Lecture 14-1: Cryosphere and climate

Outline:

We'll go over some of the characteristics of sea ice and glacier/ice sheet formation, and why they are important to climate. We'll also briefly discuss the role of ice in past climate changes.

Cryosphere and Climate

Refs: Encyclopaedia of the atmospheric sciences - entries on Glaciers (by AC Fowler) and Sea ice (by WF Weeks); the "Land ice and climate" chapter of Climate system modeling, KE Trenberth (ed.)

Table 1.4

Estimated Global Inventory of Land and Sea Ice[a]

			Area (km^2)	Volume (km^3)	Percent of total ice mass
Land ice	Antarctic ice sheet		13.9×10^6	30.1×10^6	89.3
	Greenland ice sheet		1.7×10^6	2.6×10^6	8.6
	Mountain glaciers		0.5×10^6	0.3×10^6	0.76
	Permafrost	Continuous	8×10^6	(Ice content) $0.2–0.5 \times 10^6$	0.95
		Discontinuous	17×10^6		
	Seasonal snow (average maximum)	Eurasia	30×10^6	$2\text{-}3 \times 10^3$	
		America	17×10^6		
Sea ice	Southern Ocean	Max	18×10^6	2×10^4	
		Min	3×10^6	6×10^3	
	Arctic Ocean	Max	15×10^6	4×10^4	
		Min	8×10^6	2×10^4	

[a]Not included in this table is the volume of water in the ground that annually freezes and thaws at the surface of permafrost ("active layer"), and in regions without permafrost but with subfreezing winter temperatures. [After Untersteiner (1984). Printed with permission from Cambridge University Press.]

Reference: Area of US = 9.16×10^6 km^2

Sea ice

Importance to climate:

2. Albedo: open water albedo is ~0.1 as compared to ~0.85 for newly formed snow - a 75% increase. Decreases SW absorption. Hence:
3. Ice-albedo feedback.
4. Limits exchange of ***heat and moisture*** from ocean to atmosphere. *Leads* in the ice are important in this regard, as fluxes through open ocean and thin ice can be as much as over 200 times that of multi-year ice.
5. Changes the vertical distribution of absorbed SW - more goes into the ice and less into the ocean. The upper 10cm of ice can absorb 50% of the net SW absorbed - UV and IR get absorbed more effectively, whereas visible can penetrate deeper into the ice.
6. Significant changes to the sea ice extent or thickness results to substantial changes to the climatology of the polar regions.
7. Sea ice stabilizes wave activity in the upper ocean, favoring the existence of a stable cold fresh layer on top of a warm but salty layer. This stable stratification prevents ocean heat from escaping to the surface.
8. Formation of sea ice leads to *brine rejection* - water made dense by addition of salt that sinks to the very bottom of the ocean. Typical salinities for ‘first year’ ice is 10-12‰, ‘multi-year’ ice is ~3‰.

Sea ice - formation, growth, melting

- The thicker it is, the slower it grows.
- Since **ablation** (melting) occurs during the summer, there is a maximum thickness that first year ice can attain (~2m in Arctic, up to 3m in Antarctic)
- If ice survives the first year, the growth in the second year is slower as it starts to freeze up later and it grows slower.
- After a few years a rough equilibrium is reached - steady multi-year ice are around 3.5-4.5m thick (but depends on region).
- An important factor in ablation is the formation of melt ponds on the ice surface, since they can drastically increase the SW albedo. For example, a 5cm melt pond can absorb up to 50% of the total energy absorbed by the system.
- **Antarctic formation and growth is different from the Arctic.** In the Antarctic, surface melt rates are small - rather, the sea ice melts as it is advected from the formation regions northwards out into the warmer open ocean; only small amounts of multi-year ice survive at the end of the summer. Antarctic ice do not have melt ponds - they are characteristic only of Arctic ice.

This image shows thin first-year ice along the top third, medium to thick first-year ice along the right, and new ice forming in the open water.

SOURCE: http://www.antcrc.utas.edu.au/aspect/

Mostly level first-year floes (floe=contiguous piece of sea ice). A large ridge can be seen in the central floe.

Frazil ice formation represents the first stage of sea ice growth. The frazil crystals are usually suspended in the top few centimetres of the surface layer of the ocean and give the water an oily appearance. In the open ocean the crystals may form, or be stirred to a depth of several metres by wave-induced turbulence.

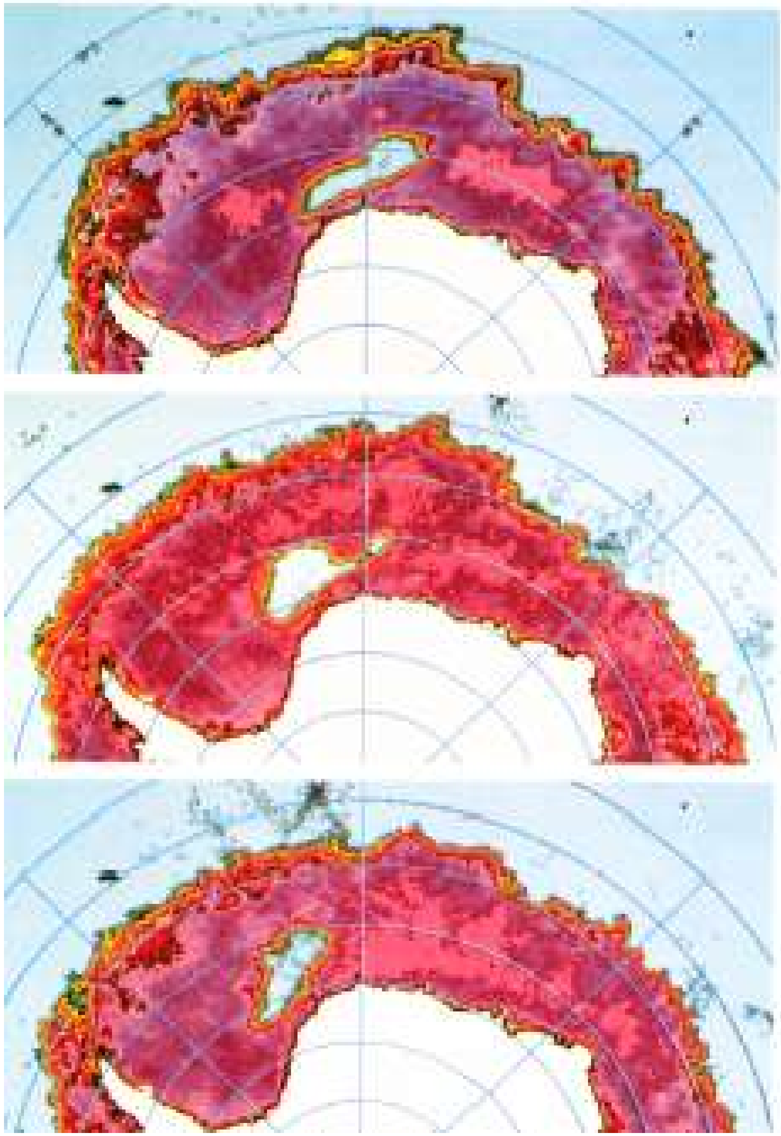
Other types of new ice: Grease, slush, shuga, nilas, pancake

Pancake ice can rapidly cover vast areas within the **pack**. The characteristic upturned edges of the pancakes result from continuous collisions.

Fracture: Any break or rupture through very close pack ice , compact pack ice , consolidated pack ice ,fast ice , or a single floe resulting from deformation processes. May vary from a few meters to many kilometers.

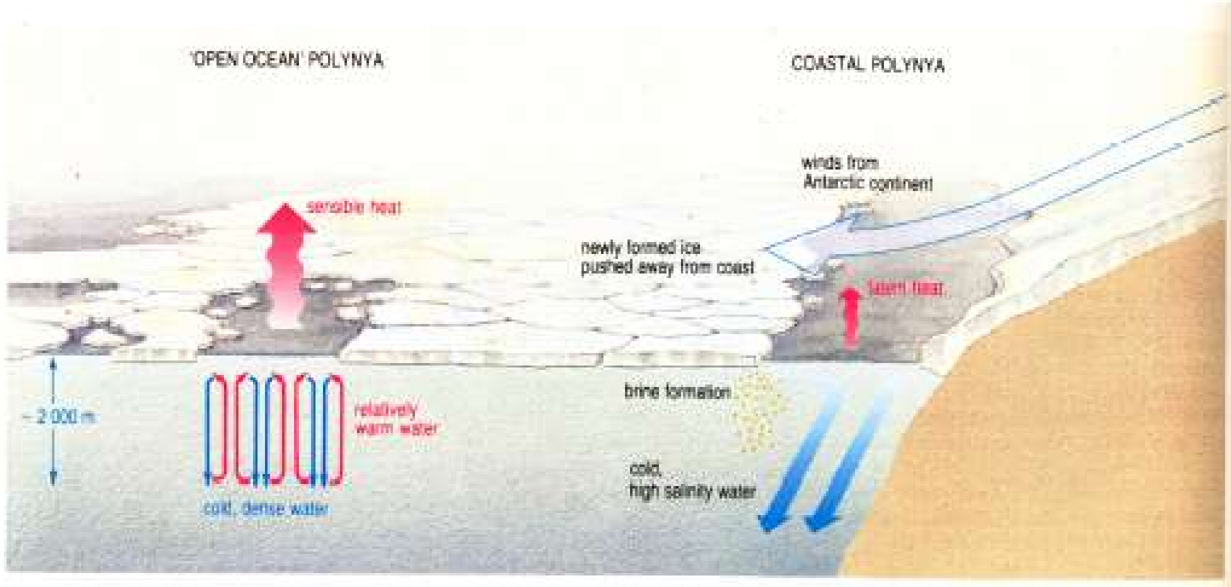
Leads permit large transports of heat and mass between the ocean and the atmosphere, visualised in this image by the water vapour rising from the open water (sea smoke).

Polynyas are areas of open ocean surrounded by sea ice. They are of two types: the first is found near coastlines and are associated with katabatic winds that drives any sea ice that is formed away through the action of the winds. The latter type is maintained by transfer of heat from the ocean interior to the surface ocean, maintaining ice-free conditions. Polynyas may be important to climate as they are regions of intense air-sea energy exchange.



Nimbus satellite image showing the position of the Weddell polynya in 1974, 75, 76. The westward motion is attributed to the generally westward flow in that region. Pink is ice covered, blue is ice free.

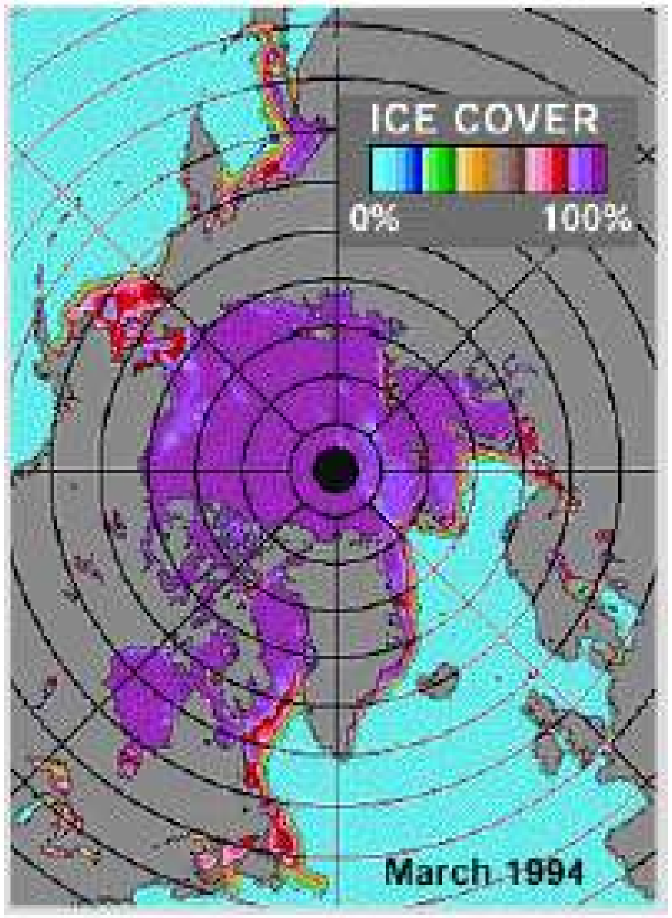
Sea ice, polynyas, and Antarctic deep water formation

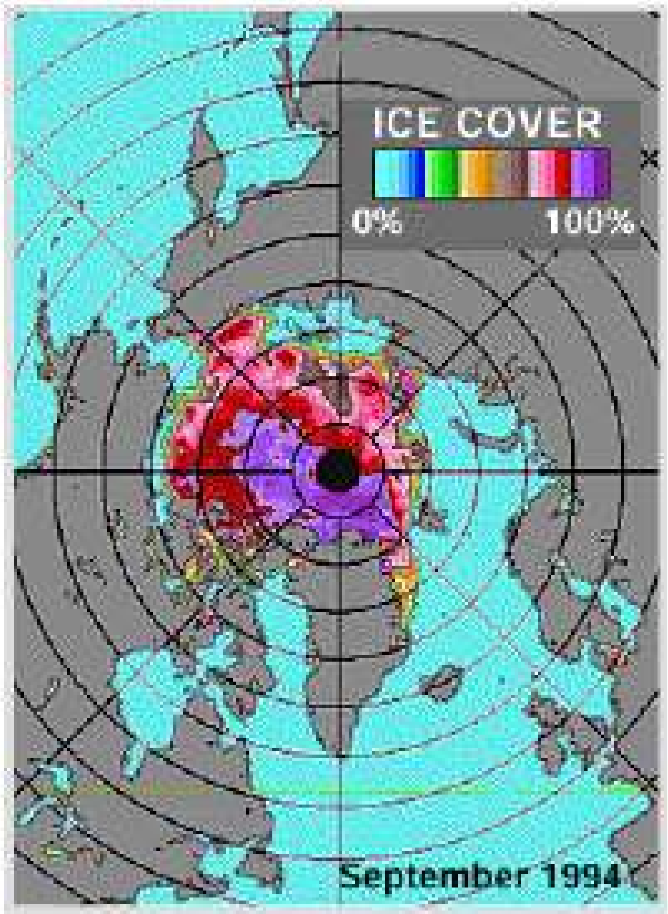


Coastal polynyas are 'factories' for sea ice - winds drive sea ice away as soon as they are formed, exposing more ice-free water for sea ice to form. Large amounts of heat is removed (latent heat of freezing) as -1.8C water converts from liquid to ice. The heat flux has been estimated at more than 300W/m^2. Brine rejection forms salty waters that sink. ***Open-ocean polynyas*** lose heat mainly by conduction/convection. Water cooled at the surface sinks, and is replaced by warmer water from below. Deep convection cells form, reaching up to 2.5km in depth for the Weddell polynya. The warm water brought up by the convection cells is also a reason why polynyas are maintained.

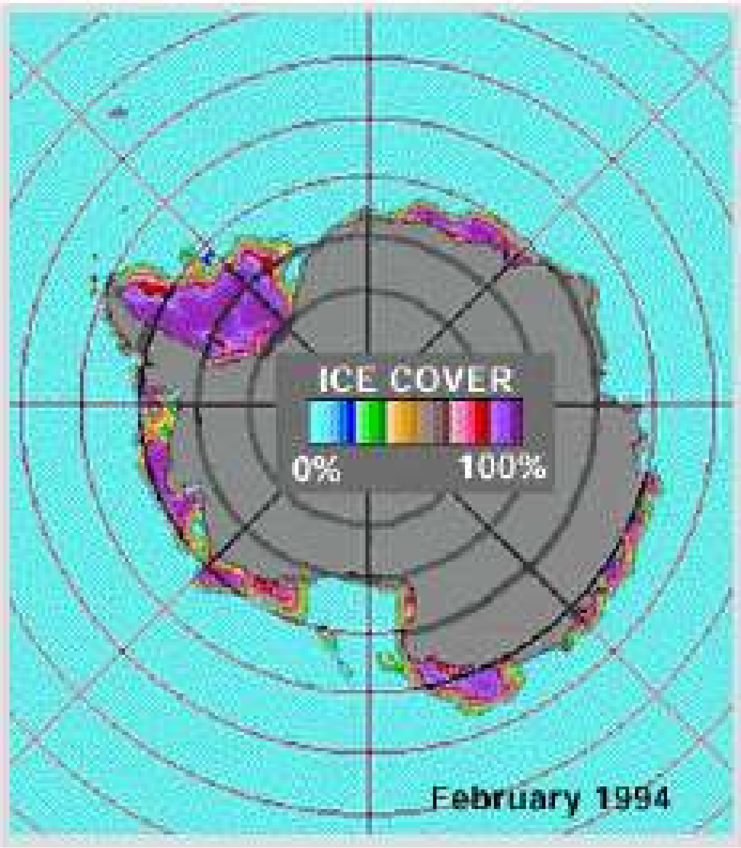
Seasonal cycle
of NH sea ice

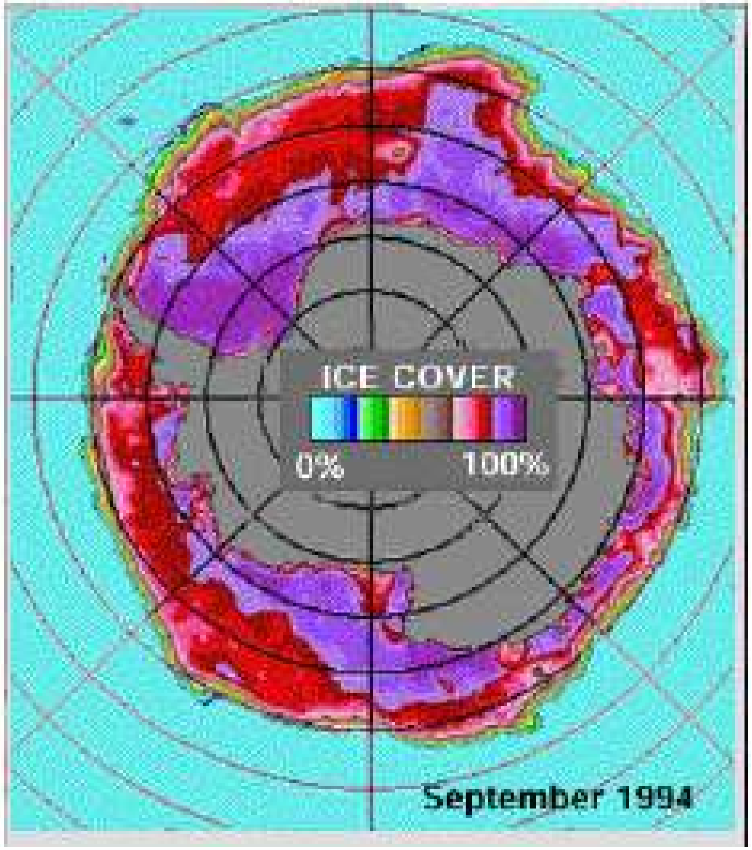
Importance to climate:
Reflection of sunlight
Insulates ocean from atmosphere





Seasonal cycle of SH sea ice





Glaciers and ice sheets

•Glaciers are rivers of ice, and ice sheets are continental-scale domes of Ice.
•Slowest component of the climate system:
the largest ice sheets may still be responding to changes that occurred 200,000 years ago.
•Found in cold regions (high latitudes and/or high altitudes).
•Typical dimensions - hundred of meters deep, kilometers in length.
•Typical velocities: tens to hundreds of meters per year.
(fastest: in Greenland, 8km/yr).
•Important for geomorphology - erosion, formation of landscapes.

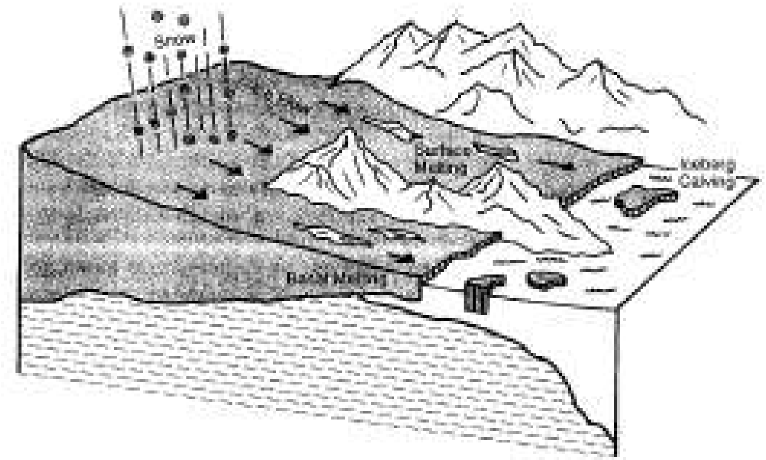
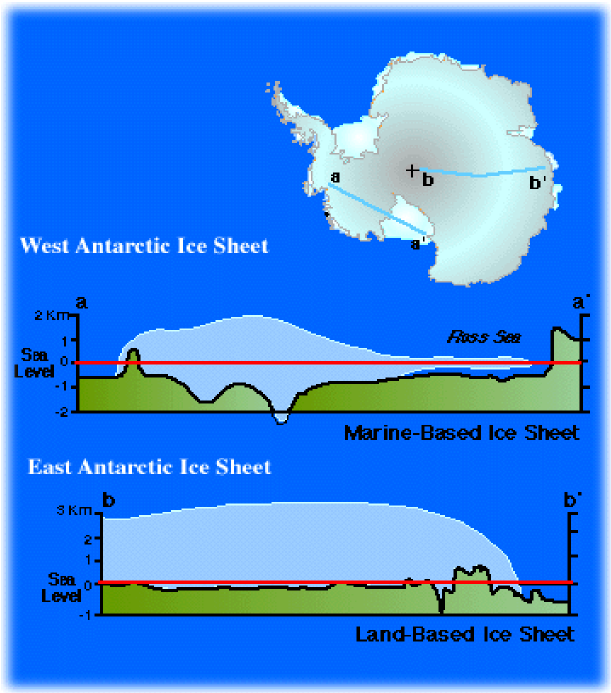


Fig. 13.1. Schematic representation of a glacier. The floating ice front shown here is characteristic of a marine ice sheet; tidewater glaciers usually have grounded calving fr



Surging Glaciers

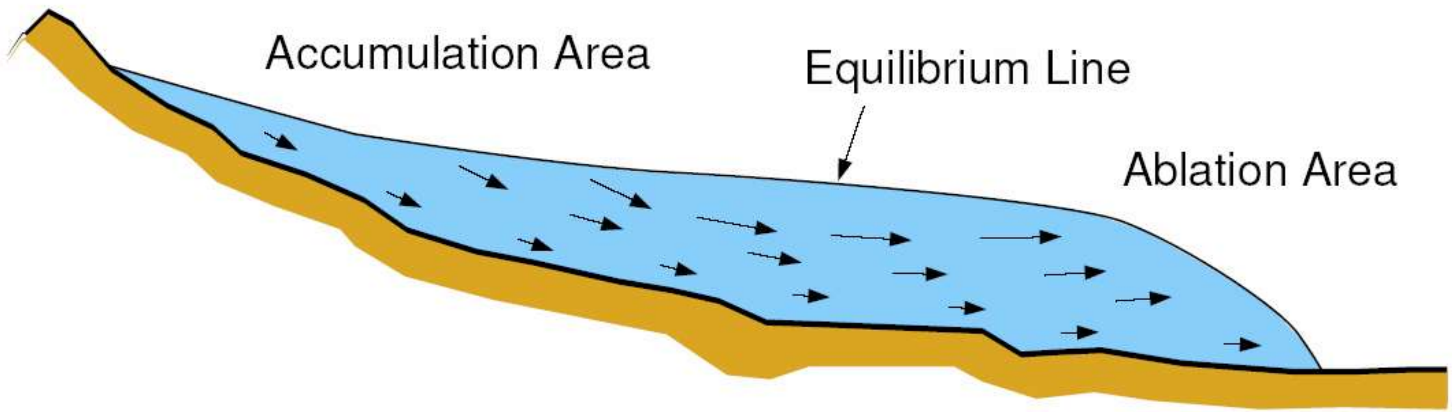
Variegated Glacier, Alaska

29 August, 1964

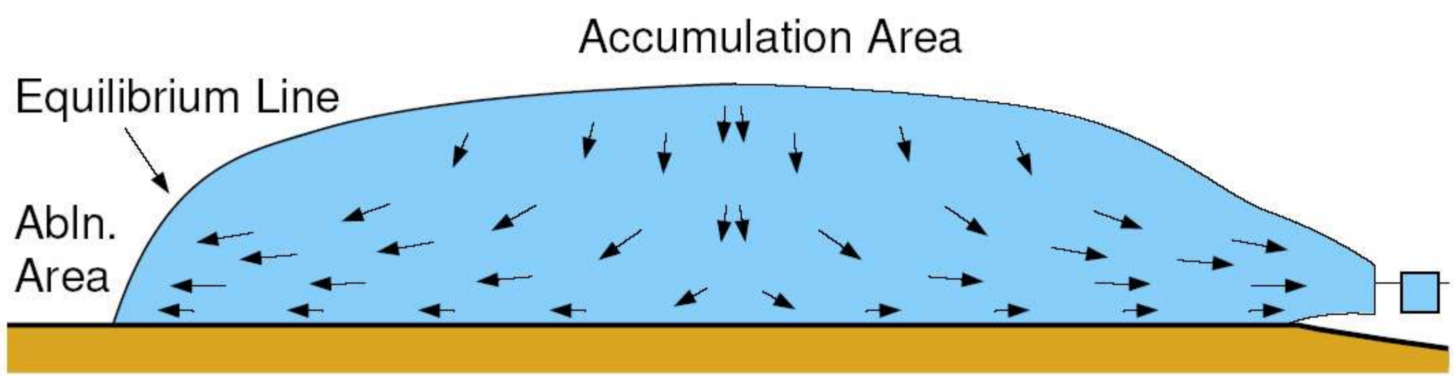
22 August, 1965

(source: Jeff Kavanaugh)

Glacier Geometry



Ice Sheet Geometry



(source: Jeff Kavanaugh)

Modeling glacier flow

•Driven by gravity - flow towards decreasing elevation.

•Resistive forces **(see next slide).**

•Deformation of subglacial till may also aid to increasing the sliding velocity.

•Ice may also deform - effective viscosity depends nonlinearly on the applied stress and the temperature - higher stress and temperature both act to make the ice less ‘sticky’. Frictional heating due to viscous dissipation may feed back positively on the viscosity. “Ice has a strongly variable viscosity, and its motion is more akin to a fairly rigid top layer being carried along on top of a softer shearing underbelly”.

•If basal (i.e. bottom) temperature is at pressure-melting point, the water layer will as a lubricant that allows ice to slide over the bed. Frictional and geothermal heating are two important sources of basal melting.

•The combination: till deformation, basal sliding, ice deformation - all contributes to a final ice velocity at the surface (two slides down).

•Flow is generally not steady - can exhibit surges.

•**Ice streams** - streams of fast moving ice (up to 10km/yr) in ice sheets

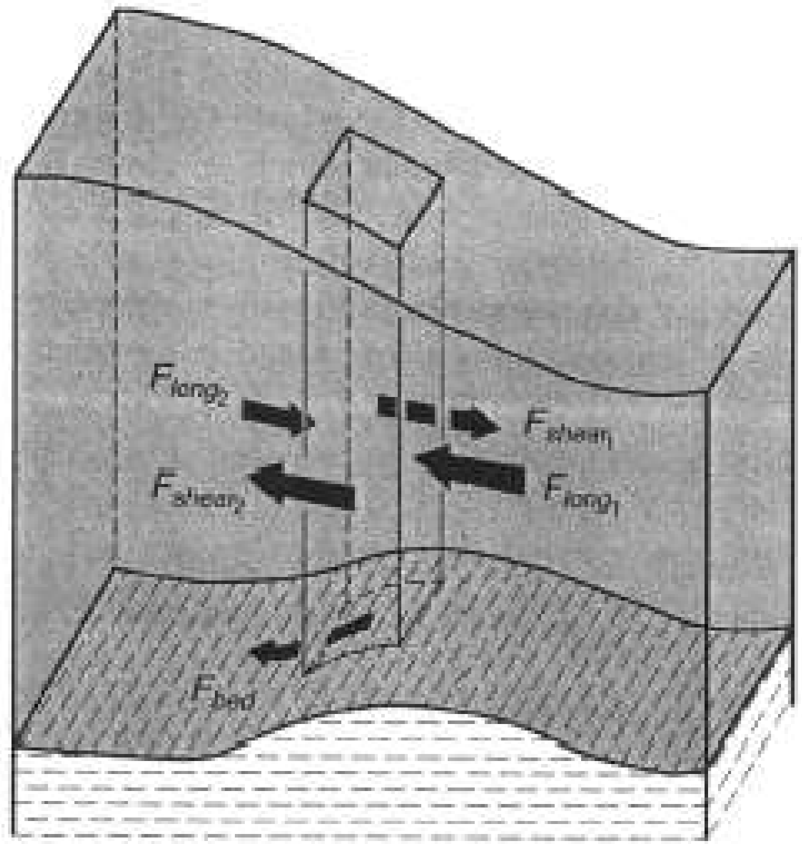


Fig. 13.2. Resistive forces acting on a glacier. Only the resistive forces in the mean direction of ice flow are shown; these are longitudinal pushes and pulls from up- and down-glacier ice (F_{long}), side shear (F_{shear}), and drag at the glacier base (F_{bed}). The sum of these resistive forces equals the driving force, directed in the direction of decreasing surface elevation.

Surface mass balance

Net surface mass balance = accumulation - ablation. In equilibrium, net surface mass balance is zero.

Ablation: surface melting is best modeled through energy balance model. Sensitive to variations in atmospheric temperature, humidity, cloudiness, wind speed. Also: calving at ice sheet edge.

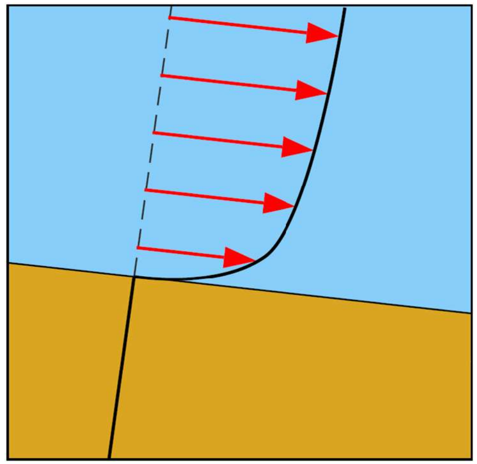
Accumulation: depends on air temperature, type of precipitation (rain or snow), amount of water vapor in the atmosphere. Surface orography also matters as precipitation occurs as a result of forced uplift.

The altitude separating the ablation (mass loss) and accumulation (mass gain) zones is called the ***equilibrium line*** or firn line.

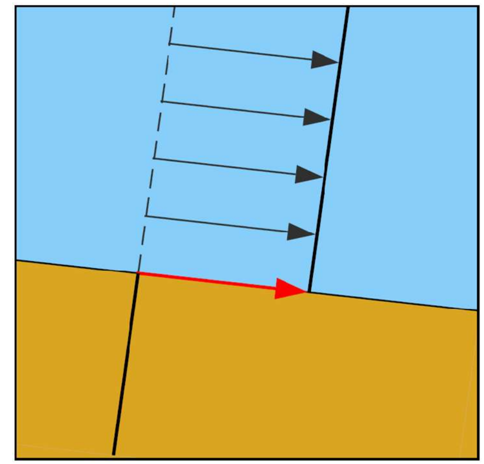
Greenland and **Antarctic ice sheets** are somewhat different. For Greenland, a lot of the ice sheet area is below the equilibrium line, so melting is a big part of the ablation. For Antarctica, most of the mass is lost through calving.

Components of Motion

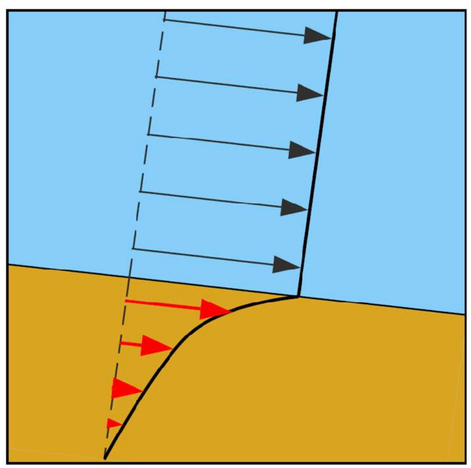
Ice Deformation



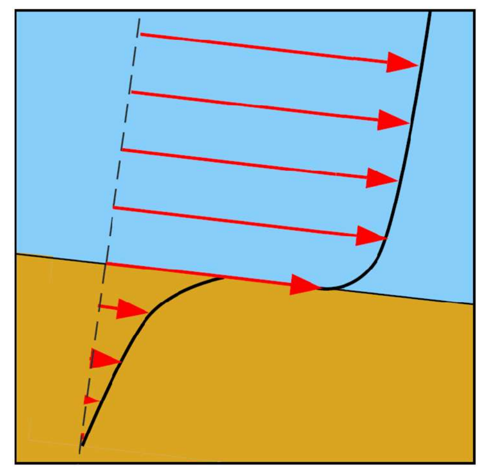
Glacier Sliding



Sediment Deformation



Total Motion



(source: Jeff Kavanaugh)

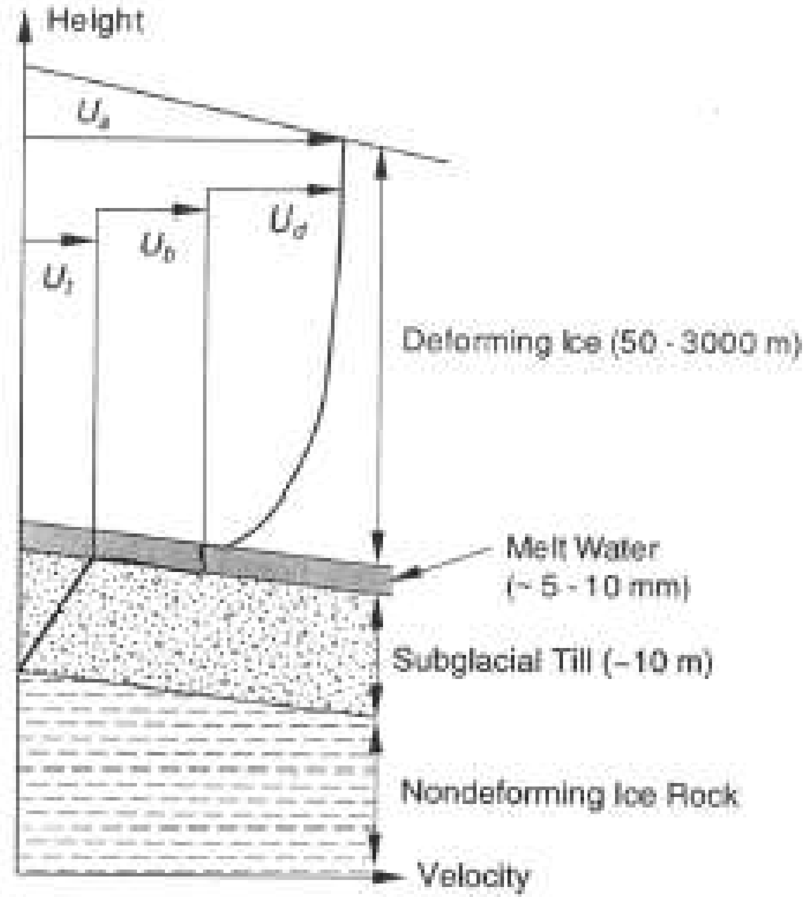


Fig. 13.3. Illustrating processes contributing to glacier flow: till deformation (U_t), basal sliding (U_b) and ice deformation (U_d). The vertical axis is not to scale; characteristic thicknesses for each layer are indicated on the right. The contribution of each process to the observable surface velocity ($U_s = U_t + U_b + U_d$) varies strongly among different glaciers. The linear increase in velocity in the till layer is based on a linear relation deformation rate and stress which has not been established unambiguously yet.

Glaciers and climate

Glaciers are sensitive to climate changes as the mass balance depends on climate. Some considerations:

•While ablation strongly depends on temperature, no simple relationship between ablation and temperature exists - ablation is more directly connected to the annual value of ‘positive air temperature’ -i.e. temperature taken only when it is above melting.

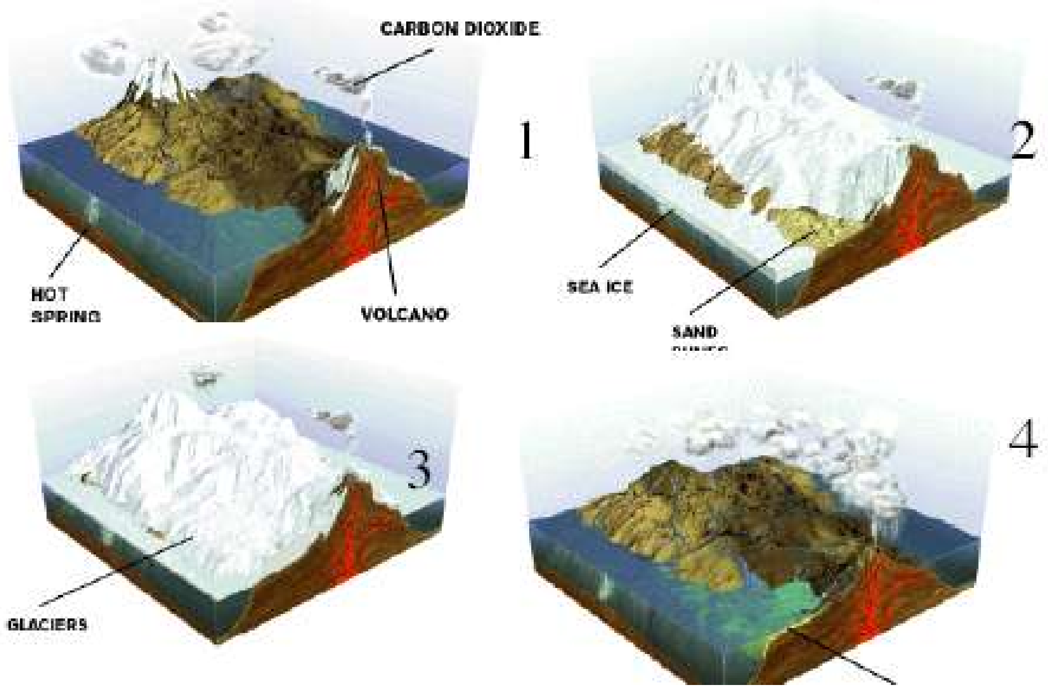
•Mass balance also depends on accumulation: if the hydrological cycle changes, then accumulation will change.

•Glacier growth feeds back on the climate: ice sheet can exert thermal (albedo) and topographic effects on the atmospheric circulations. In particular, the change in the atmospheric circulation may change the way that moisture is transported tot the ice sheet.

•Ice sheets are also capable of ‘catastrophic’ behavior - for example, with the collapse of the Larsen ‘B’ ice shelf a few years ago. It may imply that a small changes to climate may bring about large changes to ice sheet behavoir.

Land ice changes in the past

2. Snowball earth - "*Many lines of evidence support a theory that the entire Earth was ice-covered for long periods 600-700 million years ago. Each glacial period lasted for millions of years and ended violently under extreme greenhouse conditions. These climate shocks triggered the evolution of multicellular animal life, and challenge long-held assumptions regarding the limits of global change." - Hoffman and Schrag 1999.*

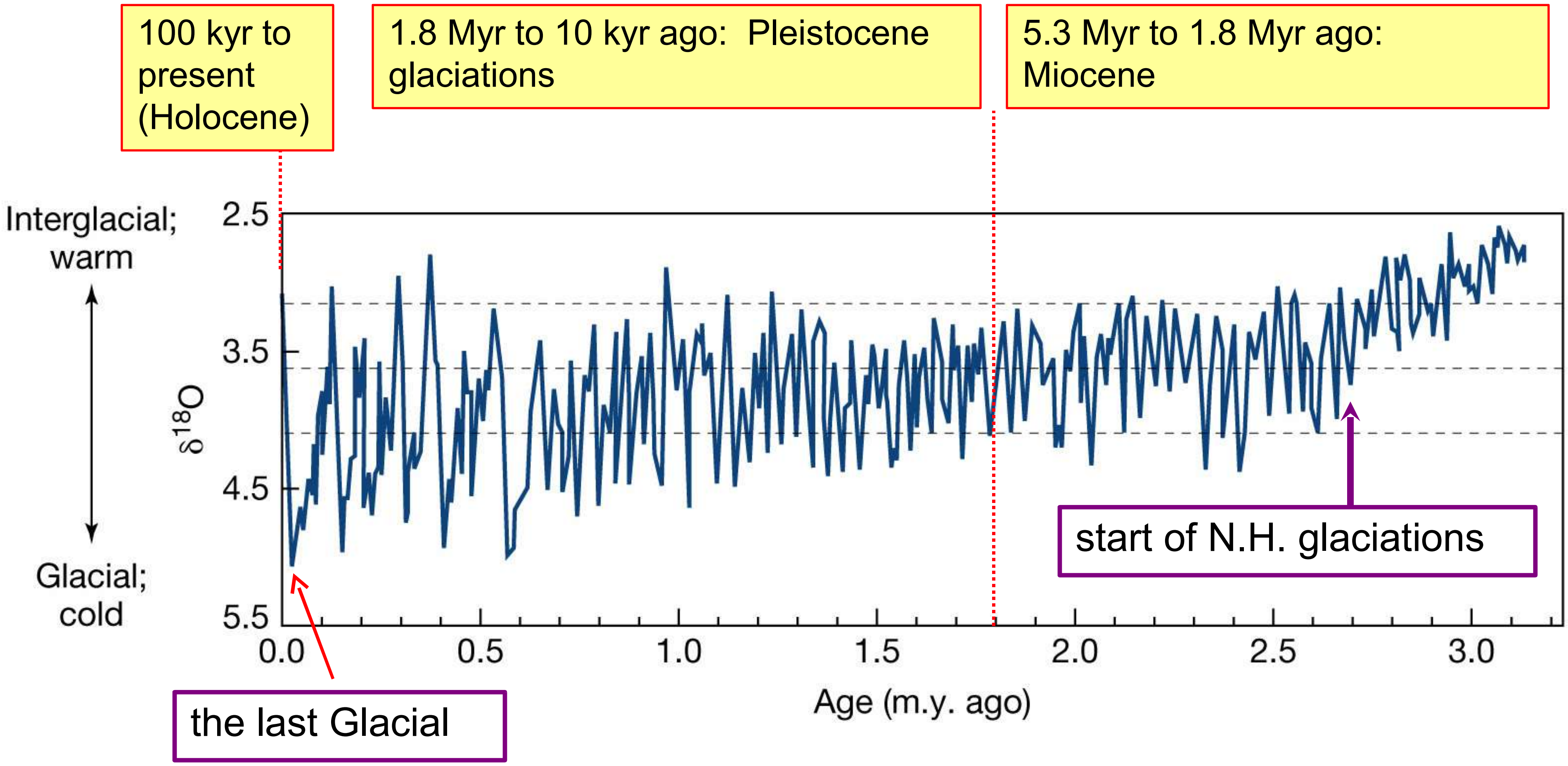


4 stages of snowball earth. 1) CO_2 drawdown by weathering 2) ice-albedo feedback leading to frozen earth 3) reduction of weathering leading to CO_2 increase 4) hothouse earth.

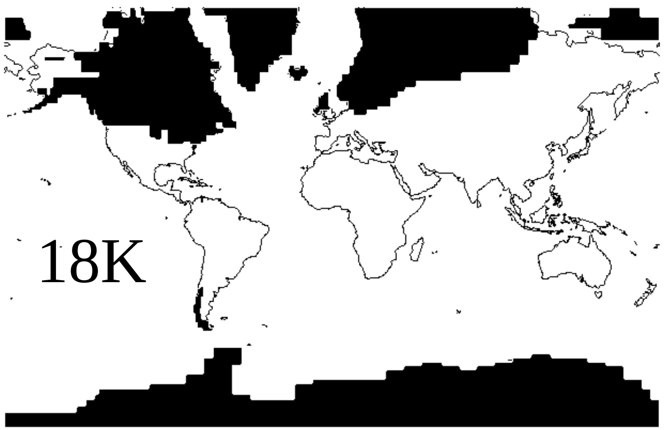
From: Hoffman and Schrag, Scientific American, Jan 21 2000.
http://www.sciam.com/print_version.cfm?articleID=00027B74-C59A-1C75-9B81809EC588EF21

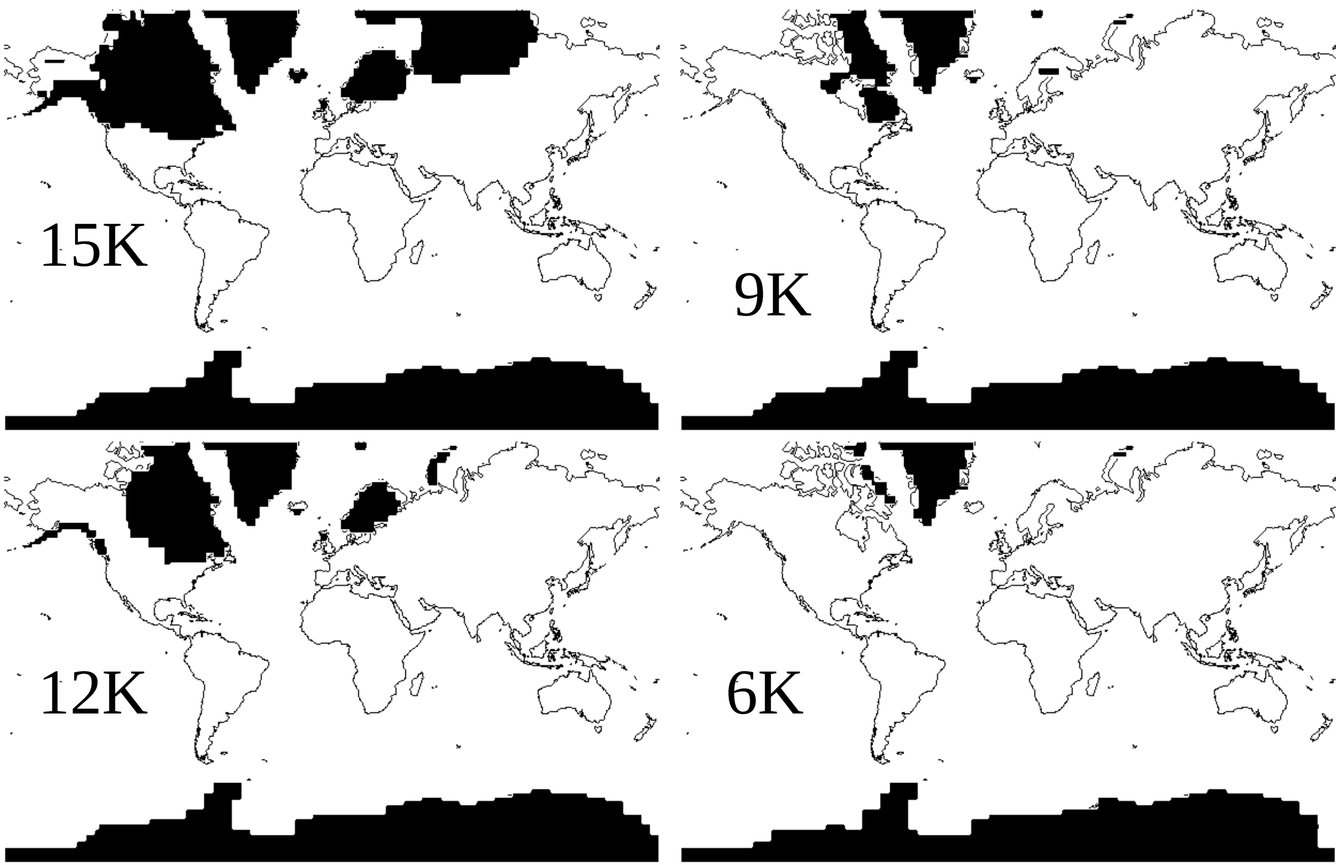
1. **Glacial-interglacial cycles**

Deep-sea record of δ18O (a measure of glacial ice volume) of seawater during the last 3 million years, as told by 2 bottom foram species in mid-latitude North Atlantic



Climate change over the last half million years have been characterized by growth and decay of huge land ice sheets over North America and Eurasia - ‘glacial-interglacial cycles’. The last glacial maximum was around 21,000 years ago, and a relatively rapid transition to interglacial conditions occurred around 12,000 years ago.





The maps show ice coverage from 18,000 years ago to 6,000 years ago (source: NOAA Paleoclimatology program).