Measuring Ice: Observation techniques that inform us about the extent and dynamics of the cryosphere

ESS431: Principles of Glaciology

ESS505: The Cryosphere

Monday, 10/01 – Knut Christianson

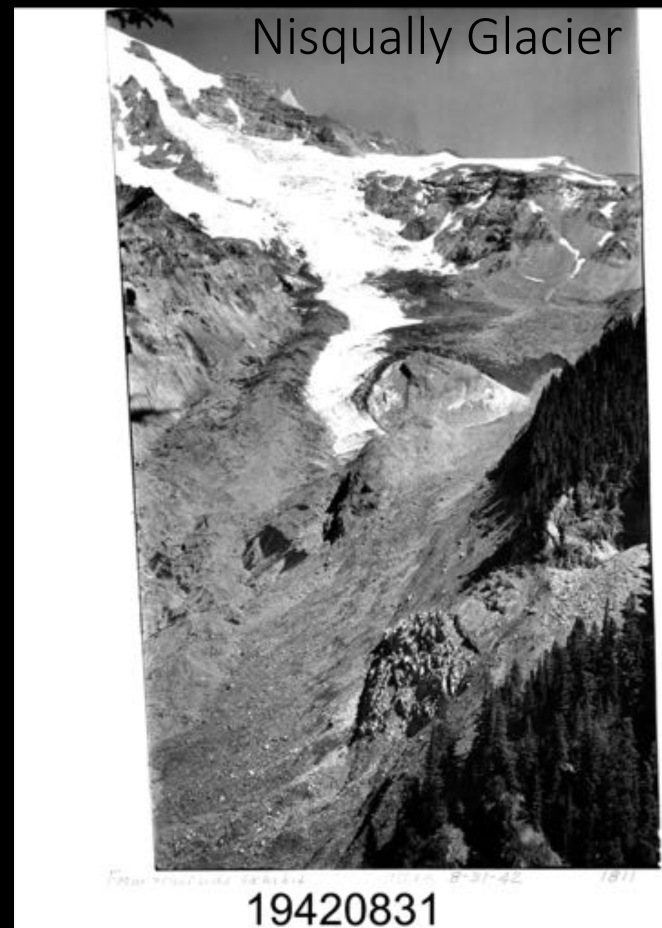
The components of the cryosphere:

	Coverage Area	Reservoir Size (m sle)
Permafrost	23	0.1
The Ice Sheets		
Antarctica	13.3	56
Greenland	1.7	7
Mountain Glaciers	1.1	0.8
Sea Ice		
Arctic	8.4 / 15	
Antarctic	3.0 / 19	
Seasonal Snow	45	

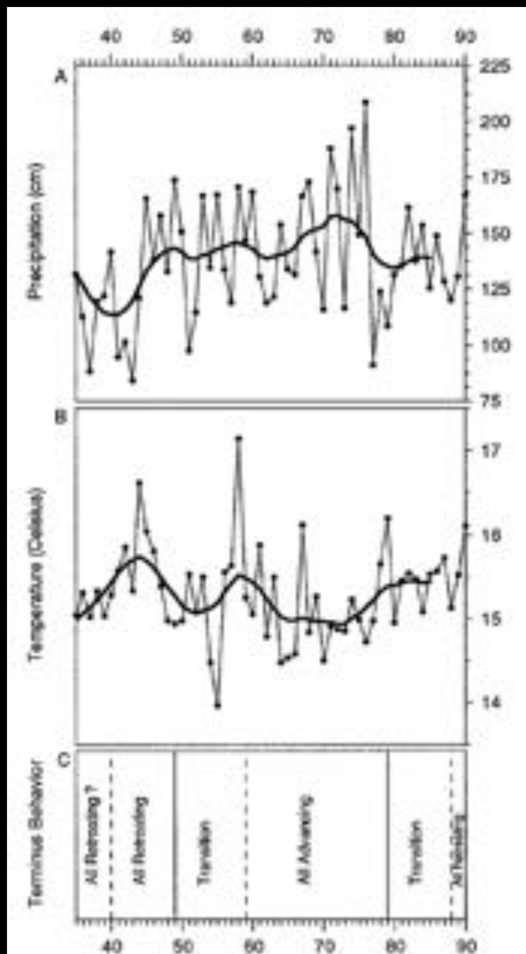
Average Ocean Depth:
~3500m

All ice on earth ~ 2%

Measuring spatiotemporal variability in the cryosphere



Blue, Black, Nisqually &
South Cascade Glaciers


A
B
C
Precipitation (cm)
Temperature (Celsius)
Terminus Behavior
40
50
60
70
80
90
225
200
175
150
125
100
75
17
16
15
14
All Retreating ?
All Retreating
Transition
All Advancing
Transition

(Harper, 1993)

Today's focus -

- What are the variables of interest in cryospheric research?
- How are these variables measured now, and how have they been historically? What are the advantages of different observation methods?
- What is the basis for remote sensing, and what are the current remote sensing techniques used in cryospheric research?

Forcings

Glacier System

Forcings

- Snow accumulation rates and distribution
- Melt rates and areas
- Atmosphere and ocean temperatures

Glacier System

- Flow behavior (speed / direction)
- Geometry (area, thickness)
- Substrate material?

Forcings

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In-situ Methods

Glacier System

- Flow behavior (speed / direction)
- Geometry (area, thickness)
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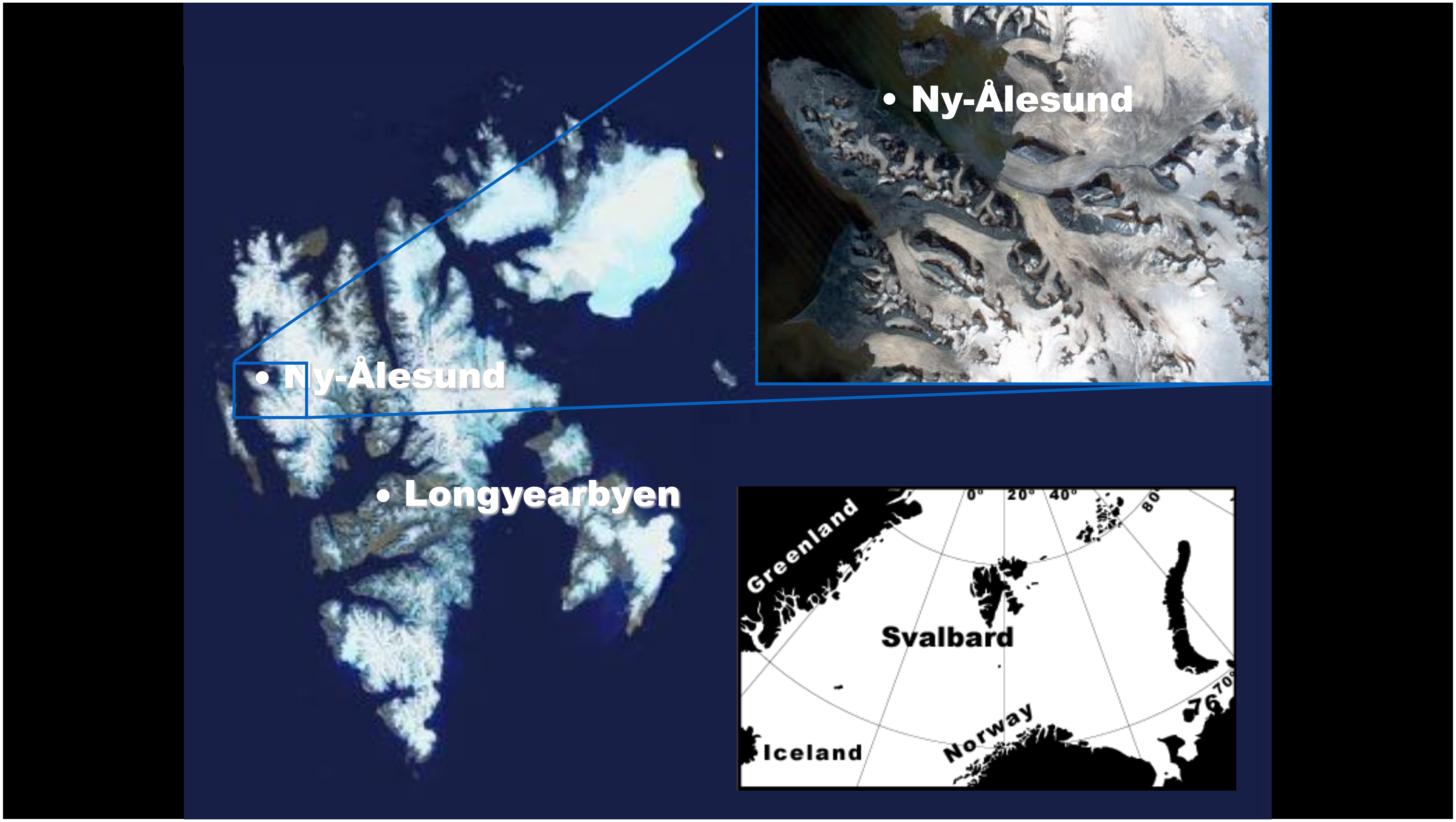
Airborne/Satellite
Remote Sensing

In-situ Measurements

In-situ Measurements

Directly collecting information about a system at a point of interest. This requires *that the instrumentation be in contact with a point of interest for the system.*


Your typical story for a Svalbard glacier:
Front position 2002
Front position 1906



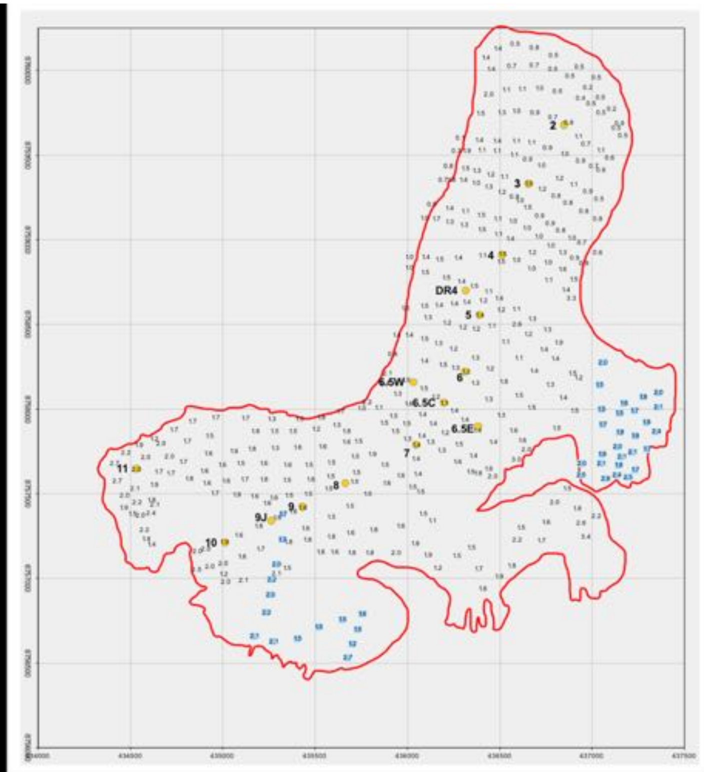
Ny-Ålesund
Ny-Ålesund
Longyearbyen
Greenland
Svalbard
Iceland
Norway
0°
20°
40°
80
76
70

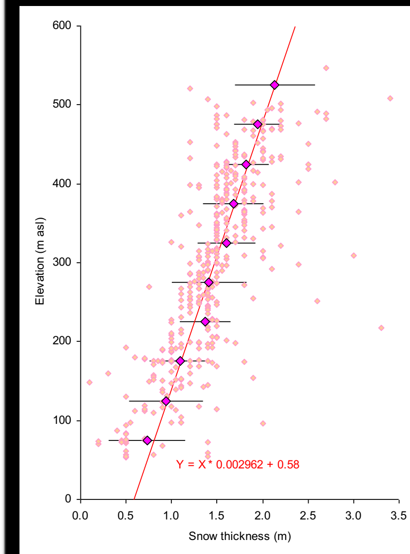

NP mass balance
0
10 km
• Ny-Ålesund
BRG
MLB
KNG
Austre Brøggerbreen (BRG) and Midre Lovénbreen (MLB) longest annually measured high Arctic mass balance time-series (started 1967, 1968, respectively).
Kongsvegen (KNG) shorter time series (since 1987).

Accumulation

- To derive total accumulation, you measure change in snow thickness + deposited snow density

Accumulation: Density Cores



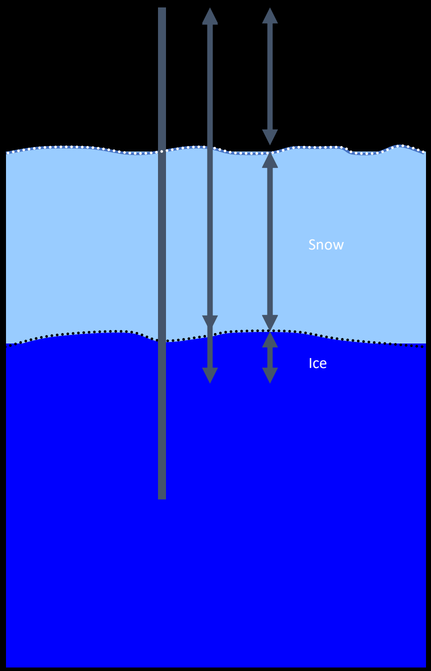


Accumulation: Density Cores

Melt

- To derive total melt in the ablation zone, you just have to measure changes in ice thickness.

Stake measurements: accumulation and ablation



Pits and cores : digging deeper in time

- Snow pits can provide information for ~decade of net snow fall information, depending on accumulation rates.

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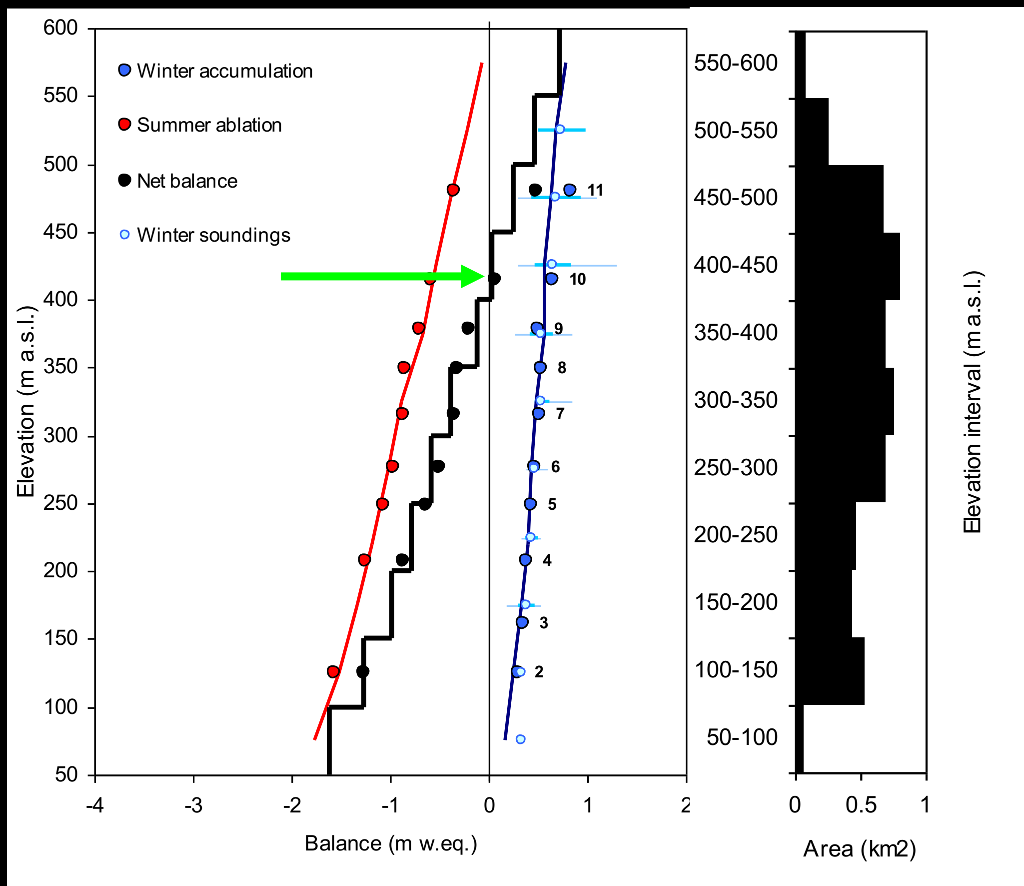
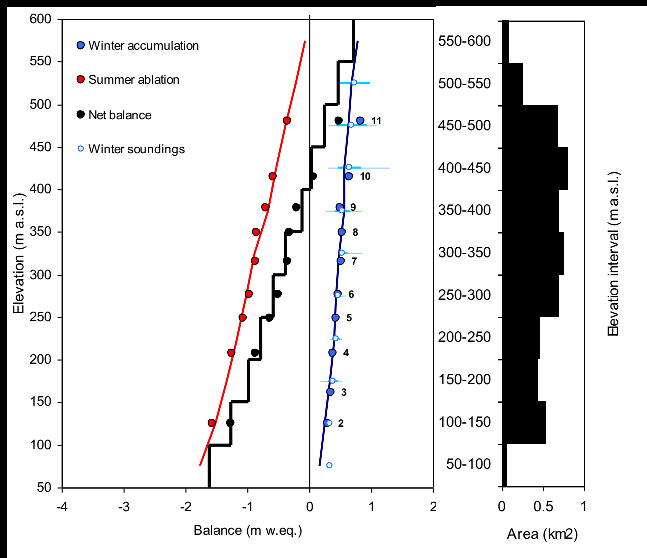
Balance : Accumulation and Ablation



Winter balance	0.49
Summer balance	-0.85
Net balance	-0.36
ELA	414

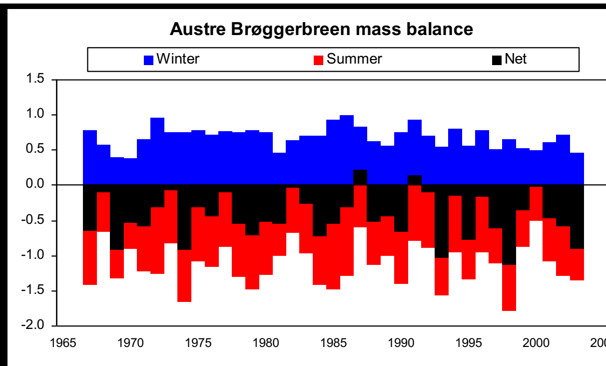


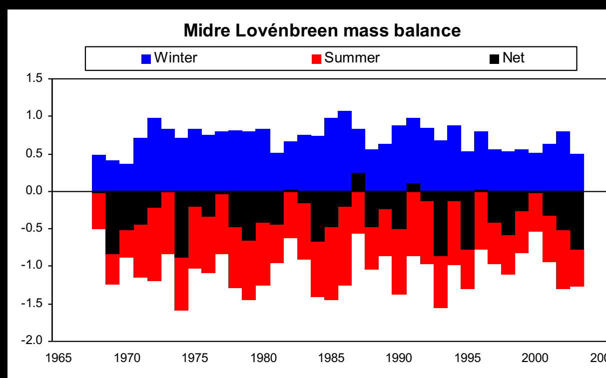
Winter balance	0.49
Summer balance	-0.85
Net balance	-0.36

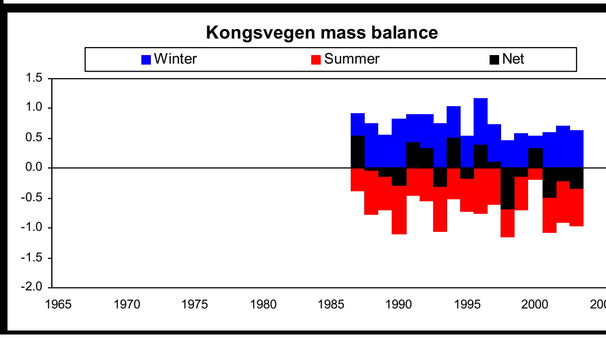
Mass balance time series

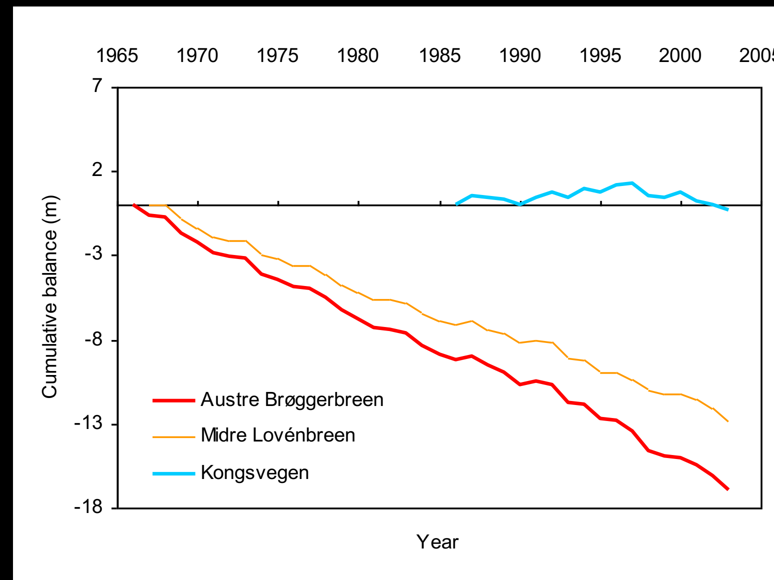
Midre Lovénbreen

year	bw	bs	bn
1967/68	0.48	-0.51	-0.03
1968/69	0.41	-1.25	-0.84
1969/70	0.36	-0.89	-0.53
1970/71	0.70	-1.16	-0.46
1971/72	0.98	-1.2	-0.22
1972/73	0.82	-0.84	-0.02
1973/74	0.70	-1.59	-0.89
1974/75	0.83	-1.04	-0.21
1975/76	0.75	-1.1	-0.35
1976/77	0.80	-0.84	-0.04
1977/78	0.81	-1.29	-0.48
1978/79	0.80	-1.46	-0.66
1979/80	0.83	-1.26	-0.43
1980/81	0.51	-0.97	-0.46
1981/82	0.66	-0.64	0.02
1982/83	0.75	-0.92	-0.17
1983/84	0.74	-1.42	-0.68
1984/85	0.98	-1.46	-0.48
1985/86	1.06	-1.27	-0.21
1986/87	0.82	-0.58	0.24
1987/88	0.56	-1.05	-0.49
1988/89	0.63	-0.87	-0.24
1989/90	0.87	-1.38	-0.51
1990/91	0.98	-0.88	0.1
1991/92	0.84	-0.98	-0.14
1992/93	0.68	-1.56	-0.88
1993/94	0.87	-1	-0.13
1994/95	0.52	-1.31	-0.79
1995/96	0.80	-0.78	0.02
1996/97	0.56	-0.98	-0.42
1997/98	0.53	-1.11	-0.58
1998/99	0.56	-0.90	-0.34
1999/00	0.49	-0.54	-0.05
2000/01	0.49	-0.85	-0.36



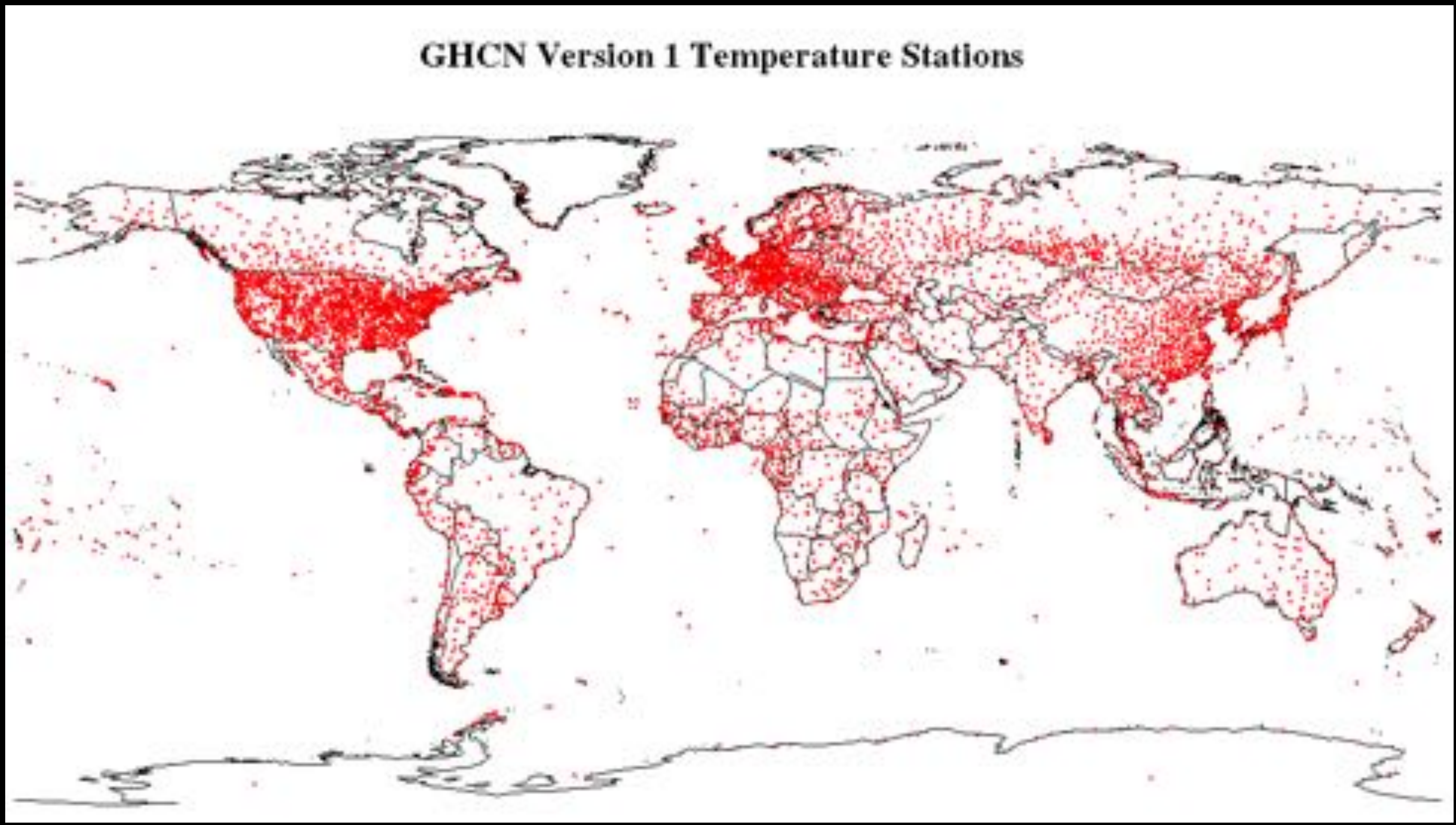






Svalbard NPI glacier mass balance time series

Temperature Observations



Temperature: Radiosonde [Atmosphere]

- Can ascend 35,000 meters
- 92 Stations managed by the NWS (800 world)

- Measure:
  - Altitude
  - Pressure
  - Temperature
  - Relative humidity
  - Wind
  - Position

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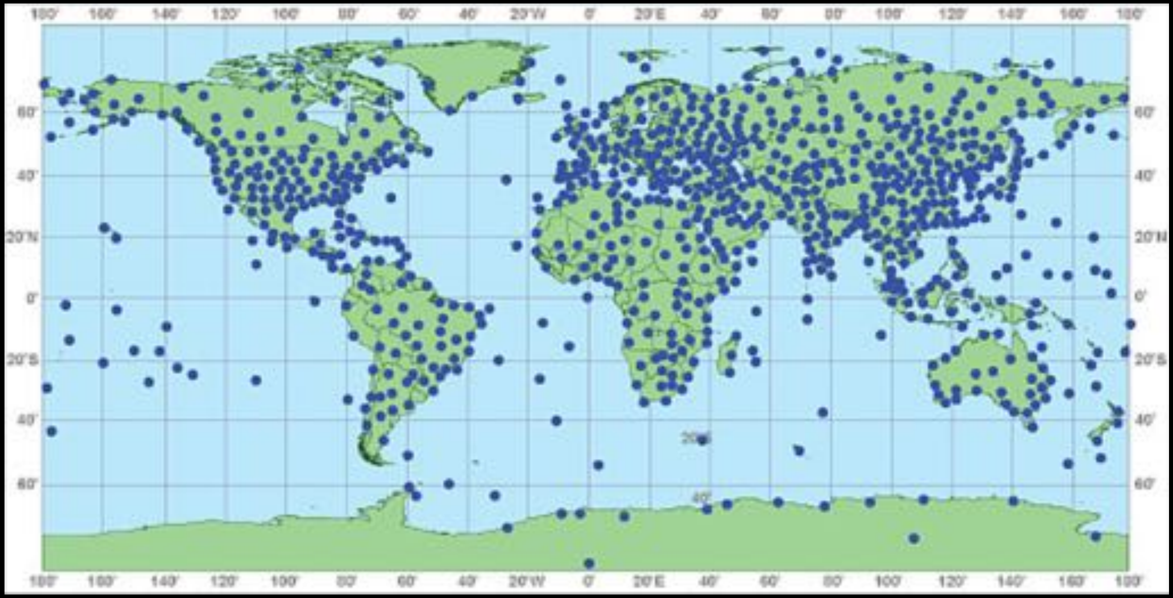
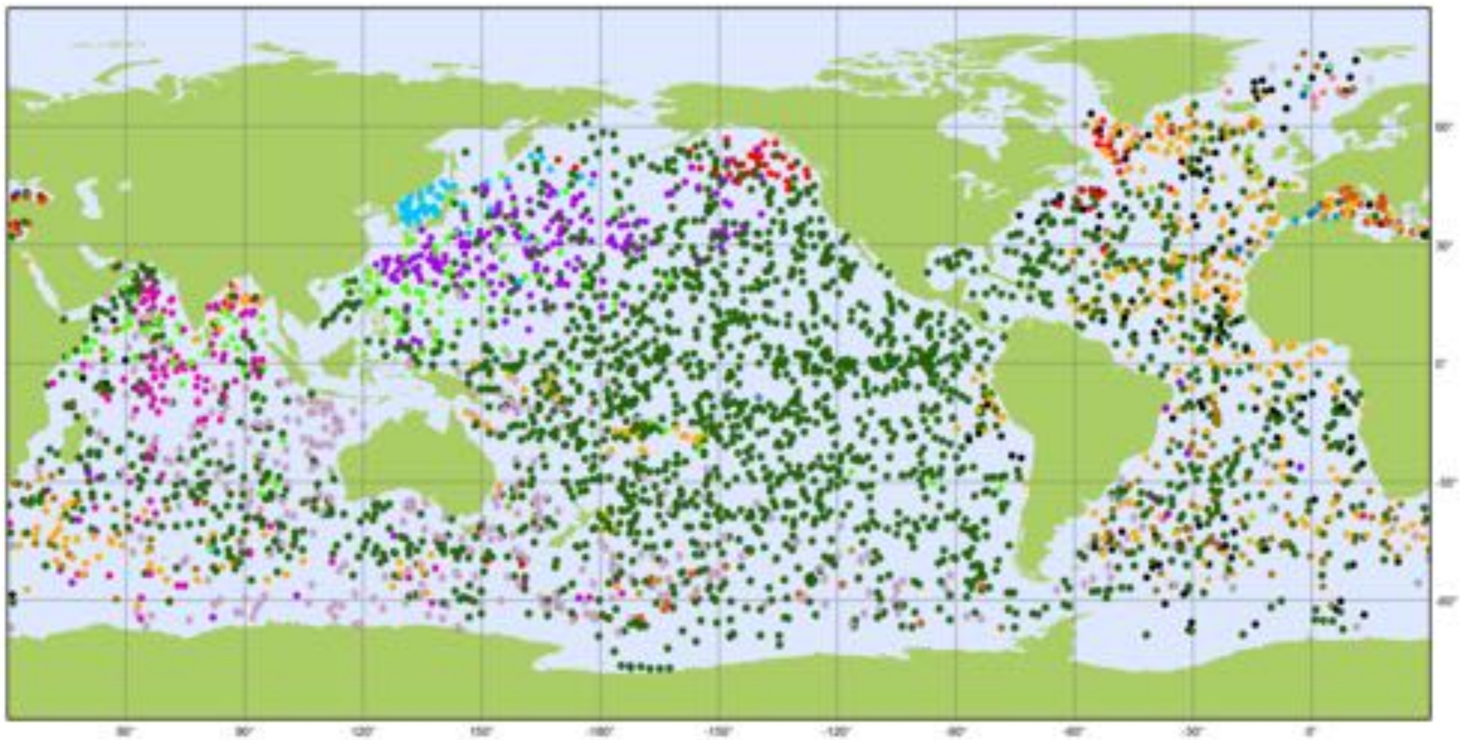


Temperature: ARGO Float [Ocean]

- Operate for ~5 years
- Dive to 2000m Depth

- Measure
  - Temperature
  - Salinity
  - Ocean Currents
  - Microstructure/turbulence



Argo — **National contributions - 3829 Operational Floats** — **April 2016**

Latest location of operational floats (data distributed within the last 30 days)

ARGENTINA (2)	CHINA (149)	GERMANY (133)	JAPAN (189)	NETHERLANDS (12)	SPAIN (9)
AUSTRALIA (380)	ECUADOR (2)	GREECE (7)	KENYA (1)	NEW ZEALAND (12)	TURKEY (3)
BRAZIL (10)	EUROPE (8)	INDIA (124)	KOREA, REPUBLIC OF (52)	NORWAY (10)	UK (134)
BULGARIA (2)	FINLAND (5)	IRELAND (10)	MAURITIUS (3)	POLAND (3)	USA (2138)
CANADA (58)	FRANCE (328)	ITALY (46)	MEXICO (2)	SOUTH AFRICA (1)	

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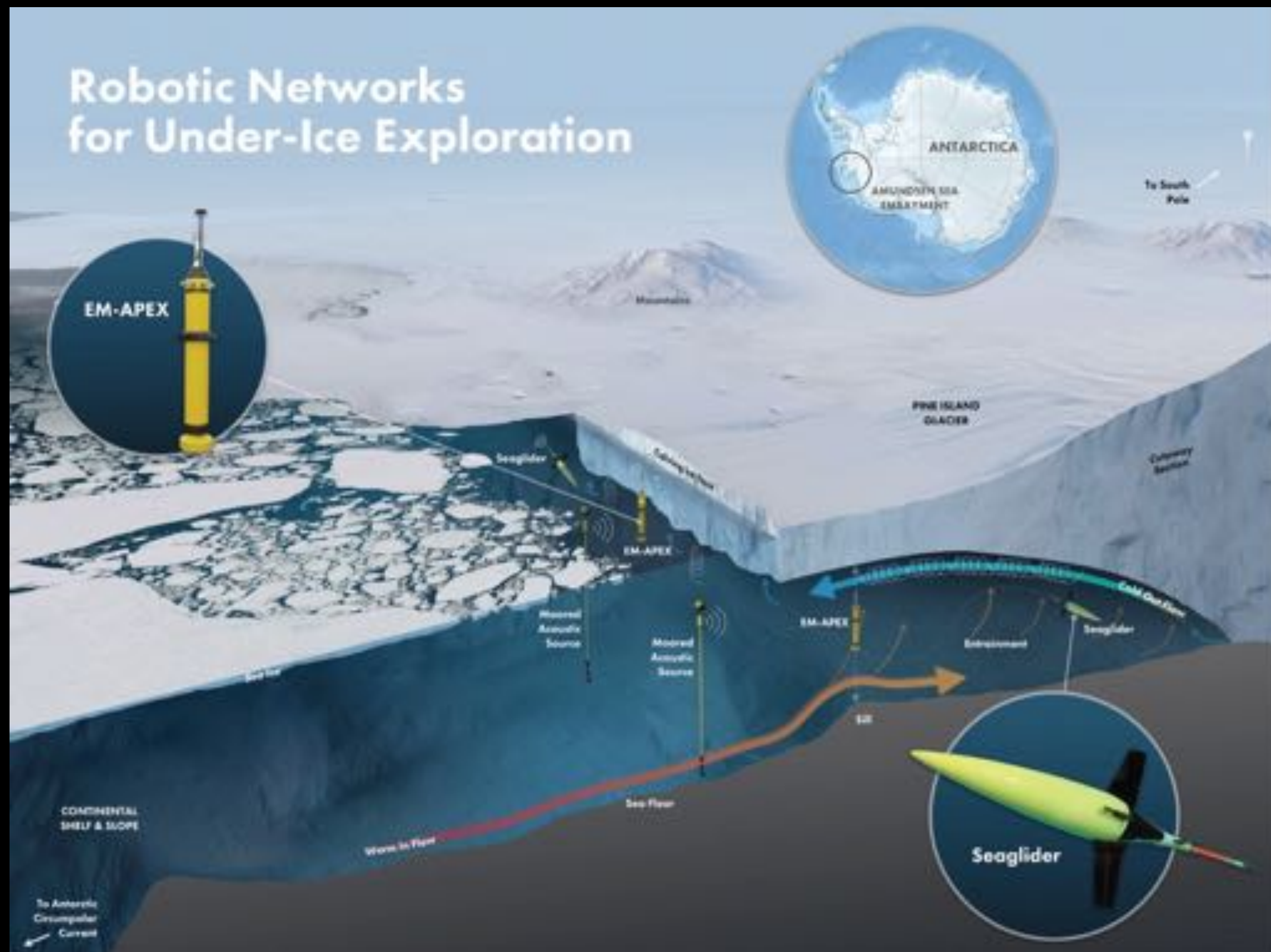
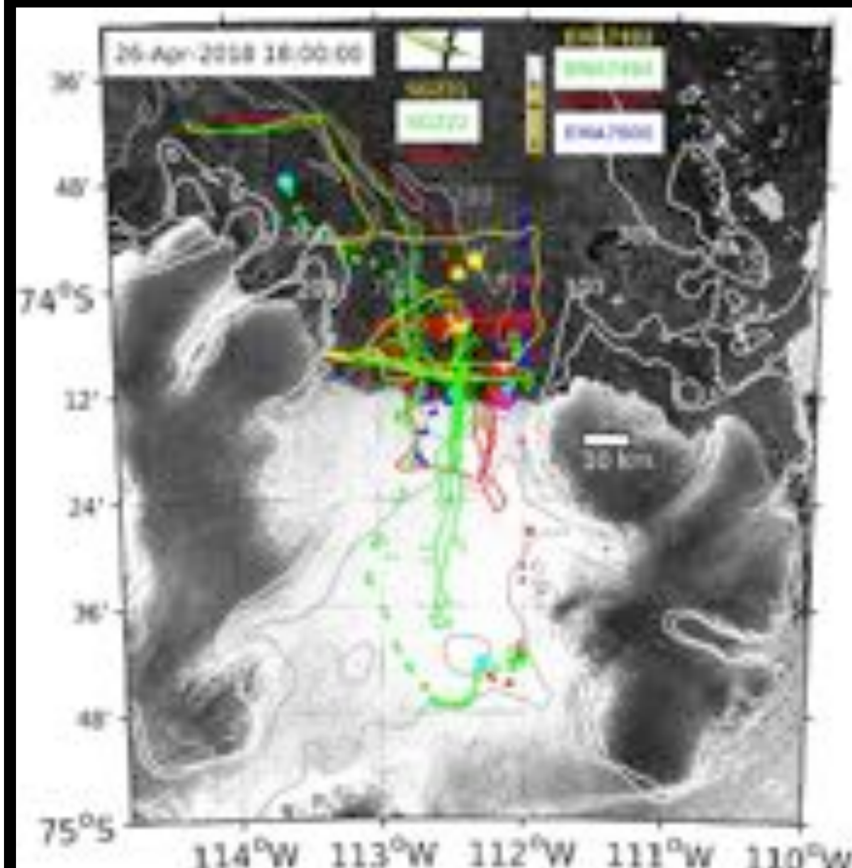
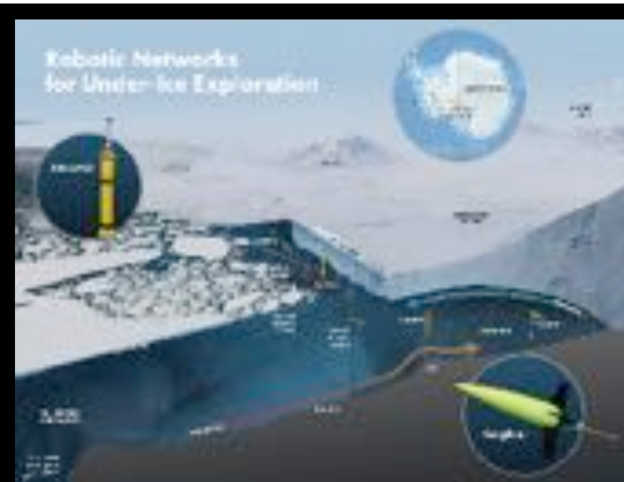
Automated Exploration under Antarctic Ice Shelves: Christianson, Dutrieux, Lee, Girton, Rainville



Robotic Exploration under Dotson Ice Shelf, Antarctica





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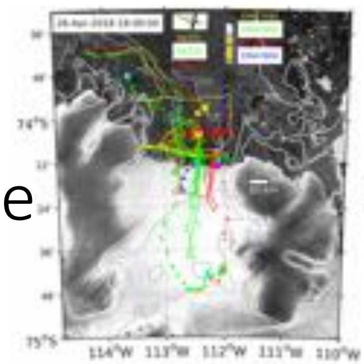
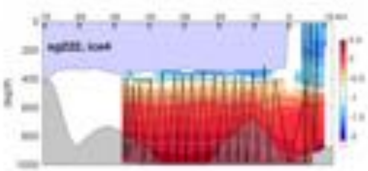
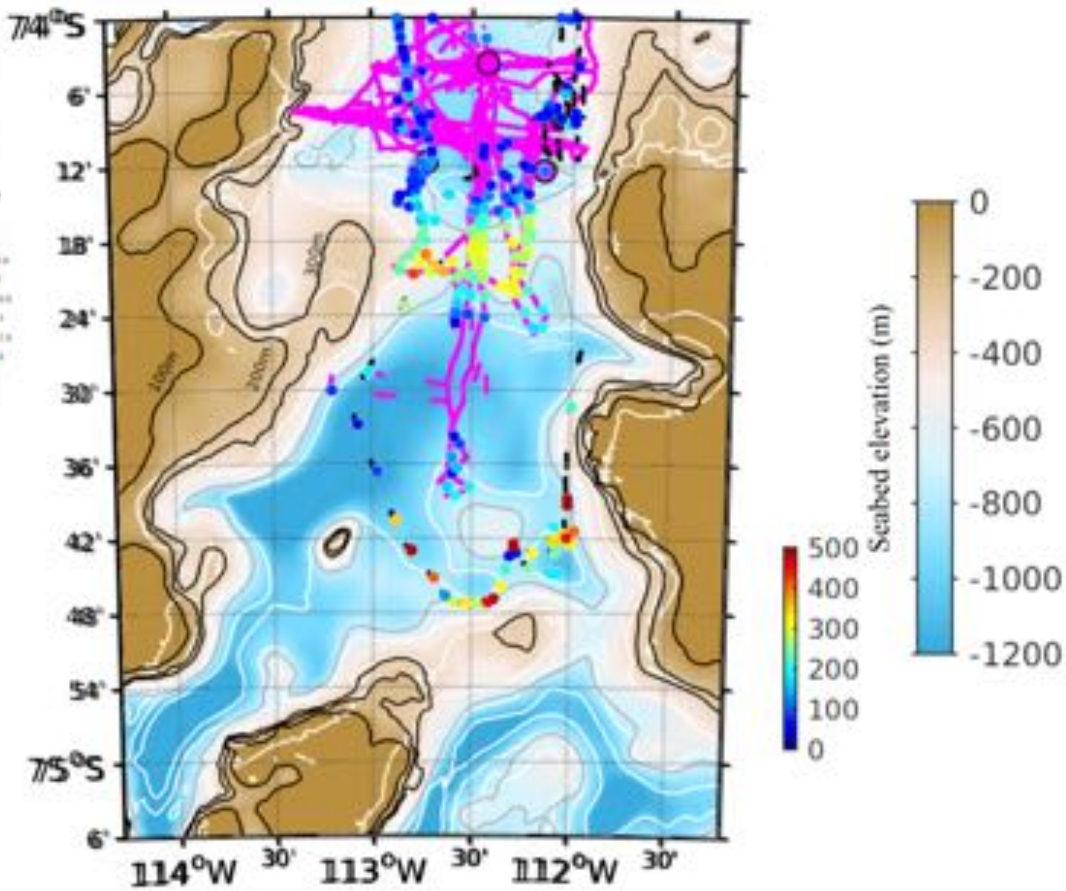




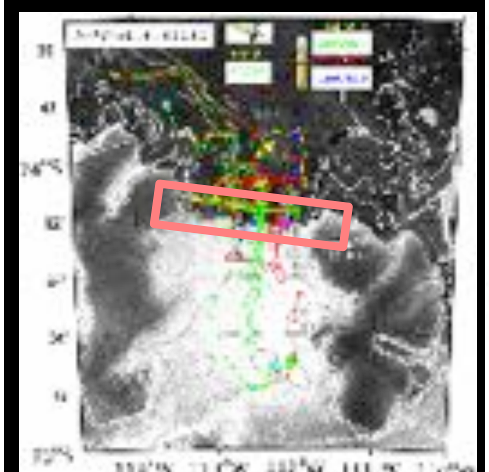
Constraints really are necessary for gravimetry inversions

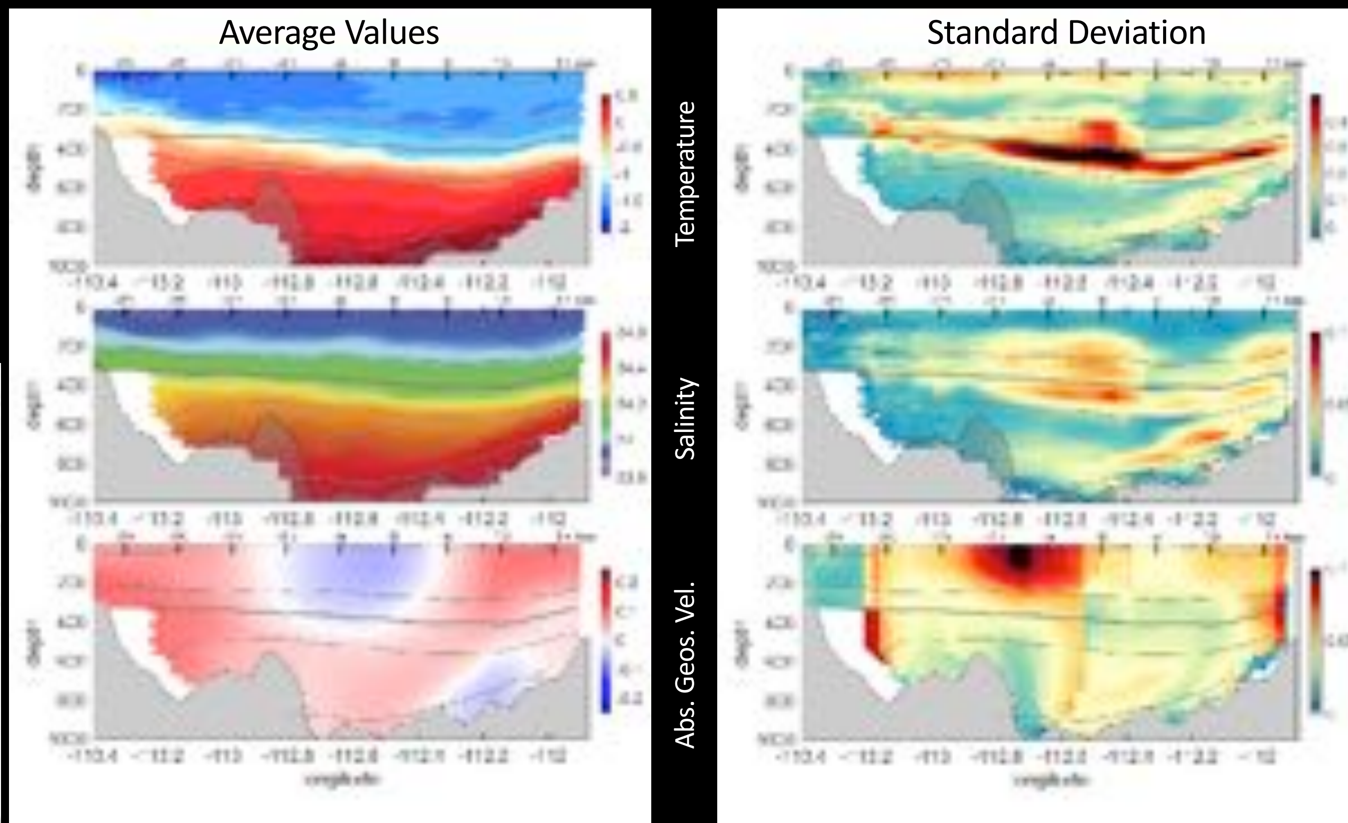


Preview for later: combining in-situ and remote-sensing tools is necessary for tricky problems

Robotic Exploration under Dotson Ice Shelf, Antarctica

Are these systems in steady state?





In Situ Measurements

- Forcings
  - Stake Measurements (Accumulation and Melt)
  - Snow Pits (Accumulation Zone)
  - Land Weather Stations (Temperature / Precip)
  - Radiosondes (Atmosphere observations)
  - Argo Floats (Ocean Observations)

- Glacier Characteristics?

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- Geometry (area, thickness)
- Substrate material?

In Situ Methods

Airborne/Satellite
Remote Sensing

Flow Behavior (Survey)

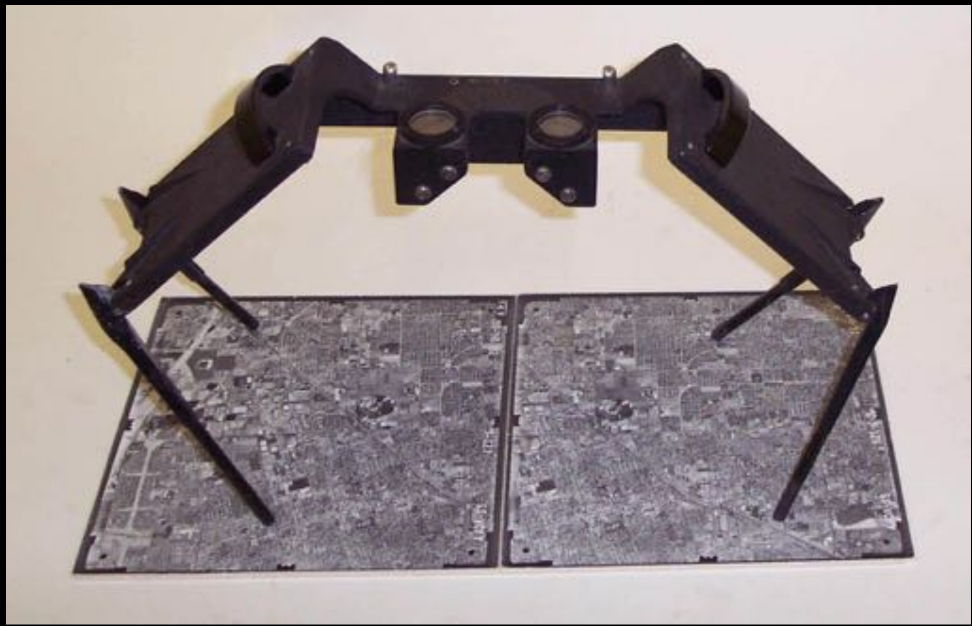
- Set up monitoring stakes
- From a fixed point, observe changes in the positions of those stakes with time

Flow Behavior (GPS)

- Long-term stations (continuous monitoring)
- Reoccupation (lower cost, lower temperature resolution)

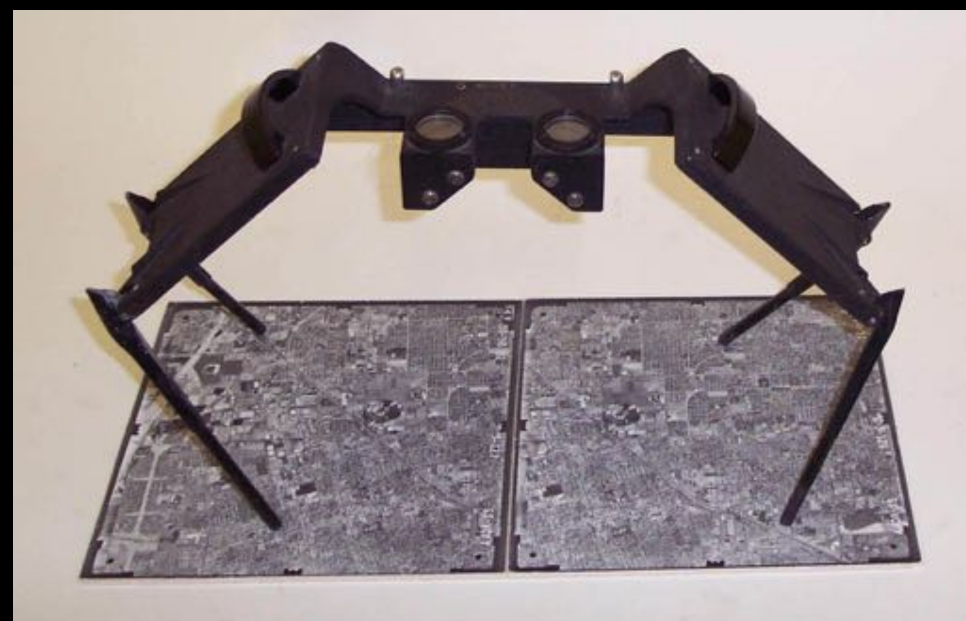
Geometry

- Rely HEAVILY on Remote sensing
- Stereo-photos collected on the ground, as well as traditional survey methods, were used to compute area.



Geometry

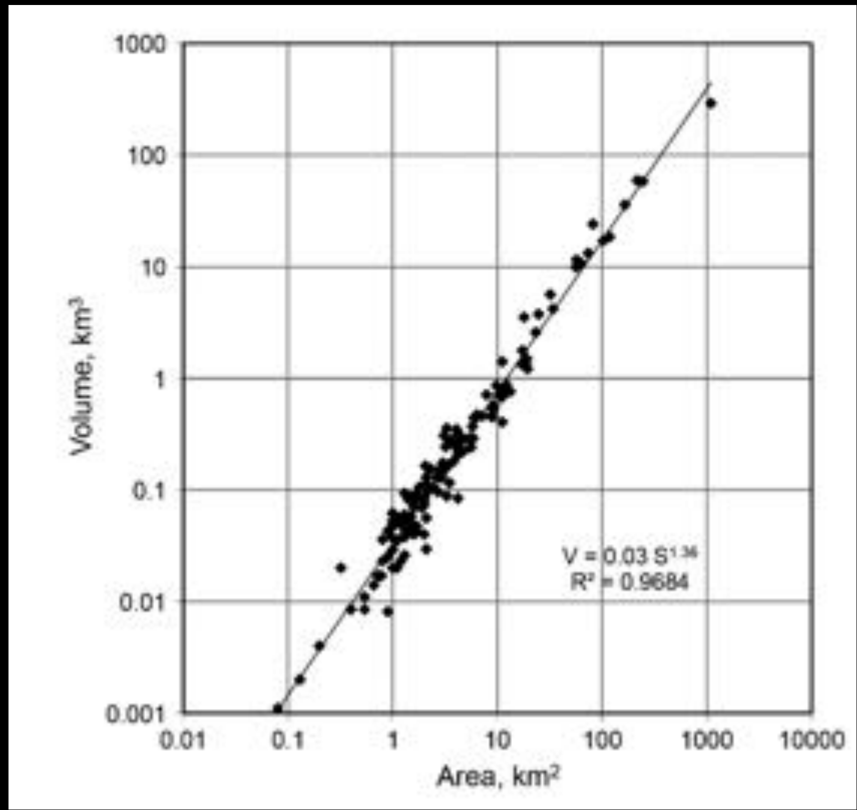
- Rely HEAVILY on Remote sensing
- Stereo-photos collected on the ground, as well as traditional survey methods, were used to compute area.
- Ice thickness was inferred from area/volume scaling relationships.



Area/Volume Scaling

$$V = cS^{\gamma}$$

V	= Glacier Volume
c and γ	= Empirical or Theoretical Constants
S	= Glacier Area



Borehole Observations

- Provides direct measurements of ice properties and thickness

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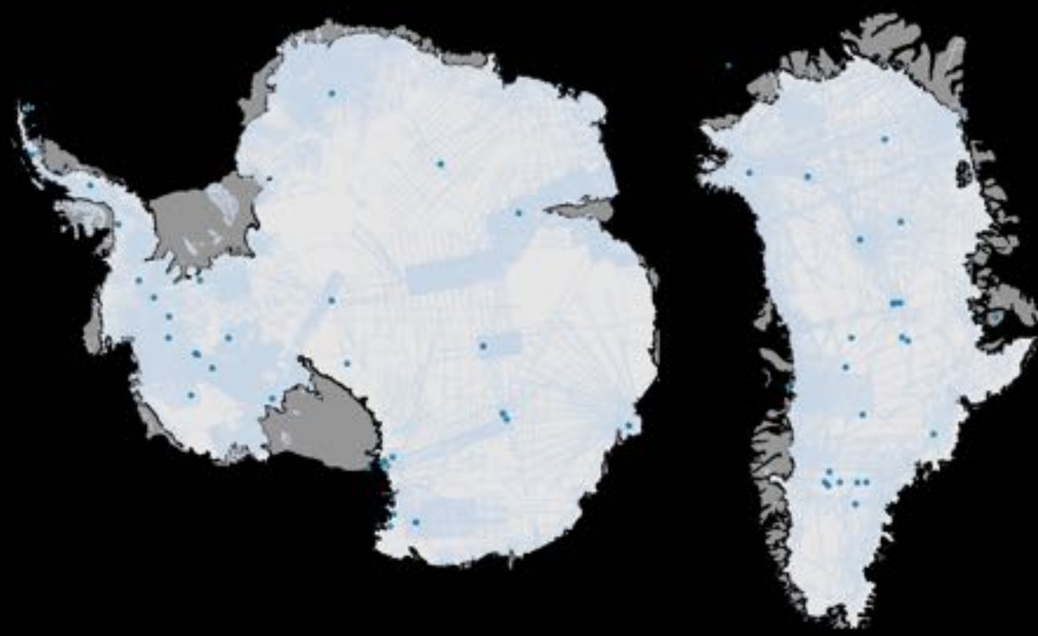
- Provides direct measurements of ice properties and thickness
- Spatially restricted, given the cost.



In Situ Measurements

- Forcings
  - Stake Measurements (Accumulation and Melt)
  - Snow Pits (Accumulation Zone)
  - Land Weather Stations (Temperature / Precip)
  - Radiosondes (Atmosphere observations)
  - Argo Floats (Ocean Observations)

- Glacier Characteristics?
  - Stake Measurements (Repeat surveys for velocity and strain)
  - Ground Surveys + Stereo Photos (Glacier Geometry)
  - Borehole observations (Geometry and Physical Properties)

Remote Sensing

Remote Sensing

Collecting information about a system at a distance. This requires *transmission of information* from the system to the instrument *without direct contact*.

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Potential Fields

Wave Theory

The Physics of Observation

Gravity

Newton's Law of Universal Gravitation:

F: The force due to gravity
G: Universal Gravitational Constant
m: Masses of the objects
d: Distance between their centers of mass

$$F = G\frac{m_1 * m_2}{d^2}$$

Wave Theory

The Wave Equation:
u: The propagating perturbation
t: Time
c: The wave speed

$$\frac{\partial^2 u}{\partial t^2} = c^2 \nabla^2 u$$

1D Solution to the Wave Equation:
u: The propagating perturbation
t: Time
x: Distance in the propagation direction
k: Wavenumber
f: Frequency
c: The wave speed

$$u(t,x) = \sin(kx - 2\pi f * t + \varphi)$$

$$c = \frac{\lambda}{f} \qquad k = \frac{1}{\lambda}$$

Wave Reflection
R: Reflection Coefficient
Z: Electric / Acoustic Properties

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

Black Body Radiation

Planck's Law:

L: Radiance (outgoing energy)
h: Planck's Constant
f: Frequency
c: Speed of Light
k: Boltzmann's Constant
T: Temperature

$$L_f = \frac{2hf^3}{c^2}\left(e^{\frac{hf}{kT}} - 1\right)^{-1}$$

$$L_f \approx \frac{2kTf^2}{c^2}$$

(Microwave Approximation)

Brightness Temperature Equations:

T_B: Brightness Temperature
ε: Emissivity
T_S: Surface Temperature

$$T_B = \varepsilon T_S$$

Remote Sensing

Ice Thickness / Material Properties

Changes in Ice Mass

Sea Ice Presence / Skin Temperature

Surface Changes and Ice Flow Speeds