Glaciers: The Work of Ice

- Ruth Glacier, Alaska

- What is a glacier?
- How do glaciers form?
  - How did Earth cool enough to form glaciers and warm enough to melt glacial ice?
- How do glaciers move?
- Glacial landscapes

What is a glacier?

- A mass of ice
  - Definite lateral limits
  - Motion in a definite direction
  - Originated from the compacting of snow by pressure

Valley or Alpine Glaciers

- Several glaciers, in Luane Nat'l Park, Yukon, Canada

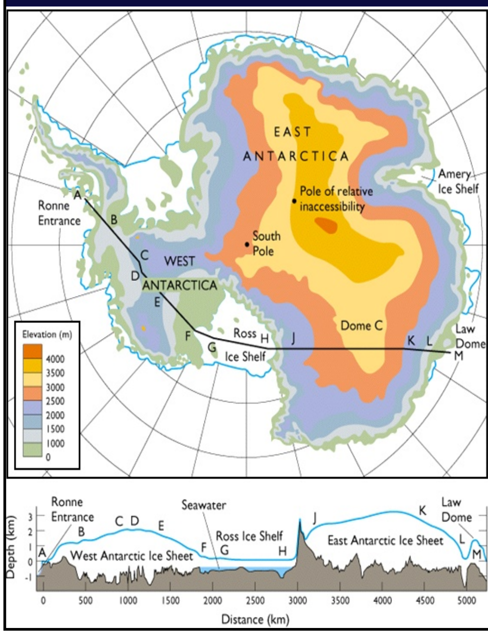
- Glacier occupying a depression or valley within or lying on a mountainous terrain
  - Usually occupies the complete width of a valley
  - Ice may be 100's meters thick
  - May be at head of valley or extend entire length of a mountain valley

Continental Glaciers

- Mountains poking through the Antarctica continental

- A slow moving ice sheet that covers a large part of a continent
- Polar continental glaciers different from ice caps
  - Most of the Arctic ice cap overlies water and is not a glacier
  - Virtually all of the Antarctic ice sheet covers land and is considered a glacier

Antarctic Ice Sheet



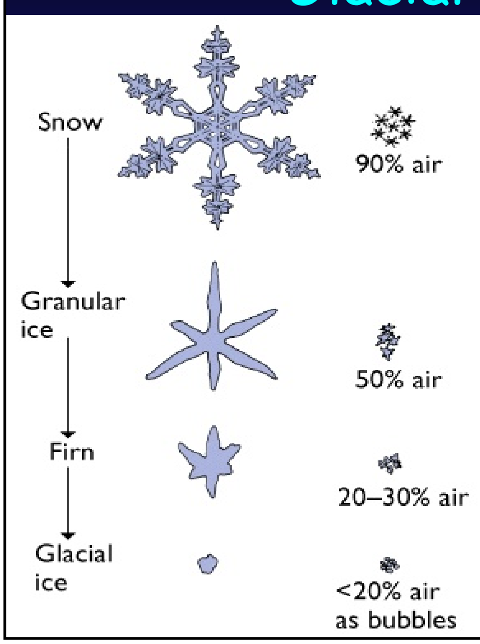
- 90% of Antarctica covered with thick accumulations of ice
- Ice forms dome in center and slopes down to margin
- Ice sheets may extend out into the Southern Ocean (*e.g.*, Ross Ice Shelf)

How Glaciers Form

- It must be cold!
  - Temperature low enough to keep snown on ground all year
    - Conditions found
      - High altitude
      - High latitude
- There must be snow!
  - Snowfall and glacier formation require moisture

Antarctic Dry Valleys

Glacial Growth

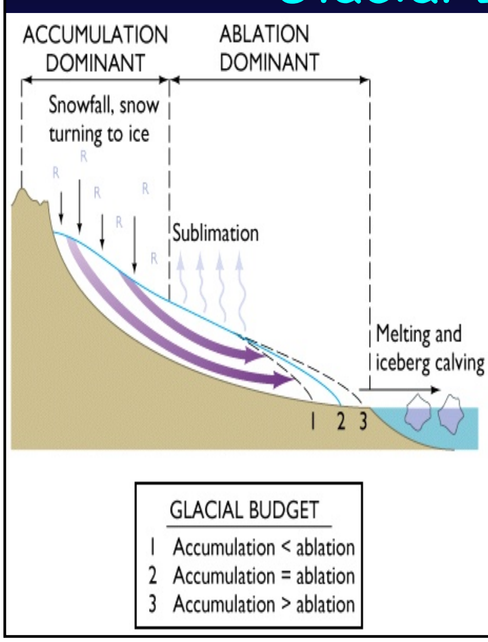


- A glacier accumulates when newly formed snow is transformed to glacial ice
  - Fresh snowfall is fluffy
  - Snow transformed to granular ice
  - As granular ice is buried, it turns into firn, a dense form of ice
  - Continued burial and aging transforms firn into glacial ice
    - Glacial ice is a mass of crystalline grains

Glacial Shrinkage

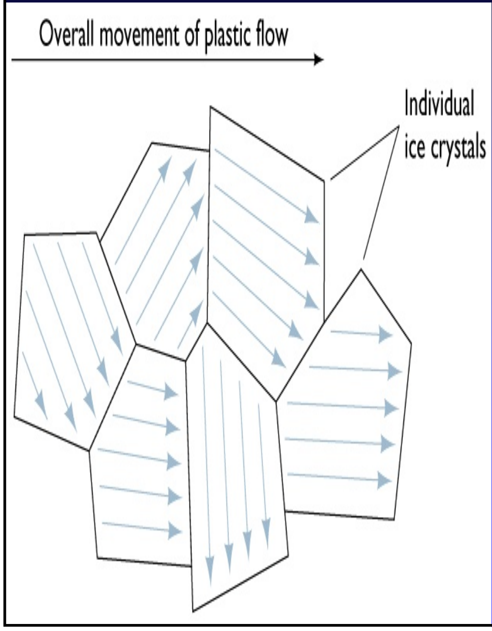
- Amount of ice a glacier loses each year is called ablation
- Four ways to lose ice:
  - Melting
  - Iceberg calving – pieces of ice that break off and form icebergs
  - Sublimation – transformation of ice directly to water vapor
  - Wind erosion – strong winds can promote melting and sublimation

Glacial Budgets



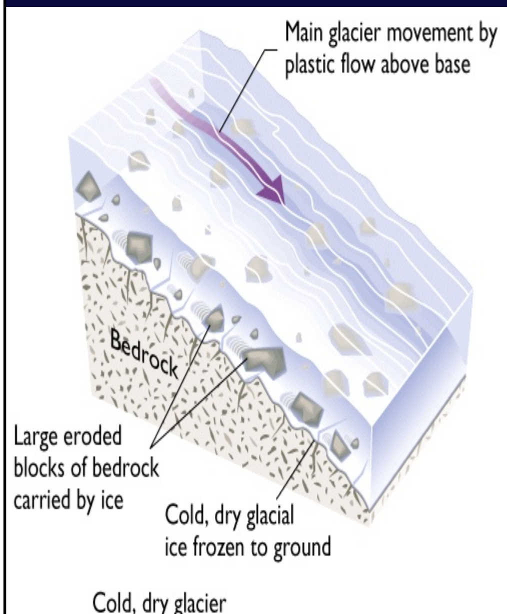
- Difference between accumulation and ablation is the glacial budget
  - When accumulation = ablation, size of glacier constant
  - If accumulation exceeds ablation, the glacier grows
  - If accumulation is less than ablation, the glacier shrinks

Plastic Flow



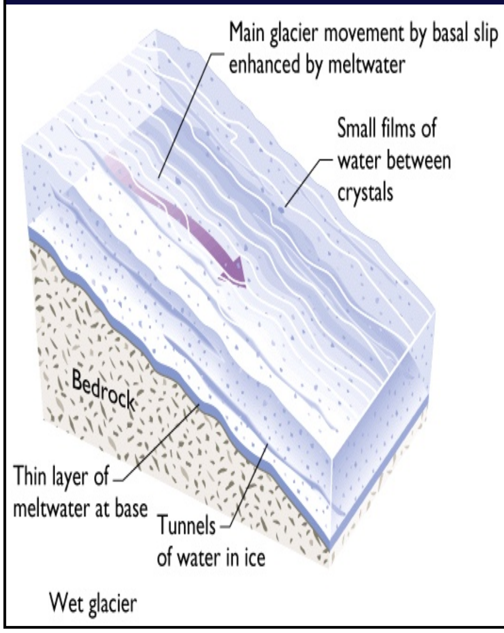
- Great pressure exists at base of glacier
- Under great pressure, ice crystals slip
- Slip along large numbers of ice crystals results in movement of glaciers down slope
- Slipping movement known as *plastic flow*

Plastic Flow



- Plastic flow is common in cold, dry glaciers
- Basal ice frozen to ground
- Movement of ice can only take place above the base by plastic deformation
- The little movement along base rips up bedrock and soil

Basal Slip

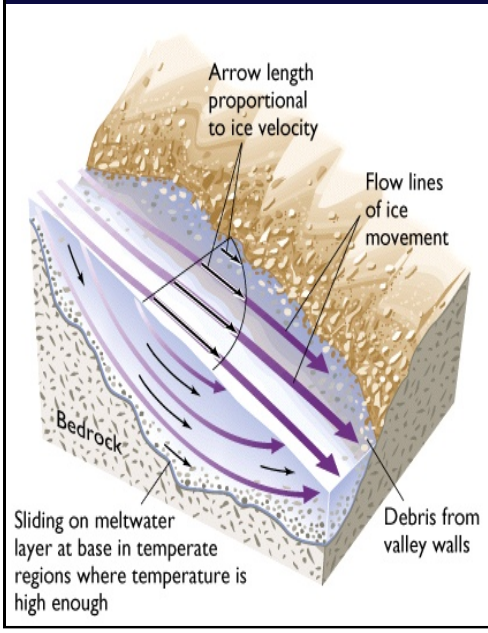


- Movement along the base of glaciers known as *basal slip*
- Weight of ice causes melting at base of glacier
  - Water from melting acts as a lubricant
- Occurs in glaciers in moderately cold areas
- Lake Vostock, a lake under the ice 14,000 km^2

Crevasses

- Upper parts of even "wet" glaciers is cold
- Ice at top of glacier acts as a rigid, brittle solid that cracks
- Cracks are called crevasses
  - Break up surface ice into large and small blocks

Flow Patterns in Ice



- Valley glaciers move at speed which vary with
  - Depth of ice
  - Position relative to valley wall
- Fastest movement in center of glacier
  - Frictional forces weak
- Slowest movement at edge of glacier
  - Frictional forces strong

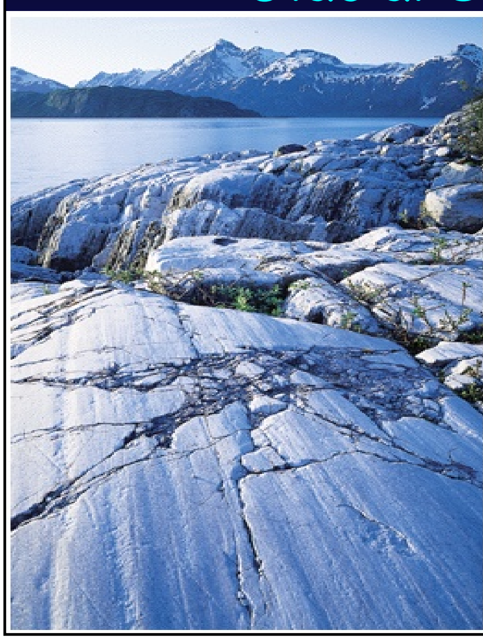
Other Mechanisms of Flow

- Ice Streams
  - Melt water mixed with glacial sediment at base of glacier
- Surges
  - Rapid period of fast movement
    - Up to 100 m/y
- Flow in continental glaciers
  - Highest rates of movement in center
    - Pressure in center greatest
    - Friction in center lowest

Glacial Erosion and Glacier Landforms

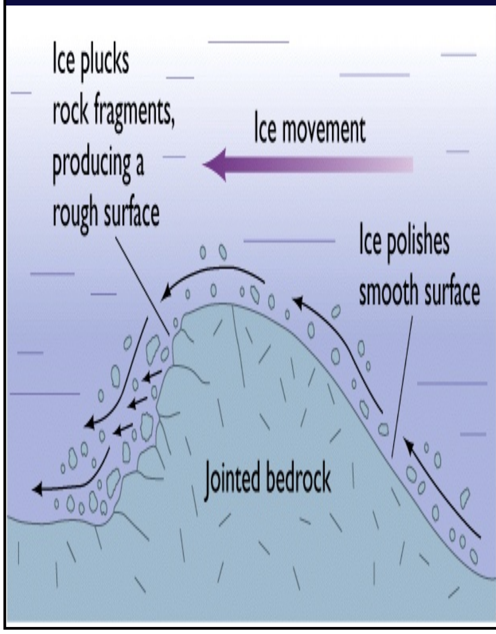
- High capacity to erode (crush and pulverize) solid rock
- Transport eroded rock down stream more efficiently than water and wind
  - Ice picks up sediment and carries it great distances
  - Competence (ability to carry sediment of certain size) and capacity (total amount of sediment transported) is very high

Glacial Striations



- Rocks dragged along base of glacier scratch or grove bedrock
- Abrasions called striations
- Strong evidence of glacial movement
- Provide direction of movement of glaciers

Roches Moutonees

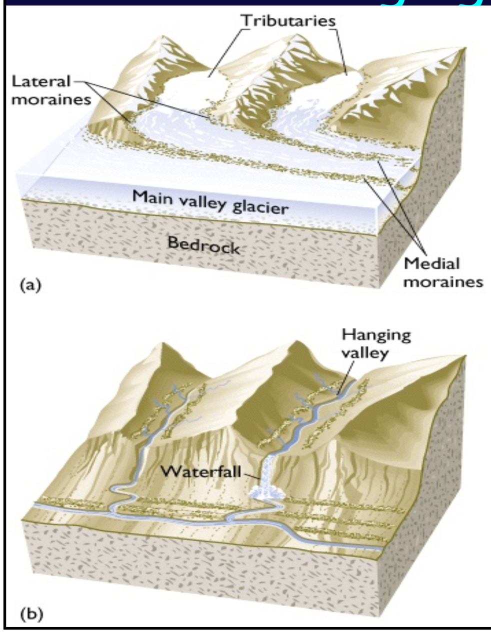


- Roches mountonees (sheep rock) are small hills of bedrock
- Ice smoothes and polishes the up-current side of hill
- Ice plucks rocks from down-stream side of hill
- Indicates direction of movement of glacier

Cirque and Aretes

- Plucking and tearing of head of valley carves an amphitheater-shaped valley called a cirque
- When cirques meet the mountain top, sharp knife-edge jagged ridges called aretes are formed
- Pyramid-like peaks are called horns

Hanging Valleys

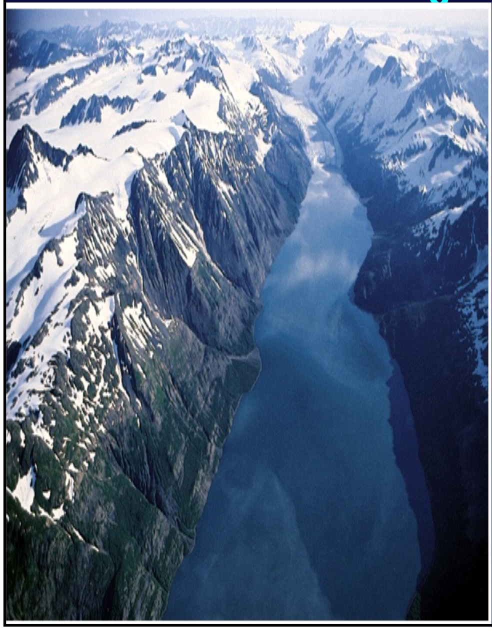


- Melting of ice in a cirque produces a valley that appears to be hanging
- Usually common where a smaller valley glacier meets a larger alpine glacier

U-Shaped Valleys

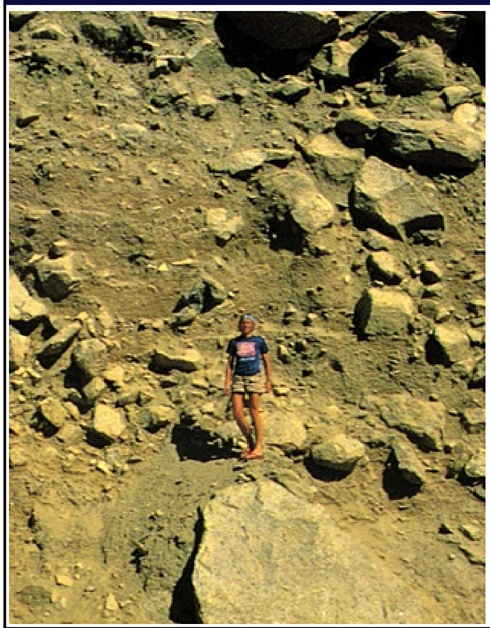
- Excavation by a glacier produces a U-shaped valley
  - Floor of valley is flat whereas walls are steep
- In contrast, erosion by streams produce a V-shaped valley

Fjords



- During glacial times sea level is low
- Valley glaciers at coastlines can erode bedrock below even glacial sea level
- When ice retreats. The U-shaped valley becomes flooded producing a fjord

Glacial Sediment



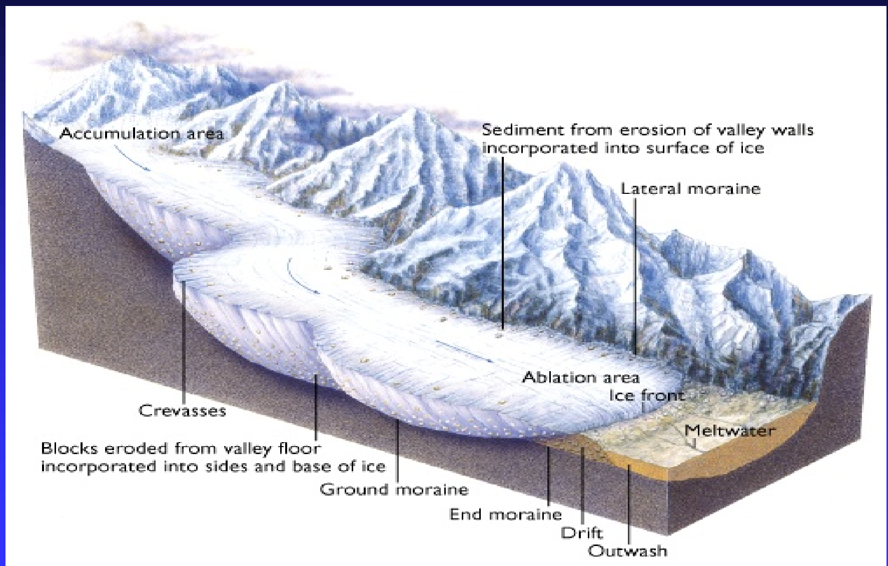
- When glacial ice melts, the heterogeneous load of sediment is released
- This poorly sorted glacial sediment is generally known as drift
- Till is the unstratified and unsorted sediment deposited directly from melting ice
- May contain large boulders called erratics

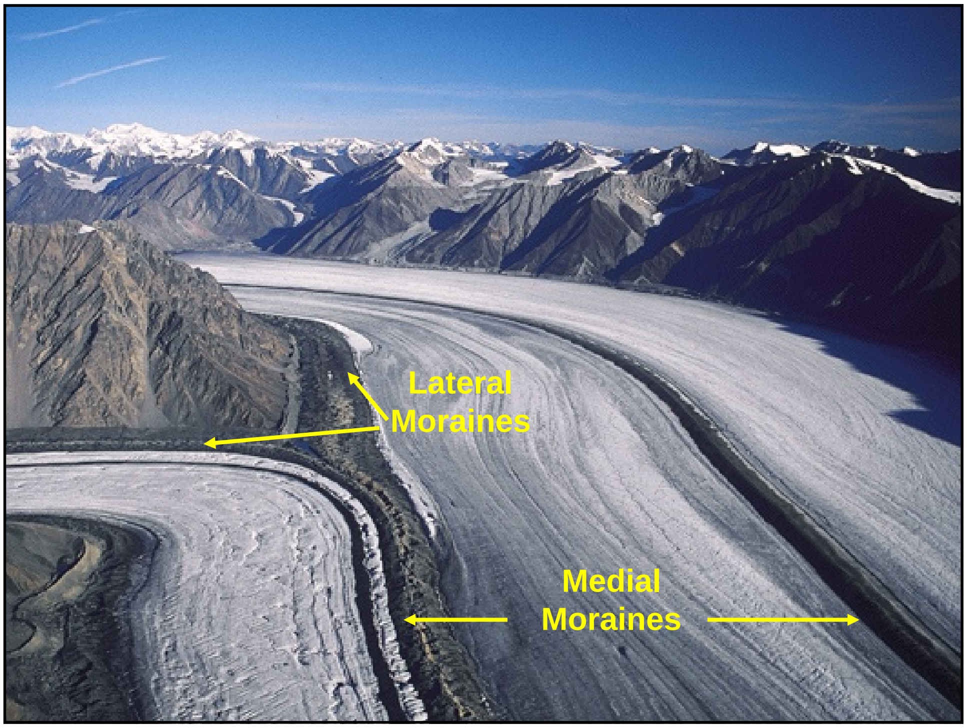
Ice-Laid Deposits

Table 15.1 Glacial Moraines

Type of Moraine	Location with Respect to Ice Front	Comments
End moraine	At ice front	After glacier melts, seen as ridge parallel to former ice front
Terminal moraine	At ice front marking farthest advance of ice (an end moraine)	See End moraine
Lateral moraine	Along the edge of glacier where it scrapes side walls of valley	Heavy sediment load eroded from valley walls; when ice melts, seen as ridge parallel to valley walls
Medial moraine	Formed as two joining glaciers merge their lateral moraines below junction	Sediment load inherited from lateral moraines that formed it; forms ridge parallel to valley walls
Ground moraine	Beneath the ice as a layer of glacial debris	Ranges from thin and patchy to a thick blanket of till

Glacial Moraines





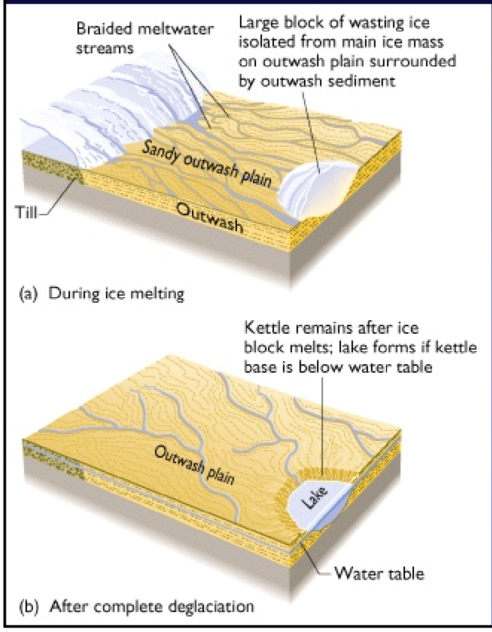
Drumlins

- Large (25 – 50 m high, 1 km long) streamlined hills consisting of glacial till and bedrock are called drumlins
- Indicate direction of glacial movement
- Produced when plastic flow of sub-glacial mixtures of ice and sediment encounters an obstacle
  - Water is lost and sediment deposited

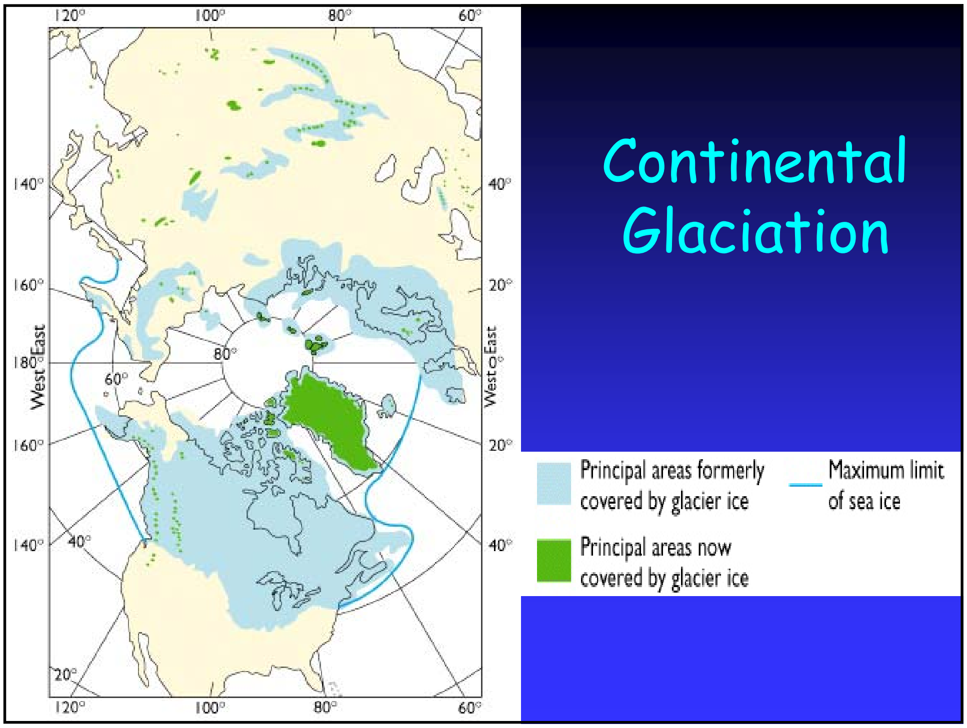
Water-Laid Glacial Deposits

- Kames
  - Small hills of sand and gravel deposited my melting ice at edge of ice
- Eskers
  - Long narrow winding ridges of well-sorted sand and gravel found in middle of ground moraines
    - Sorting implies deposition from sub-glacial streams
- Kettles
  - Undrained depressions formed by melting ice

Kettle Lakes



- Large blocks of ice may be left by retreating glacier
- Large blocks of ice may take many years to melt leaving behind a depression in out wash plain
- If bottom of depression is below groundwater table, a lake develops



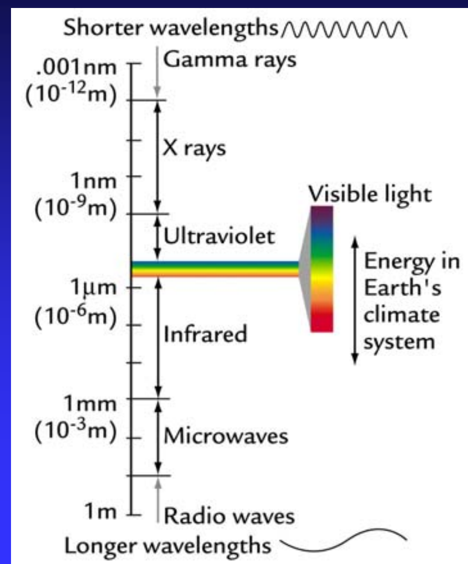
Continental Glaciation

Earth's Climate System Today

- Heated by solar energy
- Tropics heated more than poles
  - Imbalance in heating redistributed
- Solar heating and movement of heat by oceans and atmosphere determines distribution of:
  - Temperature
  - Precipitation
  - Ice
  - Vegetation

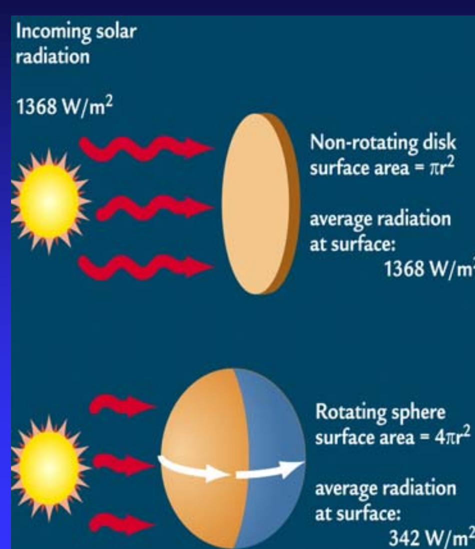
Electromagnetic Spectrum

- Electromagnetic energy travels through space
- Energy heating Earth mostly short-wave radiation
  - Visible light
  - Some ultraviolet radiation



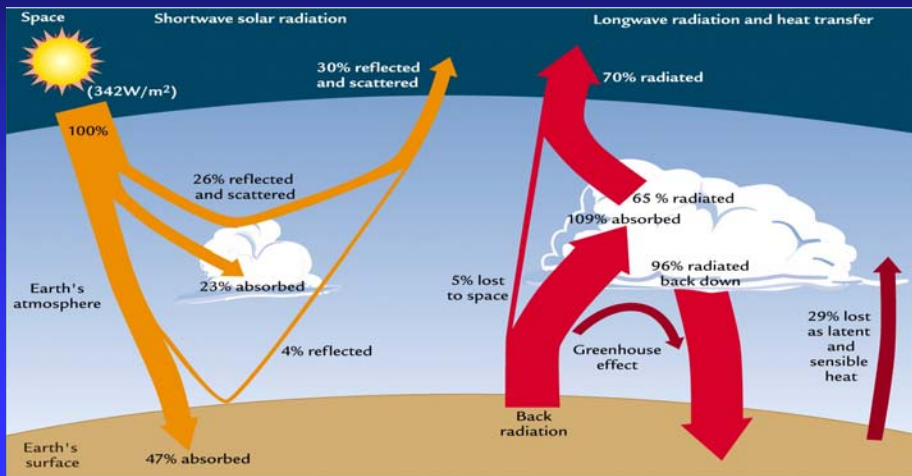
Incoming Solar Radiation

- Radiation at top of Earth's atmosphere = 1368 W m^{-2}
- If Earth flat disk with no atmosphere, average radiation = 1368 W m^{-2}
- Earth 3-dimensional rotating sphere,
  - Area = $4\pi r^2$
  - Average solar heating = 1368 ÷ 4 = 342 W m^{-2}



30% Solar Energy Reflected

- Energy reflected by clouds, dust, surface
  - Ave. incoming radiation 0.7 x 342 = 240 W m^{-2}



Energy Budget

- Earth's temperature constant ~15°C
  - Energy loss must = incoming energy
    - Earth is constantly receiving heat from Sun, therefore must lose equal amount of heat back to space
- Heat loss called back radiation
  - Wavelengths in the infrared (long-wave radiation)
- Earth is a radiator of heat
  - If T > 1°K, radiator of heat

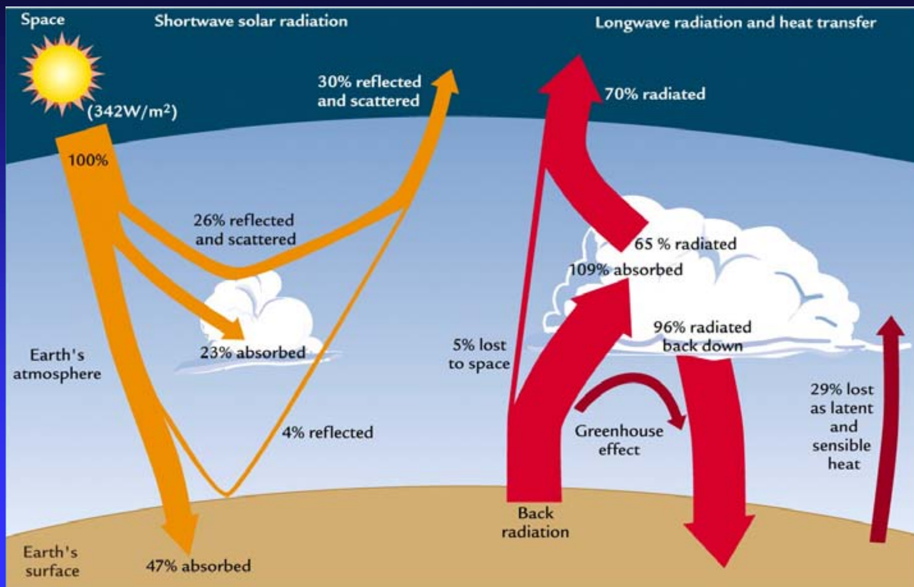
Energy Budget

- Average Earth's surface temperature ~15°C
- Reasonable assumption
  - Surface of earth radiates heat with an average temperature of 15°C
- However, satellite data indicate Earth radiating heat average temperature ~-16°C
- Why the discrepancy?
  - What accounts for the 31°C heating?

Energy Budget

- Greenhouse gases absorb 95% of the long-wave, back radiation emitted from Earth's surface
  - Trapped radiation reradiated down to Earth's surface
  - Accounts for the 31°C heating
  - Satellites don't detect radiation
  - Muffling effect from greenhouse gases
- Heat radiated back to space from elevation of about 5 km (top of clouds) average 240 W m^{-2}
  - Keeps Earth's temperature in balance

Energy Balance

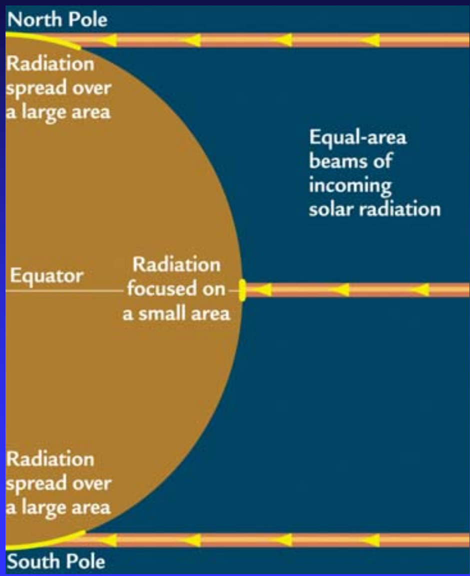


Greenhouse Gases

- Water vapor ($H_2O_{(v)}$, 1 to 3%)
- Carbon dioxide (CO_2, 0.039%; 389 ppmv)
- Methane (CH_4, 0.00019%; 1.87 ppmv)
- Nitrous oxide (N_2O, 0.00000323%; 323 ppbv)
- Clouds also trap outgoing radiation

Variations in Heat Balance

- Incoming solar radiation
  - Stronger at low latitudes
  - Weaker at high latitudes
- Tropics receive more solar radiation per unit area than Poles



Variations in Heat Balance

- What else affects variation in heat balance?
- Solar radiation arrives at a low angle
- Snow and ice reflect more radiation at high latitudes
- Albedo
  - Percentage of incoming solar radiation that is reflected rather than absorbed

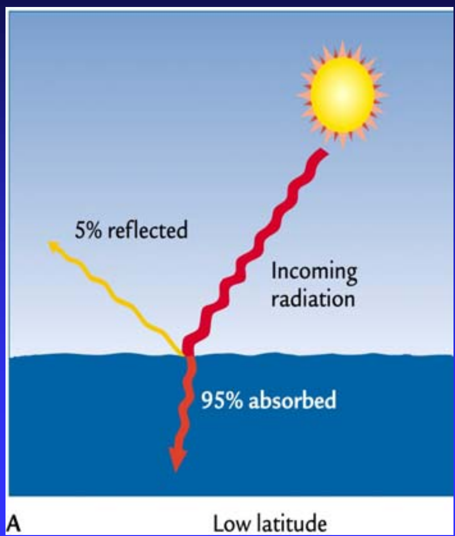
Average Albedo

TABLE 2-1 Average Albedo Range of Earth's Surfaces

Surface	Albedo range (percent)
Fresh snow or ice	60–90%
Old, melting snow	40–70
Clouds	40–90
Desert sand	30–50
Soil	5–30
Tundra	15–35
Grasslands	18–25
Forest	5–20
Water	5–10

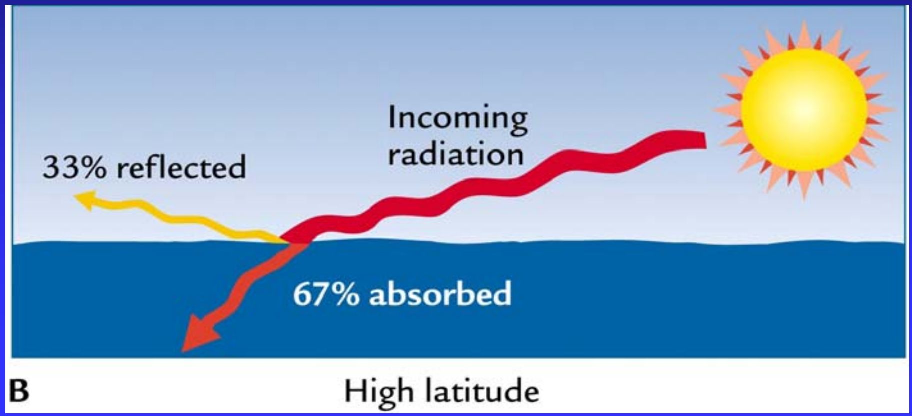
Sun Angle Affects Albedo

- All of Earth's surfaces absorb more solar radiation from an overhead sun
- Water reflects <5% radiation from an overhead Sun



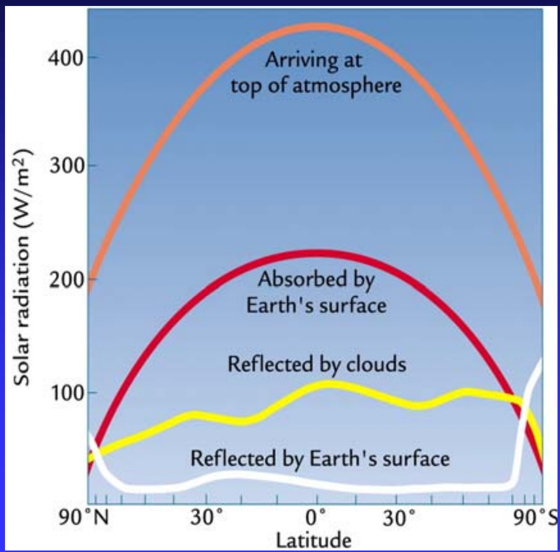
Sun Angle Affects Albedo

- Water reflects a high fraction of radiation from a low-lying Sun
- Earth average albedo = 10%



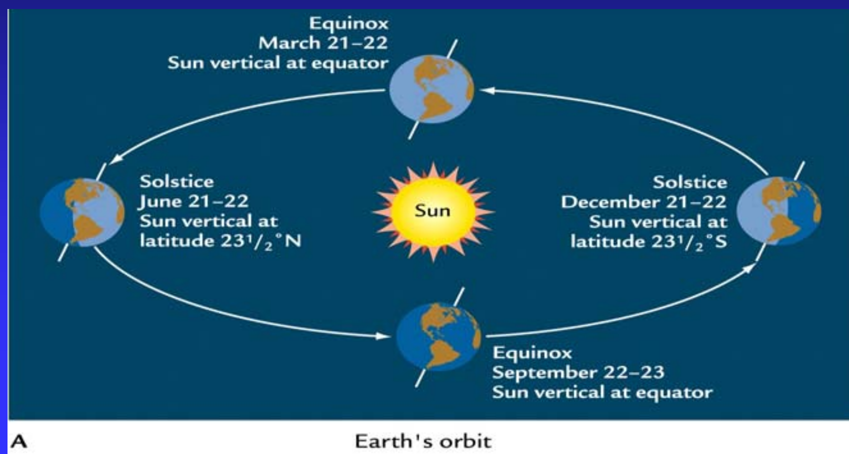
Pole-to-Equator Heat Imbalance

- Incoming solar radiation per unit area higher in Tropics than Poles
- Sun angle higher in Poles than Tropics
- Albedo higher at Poles than Tropics
- Variations in cloud cover affect heat imbalance

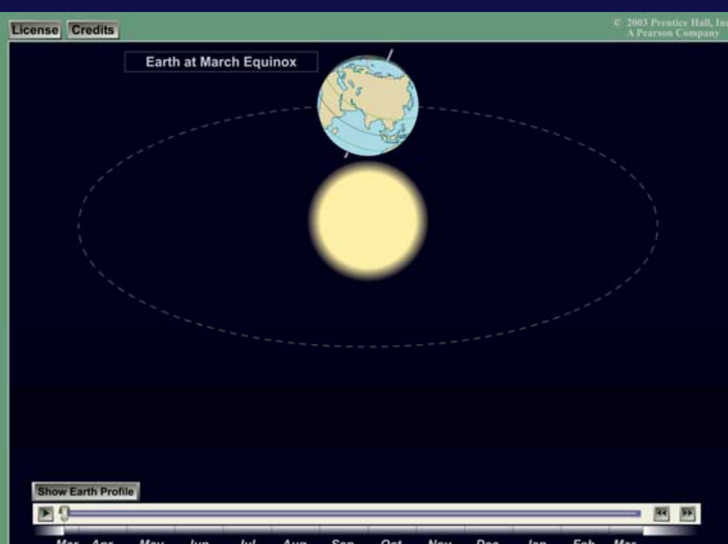


Seasonal Change in Solar Radiation & Albedo

- Tilt of Earth's axis results in seasonal change in
  - Solar radiation in each hemisphere
  - Snow and ice cover (albedo)

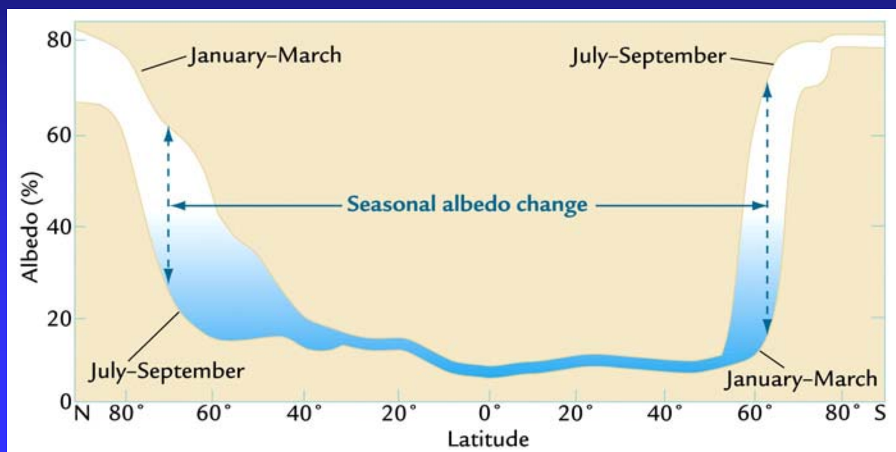


Earth-Sun Relations



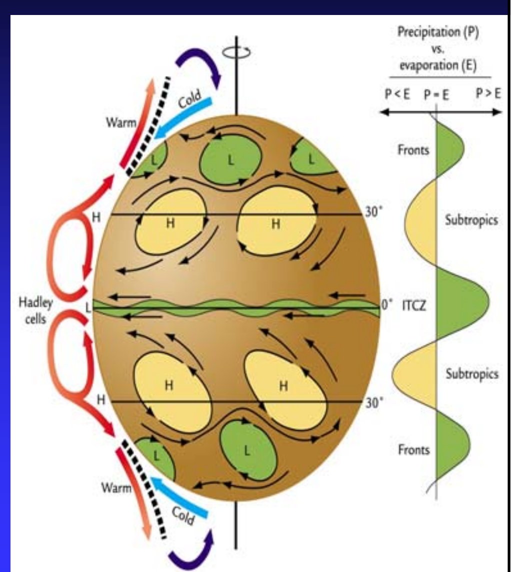
Seasonal Change in Albedo

- Increases in N. hemisphere winter due mainly to snow cover and to lesser degree Arctic sea ice
- Increases in S. hemisphere winter due to sea ice



General Circulation of the Atmosphere

- Tropical heating drives Hadley cell circulation
- Warm wet air rises along the equator
  - Transfers water vapor from tropical oceans to higher latitudes
  - Transfers heat from low to high latitudes



The Hadley Cell

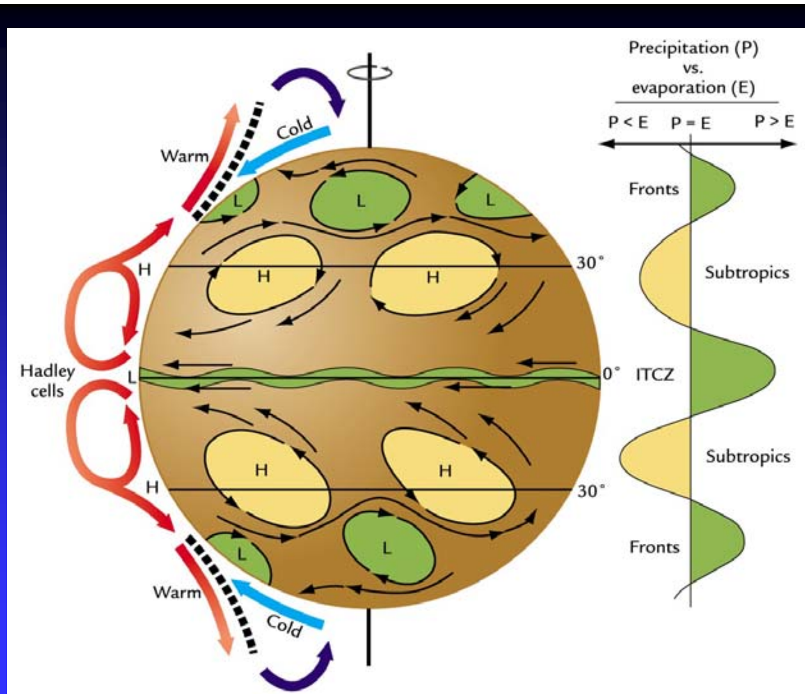
- Along equator, strong solar heating causes air to expand upward and diverge to poles
- Creates a zone of low pressure at the equator called
  - Equatorial low
  - Intertropical Convergence Zone (ITCZ)
- The upward motions that dominate the region favor formation of heavy rainfall
  - ITCZ is rainiest latitude zone on Earth
    - Rains 200 days a year – aka. *doldrums*

General Circulation

- Air parcels rise creating low pressure
  - Heat and expand
  - Become humid
- Transfer heat to poles
- Transfer of moisture towards poles
- In mid latitudes
  - Dry air sinks creating high pressure
  - Air flows away from high pressure

General Circulation

- Hadley cell circulation creates trade winds
  - Dry trade winds move from subtropics to tropics and pick up moisture
- Trade winds from both hemispheres converge in the ITCZ
  - Trade winds warm and rise
  - Contribute to low pressure and high rainfall in the ITCZ



Ocean Circulation?

- Circulation in the troposphere is caused by atmospheric pressure gradients
  - Result from vertical or horizontal temperature differences
  - Temperature variations caused by latitudinal differences in solar heating
- Ocean surfaces are heated by incoming surface radiation
- Do the oceans circulate for the same reason as the atmosphere?

No!

- 90% of solar radiation that penetrates oceans absorbed in upper 100 m
- Warm water at surface is less dense than the colder water below
  - Water column is inherently stable
  - Very little vertical mixing
- Water has a high heat capacity
  - Lots of heat required for a small change in temperature
  - Lateral temperature and salinity differences are small over large areas

Ocean Circulation

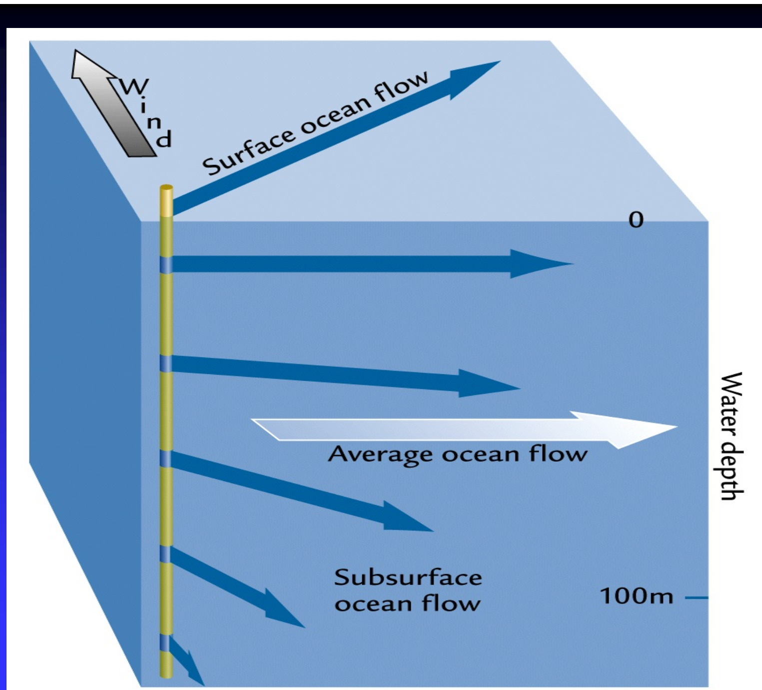
- Ultimately driven by solar energy
  - Distribution of solar energy drives global winds
  - Latitudinal wind belts produce ocean currents
    - Determine circulation patterns in upper ocean
  - Distribution of surface ocean temperatures strongly influence density structure
    - Density structure of oceans drives deep ocean circulation
- Negative feedback
  - Surface temperature gradients drive circulation
  - Net effect is to move warm water to poles and cold water towards tropics

Heat Transfer in Oceans

- Heating occurs in upper ocean
- Vertical mixing is minimal
  - Average mixed layer depth ~100 m
- Heat transfer from equator to pole by ocean currents
- Oceans redistribute about half as much heat at the atmosphere

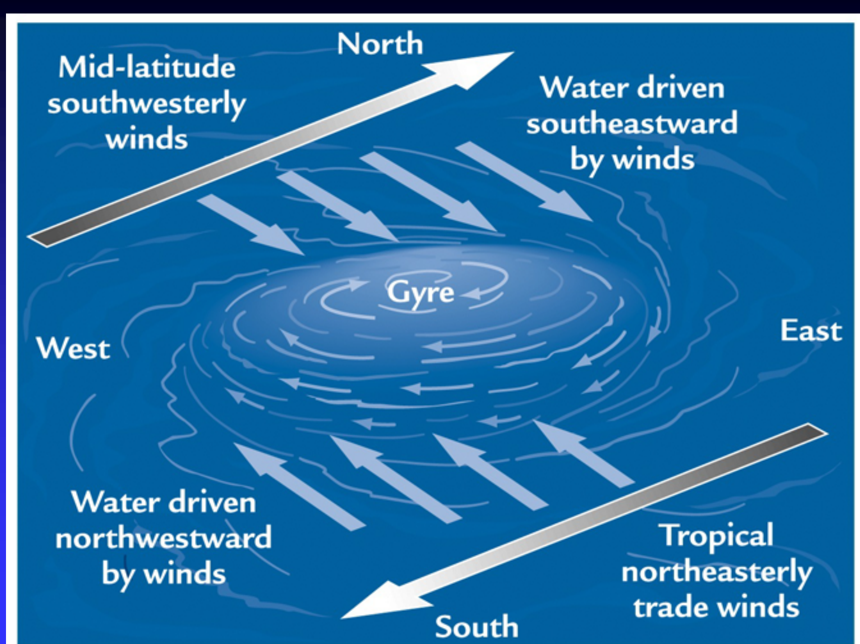
Surface Currents

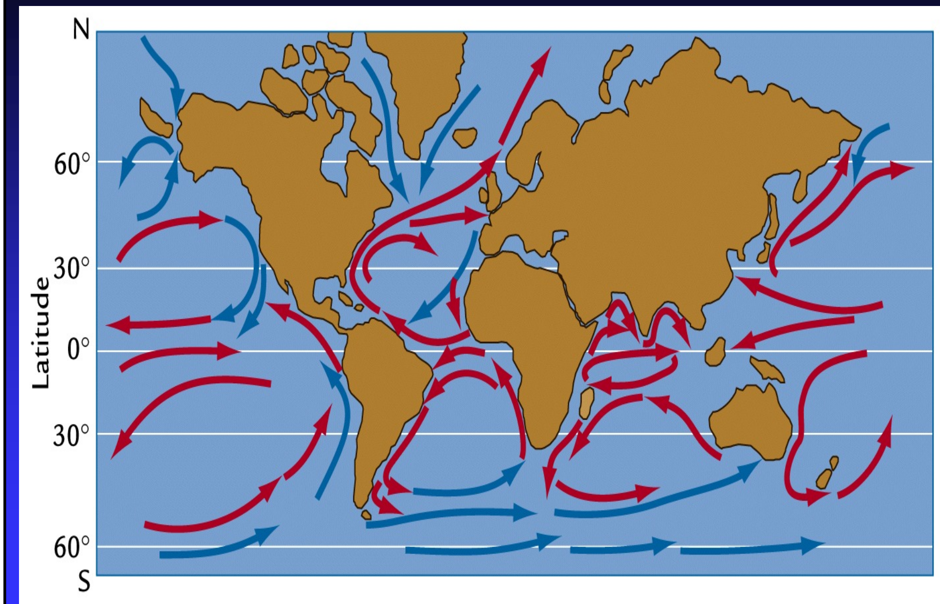
- Surface circulation driven by winds
  - As a result of friction, winds drag ocean surface
- Water movement confined to upper ~100 m
  - Although well-developed currents ~1-2 km
  - Examples, Gulf Stream, Kuroshiro Current
- Coriolis effect influences ocean currents
  - Water deflected to right in N. hemisphere
  - Water deflected to left in S. hemisphere



Eckman Spiral

- Eckman theory predicts
  - 1) surface currents will flow at 45° to the surface wind path
  - 2) flow will be reversed at ~100 m below the surface
  - 3) flow at depth will be considerably reduced in speed
- Few observations of true Eckman Spiral
  - Surface flow <45°, but still to an angle





Deep Ocean Circulation

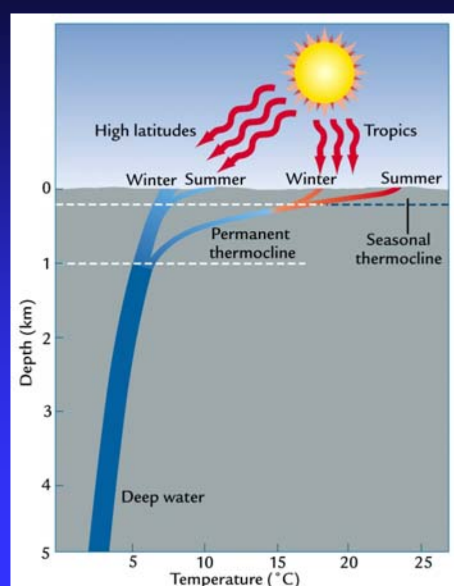
- Driven by differences in density
- Density of seawater is a function of
  - Water temperature
  - Salinity
    - Quantity of dissolved salts
      - Chlorine
      - Sodium
      - Magnesium
      - Calcium
      - Potassium

Thermohaline Circulation

- Deep ocean circulation depends on temperature (*thermo*) & salinity (*hals*)
  - Controls seawater density
    - Density increases as:
      - Salinity increases
      - Temperature decreases
- Horizontal density changes small
- Vertical changes not quite as small
  - Water column is stable
    - Densest water on bottom
  - Flow of water in deep ocean is slow
    - However, still important in shaping Earth's climate

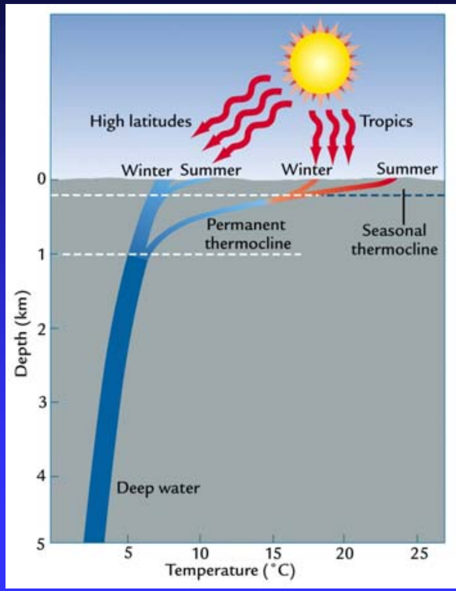
Vertical Structure of Ocean

- Surface mixed layer
  - Interacts with atmosphere
  - Exchanges kinetic energy (wind, friction) and heat
  - Typically well mixed (20-100 m)



Vertical Structure of Ocean

- Pychnocline (~1 km)
  - Zone of transition between surface and deep water
  - Characterized by rapid increase in density
    - Some regions density change due to salinity changes – halocline
    - Most regions density change due to temperature change – thermocline
  - Steep density gradient stabilizes layer



Bottom Water Formation

- Deep-ocean circulation begins with production of dense (cold and/or salty) water at high latitudes
- Ice formation in Polar oceans excludes salt
  - Combination of cold water and high salinity produces very dense water
  - Dense water sinks and flows down the slopes of the basin towards equator

Antarctic Bottom Water (AABW)

- Weddell Sea major site of AABW formation
- AABW circles Antarctica and flow northward as deepest layer in Atlantic, Pacific and Indian Ocean basins
- AABW flow extensive
  - 45°N in Atlantic
  - 50°N in Pacific
  - 10,000 km at 0.03-0.06 km h^{-1}; 250 y

North Atlantic Deep Water (NADW)

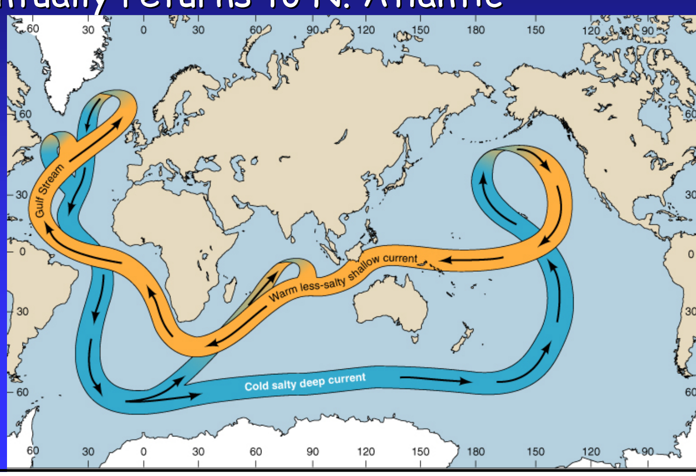
- Coastal Greenland (Labrador Sea) site of NADW formation
- NADW comprises about 50% of the deep water to worlds oceans
- NADW in the Labrador Sea sinks directly into the western Atlantic
  - NADW forms in Norwegian Basins
    - Sinks and is dammed behind sills
      - Between Greenland and Iceland and Iceland and the British Isles
    - NADW periodically spills over sills into the North Atlantic

Ocean Circulation

- Surface water at high latitudes forms deep water
- Deep water sinks and flows at depth throughout the major ocean basins
- Deep water upwells to replace the surface water that sinks in polar regions
- Surface waters must flow to high latitudes to replace water sinking in polar regions
- Idealized circulation – Thermohaline Conveyer Belt

Thermohaline Conveyor Belt

- NADW sinks, flows south to ACC and branches into Indian and Pacific Basins
- Upwelling brings cold water to surface where it eventually returns to N. Atlantic



Ocean Circulation and Climate

- Warm surface waters move from equator to poles transferring heat pole-ward and into the deep oceans
- Oceans vast reservoir of heat
  - Water heats and cools slowly
  - Pools of water warmer than normal heat the atmosphere
  - Pools of water colder than normal cool the atmosphere
  - Timescale of months to years
    - Time needed for heating/cooling of water

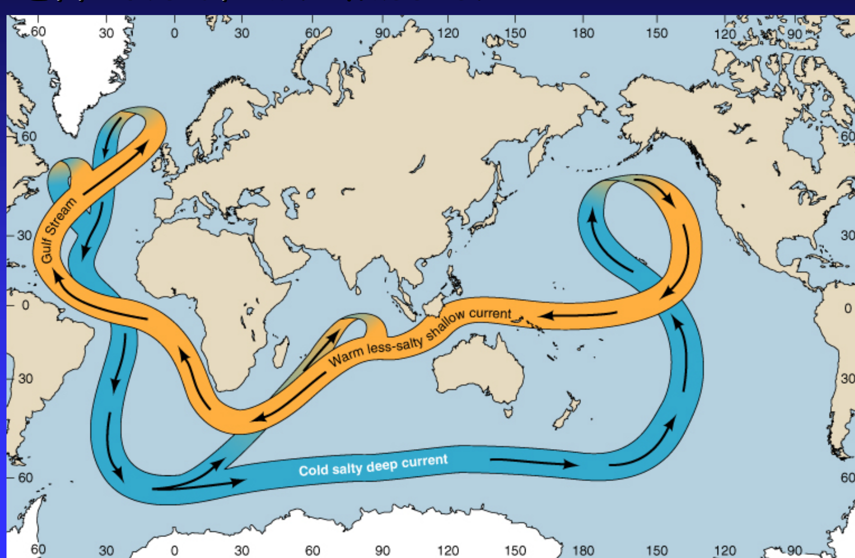
Ocean Circulation and Climate

- On long timescales, average ocean temperature affects climate
- Most water is in deep ocean
  - Average temperature of ocean is a function of
    - Process of bottom-water formation
    - Transport of water around ocean basins
- Deep water recycle times is ~1000 y
  - Thermohaline circulation moderates climate over time periods of ~ 1000 y

Ocean Circulation and Climate

Thermohaline Conveyor Belt

- Effects of landmasses?

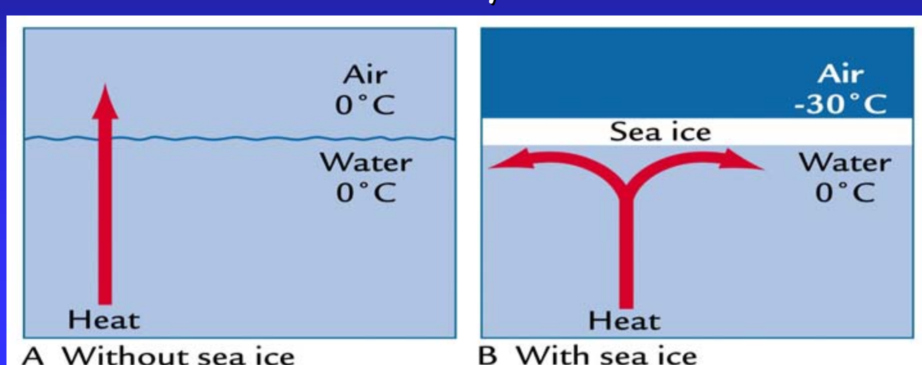


Ice on Earth

- Important component of climate system
- Ice properties are different from water, air and land
  - Two important factors affecting climate
    - High albedo
    - Latent heat stored in ice

Sea Ice

- Salt rejection during sea ice formation
  - Important for bottom water formation
- Sea ice stops atmosphere from interacting with surface mixed layer

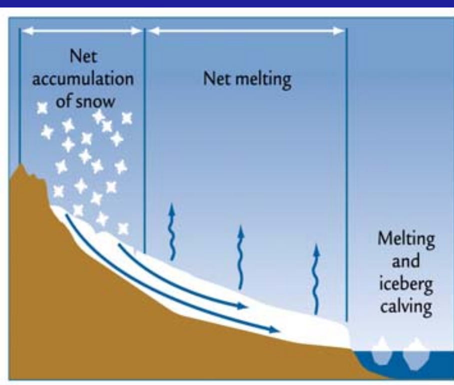


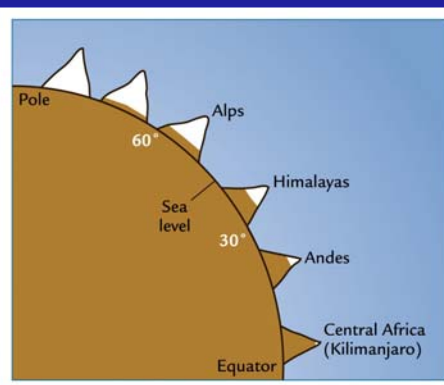
Sea Ice Distribution

- Most sea ice in Southern Ocean
  - Enormous amount form and melt each season
  - Average thickness ~1 m
- Landmasses in Arctic prevent sea ice movement
  - Arctic sea ice persists for 4-5 years
  - Reach thickness of 4 m in central Arctic and 1 m on margins

Glacial Ice

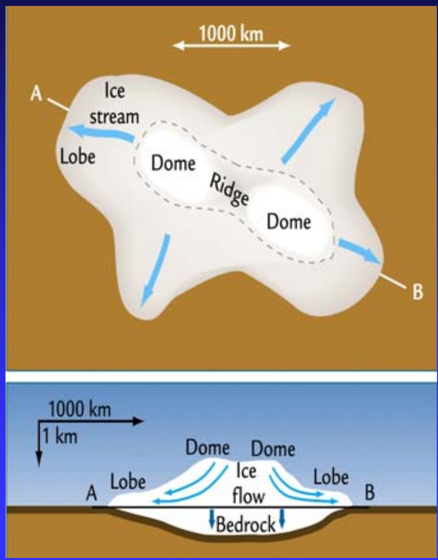
- Mountain glaciers
  - Equatorial high altitude or polar lower altitude
  - Few km long, 100's m wide and 100's m thick





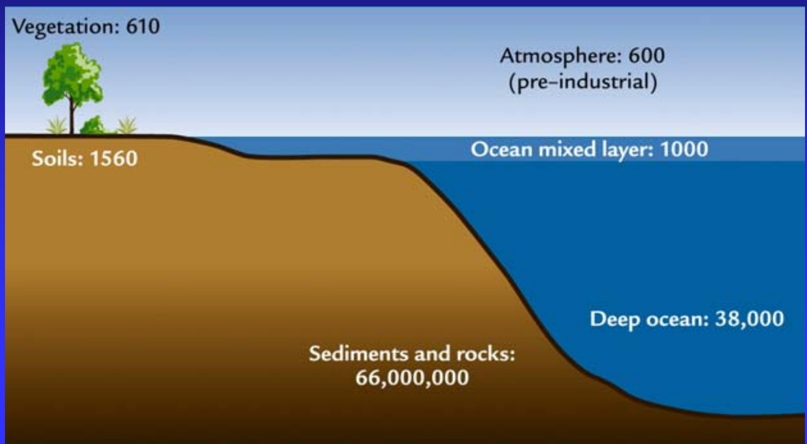
Glacial Ice

- Continental ice sheets
  - Large ice cube
  - Existing ice sheets
    - Antarctica and Greenland
      - ~3% of Earth's surface or 11% of land surface
      - 32 million km^3 (= 70 m of sea level)



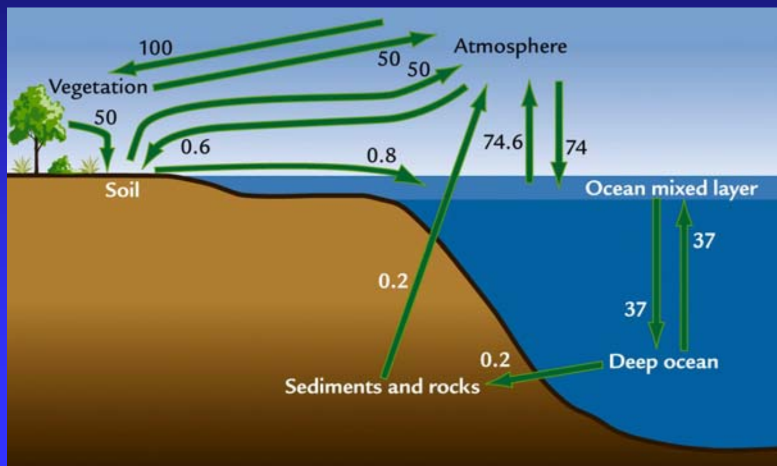
Earth's Biosphere

- Interaction of physical processes in Earth's climate system with biosphere
  - Results from the movement of carbon



Carbon Cycle

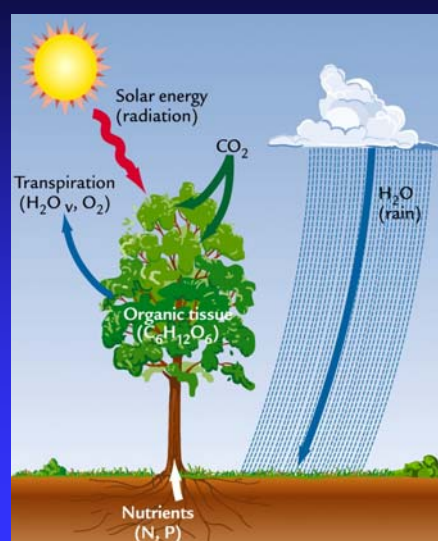
- Carbon moves freely between reservoirs
  - Flux inversely related to reservoir size



Photosynthesis

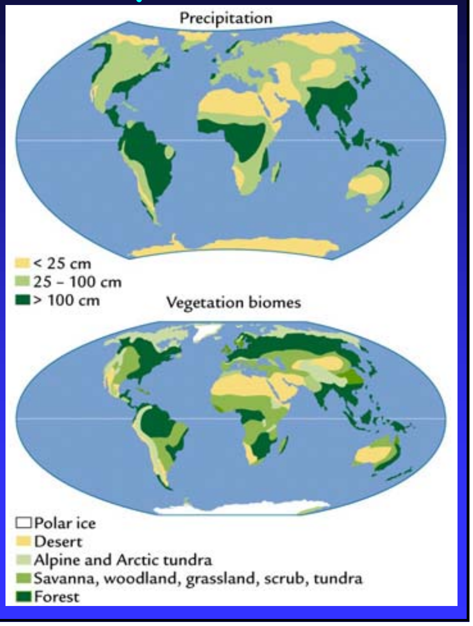
$$6CO_2 + 6H_2O \underset{oxidation}{\overset{photosynthesis}{\rightleftharpoons}} C_6H_{12}O_6 + 6O_2$$

- Sunlight, nutrients, H_2O
- Transpiration in vascular plants
  - Efficient transfer of $H_2O(v)$ to atmosphere
- Oxidation of C_{org}
  - Burning
  - Decomposition



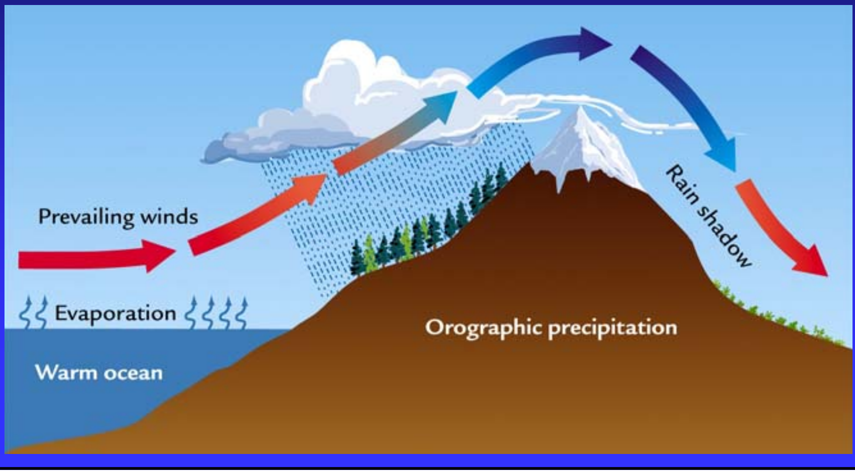
Terrestrial Photosynthesis

- CO_2 and sunlight plentiful
- H_2O and correct temperature for specific plants not always sufficient
- Biomass and biome distribution controlled by rainfall and temperature



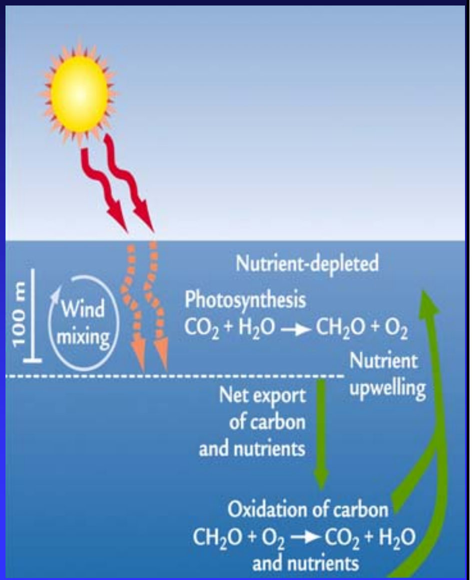
Local Influence on Precipitation

- Orographic precipitation influences distribution of biomass and biomes
- Influences the distribution of precipitation



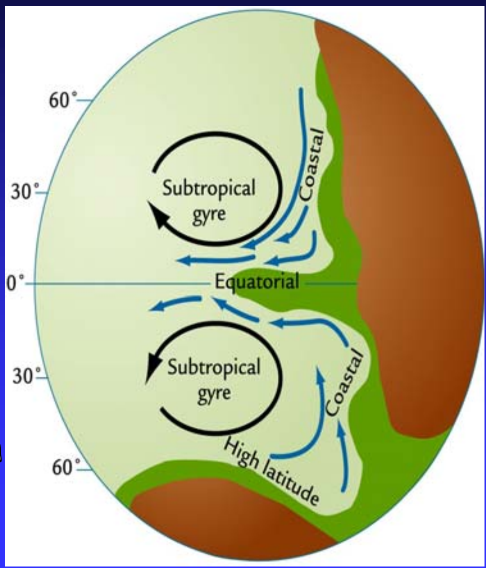
Marine Photosynthesis

- H_2O, CO_2 and sunlight plentiful
- Nutrients low (N, P)
- Nutrients extracted from surface water by phytoplankton
- Nutrients returned by recycling
  - Upper ocean (small)
  - Upwelling (high)
  - External inputs (rivers, winds)



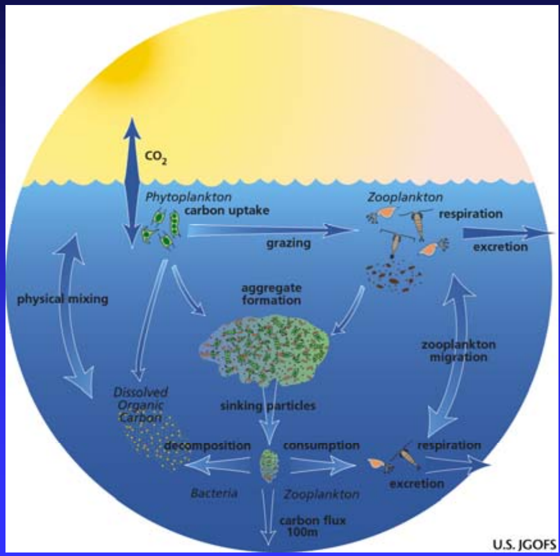
Ocean Productivity

- Related to supply of nutrients
- Nutrient supply high in upwelling regions
  - Equatorial upwelling
  - Coastal upwelling
- Southern Ocean
  - Wind-driven mixing
  - Short growing season
  - Light limitation



Productivity – Climate Link

- "Biological Pump" – photosynthesis takes up CO_2 and nutrients, plants eaten by zooplankton, dead zooplankton or excreted matter sinks carrying carbon to sediments

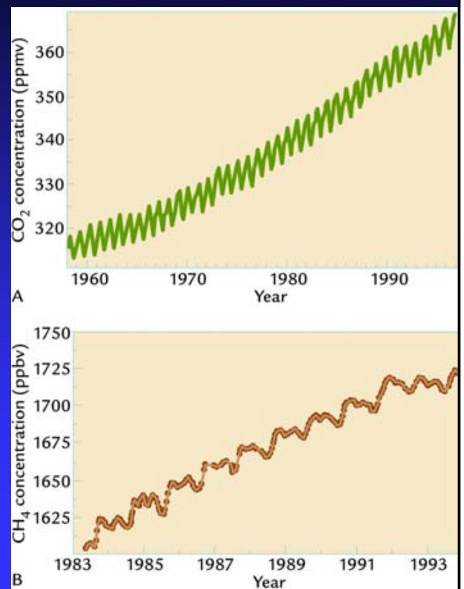


Effect of Biosphere on Climate

- Changes in greenhouse gases (CO_2, CH_4)
- Slow transfer of CO_2 from rock reservoir
  - Does not directly involve biosphere
  - 10-100's millions of years
- CO_2 exchange between shallow and deep ocean
  - 10,000-100,000 year
- Rapid exchange between ocean, vegetation and atmosphere
  - Hundreds to few thousand years

Increases in Greenhouse Gases

- CO_2 increase anthropogenic and seasonal
  - Anthropogenic – burning fossil fuels and deforestation
  - Seasonal – uptake of CO_2 in N. hemisphere terrestrial vegetation
- Methane increase anthropogenic
  - Rice patties, cows, swamps, termites, biomass burning, fossil fuels, domestic sewage



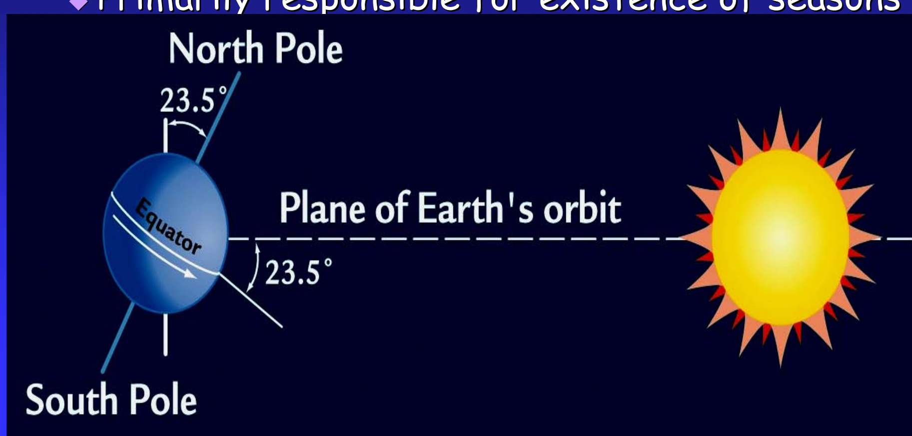
Glaciers

Astronomical Control of Solar Radiation

- Earth's present-day orbit around the Sun
  - Not permanent
  - Varies at cycles from 20,000-400,000 years
    - Changes due to
      - Tilt of Earth's axis
      - Shape of Earth's yearly path of revolution around the Sun

What is the Reason For Seasons?

- The Tilt or Obliquity of Axis of rotation relative to the plane of the Earth's Orbit about the Sun
  - Primarily responsible for existence of seasons

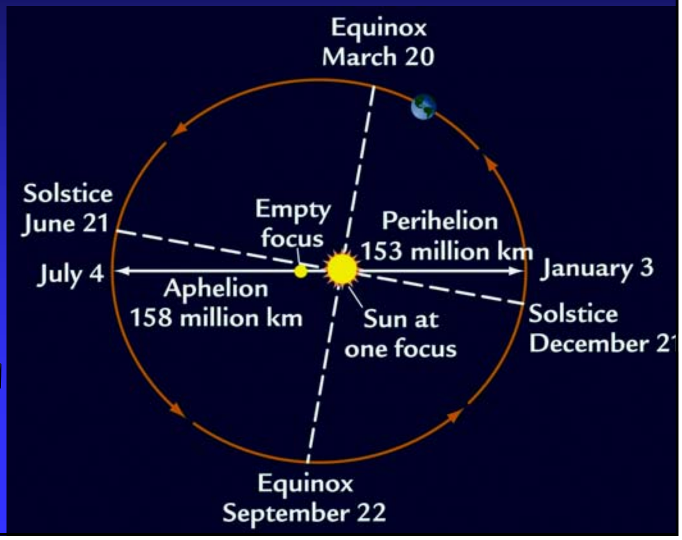


What is the Reason For Seasons?

- Eccentricity of Earth's Orbit is a secondary factor

Earth's orbit is not perfectly circular, but has an elliptical shape

Orbit shaped by the gravitational pull of nearby planets

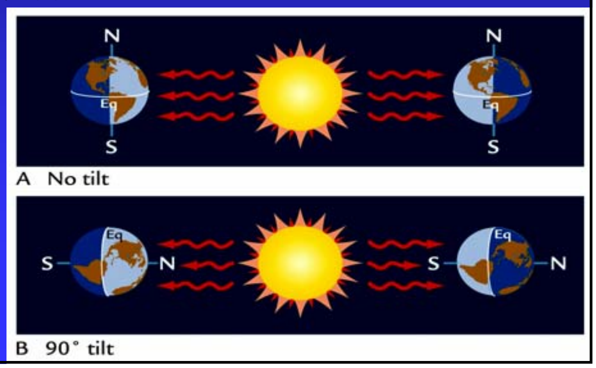


Long-Term Changes in Orbit

- Known for centuries that Earth's orbit not fixed around Sun
  - Varies in regular cycles
  - Gravitational attraction between Earth, its moon, the Sun and other planets
    - Variations in Earth's tilt
    - Eccentricity of orbit
    - Relative positions of solstices and equinoxes around the elliptical orbit

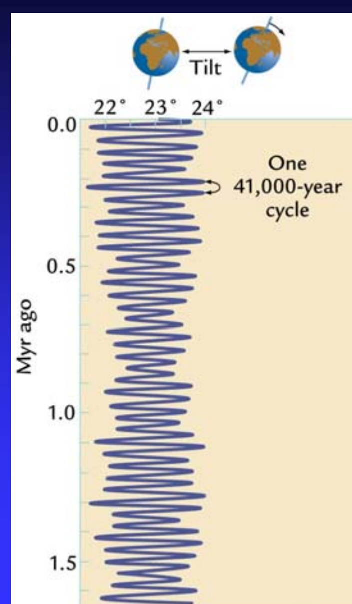
Simple Change in Axial Tilt

- No tilt, solar radiation always over equator
  - No seasonal change in solar radiation
  - Solstices and equinoxes do not exist
- 90° tilt, solar radiation hits poles
  - Day-long darkness
  - Day-long light
  - Extreme seasonality



Long-term Changes in Axial Tilt

- Change in tilt not extreme
  - Range from 22.5° to 24.5°
  - Gravitational tug of large planets
- Changes in tilt have a period of 41,000 years
  - Cycles
    - Regular period
    - Irregular amplitude
  - Affects both hemispheres equally

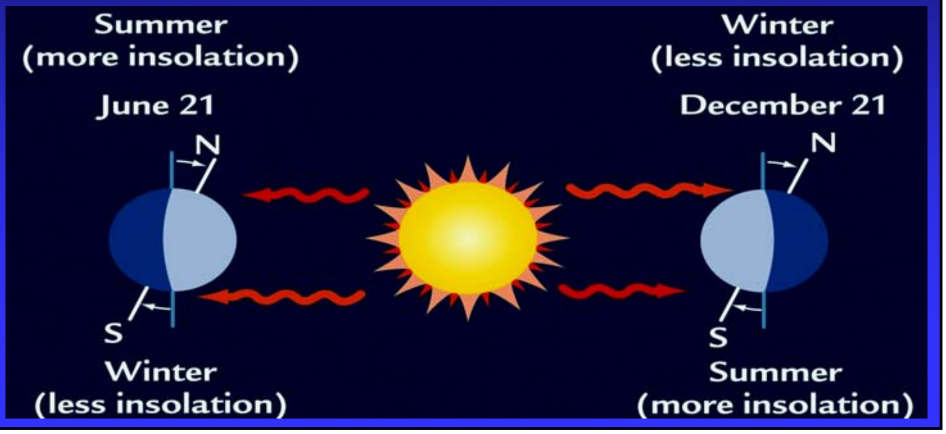


Effect of Changes in Axial Tilt

- Changes in tilt produce long-term variations in seasonal solar radiation
  - Especially at high latitudes
- Mainly effects seasonality
  - Increased tilt amplifies seasonality
  - Decreased tilt reduces seasonality

Effect of Increased Tilt on Poles

- Larger tilt moves summer-hemisphere pole more towards the Sun and winter season away from Sun
  - Increased amplitude of seasons
- Decreased tilt does the opposite decreasing seasonality

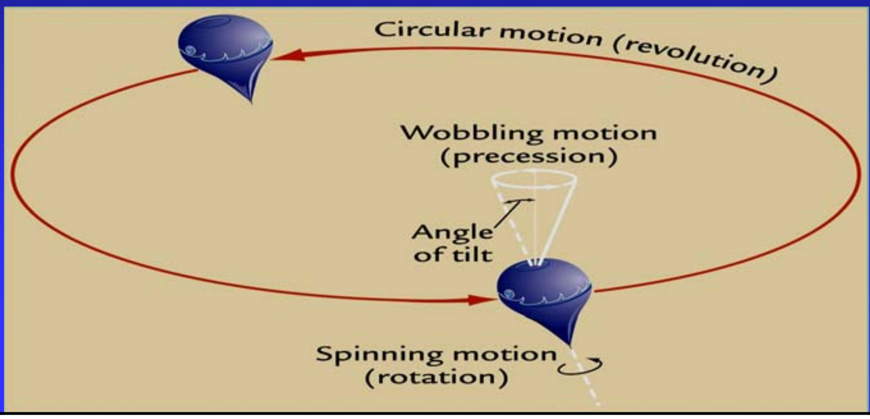


Precession of Solstices and Equinoxes

- Positions of solstices and equinoxes change through time
  - Gradually shift position with respect to
    - Earth's eccentric orbit and its perihelion and aphelion

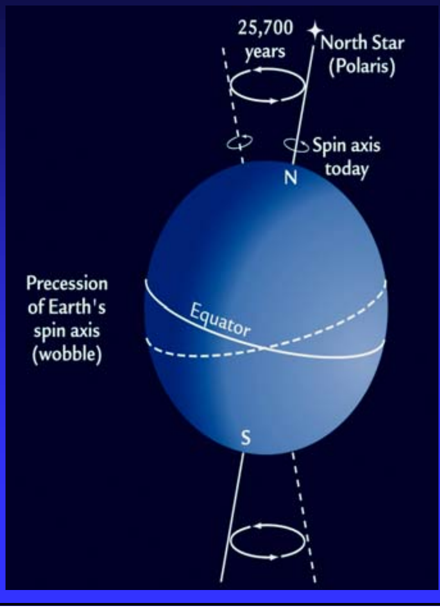
Earth's Axial Precession

- In addition to spinning about its axis
  - Earth's spin axis wobbles
    - Gradually leaning in different directions
    - Direction of leaning or tilting changes through time



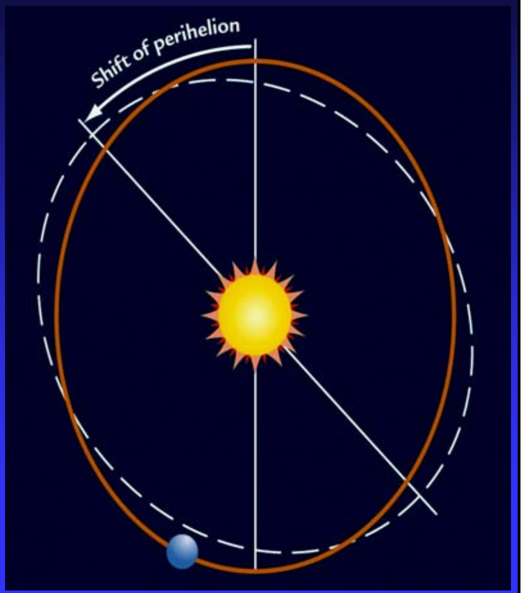
Earth's Axial Precession

- Caused by gravitational pull of Sun and Moon
  - On the bulge in Earth diameter at equator
- Slow turning of Earth's axis of rotation
  - Causes Earth's rotational axis to point in different directions through time
  - One circular path takes 25,700 years



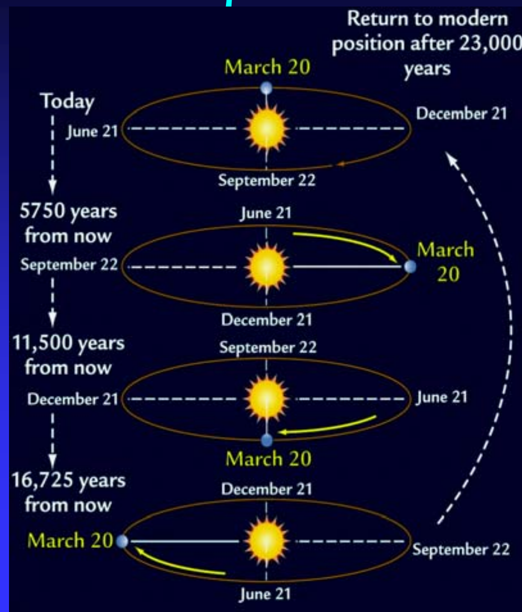
Precession of the Ellipse

- Elliptical shape of Earth's orbit rotates
  - Precession of ellipse is slower than axial precession
  - Both motions shift position of the solstices and equinoxes



Precession of the Equinoxes

- Earth's wobble and rotation of its elliptical orbit produce precession of the solstices and equinoxes
  - One cycles takes 23,000 years
- Simplification of complex angular motions in three-dimensional space

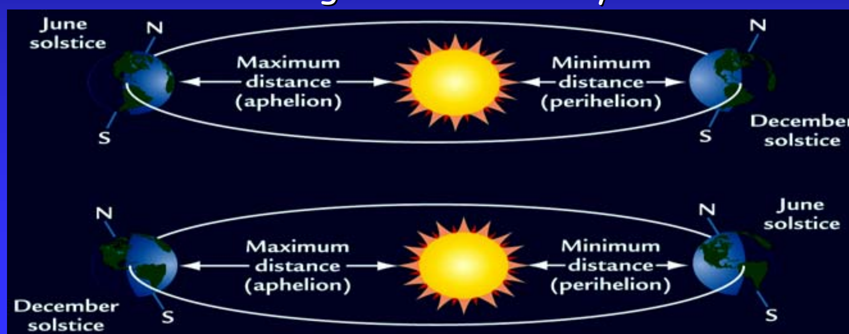


Change in Insolation by Precession

- No change in insolation
  - Precession of solstices and equinoxes
    - Around perfectly circular orbit
- Large change in insolation
  - Precession of solstices and equinoxes
    - Around an eccentric orbit
    - Depending on the relative positions of
      - Solstices and equinoxes
      - Aphelion and perihelion
      - Precessional change in axial tilt

Extreme Solstice Positions

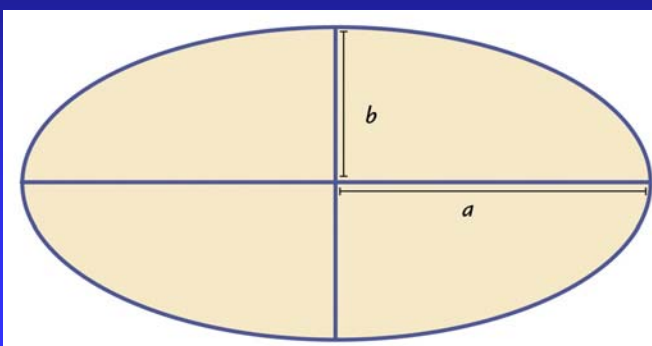
- Today June 21 solstice at aphelion
  - Solar radiation a bit lower
- Configuration reversed ~11,500 years ago
  - Precession moves June solstice to perihelion
  - Solar radiation a bit higher
  - Assumes no change in eccentricity



Changes in Eccentricity

- Shape of Earth's orbit has changed
  - Nearly circular
  - More elliptical or eccentric

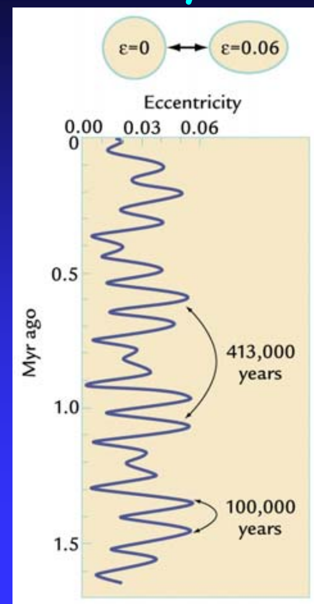
Eccentricity increases as the lengths of axes become unequal – when $a = b$, $\varepsilon = 0$ and the orbit is circular



$$\text{Eccentricity } \varepsilon = \frac{(a^2 - b^2)^{1/2}}{a}$$

Variations in Eccentricity

- ε changed from ~0.005 to ~0.0607
  - Today ε is ~0.0167
- Two main periods of eccentricity
  - 100,000 year cycle (blend of four periods)
  - 413,000 years
- All other things equal
  - Greater ε leads to greater seasonality
  - Changes in ε affect both hemispheres equally



Summary

- Gradual changes in Earth's orbit around the Sun result in changes in solar radiation
  - Received by season
  - Received by hemisphere
    - The axial tilt cycle is 41,000 years
    - The precession cycle is 23,000 years
  - Eccentricity variations at 100,000 years and 413,000 years
    - Modulate the amplitude of the precession cycle

What Controls Ice Sheet Growth?

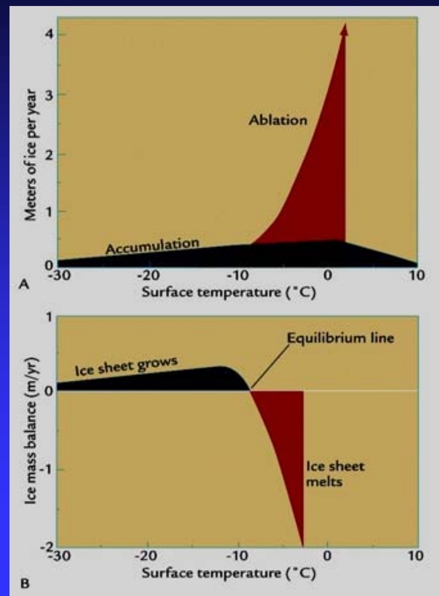
- Ice sheets exist when
  - Growth > ablation
  - Temperatures must be cold
    - Permit snowfall
    - Prevent melting
  - Ice and snow accumulate MAT < 10°C
    - Accumulation rates 0.5 m y^{-1}
      - MAT > 10°C rainfall
        - No accumulation
      - MAT << 10°C dry cold air
        - Very low accumulation

What Controls Ice Sheet Growth?

- Accumulation rates low, ablation rates high
  - Melting begins at MAT > -10°C (summer T > 0°C)
    - Ablation rates of 3 m y^{-1}
    - Ablation accelerates rapidly at higher T
- When ablation = growth
  - Ice sheet is at equilibrium
  - Equilibrium line =
    - Boundary between positive ice balance
    - Net loss of ice mass

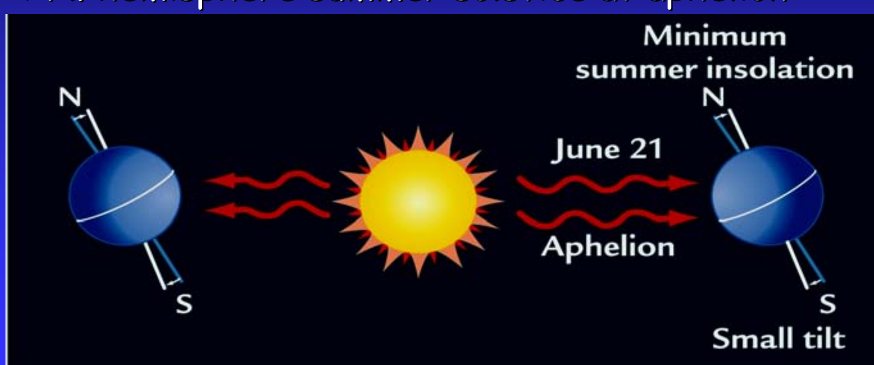
Temperature and Ice Mass Balance

- Temperature main factor determining ice growth
  - Net accumulation or
  - Net ablation
- Since ablation rate increases rapidly with increasing temperature
  - Summer melting controls ice sheet growth
  - Summer insolation must control ice sheet growth



Milankovitch Theory

- Ice sheets grow when summer insolation low
  - Axial tilt is small
    - Poles pointed less directly towards the Sun
  - N. hemisphere summer solstice at aphelion



A Northern hemisphere ice growth

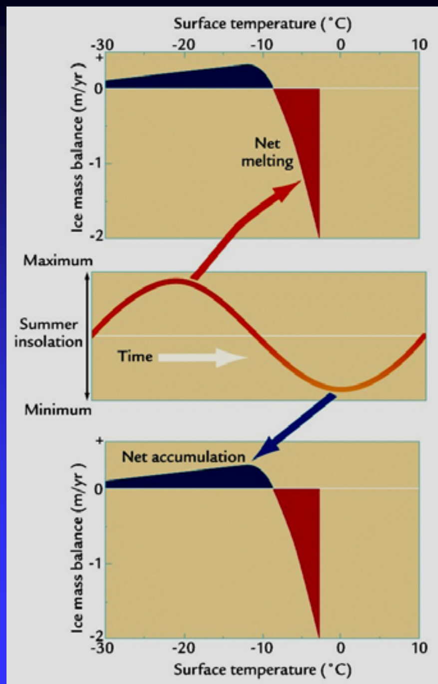
Milankovitch Theory

- Ice sheets melt when summer insolation high
  - Axial tilt is high
  - N. hemisphere summer solstice at perihelion

B Northern hemisphere ice decay

Milankovitch Theory

- Recognized that Earth has greenhouse effect
  - Assumed that changes in solar radiation dominant variable
- Summer insolation strong
  - More radiation at high latitudes
    - Warms climate and accelerates ablation
      - Prevents glaciations or shrinks existing glaciers
- Summer insolation weak
  - Less radiation at high latitudes
    - Cold climate reduces rate of summer ablation
      - Ice sheets grow



High summer insolation heats land and results in greater ablation

Dominant cycles at 23,000 and 41,000 years

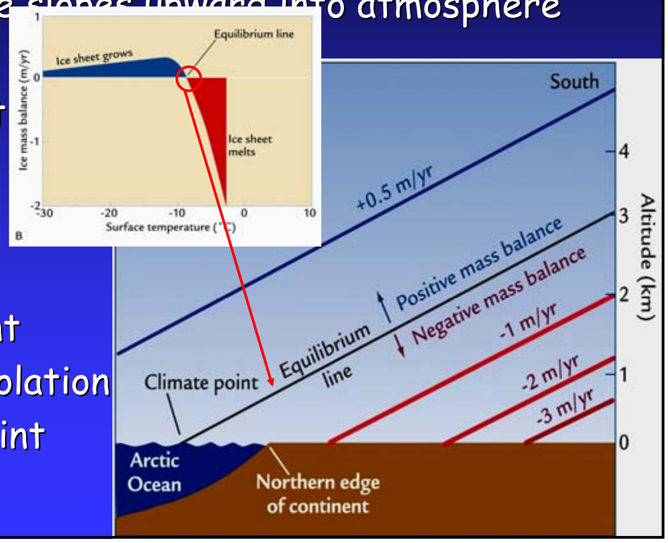
Low summer insolation cools land and results in diminished ablation

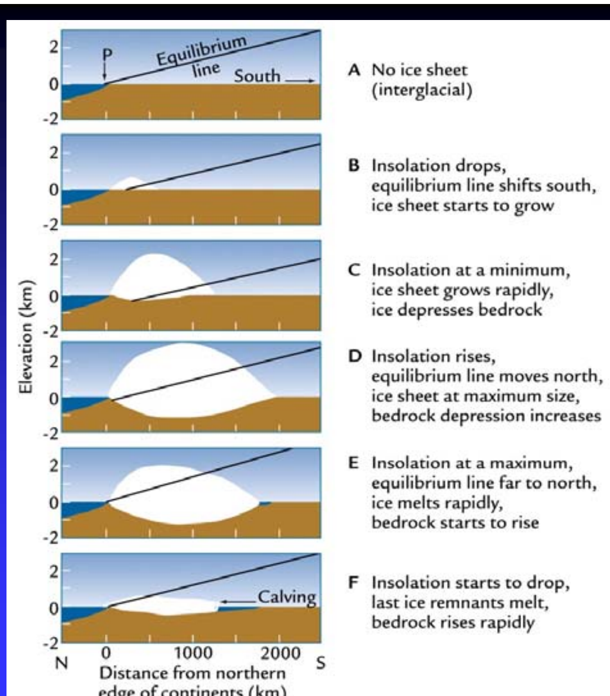
Ice Sheet Behavior

- Understood by examining N. Hemisphere
- At LGM ice sheets surrounded Arctic Ocean

Insolation Control of Ice Sheet Size

- Examine ice mass balance along N-S line
- Equilibrium line slopes upward into atmosphere
  - Above line
    - Ice growt
  - Below line
    - Ablation
- Intercept
  - Climate point
  - Summer insolation
    - Shifts point



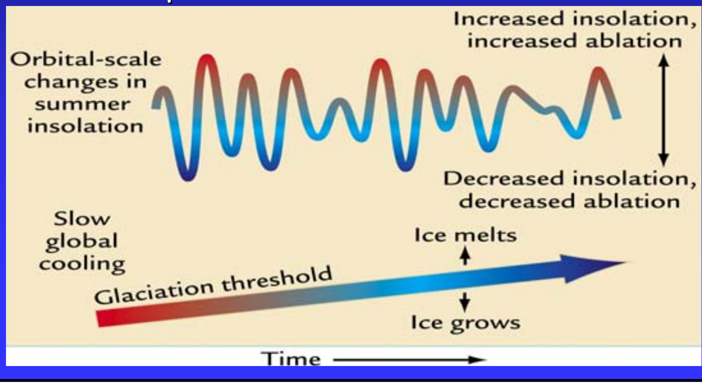


- Ice sheet moves towards south following climate point and due to internal flow
- Bedrock lag keeps elevation high

- Combined north-ward movement of climate point and bedrock depression increases ablation mass balance turns negative

N. Hemisphere Ice Sheet History

- Tectonic-scale cooling began 55 mya
  - Last 3 my should be affected by this forcing
- Ice sheet growth should respond to orbital forcing
  - Growth and melting should roughly follow axial tilt and precession cycles
  - Glaciations depend on threshold coldness in summer

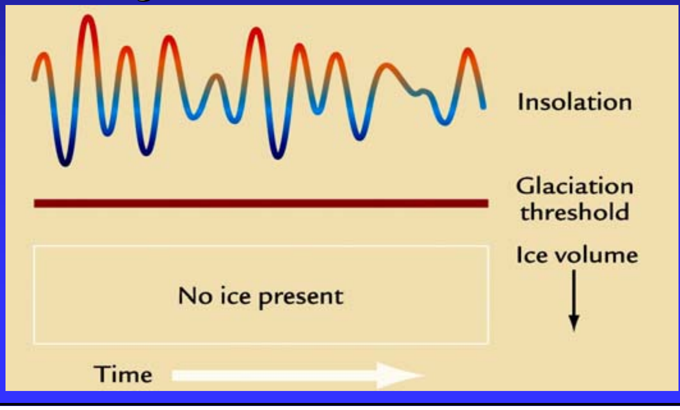


N. Hemisphere Ice Sheet History

- Ice sheet response to external forcing (tectonic or orbital)
  - Results from interactions between
    - Slowly changing equilibrium-line threshold
    - Rapidly changing curve of summer insolation
      - Insolation values below threshold
        - Ice sheets grow
      - Insolation values above threshold
        - Ice sheets melt
    - Growth and melting lag thousands of years behind insolation forcing

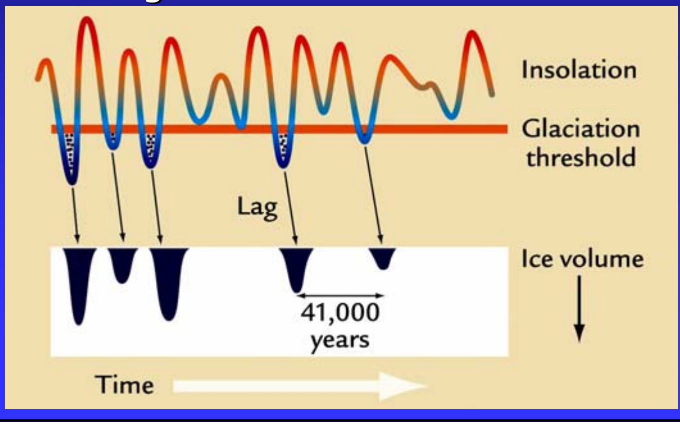
Ice Sheet Growth

- Four phases of glacial ice growth
  - Preglaciation phase
    - Insolation above threshold
      - No glacial ice formed



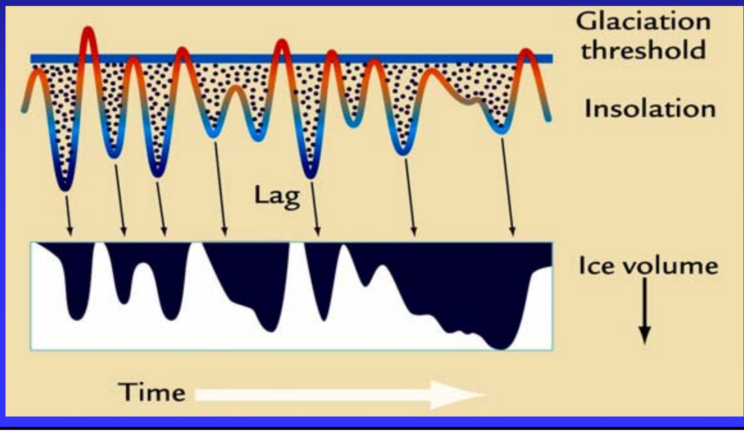
Ice Sheet Growth

- Small glacial phase
  - Major summer insolation minima
    - Fall below threshold
      - Small glaciers form



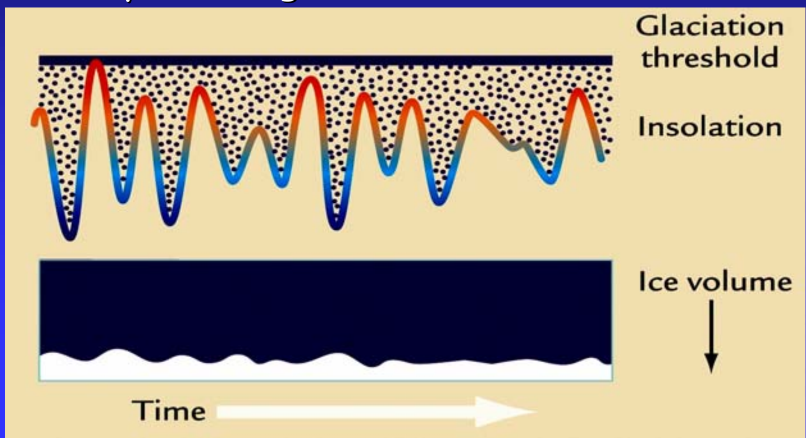
Ice Sheet Growth

- Large glacial phase
  - Most summer insolation maxima below threshold
    - Ice sheets shrink but do not disappear during small maxima
    - Ice sheets disappear only during major insolation maxima



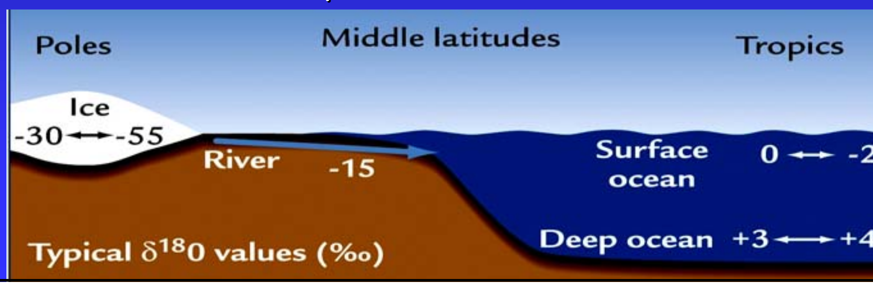
Ice Sheet Growth

- Permanent glacial phase
  - Summer insolation maxima
  - Always below glacial threshold

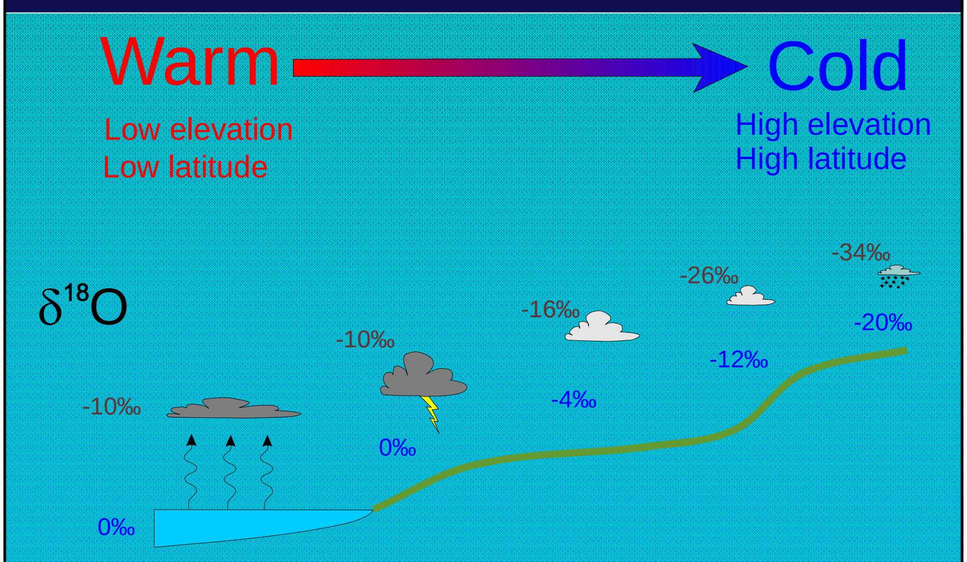


Evolution of Ice Sheets Last 3 my

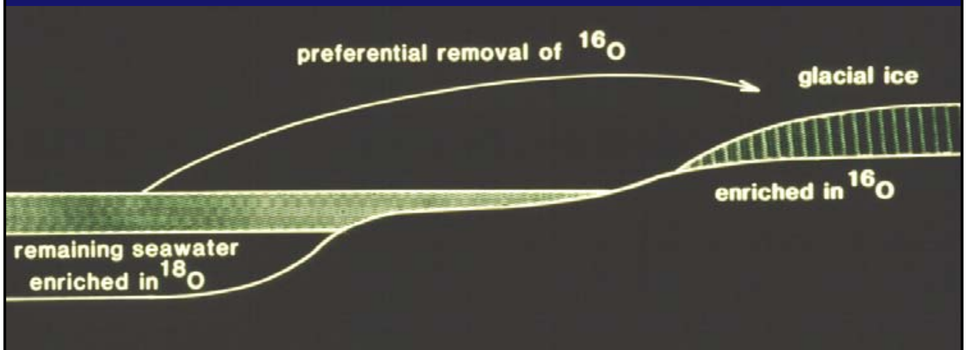
- Best record from marine sediments
  - Ice rafted debris
    - Sediments deliver to ocean by icebergs
  - $\delta^{18}O$ of calcareous foraminifera
    - Quantitative record of changes in
      - Global ice volume
      - Ocean temperature



Rainout and Rayleigh Distillation

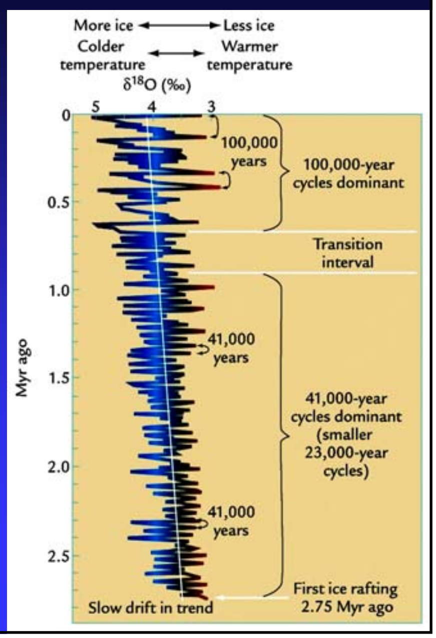


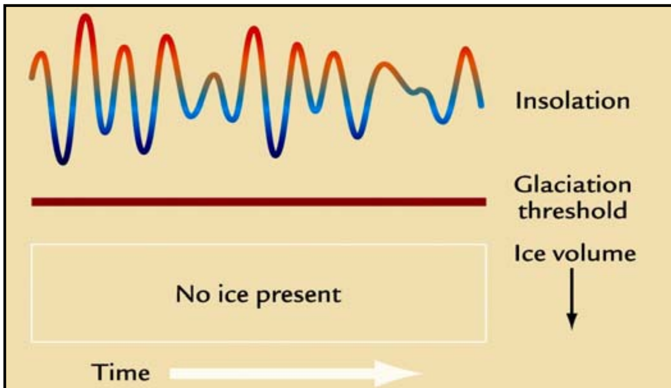
Sealevel and $\delta^{18}O$

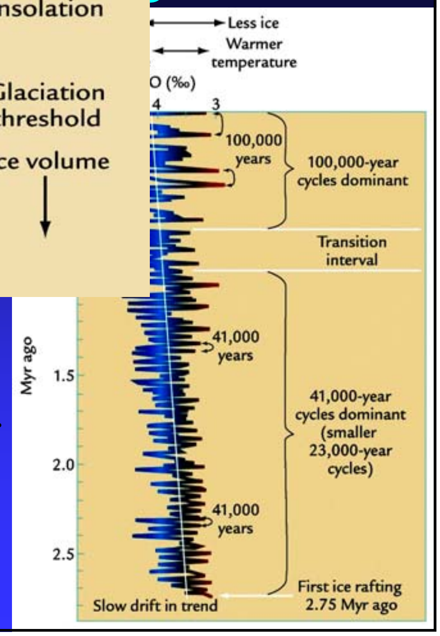


$\delta^{18}O$ Record from Benthic Foraminifera

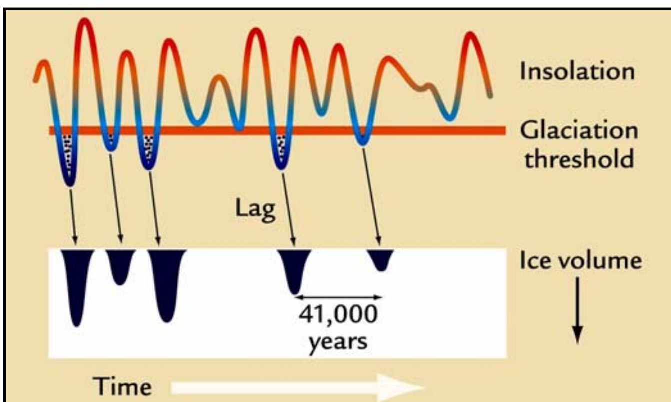
- Ice volume and T move $\delta^{18}O$ in same direction
- Two main trends
  - Cyclic oscillations
    - Orbital forcing
      - Dominant cycles changed over last 2.75 my
  - Long-term slow drift
    - Change in CO_2
    - Constant slow cooling

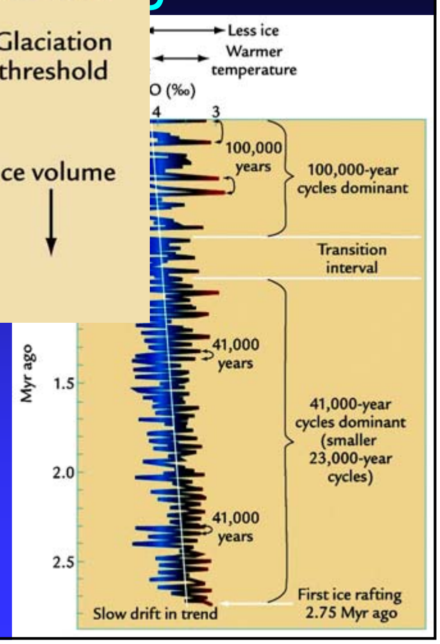




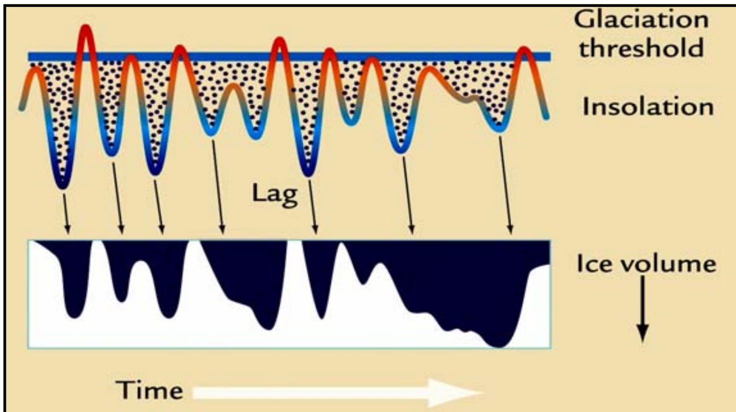


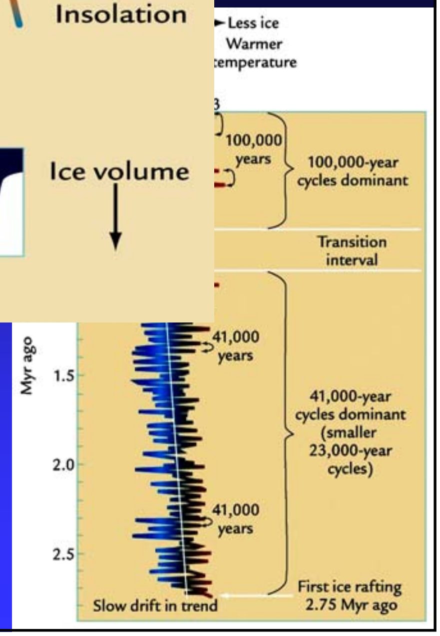
- Effect on $\delta^{18}O$ variations small
  - Probably mostly a T effect?
- Equals the preglacial phase





- Small glacial phase
  - Ice sheet growth only during most persistent low summer insolation
  - ~50 glacial cycles
  - $\delta^{18}O$ drifting to lower values – glacial world



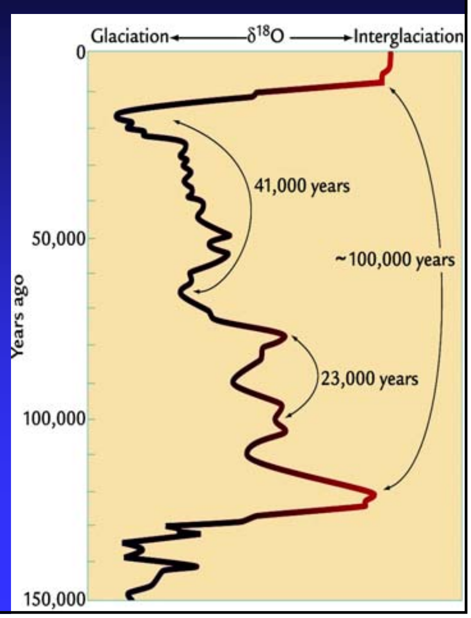


0.6 my

- Rapid $\delta^{18}O$ change
  - Abrupt melting
- Characteristics of large glacial phase

Ice Sheets Over Last 150,000 y

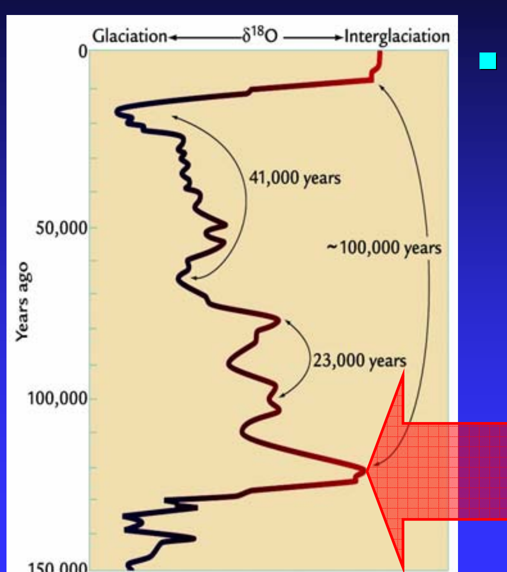
- 100,000 year cycle dominant
  - 23,000 and 41,000 year cycles present
  - Two abrupt glacial terminations
    - 130,000 yeas ago
    - ~15,000 years ago
- Is the 100,000 year cycle real?



Confirming Ice Volume Changes

- Corals reefs follow sea level and can quantify change in ice volume
  - Ideal dipstick for sea level
    - Corals grow near sea level
    - Ancient reefs preserved in geologic record
    - Can be dated ($^{234}U \rightarrow {}^{230}Th$)
  - Best sea level records from islands on tectonically stable platforms (*e.g.*, Bermuda)
    - 125,000 year old reefs at 6 m above sea level
    - Confirms shape of $\delta^{18}O$ curve from last 150,000 years

125,000 year Reef on Bermuda

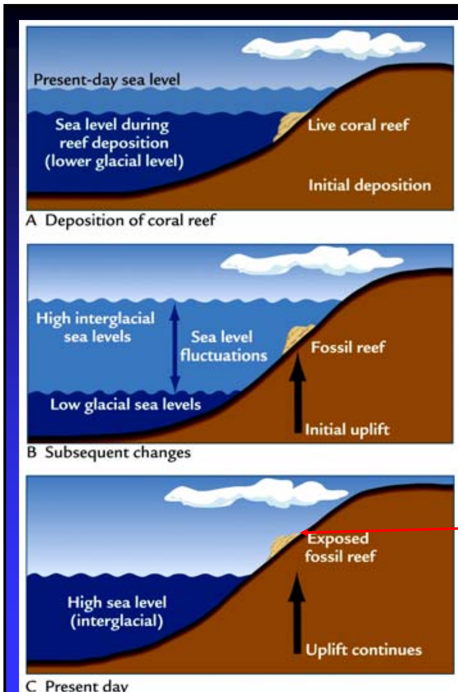


- Interglacial is where δ_w lowest, bottom water temperature hottest and sea level highest

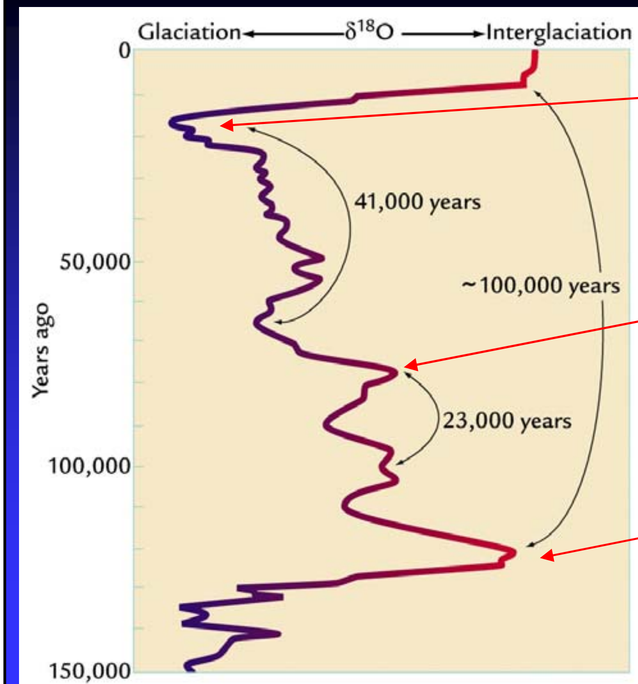
Do Other Reefs Date Sea Level?

- Yes and no
- Glacial ice existed from 125,000 to present
  - Coral reefs that grew between about 10,000 and 125,000 years ago
    - Are now submerged
      - Can be recognized and sampled
  - Also raised reefs
  - On uplifted islands

Uplifted Coral Reefs



- Coral reefs form on uplifting island
- Submerged as sea level rises
- Exposed as sea level falls and island uplifts
- Situation exist on New Guinea



Lowest level of submerged corals is 120 meters below present-day sea level

Corals formed at 15-20 meters below present-day sea level

Corals found about 6 meters above present-day sea level

$\delta^{18}O$ records Ice Volume

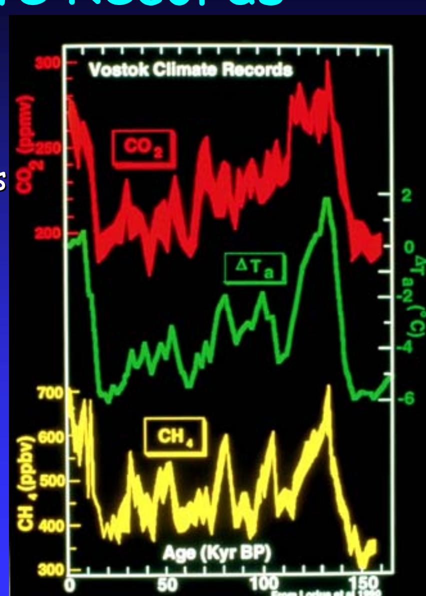
- Every 10-m change in sea level produces an ~0.1‰ change in $\delta^{18}O$ of benthic foraminifer
  - The age of most prominent $\delta^{18}O$ minima
  - Correspond with ages of most prominent reef recording sea level high stands
    - Absolute sea levels estimates from reefs
      - Correspond to shifts in $\delta^{18}O$
  - Reef sea level record agreement with assumption of orbital forcing
    - 125K, 104K and 82K events forced by precession

Orbital-Scale Change in CH_4 & CO_2

- Important climate records from last 400 kya
  - Direct sampling of greenhouse gases in ice
- Critical questions must be addressed
  - Before scale of variability in records determined
    - Reliability of age dating of ice core?
    - Mechanisms and timing of gas trapping?
    - Accuracy of the record?
      - How well gases can be measured?
      - How well do they represent atmospheric compositions and concentrations?

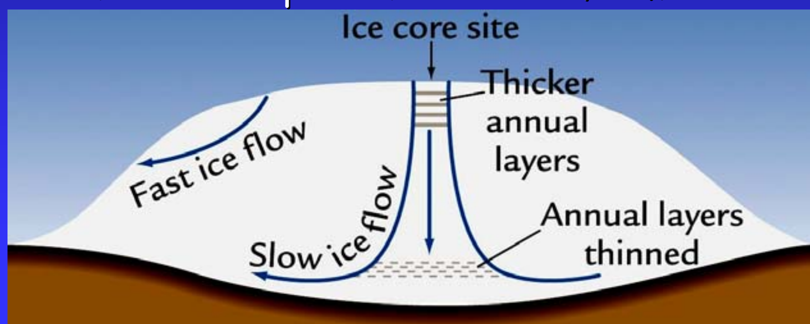
Vostok Climate Records

- Illustrates strong correlation between paleotemperature and the concentration of atmospheric greenhouse gases
- Concentrations of CO_2 and CH_4 moved in tandem with paleotemperatures derived from stable isotope records
- Mechanisms of relationships poorly understood
- To what extent did higher greenhouse gases cause greater radiative warming of the Earth's atmosphere?



Dating Ice Core Records

- Ice sheets thickest in center
  - Ice flow slowly downward
  - Then flows laterally outward
- Annual layers may be preserved and counted
  - Deposition of dust during winter
    - Blurred at depth due to ice deformation

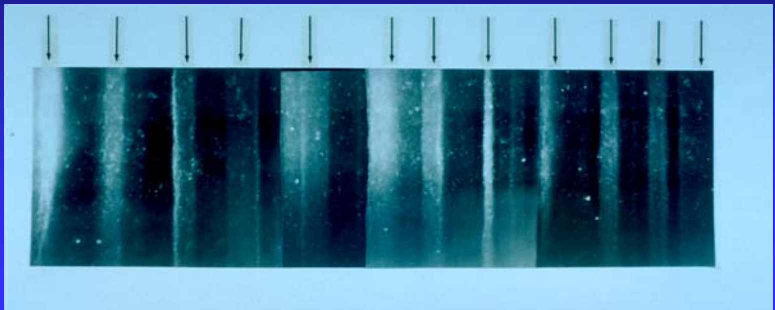


Reliability of Dating

- Dust layer counting
  - Best when ice deposition rapid
    - Greenland ice accumulates at 0.5 m y^{-1}
      - Layer counting good to 10,000 years
    - Antarctica ice accumulates at 0.05 m y^{-1}
      - Layering unreliable due to slow deposition
  - Where unreliable, ice flow models used
    - Physical properties of ice
    - Assumes smooth steady flow
      - Produces "fairly good estimates" of age

Dust Layers

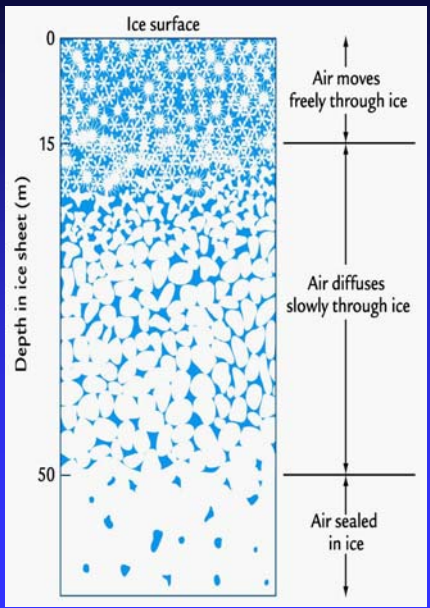
- Greenland has two primary sources for dust
  - Particulates from Arctic Canada and coastal Greenland
  - Large volcanic eruptions anywhere on the globe



19 cm long section of GISP 2 ice core from 1855 m showing annual layer structure illuminated from below by a fiber optic source. Section contains 11 annual layers with summer layers (arrowed) sandwiched between darker winter layers.

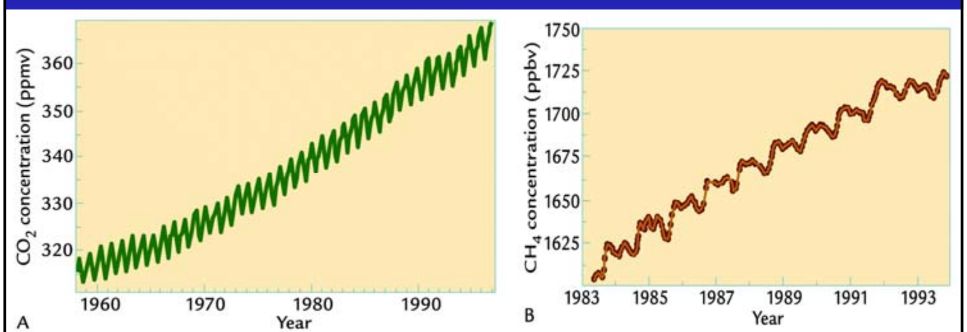
Gas Trapping in Ice

- Gases trapped during ice sintering
  - When gas flow to surface shut down
  - Crystallization of ice
  - Depths of about 50 to 100 m below surface
    - Gases younger than host ice
- Fast accumulation minimizes age difference (100 years)
- Slow deposition maximizes age difference (1000-2000 years)



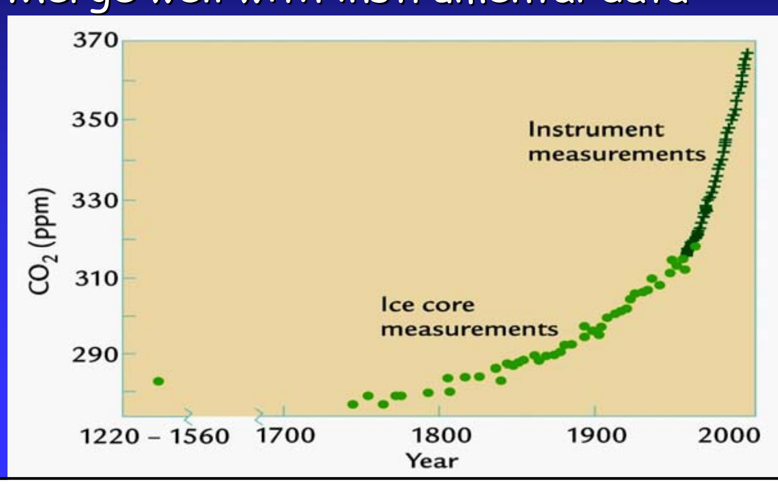
Reliability and Accuracy of Records

- Can be evaluated by comparing instrumental record
  - With records from rapidly accumulating ice sheets
    - Instrumental records date to 1958 for CO_2 and 1983 for CH_4
      - Mauna Loa Observatory (David Keeling)



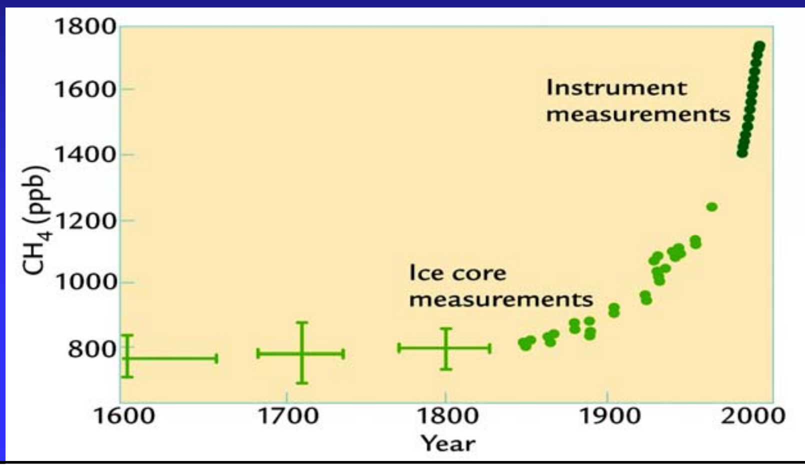
Carbon Dioxide

- Measurements of CO_2 concentration
  - Core from rapidly accumulating ice
  - Merge well with instrumental data



Methane

- Measurements of CH_4 concentration
  - Core from rapidly accumulating ice
  - Merge well with instrumental data

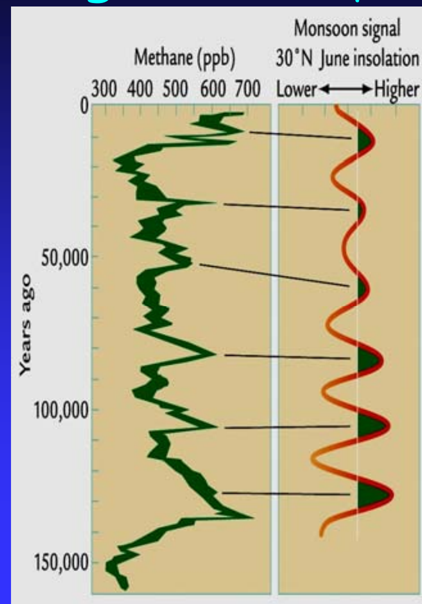


CH_4 and CO_2 in Ice Cores

- Given agreement between records from rapidly accumulating ice
  - Instrumental data
    - Accuracy and variability about the trends
  - Assume that longer-term records collected from ice cores
    - Reliable for determining the scale of variability

Orbital-Scale Changes in CH_4

- CH_4 variability
  - Interglacial maxima 550-700 ppb
  - Glacial minima 350-450 ppb
- Five cycles apparent in record
  - 23,000 precession period
    - Dominates low-latitude insolation
    - Resemble monsoon signal
      - Magnitude of signals match

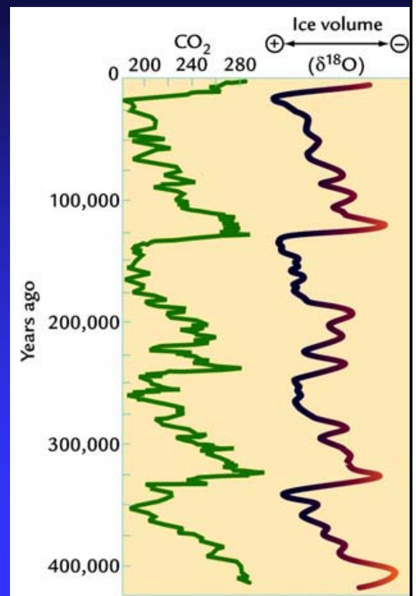


Monsoon forcing of CH_4

- Match of high CH_4 with strong monsoon
  - Strongly suggests connection
- Monsoon fluctuations in SE Asia
  - Produce heavy rainfall, saturate ground
    - Builds up bogs
      - Organic matter deposition and anaerobic respiration likely
        - Bogs expand during strong summer monsoon
        - Shrink during weak summer monsoon

Orbital-Scale Changes in CO_2

- CO_2 record from Vostok
  - Interglacial maxima 280-300 ppm
  - Glacial minima 180-190 ppm
- 100,000 year cycle dominant
- Match ice volume record
  - Timing
  - Asymmetry
    - Abrupt increases in CO_2 match rapid ice melting
    - Slow decreases in CO_2 match slow build-up of ice



Orbital-Scale Changes in CO_2

- Vostok 150,000 record
  - 23,000 and 41,000 cycles
  - Match similar cycles in ice volume
- Agreement suggests cause and effect relationship
  - Relationship unknown
    - e.g., does CO_2 lead ice volume?
  - Correlations not sufficient to provide definite evaluation