area comprising about a third of the northern marine cryosphere at maximum. This area is primarily within the multi-year pack ice domain.

Our best map of Arctic ice draft [below left] is based on these data (Bourke & Garrett 1987).

The annual number transits has declined significantly since the late 1980's.

Lyon, WK. 1984. The navigation of Arctic polar submarines. Journal of Navigation 37, 155-179.

Bourke, RH and RP Garrett. 1987. Sea ice thickness distribution in the Arctic Ocean. Cold Regions Science and Technology 13, 259-280.



## 5: Thickness of First-year Fast Ice

Our longest thickness records are in first-year fast ice. Drillings 3-4 times monthly were started at Russian coastal stations in the late 1930's and in Canada in the late 1940's [see map below left].

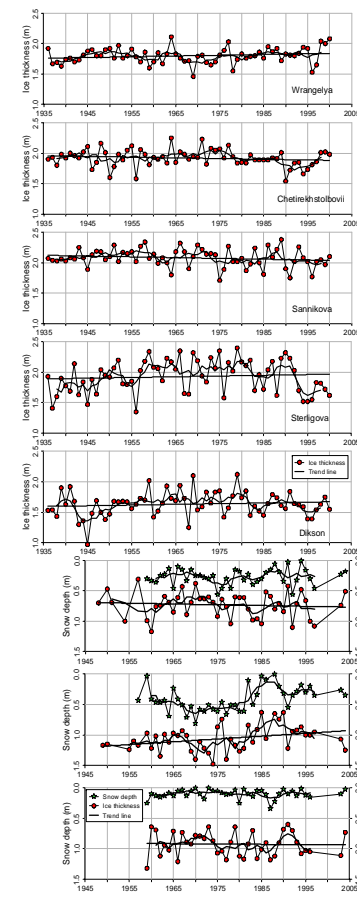
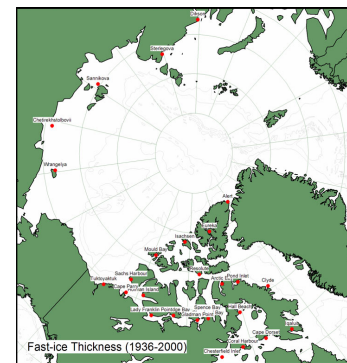
Analysis reveals half-century trends that are small and inconsistent across the Arctic, despite 1-2°C warming during this time [see below, after Brown and Coté 1992 & Polyakov et al. 2003].

Ice thickness has varied inversely with snow depth [see graphs for Canadian stations].

Observations at Canadian stations had ceased by the mid 1990's. A revival in the 2000's was brief.

Brown, RD & P Coté. 1992. Inter-annual variability of land-fast ice thickness in the Canadian High Arctic, 1950-89. Arctic 45, 273-284.

Polyakov, IV, GV Alekseev, RV Berkryaev, US Bhatt, R Colony, MA Johnson, VP Karlink, D Walsh & AV Yulin. 2003. Long-term ice variability in Arctic marginal seas. Journal of Climate 16, 2078-2085.

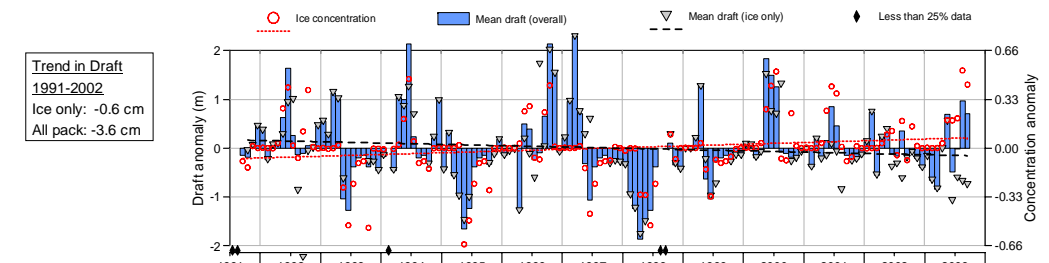
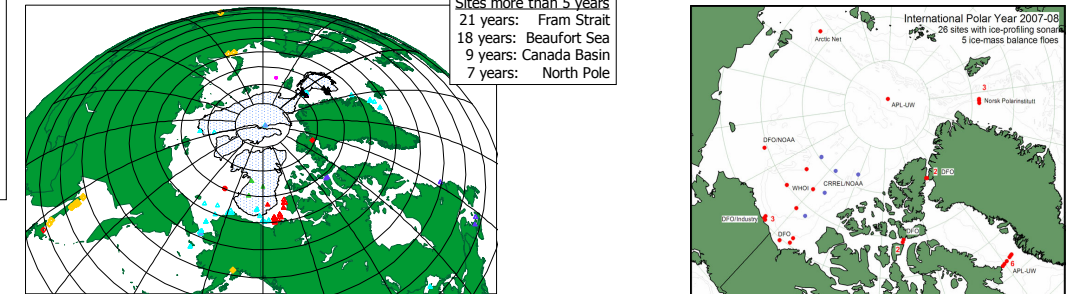


## 6: Draft of First-year Pack Ice

Self-contained ice-profiling sonar on sub-sea moorings have been used for year-round observation of Arctic pack ice since the late 1980's. Instruments have been deployed at sites shown on the hemispheric map [below left]. The longest records are from the Canadian Beaufort Sea and Fram Strait. Installations for the IPY are plotted on the map [below right] as red dots, with the number of units indicated where dots merge.

12 years of monthly draft anomalies for first-year pack ice in the Beaufort Sea are displayed in the bar graph (Melling et al 2005). The measured trend is very small and statistically indistinguishable from zero. This series (now nearly 18 y) is our longest from the first-year pack ice domain.

Melling, H, DA Riedel and Z Gedalof. 2005. Trends in the draft and extent of seasonal pack ice, Canadian Beaufort Sea. Geophysical Research Letters 32, L24501, doi:10.1029/2005GL024483



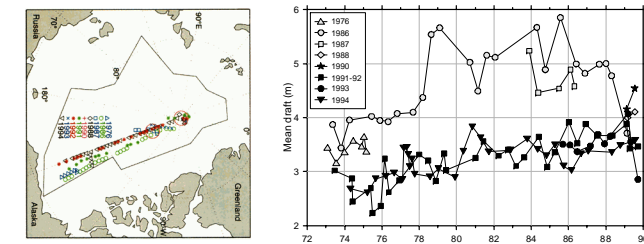
Trend in Draft 1991-2002  
Ice only: -0.6 cm  
All pack: -3.6 cm

## 7: Draft of Multi-year Pack Ice, central Arctic

Surveys from submarines traveling to the Pole [below right] reveal a 1-2 m thinning within the multi-year pack ice domain in the late 1980's [below left, from Tucker et al. 2001].

The disparate trends in first-year and multi-year ice domains suggest that a shrinking presence of multi-year ice is the primary cause of this dramatic change.

Tucker, WB III, JW Weatherly, DT Epler, LD Farmer and DL Bentley. 2001. Evidence for rapid thinning of sea ice in the western Arctic Ocean at the end of the 1980s. Geophysical Research Letters 28, 2851-2854.

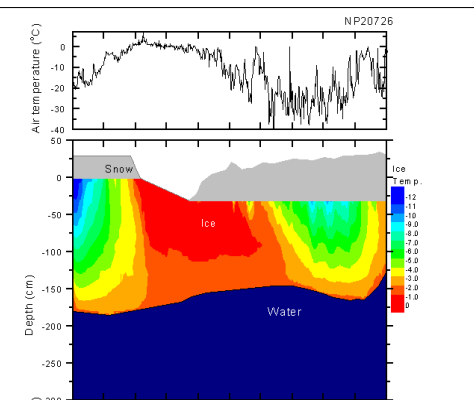


## 8: Thickness of Multi-year Floes

Chains of thermistors embedded in sea ice allow monitoring of the ice-mass (viz. thickness) and energy balances of drifting floes [below, from Perovich & Elder 2001].

Present locations of ice-mass balance installations for the IPY are plotted as blue dots on the map above.

Perovich, DK, and BC Elder. 2001. Temporal evolution of Arctic sea ice temperature. Annals of Glaciology 33, 207-211.



## 9: The Future

Wide coverage via radar or laser altimeters (imprecise?) on Earth satellites [see left, from Laxon et al 2003], accurate detailed local time-series (moored sonar), repeated surveys (submarine sonar, airborne EMI) and ice-mass balance series are assimilated with oceanic and atmospheric data into a numerical sea-ice simulation model to provide thickness maps for the northern marine cryosphere at frequent intervals.

Laxon, S, N Peacock and D Smith. 2003. High inter-annual variability of sea ice thickness in the Arctic region. Nature 425 947-950, doi:10.1038/nature02050.