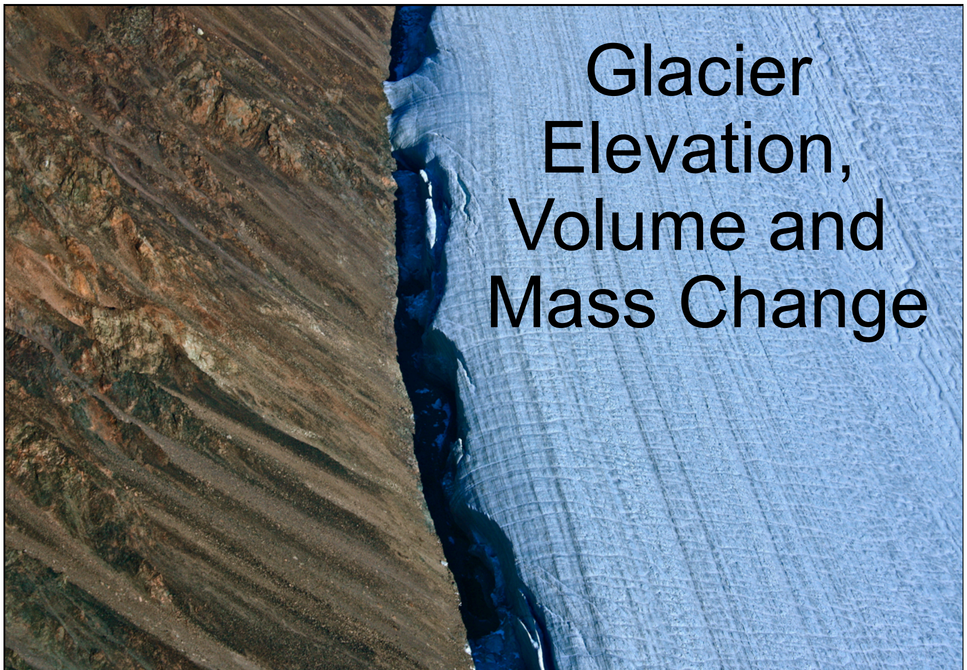


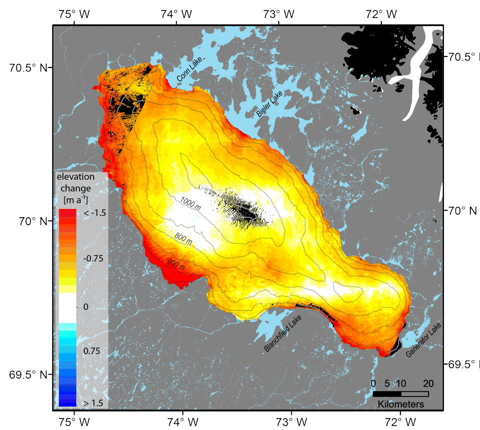
Glacier Elevation, Volume and Mass Change

Outline: Elevation, Volume and Mass Change

① Elevation change fundamentals
② Elevation measurement platforms
③ Calculating elevation change
④ Calculating volume change
⑤ Estimating mass change
⑥ Case study

What can we learn from elevation change?

- Good spatial sampling
- Coarse temporal sampling
- Volume change
- Non-steady state dynamics
- Contributions to sea level
- Proxy for climate
- Can have small uncertainty bounds



Elevation change (m a^{-1}) of the Barnes Ice Cap between 1960 and 2010 as determined from DEMs generated from airborne and SPOT-5 satellite stereoscopic imagery.

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Gardner, A. S., et al. (2012), *The Cryosphere Discuss.*, *6*(2), 1563-1610.

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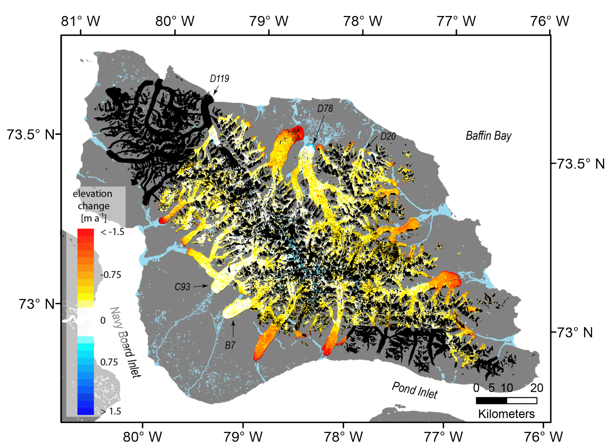
What can we learn?



Elevation change rate (m a^{-1}) of the glaciers of Bylot Island between 1979 and 2008 as determined from DEMs generated from airborne and SPOT-5 satellite stereoscopic imagery. Areas of black indicate no data.

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Gardner, A. S., et al. (2012), *The Cryosphere Discuss.*, *6*(2), 1563-1610.

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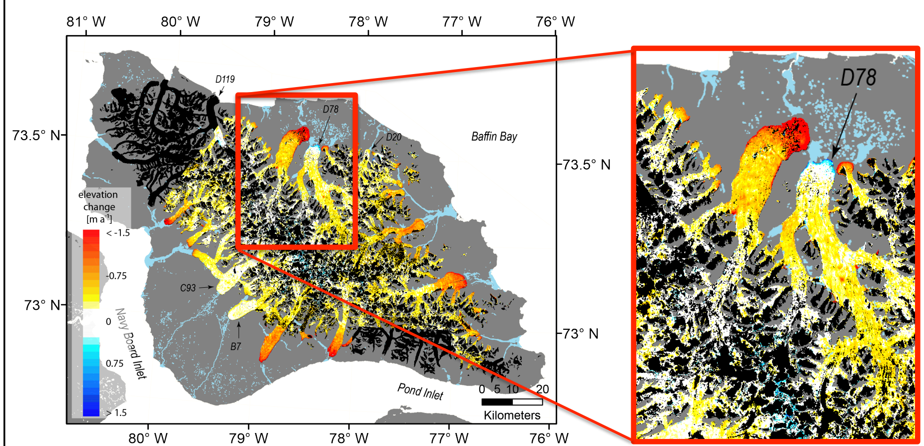
What can we learn?



Elevation change rate (m a^{-1}) of the glaciers of Bylot Island between 1979 and 2008 as determined from DEMs generated from airborne and SPOT-5 satellite stereoscopic imagery. Areas of black indicate no data.

Gardner, A. S., et al. (2012), *The Cryosphere Discuss.*, *6*(2), 1563-1610.

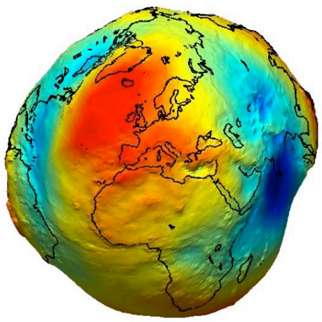
Volume Change vs. Mass Turnover and SLR

- There can be a:
  - changes in volume without changes in mass or visa versa
  - calving without changes in elevation or volume
  - changes in mass without changes in sea level

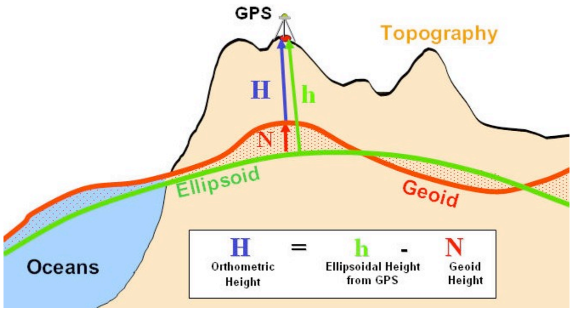
$$\frac{dV}{dt} \neq \frac{dM}{dt} \neq \frac{dSL}{dt}$$

Geoids and Ellipsoids

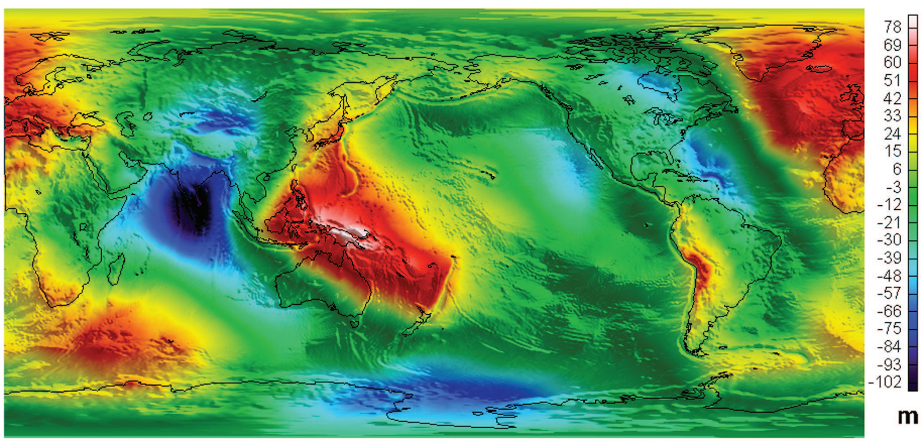
- **Ellipsoid** = a smooth elliptical model of the earth's surface
- **Geoid** = equipotential surface that mean sea level follows



GOCE Geoid (ESA)



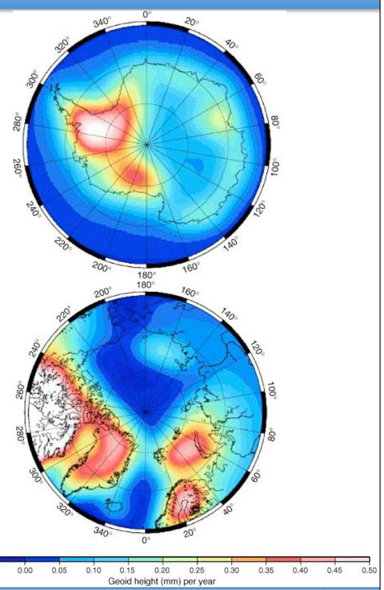
Geoid vs. Ellipsoid



Height of the Earth Gravitational Model 1996 (EGM96 **Geoid**) above the World Geodetic System 1984 (WGS84 **Ellipsoid**)

Uncertainties in reference plane

- Glacial Isostatic Adjustment:
  - Viscous change in the Earth's geoid in response to the removal of massive ice sheets that existed during the LGM (e.g. Laurentide, Cordilleran, Scandinavian ect..) and that existed during the LIA (e.g. Glacier Bay Icefield)
  - Up to 3.3 cm per year of uplift in Glacier Bay Region
- Control point errors
- Geoid/ellipsoid transformation errors



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http://rses.anu.edu.au/geodynamics/climate_change.html

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Measuring glacier topography

- Laser Altimetry: ICESat, NASA ATM/IceBridge, ICESat-2
  - 1 m - 70 m footprint
- Stereoscopic imagery: (Aircraft, ASTER, SPOT)
  - 30 – 40 m resolution
- Radar: (SRTM)
  - 30 second resolution

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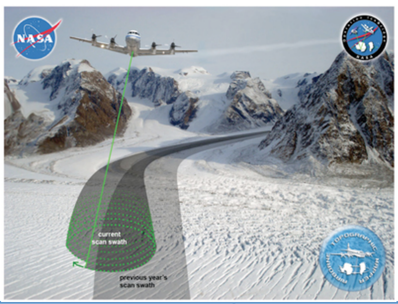
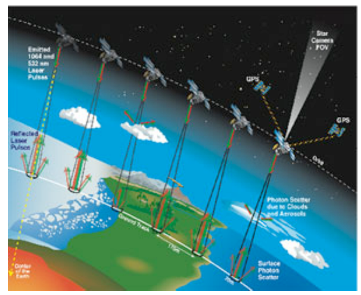
Laser Altimetry

- The position of the instrument is precisely known with GPS and star tracking (ICESat)
- A laser pulse is emitted and the time to retrieval is measured.
- Nadir-pointing versus scanning laser (conical mirror, pushbroom, etc.)





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www.nasa.gov/icebridge/

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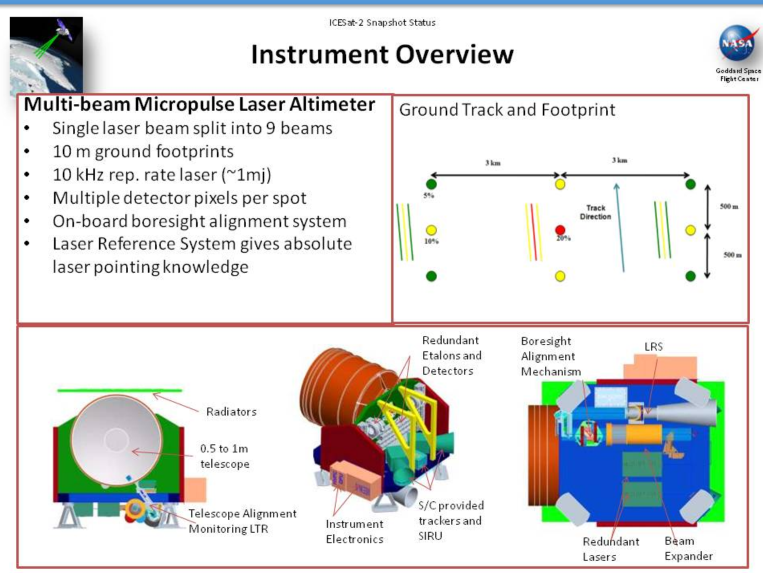
ICESat-2



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http://icesat.gsfc.nasa.gov

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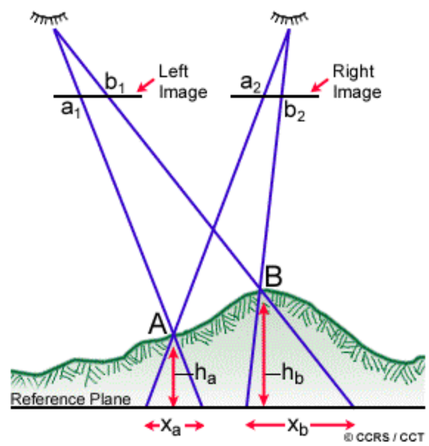
Stereoscopic imagery (SPOT, ASTER, Air Photos)

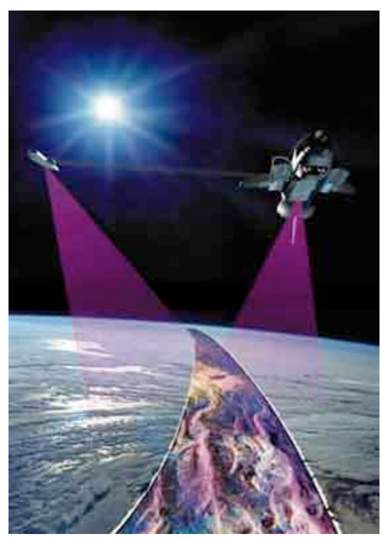
- Elevations are derived from stereoscopic images (image of the the same object but from different locations) by measuring the parallax displacement
- If the position of the sensor is known relative to the reference plane then you can use trigonometry to solve for topographic height
- Solution improves with GCPs
- Can have large blunders over low-contrast snow and ice surfaces.



http://www.crssa.rutgers.edu/courses/airphoto/airphoto7_files/frame.htm

Radar

- Shuttle Radar Topography Mission (SRTM)
- From phase difference measurements derived from two radar images (InSAR)
- Horizontal resolution: 3-arc second (~90m)
- Collected over 11 days (Feb 2000, flew on Endeavour)
- Coverage 60°N to 56°S
- Some penetration into snow/firn

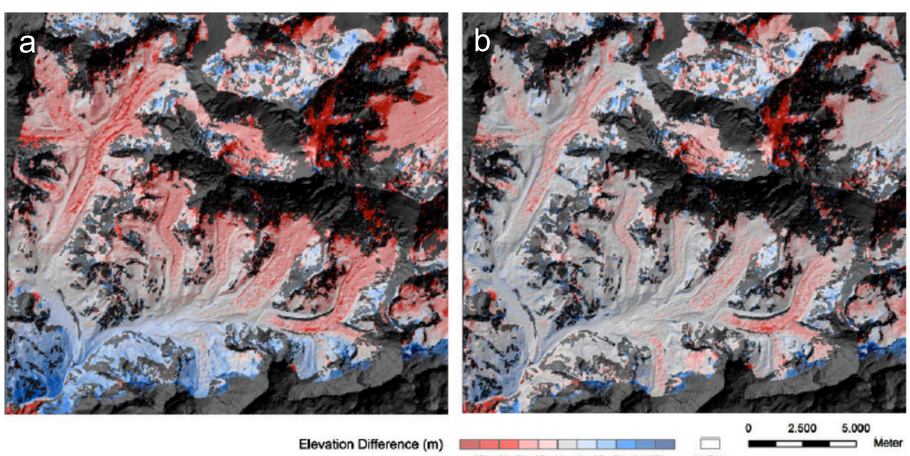


http://srtm.usgs.gov/mission.php
Farr, T. G., et al. (2007), Rev. Geophys., 45(2), RG2004.

Elevation Change

- Corrections prior to differencing:
  1. Co-registration
  2. Cross-track slope
  3. Spatially correlated bias
  4. Elevation dependent bias
  5. Other

Co-registration



1970 to 2007 glacier elevation change in the Everest area (a) before and (b) after co-registration

Bolch, et al. (2011), Cryosphere, 5(2), 349-358.

Co-registration

dh = vertical difference
α = terrain slope
Ψ = terrain aspect
a = horizontal offset
b = direction of shift vector
c = cosine parameter

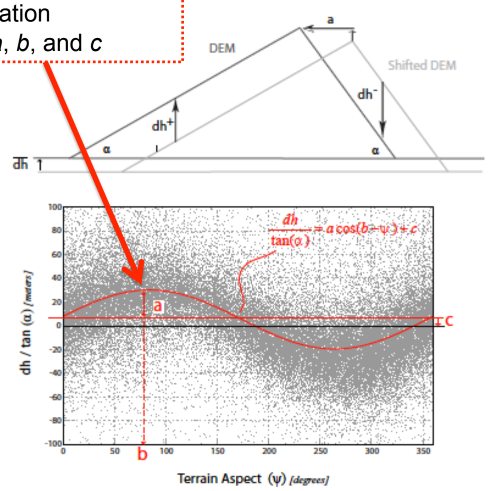
least squares minimization to find *a*, *b*, and *c*

$$\frac{dh}{\tan(\alpha)} = a \cdot \cos(b - \Psi) + c$$

where

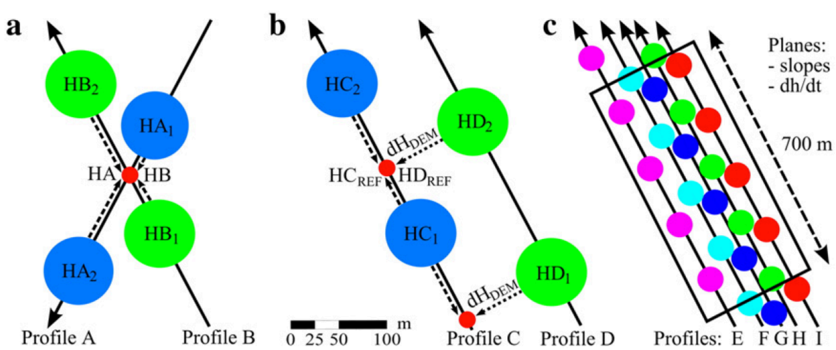
$$c = \frac{\overline{dh}}{\overline{\tan(\alpha)}}$$

Need slope threshold *dh/tan(0) = inf*



Nuth, C., and A. Kaab (2011), *Cryosphere*, *5*(1), 271-290.

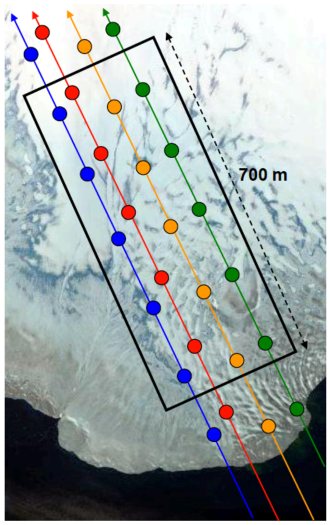
Cross-track slope correction



- **a.** **crossover points** between ascending and descending tracks (dh=HA–HB)
- **b.** **cross-track DEM** projection and linear interpolation to compare two repeat-tracks (dh=HDREF–HCREF)
- **c.** **Fitting** least-squares regression **planes** to repeat-track observations to estimate slopes and average dh/dt.

Moholdt, G., et al. (2010), Remote Sens. Environ., 114(11), 2756-2767.

Cross-track slope correction



Least-squares estimation of slope (α_E,α_N) and average elevation change rate (*dh/dt*):

$$\begin{bmatrix} dH_1 \\ \vdots \\ dH_n \end{bmatrix} = \begin{bmatrix} dE_1 & dN_1 & dt_1 \\ \vdots & \vdots & \vdots \\ dE_n & dN_n & dt_n \end{bmatrix} \cdot \begin{bmatrix} \alpha_E \\ \alpha_N \\ dh/dt \end{bmatrix} + \begin{bmatrix} r_1 \\ \vdots \\ r_n \end{bmatrix}$$

where *E,N,H and t* are the position and time for each of the *n* observations in the plane.

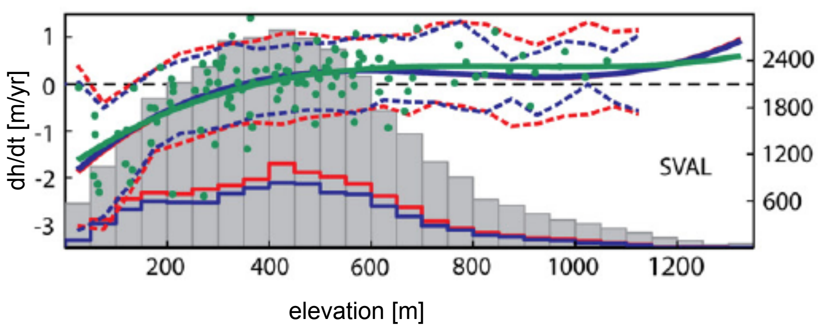
Campaign-to-campaign elevation changes are estimated from the residuals (*r*):

$$dh_{12} = (\bar{t}_2 - \bar{t}_1) \cdot dh/dt + (\bar{r}_2 - \bar{r}_1)$$

where *t* is the time of campaign *1* and *2*.

(adapted from *Howat et al. 2008*)

Cross-slope correction



Comparison between cross-slope corrections methods: 2003-2008 dh/dt over Svalbard from crossover points (green), cross track DEM (red), regression planes (blue).

Elevation-dependent bias:

- Penetration of radar at higher elevations
  - Can use laser altimetry to try and determine correction.
  - Compare X-band and C-band DEMs
- Elevation-dependent bias from resolution differences can be corrected based on "maximum curvature". Bias determined over ice free ground.

Gardelle, J., et al. (2012), *J. Glaciol.*, *58*(208), 419-422.

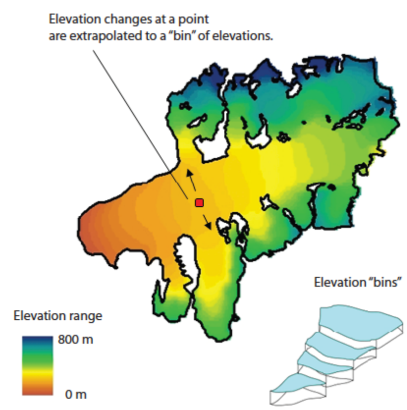
Other Considerations

- Correlation score:
  - Elevation errors increase, sometimes rapidly, with decreasing SPOT HRS DEM correlation score
  - Exclude interpolated pixels
- Spatially dependent bias correction:
  - Surface fitting to spatially binned elevation biases over ice-free ground.
    - Exclude land within buffer distance of glacier to avoid capturing glacier recession
    - Exclude in-land water bodies that can very in elevation

Gardner, A. S., et al. (2012), *The Cryosphere Discuss.*, *6*(2), 1563-1610.

Elevation change [dh/dt] to volume change [dV/dt]

- Digitize glacier outlines
- Determine dh/dt
- Extract glacier hypsometry (glacier area per elevation bin) using outlines and a DEM
- Parameterize dh/dt as a function of elevation

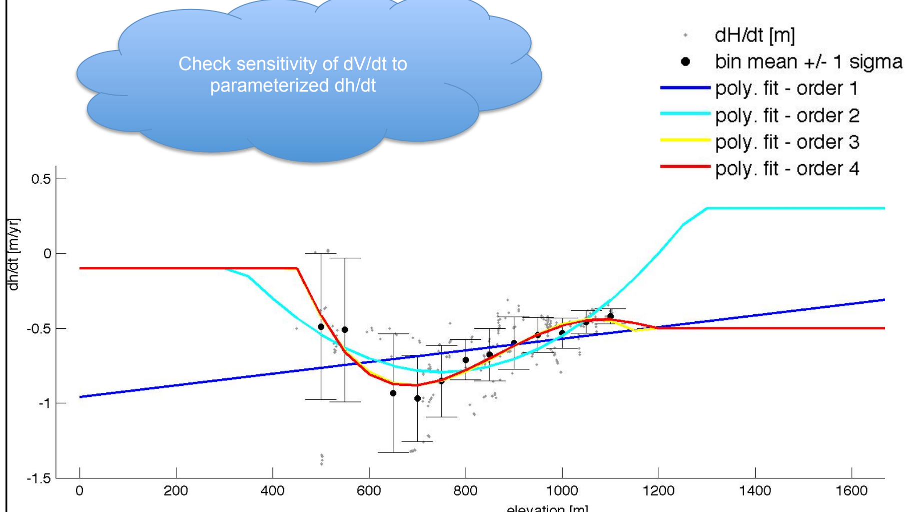


$$\frac{dV}{dt} = \frac{dh}{dt}(elevation) \times hypsometry$$

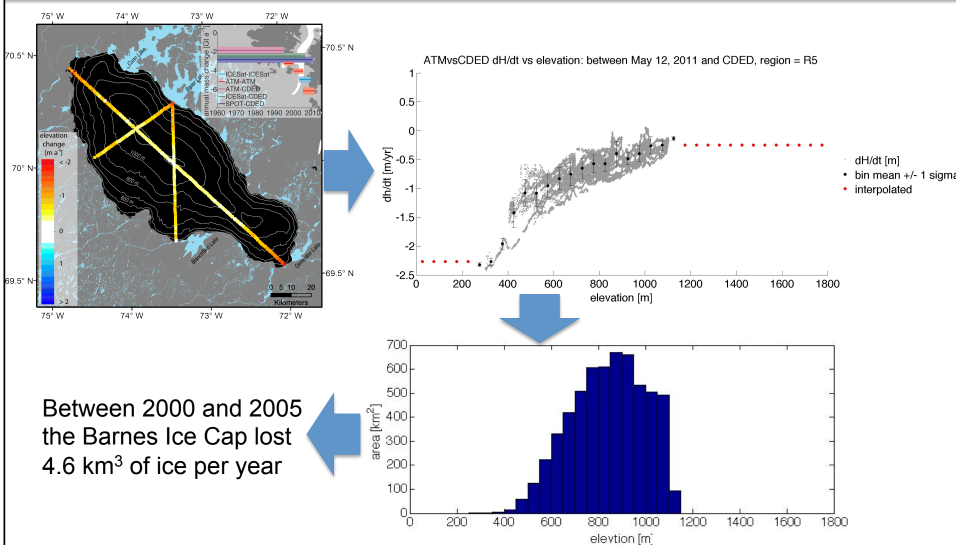
Credit: Anthony Arendt

Volume change

Check sensitivity of dV/dt to parameterized dh/dt



Elevation Change to Volume Change

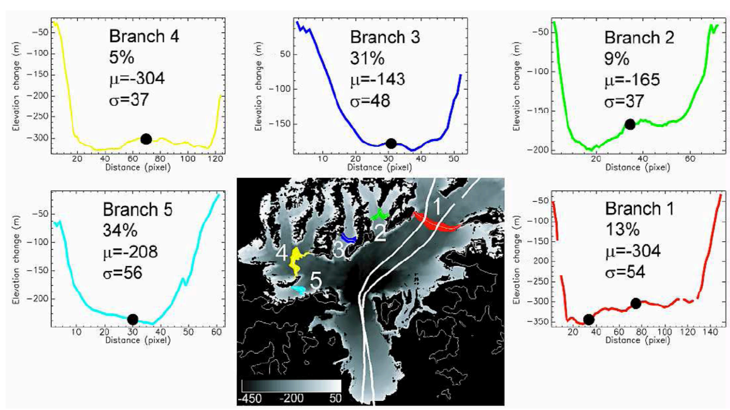


Between 2000 and 2005 the Barnes Ice Cap lost 4.6 km^3 of ice per year

Gardner, A. S., et al. (2012), *The Cryosphere Discuss.*, *6*(2), 1563-1610.

Error in extrapolation centerline data

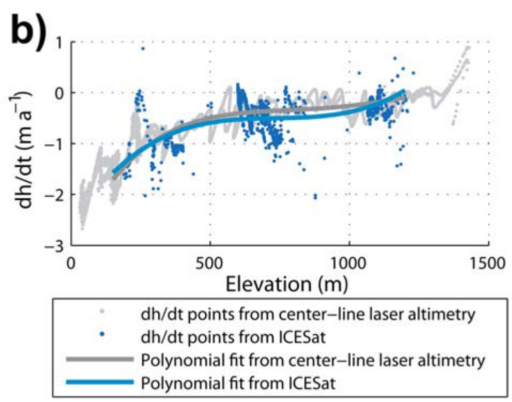
- Center-line vs. cross-glacier elevation change

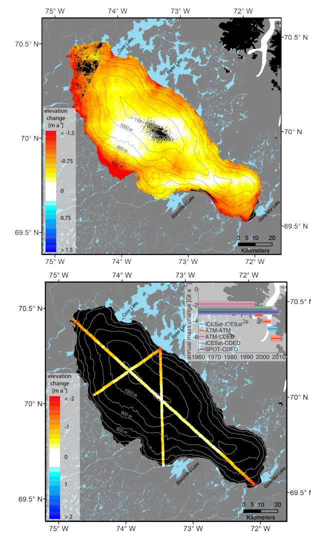


Transverse elevation changes during 1957-2007 for five different branches of Columbia Glacier at ~700 m a.s.l. The relative difference (%) between the centreline and the mean transverse elevation change is given

Berthier, et al. (2010), *Nature Geosci.*, *3*(2), 92-95.

Sparse dh/dt can produce accurate dV/dt





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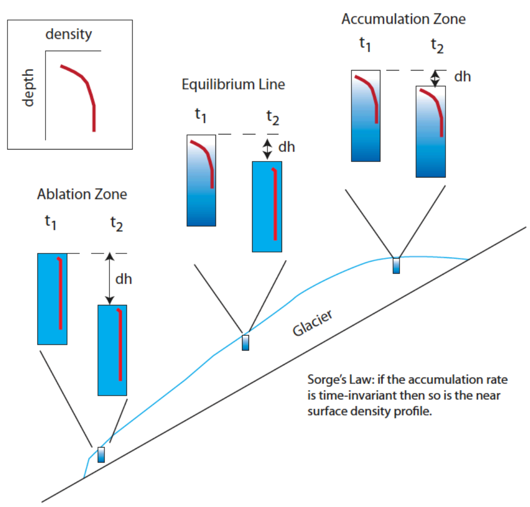
Gardner, A. S., et al. (2012), *The Cryosphere Discuss.*, *6*(2), 1563-1610.
Nuth, et al. (2010), *J. Geophys. Res.*, *115*(F1), F01008.

Volume change [dV/dt] to mass change [dM/dt]



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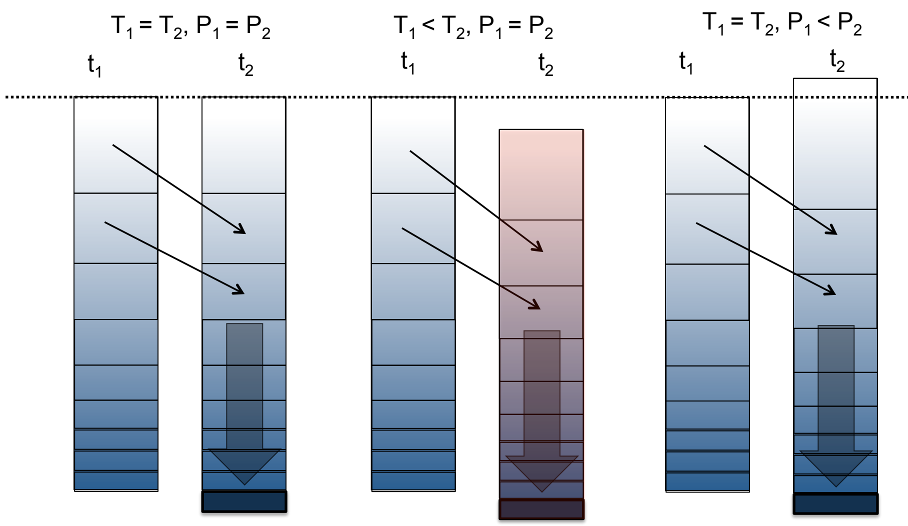
Credit: Anthony Arendt

Snow and firn density: dry snow zone:



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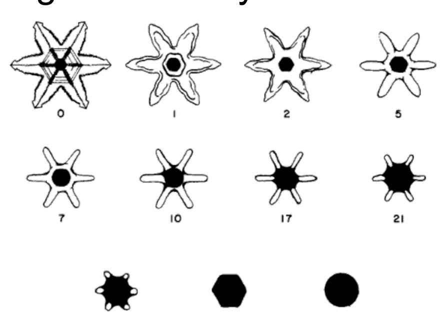
Short-term: Snow crystal metamorphism

- Deposition density
- Right after deposition: drifting, disintegration and initial settling of snow crystals



Snow crystal metamorphism in days, no temperature gradient

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Colbeck, 1982

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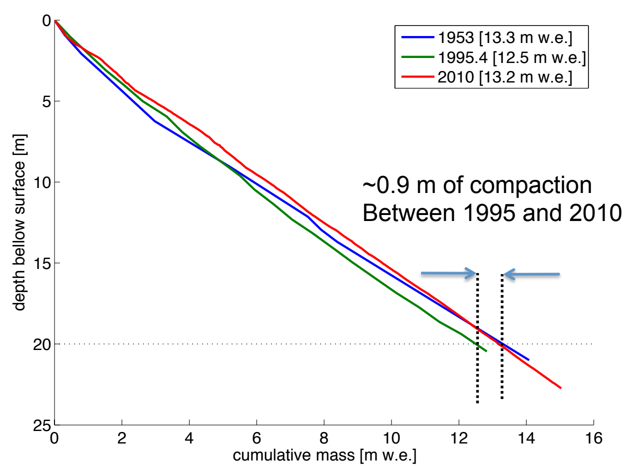
Long-term densification rates

- Temperature
- Precipitation/overburden pressure
- Grain sliding/settling
  - important for lower densities
- Lattice Creep
- Sintering/vapor diffusion
  - large grains grow at the expense of small grains
  - higher to lower temperature diffusion
  - Vapor flux away from points of crystal contact

Repeat ice core density profiles



Comparison of 3 ice cores (1953, 1995, 2010) from the Penny Ice Cap

Zdanowicz, 2012. JGR. v117

Sources of uncertainty

- ICESat
  - Cross slope errors
  - Assumption of temporally invariant dh/dt
  - Flat planes can be a poor assumption of slope

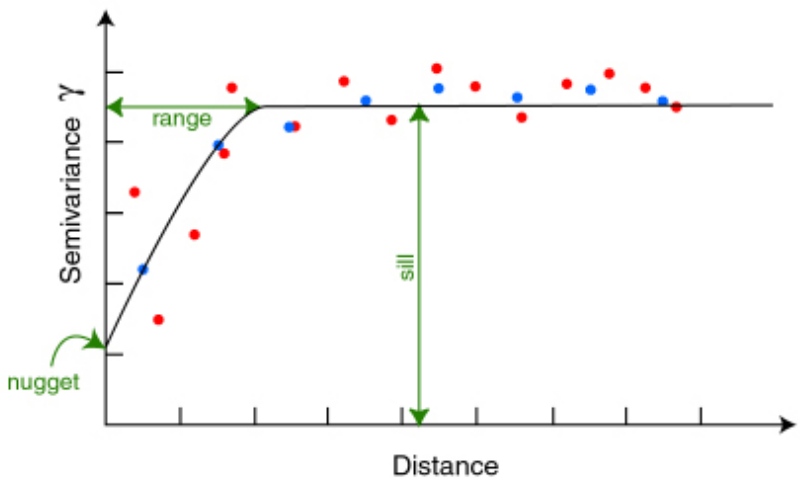
Semivariogram analysis

- *u* = coordinate vector
- z(*u*) = variable as a function of location
- h = lag vector between points
- $\gamma(h)$ = semivariance of lag distance *h*
- Semivariance:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{a=1}^{N(h)} \left[z(u_a + h) - z(u_a) \right]^2$$

semivariance versus lag is the *semivariogram*

Semivariogram analysis



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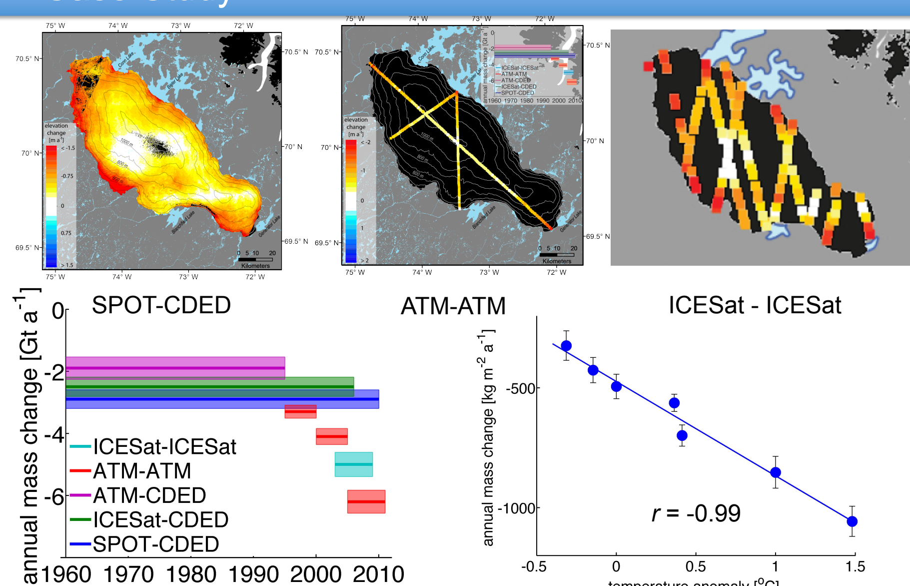
Case Study



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Gardner, A. S., et al. (2012), *The Cryosphere Discuss.*, *6*(2), 1563-1610.

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Summary

- Vertical datum
  - Geoid vs. ellipsoid
- Measurement methods
  - Laser altimetry, stereo imagery, radar
- Calculating elevation change
- Calculating volume change
- Estimating mass change

Motivation