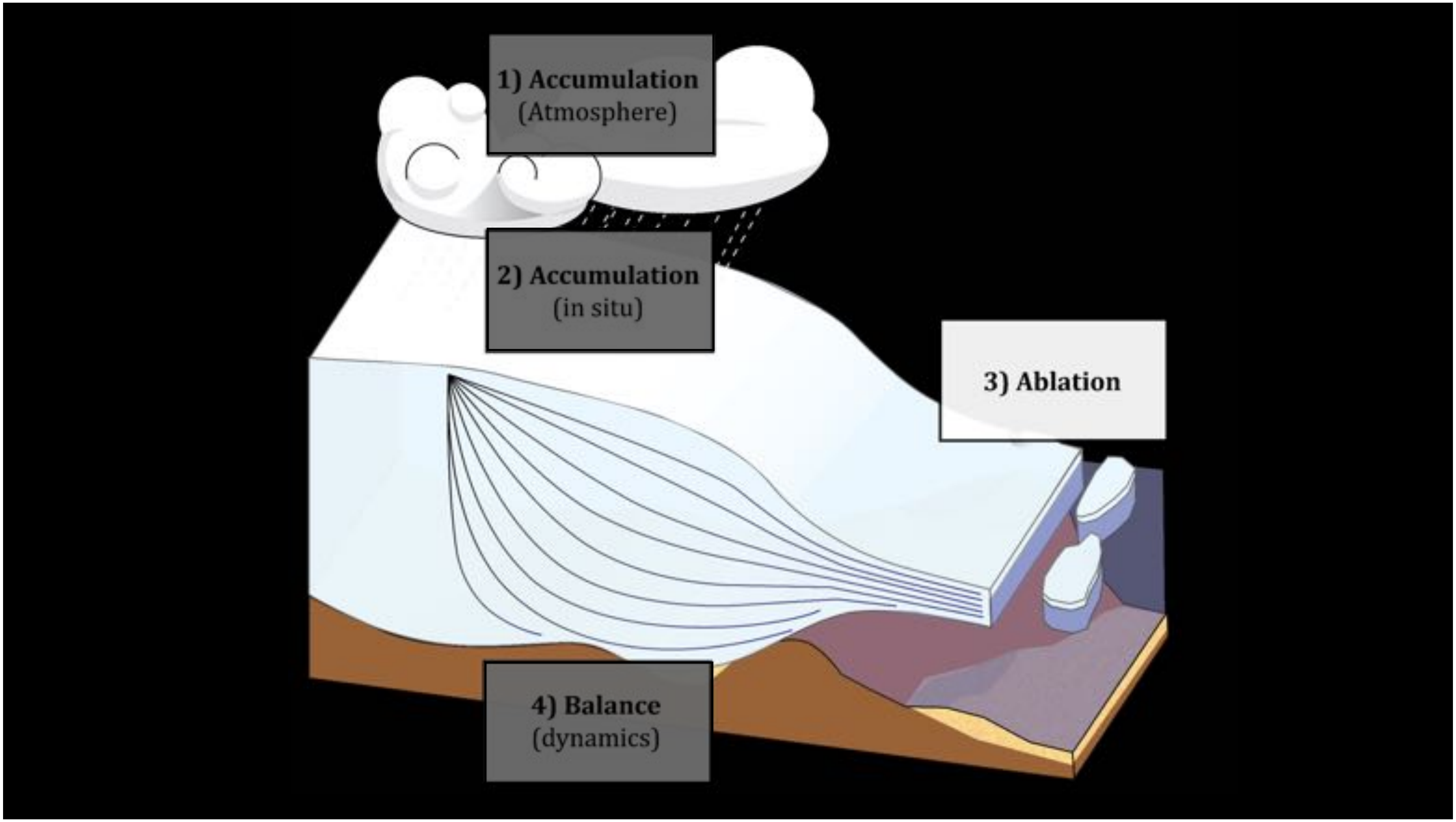
Ablation: Mass and Energy Budget in the Cryosphere

ESS431: Principles of Glaciology
ESS505: The Cryosphere

Monday, 10/15 – Knut Christianson


1) Accumulation
(Atmosphere)
2) Accumulation
(in situ)
3) Ablation
4) Balance
(dynamics)

Today's focus -

- What is ablation? What are the different mechanisms for ablation and how are they distributed in different cryospheric systems?

- What are the different components of the surface energy balance of glaciers and ice sheets?

- What is the role of ice flow in maintaining glacier equilibrium?

The coverage starts in December 2012 and ends 25 months later in January 2015

Brought to you by

FRANZ JOSEF NZ GLACIER GUIDES

Department of Conservation
Te Papa Atawhai


EIS

Ablation

- All processes that remove ice from a snowfield or glacier surface

  - Melt
  - Sublimation
  - Wind Scour / Erosion
  - Basal Melt (melt at the bottom of a glacier)
  - Calving (iceberg detachment)
  - Cliff Failure

Surface Ablation:
Constituents of the Energy Balance

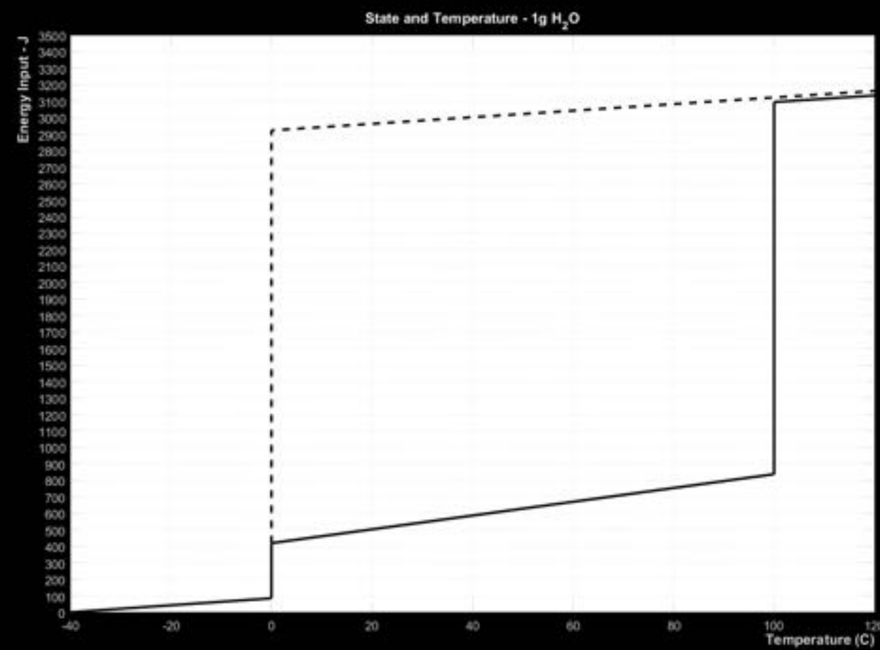
Latent Heat Transfer

Phases changes either take in heat or release it, according to their thermodynamic properties:

Fusion: *~334 J/g*

Vaporization: *~2230 J/g*

Sublimation: *~2800 J/g*



Typical Latent Heat Fluxes

Air	**dry**	**humid (warm)**
	LH$\uparrow$ sublimation evaporation	$LH\downarrow$ deposition condensation
Snow	**humid**	**humid (cold)**

Latent Heat II

Importance of transitions varies with location:

Sublimation -2830 J g^{-1}

- Antarctic slopes, 50% of annual snowfall

Frost Deposition +2830 J g^{-1}

- Antarctic plateau, adds energy, not much mass

Freezing (rime) +330 J g^{-1}

- Mt. Olympus, adds both mass and energy
- Keeps glacier warm

Condensation (dew) +2500 J g^{-1}

- warm humid winds over melting glacier
- Adds energy but no solid mass

Evaporation of Meltwater -2500 J g^{-1}

- Warm dry air over melting glacier

Constituents of the Energy Balance

Transfer through Phase Change

Inputs/Outputs – Latent Heat Transfer

Sensible Heat Transfer

Fourier's law:

$$Q = -k\,\frac{dT}{dz}$$

Heat conducted into the snow / glacier surface driven by temperature gradients from the air into the snowpack

Constituents of the Energy Balance

Transfer through Phase Change

<u>Inputs/Outputs</u> – Latent Heat Transfer

Transfer by Conduction

<u>Inputs/Outputs</u> – Sensible Heat Transfer

Radiation Balance at Snow Surface

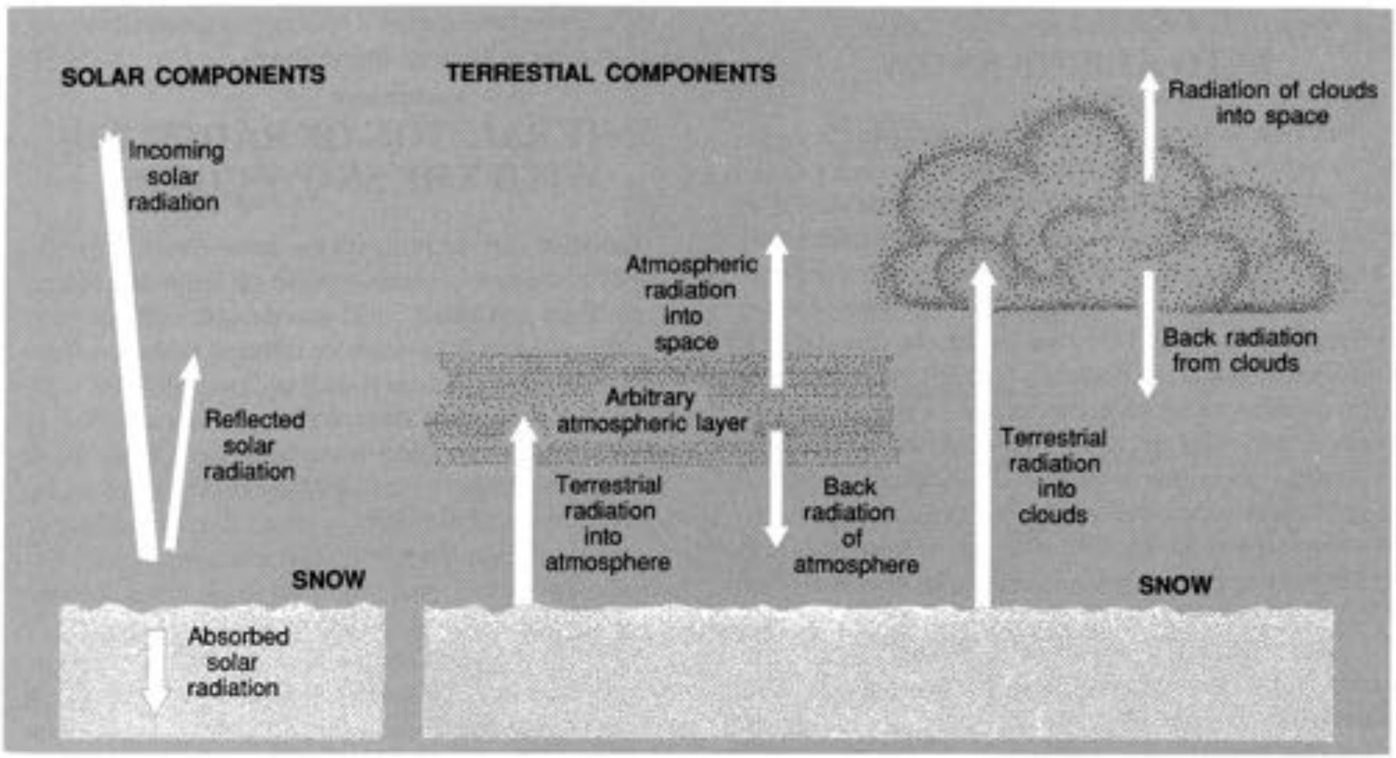


Figure 2.23. Radiation balance at snow surface. Incoming, absorbed, and reflected solar radiation is short wave (visible and ultraviolet). The other components from terrestrial sources are long wave (infrared).

Avalanche Handbook

Shortwave Complications - Albedo (α)

$$\alpha = \frac{SW\uparrow}{SW\downarrow}$$

$0 < \alpha < 1$

Black — Reflective white

- Clean snow typically reflects 80% of sunlight $\alpha = 0.8$
- Old melting snow $\alpha = 0.65$
- Glacier ice $\alpha = 0.4 - 0.6$
- High albedo helps to maintain snow (keeps it cold): *"albedo-temperature feedback"*

Energy-balance equation becomes:

$$R = SW\downarrow(1-\alpha) + LW\downarrow - LW\uparrow$$

Longwave Radiation

Usually compared to an ideal "black body"

A ***black body*** emits radiation depending on its temperature:

$$LW\uparrow = \sigma T^4$$

Stefan-Boltzmann constant:

$\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} (K = deg Kelvin)

Non-black body:

$$LW\uparrow = \varepsilon\sigma T^4$$

Emissivity $0 < \varepsilon < 1$

$\varepsilon = 1$ for perfect black body

Snow has emissivity ~0.98

(If we had infrared eyes, snow would look black!)

Radiative Cooling I

LW↓ determined by temperature of clouds or air

- Thick cloud is a blackbody in infrared
- Cloud impedes surface cooling at night
- Clear night sky encourages surface cooling

At night, *SW*↓=0, R<0

$$R = 0 + \varepsilon_{air}\sigma T_{air}^4 - \varepsilon_{snow}\sigma T_{snow}^4$$

On a long clear night (e.g. in Antarctica) R→0 (equilibration with atmosphere; SH and LH are small)

$$\varepsilon_{air} T_{air}^4 = \varepsilon_{snow} T_{snow}^4$$

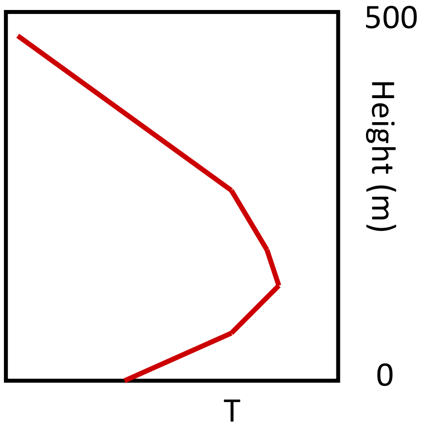
Radiative Cooling II

On clear nights $$\varepsilon_{air} T_{air}^4 = \varepsilon_{snow} T_{snow}^4$$

Snow is more emissive than atmosphere $$\varepsilon_{air} < \varepsilon_{snow} \approx 1$$

Surface must be colder than air $$T_{air} > T_{snow}$$

- Inversion layer can be tens to hundreds of meters thick



Temperature profiles in winter at South Pole Station (Hudson & Brandt, J. Climate 2005)

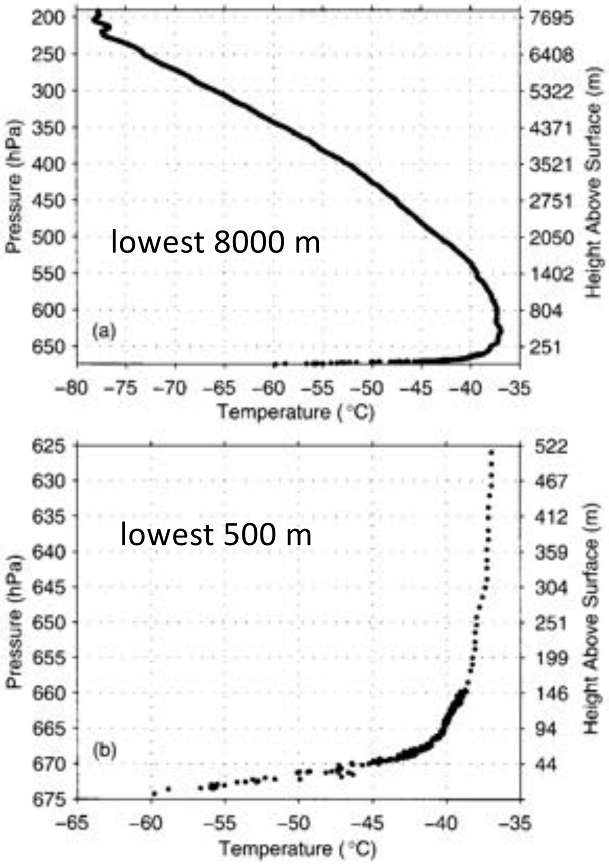


FIG. 3. Temperature profile measured at South Pole Station on 25 Sep 2001. Data above 660 hPa are from a routine radiosounding with an RS80; those below 660 hPa are from a tethered sounding with an RS80. (a) The full tropospheric sounding is shown, and (b) the lowest 500 m are enlarged. The surface pressure was 674 hPa.

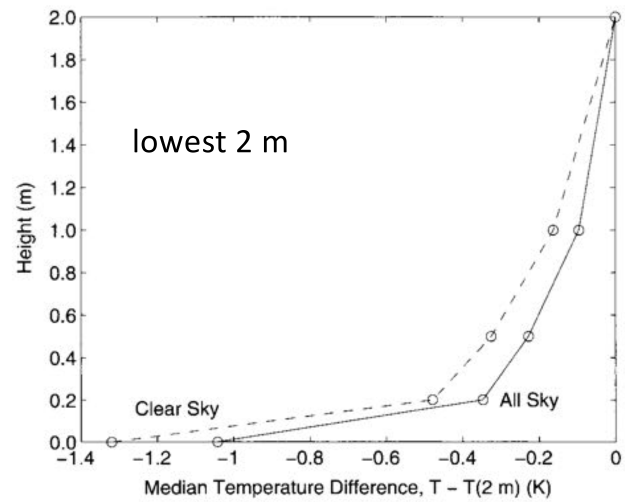


FIG. 13. Median temperature difference relative to 2 m. Data are from South Pole during the 2001 polar night. Separate profiles are shown for the overall median (All Sky, solid line) and the clear-sky median (dashed line).

Energy Balance - Sinks

Where does the energy go in snow pack?

If (R+SH+LH) >0

- Raise temperature of snow *if T<0*^{o}C
- Melt snow (or ice) *if T=0*^{o}C

If (R+SH+LH) <0

- Cool snow
- Freeze pore water (can be 2-3% water by volume in temperate ice)

$$R = SW\downarrow(1-\alpha) + LW\downarrow - LW\uparrow$$

What does each term depend on?

***SW*↓** - season, latitude, time of day, clouds

a - snow vs. ice, age of snow, depth of snow, impurities

***LW*↓** - air temperature, clouds, humidity

***LW*↑** - snow-surface temperature

Typical Radiation Fluxes

$$R = SW\downarrow - SW\uparrow + LW\downarrow - LW\uparrow$$

Approx. average over Earth's surface

200 W m^{-2} - 30 + 330 - 390 ≈ +110 W m^{-2}

(balanced by SH, LH to atmosphere)

Typical melting glacier in summer

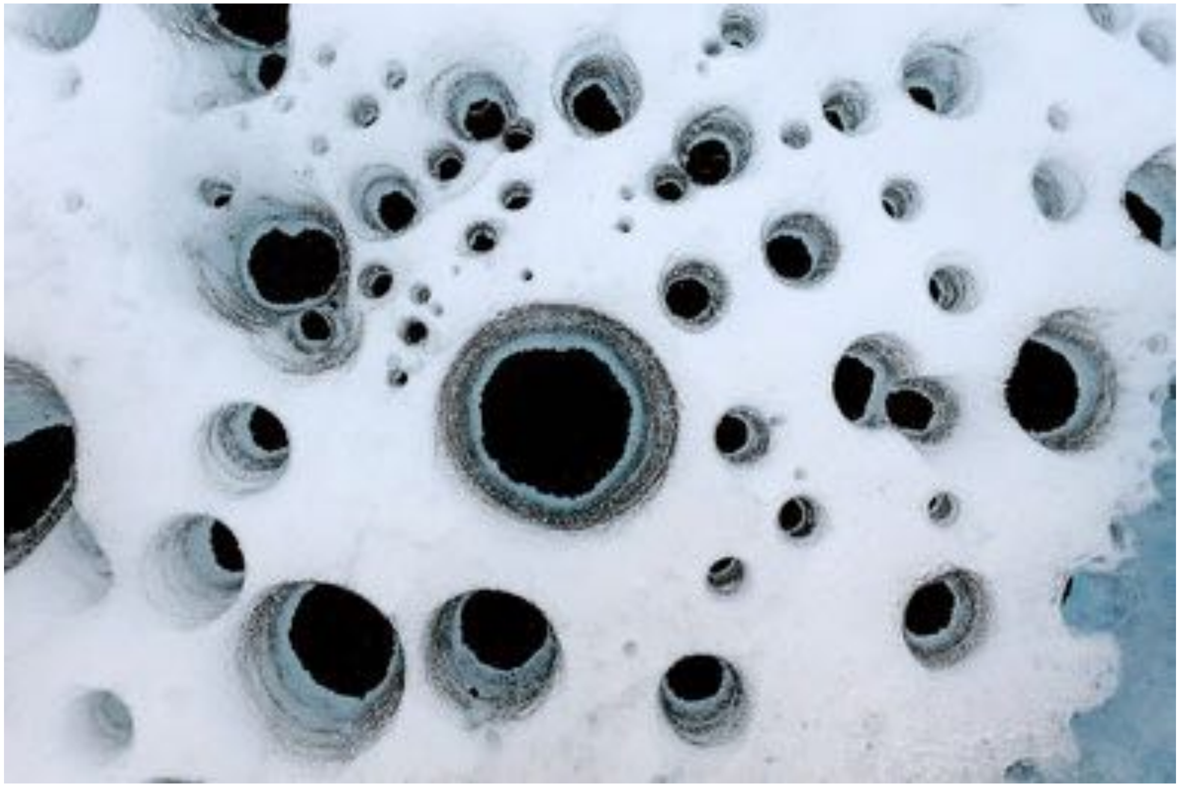
200 W m^{-2} - 120 + 275 - 315 ≈ +40 W m^{-2}

(used for melting)

Lower sun but longer days	Brighter surface	Colder clouds and air	Colder surface (0°C)


Atacama Desert - http://www.eso.org/public/images/potw1522a/

Albedo Feedback



Eyjafellajokull Iceland Sept 2012

Eyjafellajokull Iceland, Sept 2012

Eyjafellajokull Iceland Sept 2012

Eyjafellajokull Iceland Sept 2012

Constituents of the Energy Balance

Transfer through Phase Change

Inputs/Outputs – Latent Heat Transfer

Transfer by Conduction

Inputs/Outputs – Sensible Heat Transfer

Transfer by Radiation *(sw - 0.2-4 μm / lw – 4-50 μm)*

Inputs	*Outputs*
Solar Radiation (sw)	Outgoing Blackbody Radiation (lw)
Atmospheric Radiation (lw)	
Cloud Radiation (lw)	

Energy in Melt Season

Source	Typical Importance	Blue Glacier (Mt. Olympus):
Radiation	50-85%	57%
Sensible heat	} 15-50%	34%
Latent heat		9%

Typically R > SH > LH

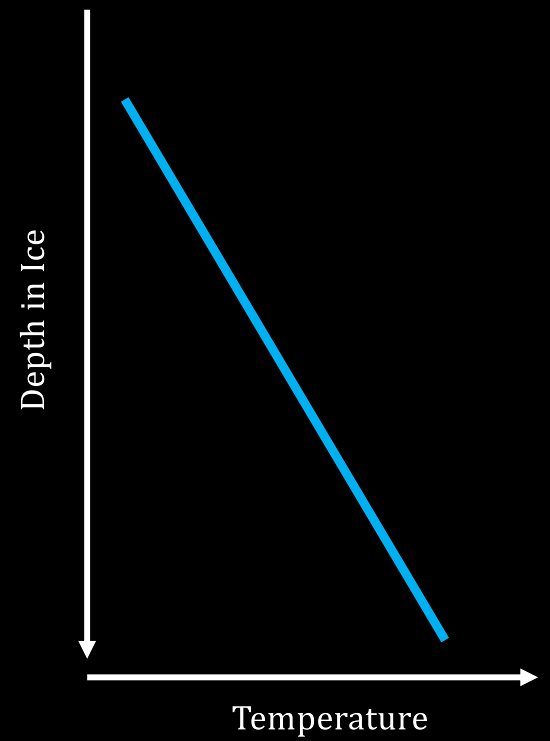
Basal Ablation:
Sub-Ice Sheet and Ice Shelf Melt

Ice Bottom Temperature (Land)

Advection:
- Vertical (Snowfall)
- Horizontal (Ice Flow)

Diffusion (Conduction):
- Geothermal Flux
- Conductive Heat Transfer (air)

Production:
- Work done on the Ice (Friction)

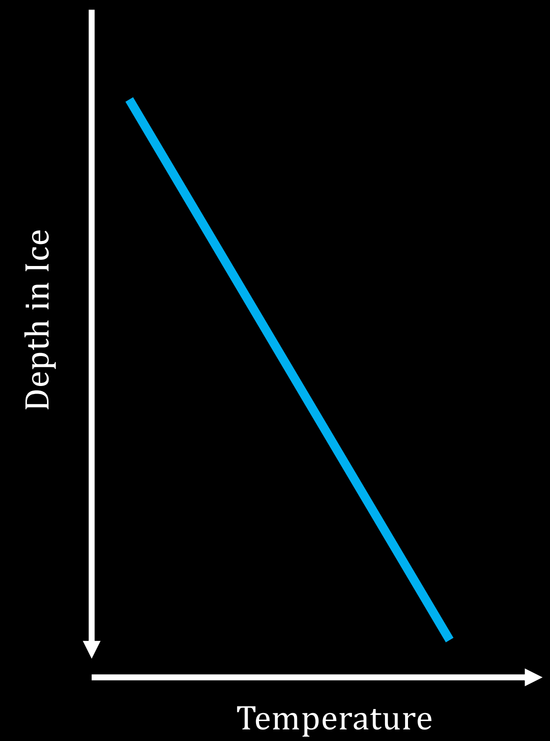


Warm Basal Ice

- Warm Air Temperature
- Low Accumulation Rates
- High Flow Speeds
- Thick Ice

Cold Basal Ice

- Cold Air Temperature
- High Accumulation Rates
- Slow Flow Speeds
- Thin Ice

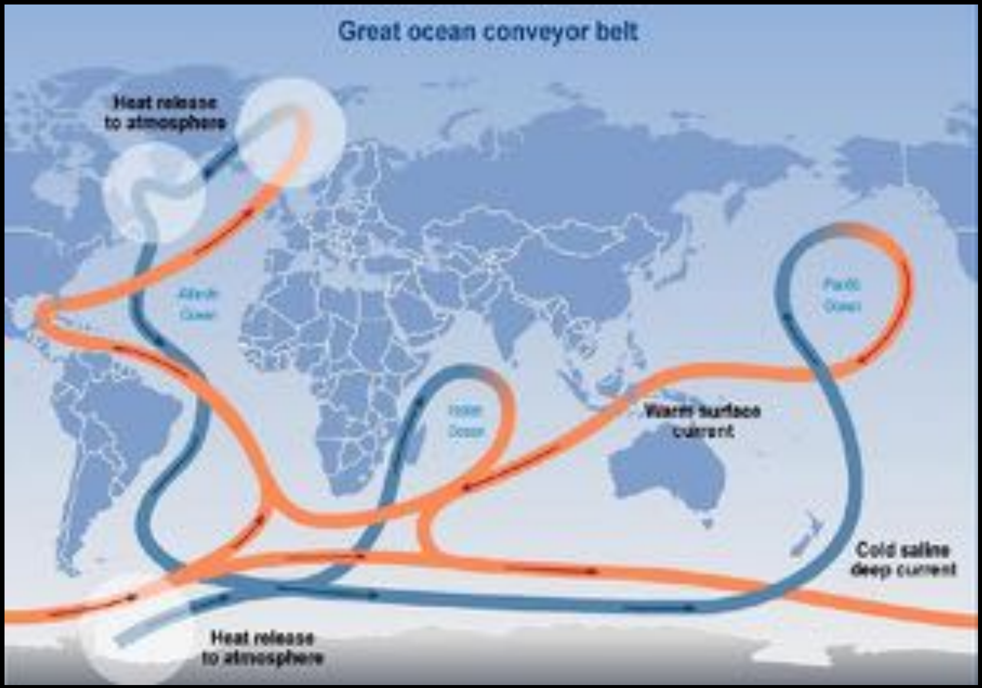


Ice Bottom Melt (Water Terminating)

- Depends on heat transport to the ice front

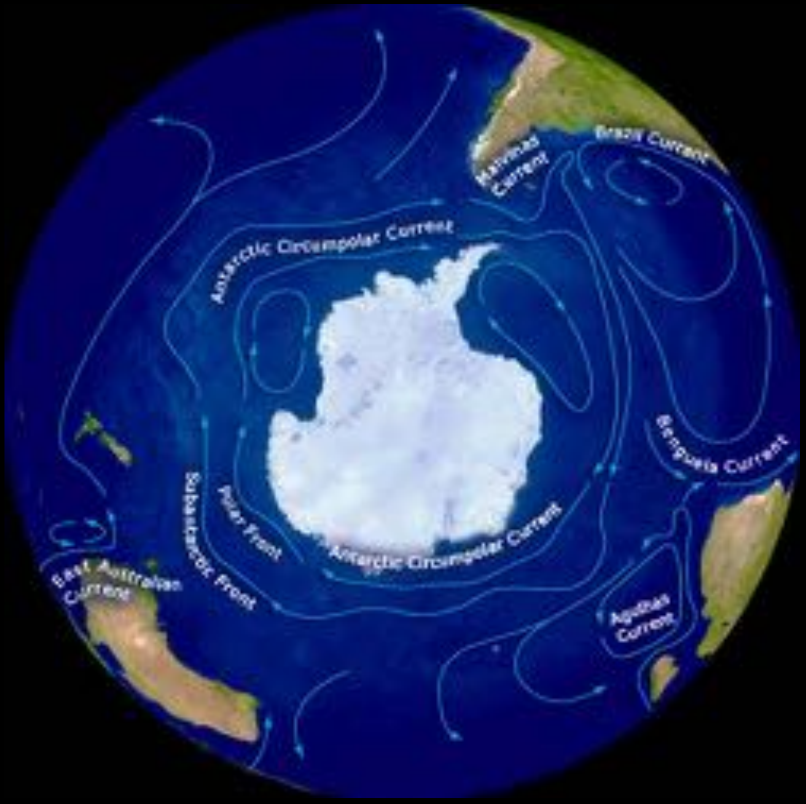
Ice Bottom Melt (Water Terminating)

- Depends on heat transport to the ice front



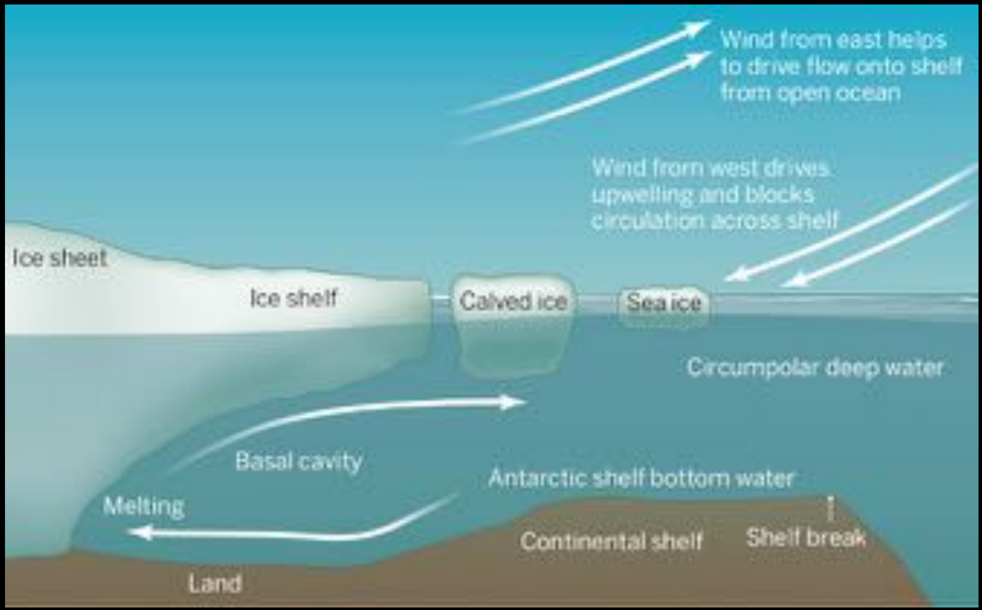
Ice Bottom Melt (Water Terminating)

- Depends on heat transport to the ice front



Ice Bottom Melt (Water Terminating)

- Depends on heat transport to the ice front



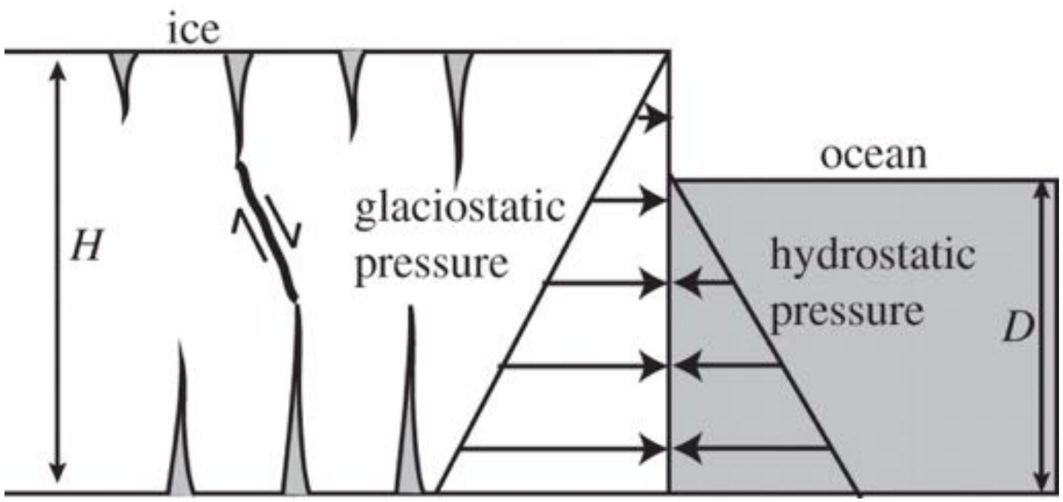
Dynamic Ablation:

Calving and Cliff Failure

Terminal Force Balance

Ice and Water apply Stress/Pressure to the material they sit on, based on their density:

$$P = \rho g H$$



P – Pressure

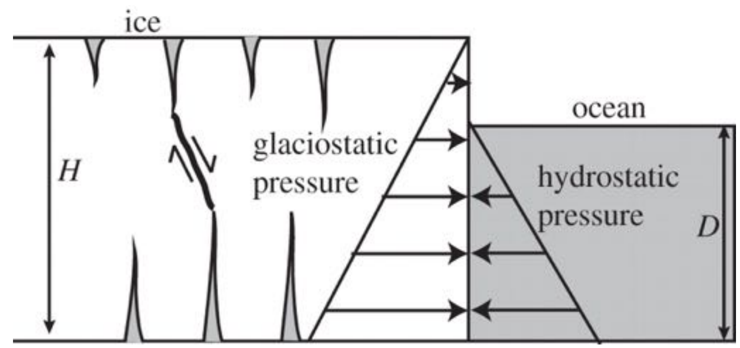
ρ – Density

H – Column Thickness

Terminal Force Balance

Calving rate likely depends on:

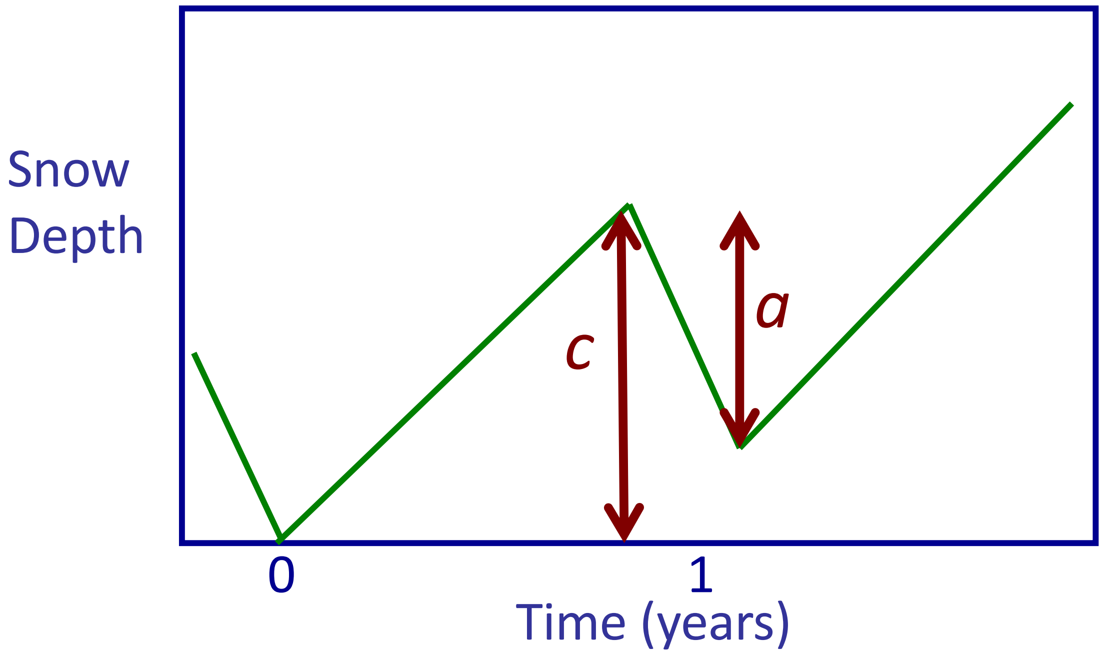
- Ice Thickness at Terminus
- Flow Speed of the Glacier
- Meltwater at the Surface
- Pre-existing Ice Weakness



Spatial and Temporal Distribution of Ablation

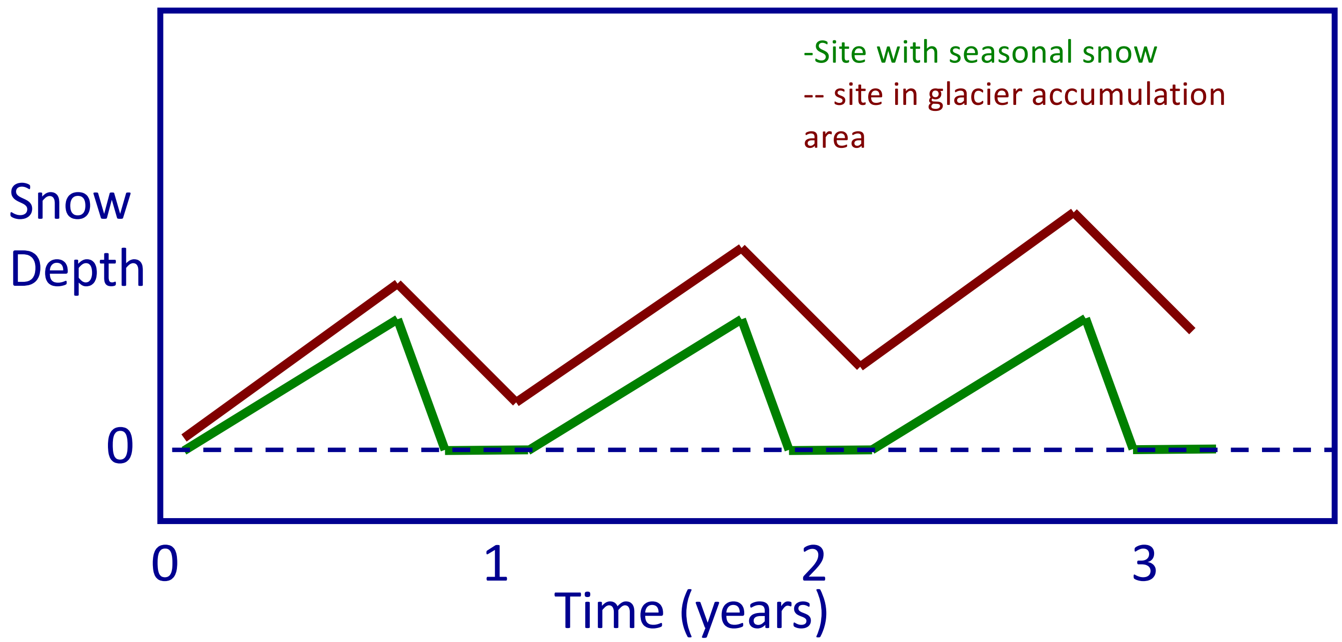
Mass-Balance Definitions

- Accumulation *c*
- ablation *a*



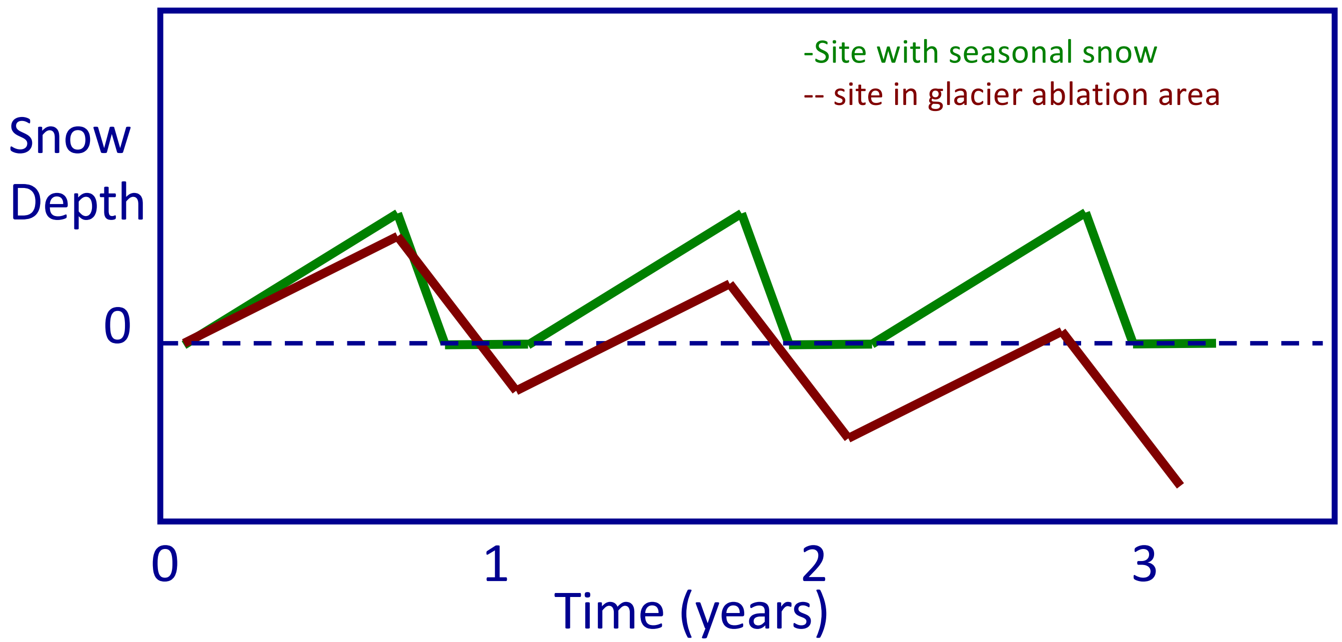
Mass budget – high on a glacier

- Snow on surface at all times
- Accumulation *c* is greater than ablation *a*
- This is the situation high on Easton Glacier

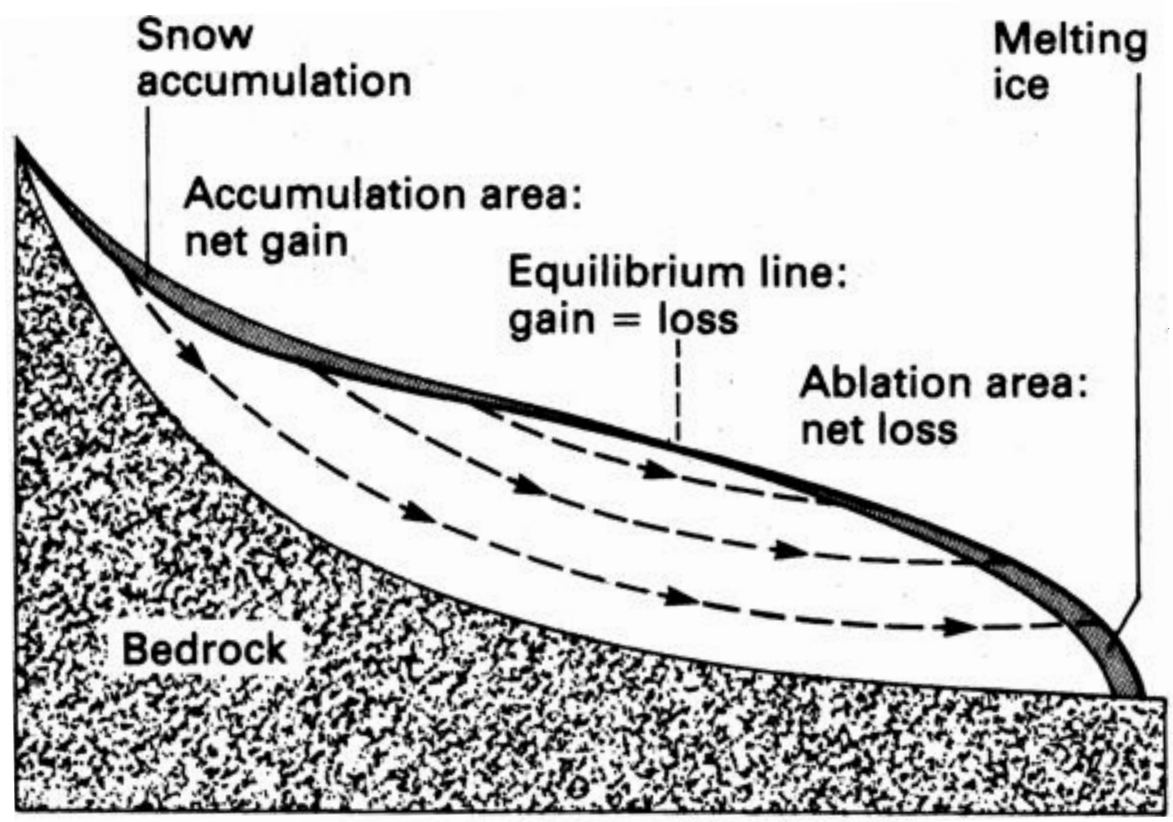


Mass budget – low on a glacier

- No snow on surface in late summer
- Accumulation *c* is less than ablation *a*
- This is the situation at Easton Glacier terminus



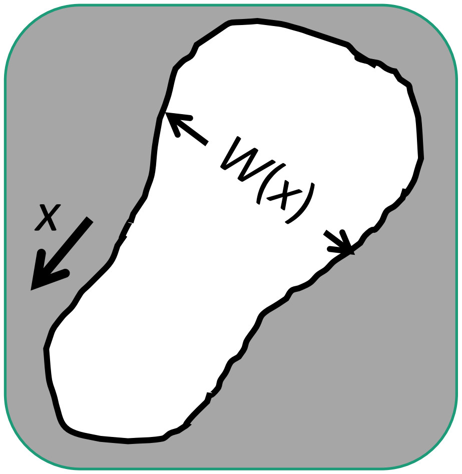
How does a Glacier Work?



Steady-State Glacier

For glacier with terminus above sea level

- In accumulation area: *c>a*
- In ablation area: *a>c*



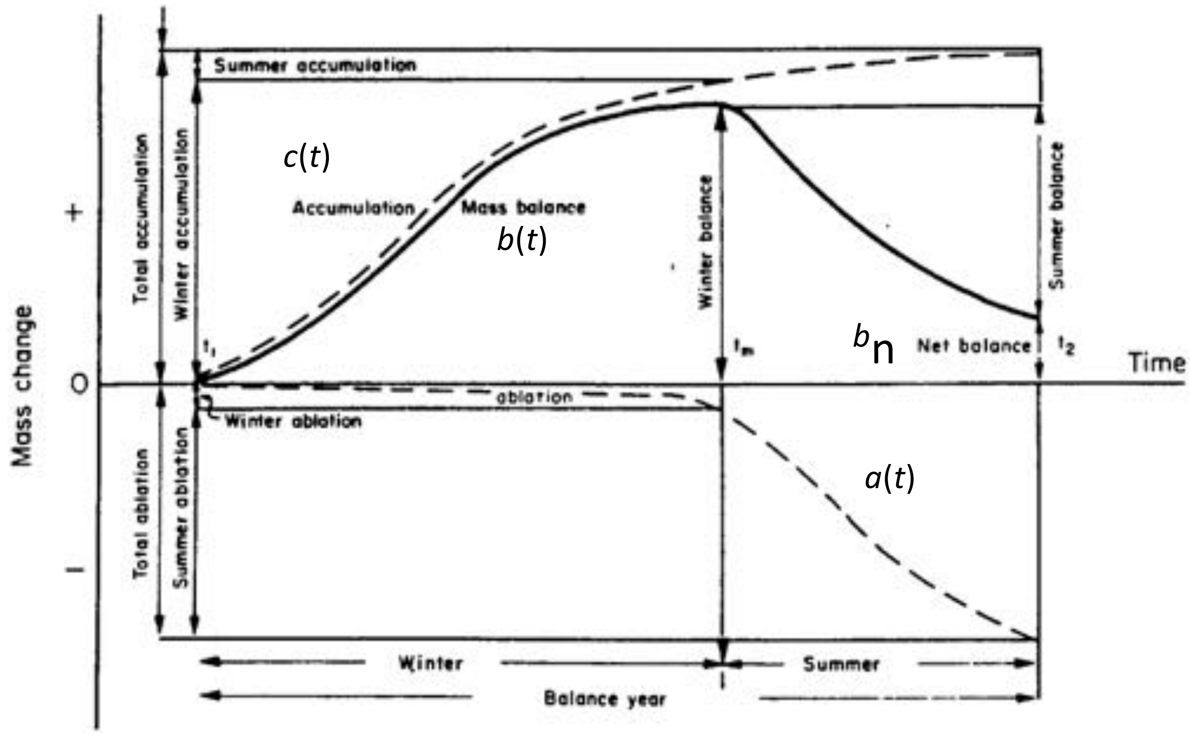
W(*x*) is glacier width
L is terminus position

$$\bar{c} = \int_0^L c(x)W(x)dx$$

$$\bar{a} = \int_0^L a(x)W(x)dx$$

If $\bar{c} = \bar{a}$ then glacier is in balance (steady state), not growing, or shrinking.

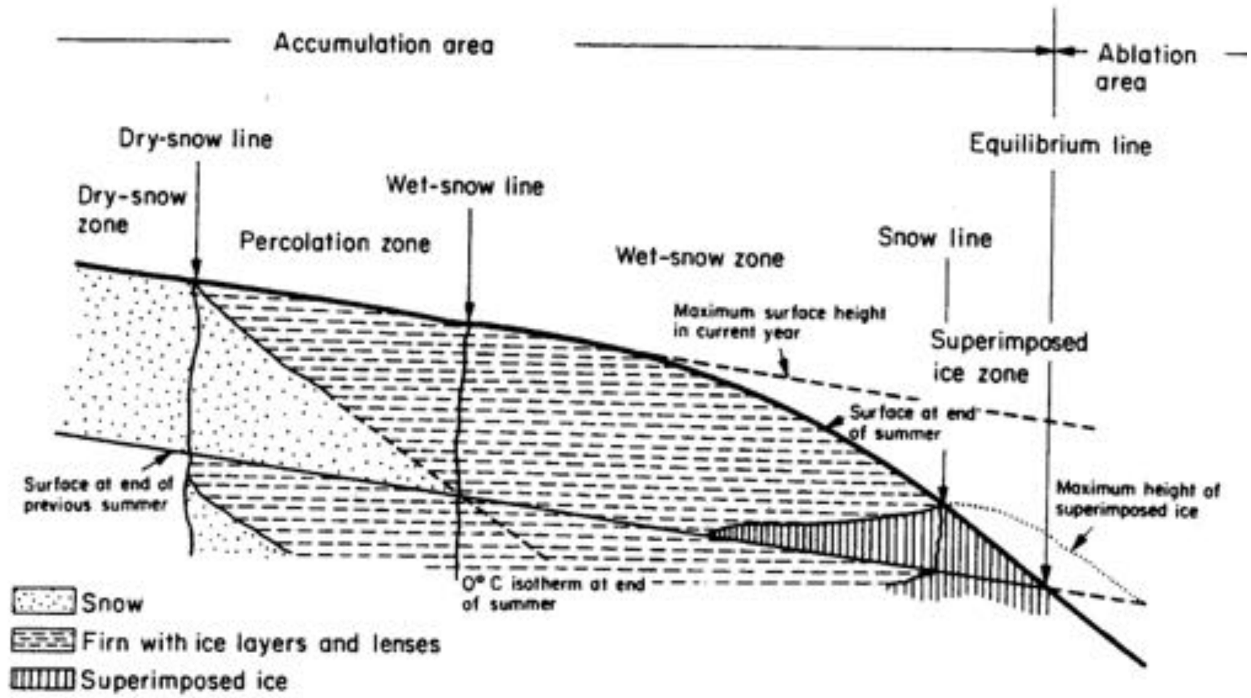
Mass-balance Terminology



To fully characterize a glacier, we need this information at many points on its surface,

Mass balance terms (J.T. Andrews)

Zones on a Glacier



Can superimposed ice form if firn temperature is 0^{o}C?

- Temperate glaciers have only wet-snow zone and ablation zone

(W.S.B.Paterson. 1994, based on C. Benson (1961)

Measurements in Accumulation Area

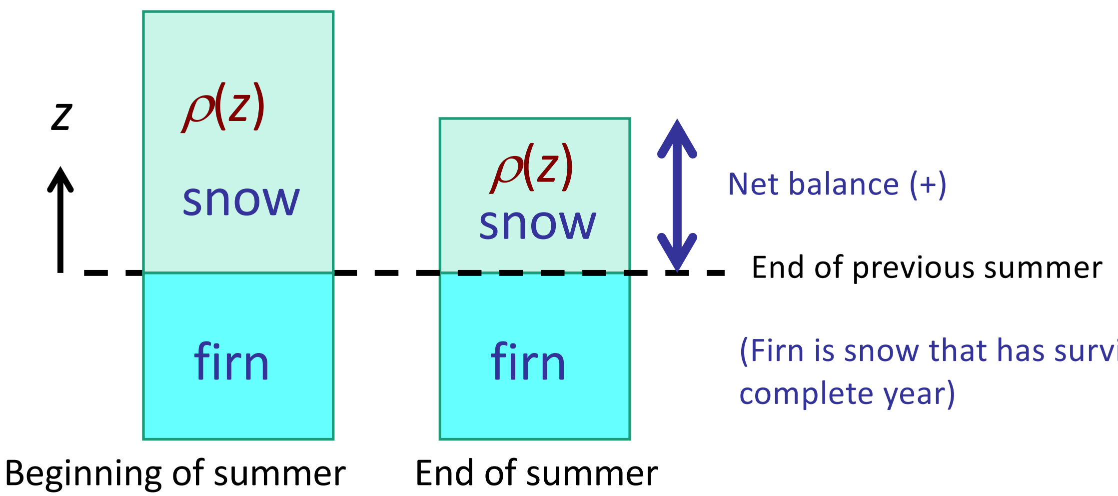
(Not all snow melts)

Winter Accumulation

- Dig snow pit at start of summer
- Find previous summer surface (how?)
- Measure density $\rho(z)$

Net Mass Balance

- Dig snow pit at end of summer
- Find previous summer surface
- Measure density $\rho(z)$



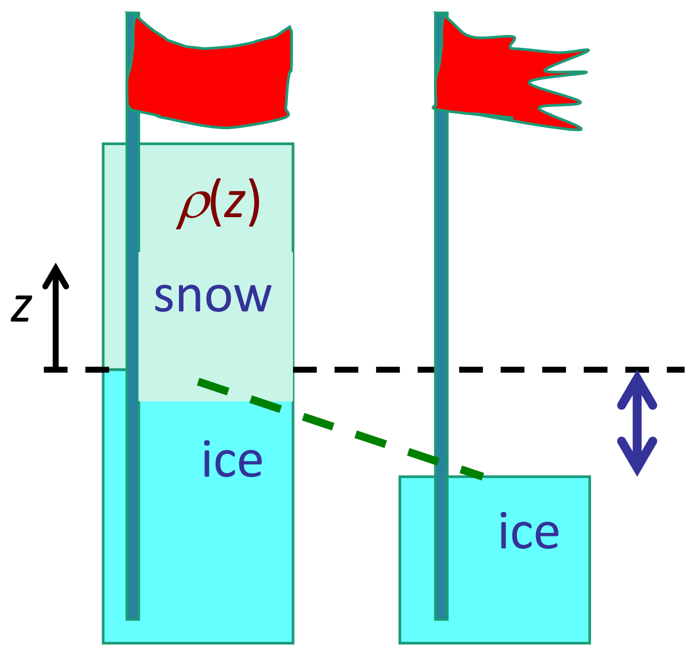
(Firn is snow that has survived through a complete year)

Measurements in Ablation Area

(Some ice from previous years also melts)

Winter Accumulation

- Install poles into ice in fall, measure height above ice
- Find snow depth in spring, measure density $\rho(z)$



Net Mass Balance

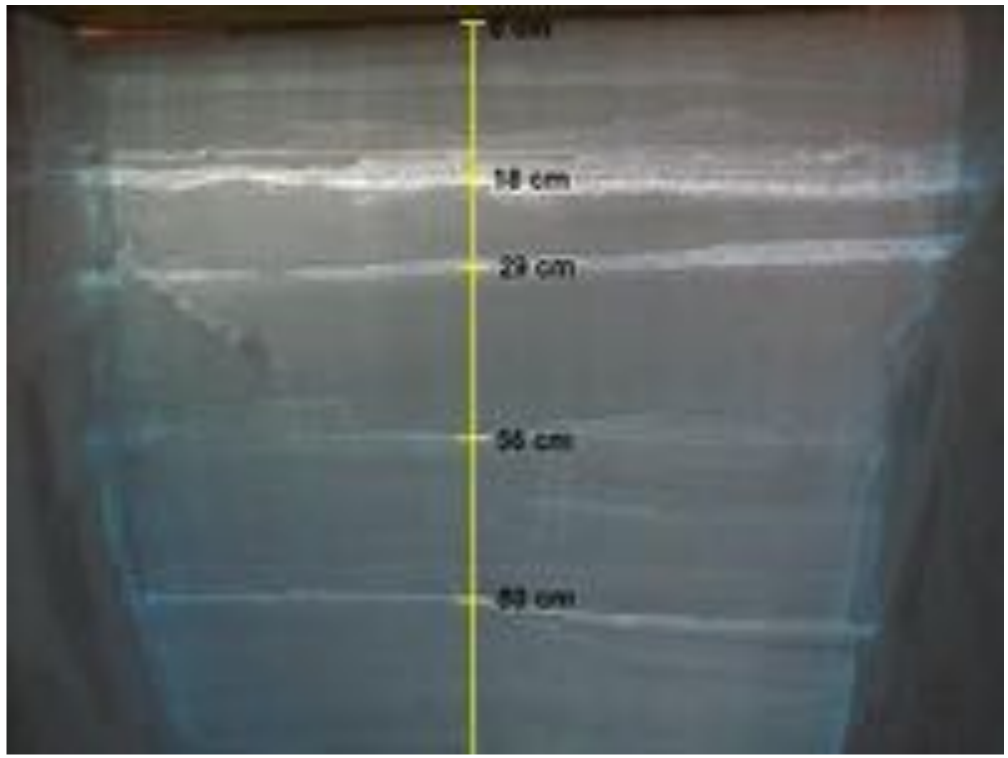
- Measure height of pole above ice next autumn

Net balance (-)

Works in polar regions too

Net Mass Balance

- Dig snow pit
- Find previous summer surfaces (how?)
- Measure density $\rho(z)$



back-lit snow pit
at Siple Dome
(Rolf Tremblay)

http://tea.armadaproject.org/tremblay/12.1.2000.html

Balance Year

Mass Balance $b(t) = c(t) - a(t)$

- $b(t)$ reaches maximum at end of winter.
- net balance b_n is balance at end of summer.

End of balance year is when ablation rate no longer exceeds accumulation rate

- In practice it is easier to define a fixed date each year for each glacier.
- October 1 is a convenient date in Washington

Snow Line

Transient boundary on glacier surface between snow and ice/firn

- glacier is snow-covered by spring
- snow line moves upward during summer
- uppermost location of snow line at end of summer (on average) is called "firn line" or "equilibrium line"
- b_n=0 at equilibrium line

Late-summer snow line on
Blue Glacier, Mt. Olympus

Steady State

Mass Balance $b(t) = c(t) - a(t)$

$\overline{b}_n(x)$ is average mass balance across glacier width

- net balance b_n is balance at end of summer

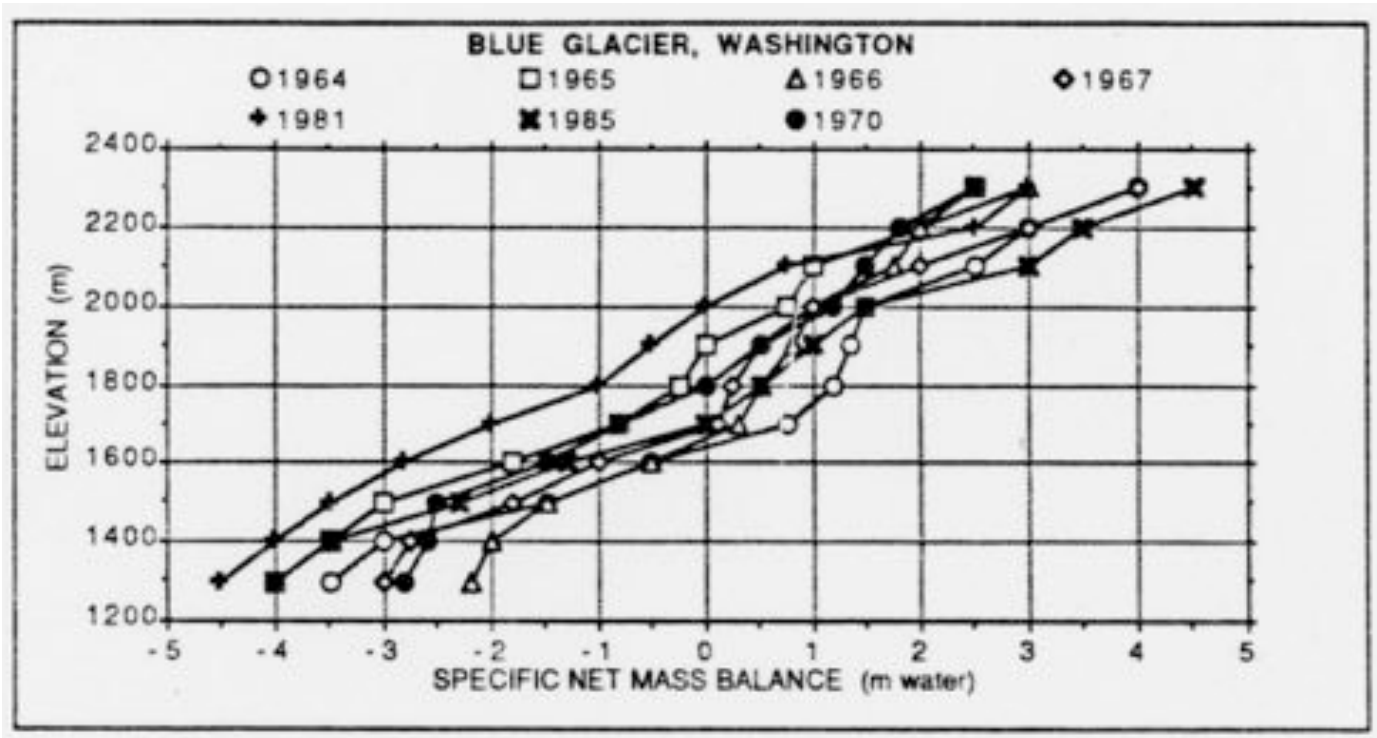
$$\int_0^{x_E} \overline{b}_n(x)W(x)dx = -\int_{x_E}^{L} \overline{b}_n(x)W(x)dx$$

For Steady State:
Amount of snow (mass) left above ELA at end of summer is exactly equal to mass of ice lost in ablation area.

$W(x)$ is glacier width
$x = 0$ is head of glacier
x_E is Equilibrium line
$X = L$ is terminus

Or stated another way, $\int_0^{L} \overline{b}_n(x)W(x)dx = 0$

Mass-balance gradient on Blue Glacier, Mt. Olympus



← Mass loss Mass gain →

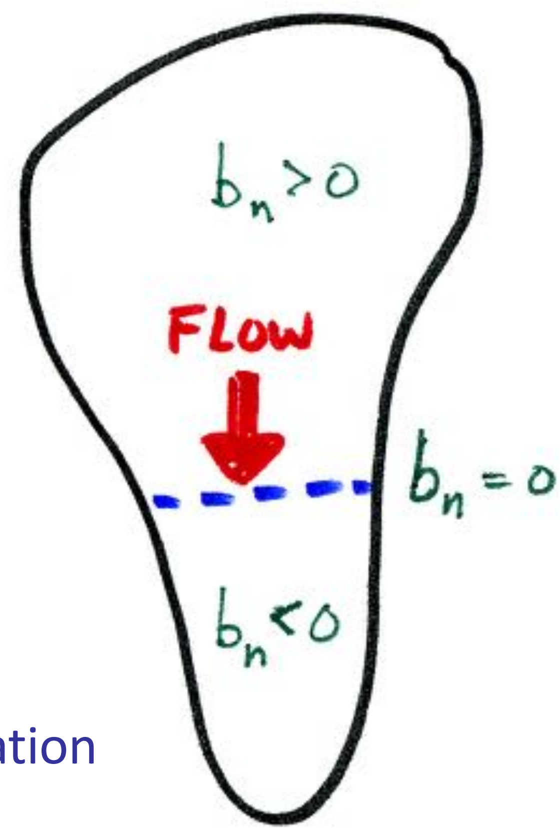
AAR (Accumulation-Area Ratio)

$$AAR = \frac{\text{Accum. Area}}{\text{Total Area}}$$

Net accumulation

Balanced by flow

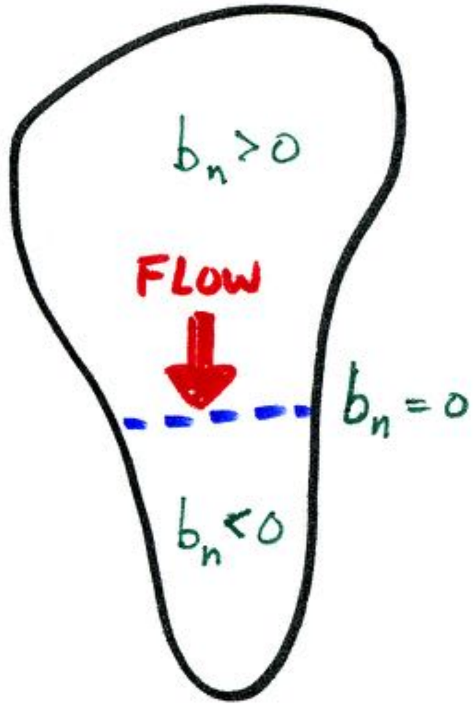
Net ablation



Accumulation-Area Ratio

Balanced glaciers (that end on land) have
AAR ~ 0.5 – 0.8

Why is AAR ≠ 0.5?



Why is AAR$\neq$0.5?

- Glaciers tend to start in broad snow fields, then funnel into glacier tongues.
- Tongues tend to descend long distances into regions of very high ablation.
- With high ablation rate, ablation area must be small in order to achieve balance.

- Accumulation and ablation are very different processes, so they don't necessarily scale the same way.

AAR and Glacier Health

If AAR ≤ 0.5 (for a glacier that ends on land)

- Glacier is in trouble, unless it has a highly unusual accumulation/ablation pattern

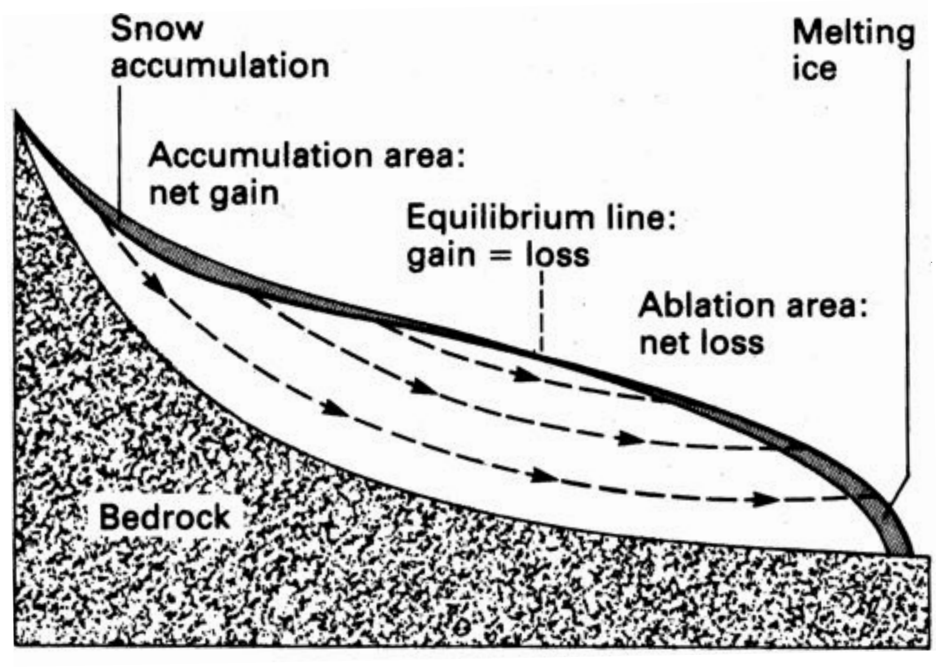
AAR and Past Climate

Geologists use AAR ~0.6 to reconstruct ELA (Equilibrium Line Altitude) and climate for past glaciers

- However, AAR is only an approximate gauge of glacier balance

Equilibrium

A glacier in Steady State has flow that exactly balances $b_n(x)$



Disequilibrium

Ablation and Accumulation are not exactly balanced

$$\int_0^L \overline{b}_n(x)W(x)dx \neq 0$$

- Glacier will grow or shrink in volume
- Elevation changes due to flow will no longer exactly balance elevation changes due to melting or accumulation
- Glacier length and height will change

Regional Differences in Ablation Regime

Energy Budget for a Tropical Glacier

Air is generally very dry over tropical glaciers

- Sunlight can sublimate ice rather than melting
  Sublimation (2830 J g^{-1}) vs. melting (330 J g^{-1})

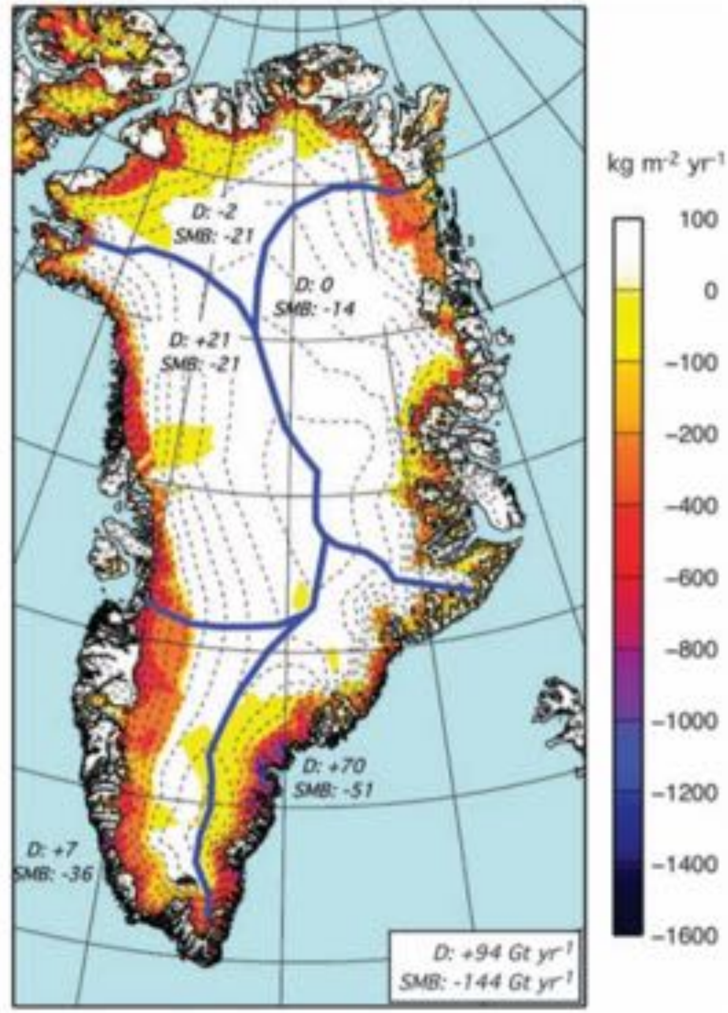
- Each Joule of sunlight eliminates less than 1/8 as much ice if it causes sublimation rather than melting.

- Tropical glaciers may exist only because the air is dry and ablation is dominated by sublimation.

- If air becomes more humid, glaciers may convert to melting regime; rate of mass loss would increase by factor of 8.

Greenland Ablation

- 50% Surface Mass Balance
- 50% Dynamic Losses (Calving + terminus face melt)

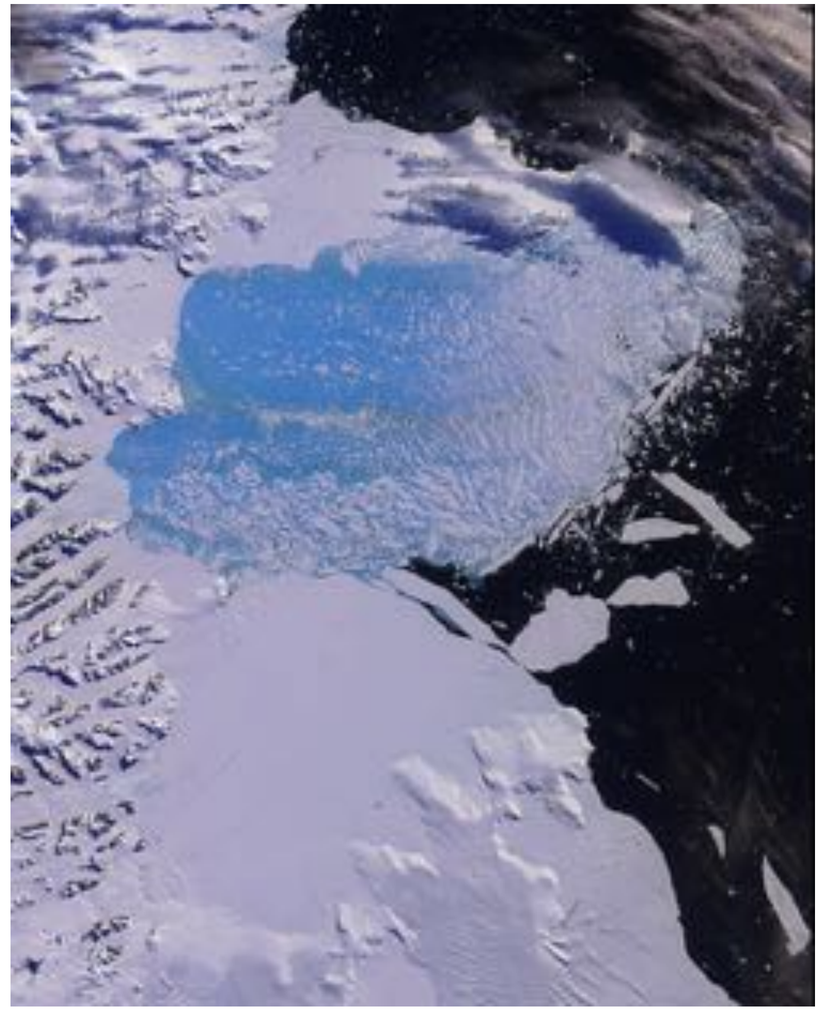


Partitioning Recent Greenland Mass Loss

Michiel van den Broeke,[1*] Jonathan Bamber,[2] Janneke Ettema,[1] Eric Rignot,[3,4] Ernst Schrama,[5] Willem Jan van de Berg,[1] Erik van Meijgaard,[6] Isabella Velicogna,[3,4] Bert Wouters[5,6]

Antarctic Ablation

- 50% Ice-Shelf Basal Melt
- 50% Calving and Dynamic Losses



c and *a* are fundamentally different

Many factors, both local and distant, can affect snow accumulation

- Moisture source
- Storm tracks
- Local temperature
- Local wind

Local factors (energy) affect melting

- Sunlight
- Infrared (IR) radiation
- Sensible heat (warm air)