Earth’s Climate System

- Objectives:
  - Basics of the global climate system
  - Climate of Hawai‘i
  - Human impacts on local and global climate

Earth's Climate System

- Why should we spend time talking about Earth's climate in a class on ecosystem ecology?
  - Globally, climate is the single most important predictor of ecosystem distribution, and ecosystem processes
  - Climate is the most important driver of soil development
  - Global climate is relatively predictable for a given place on Earth from general principles
    - → Distribution of ecosystem types/biomes and ecosystem process rates are relatively predictable

Earth’s Climate System

- What is the difference between weather and climate?
  - Weather is what is happening now (today, this week, this month)
  - Climate is average weather over a time period of decades to centuries (~30+ years)

Earth’s Climate System

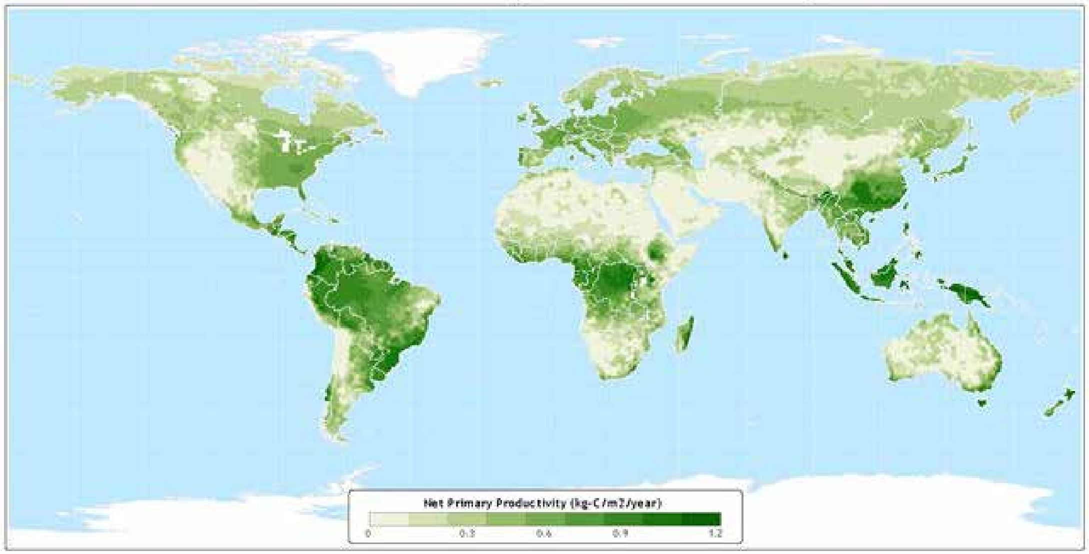
- What controls Earth’s climate, and global variation in climate spatially and temporally?
  1. Incoming solar radiation (energy input)
  2. Atmospheric composition and chemistry
  3. Earth’s surface properties

  – By understanding causes of spatial and temporal variation in climate, you can predict:
    - What ecosystem type will occur where
    - An ecosystem’s general characteristics (structure and function)
    - Impact of human-induced climate change on both of these

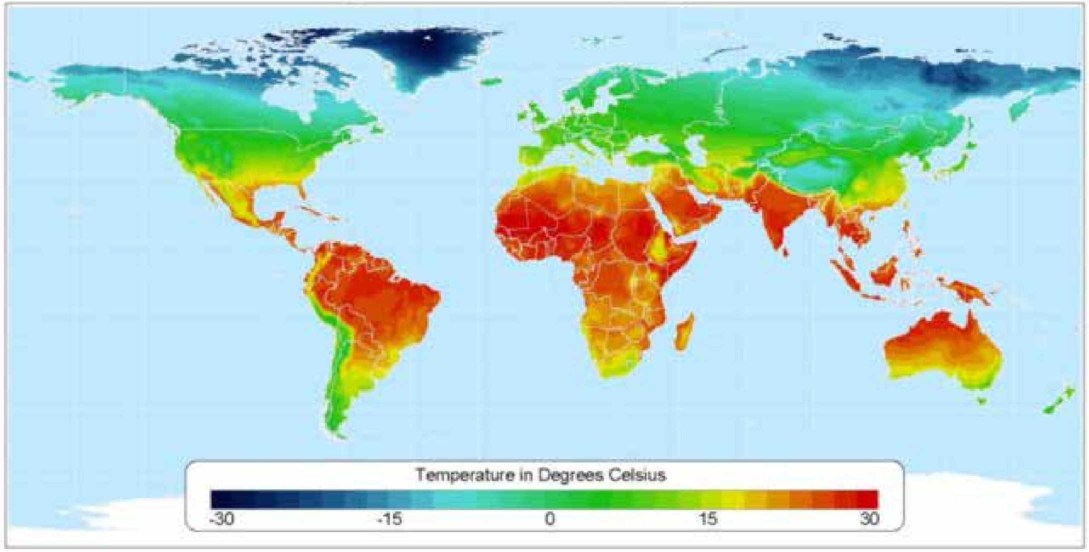
Where is NPP highest? Lowest?
What are the latitudinal patterns? Other patterns?

How do temperature patterns compare with those of NPP?

Net Primary Productivity

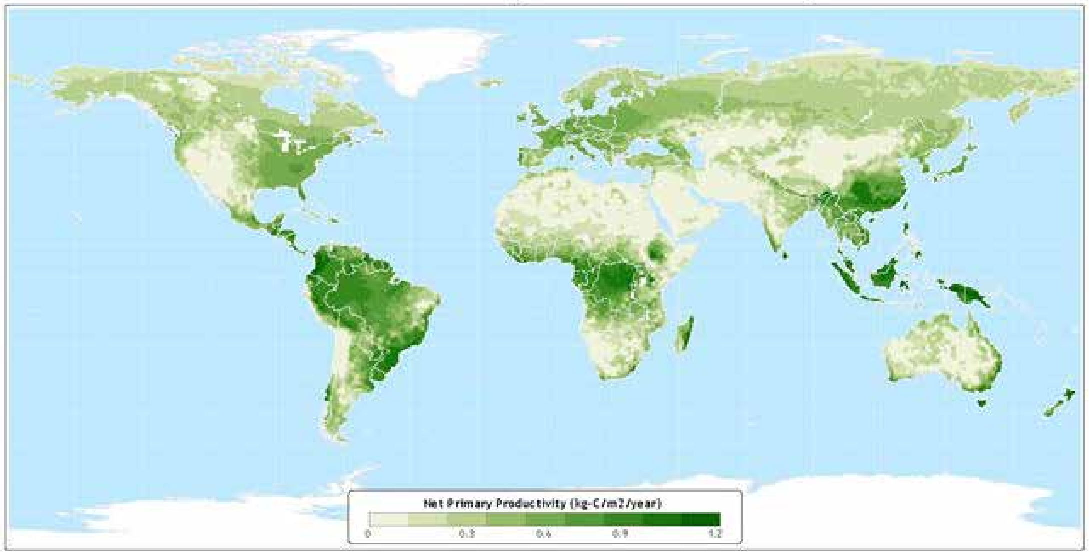


Average Annual Temperature

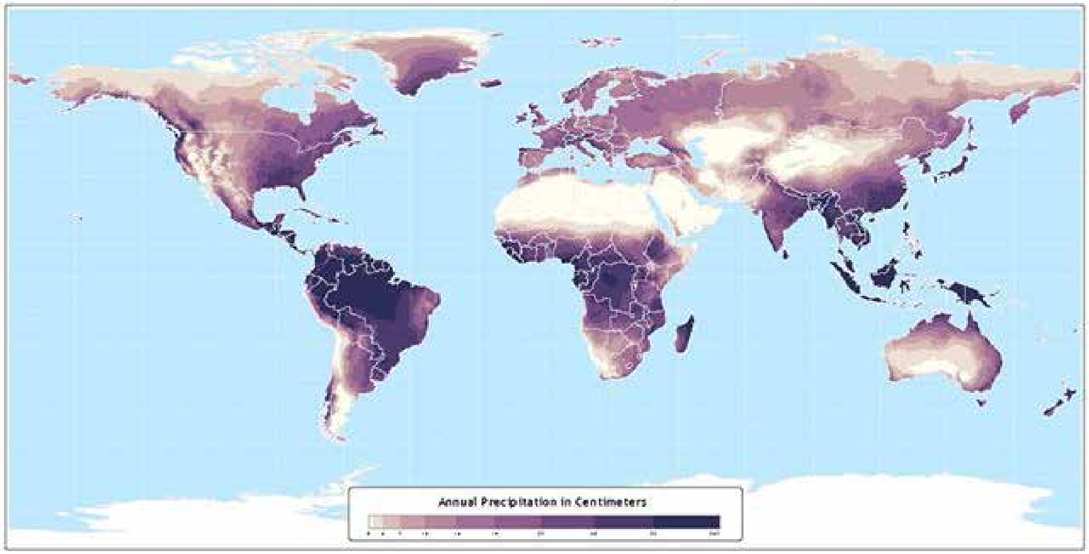


How do precipitation patterns compare with those of NPP?

Net Primary Productivity

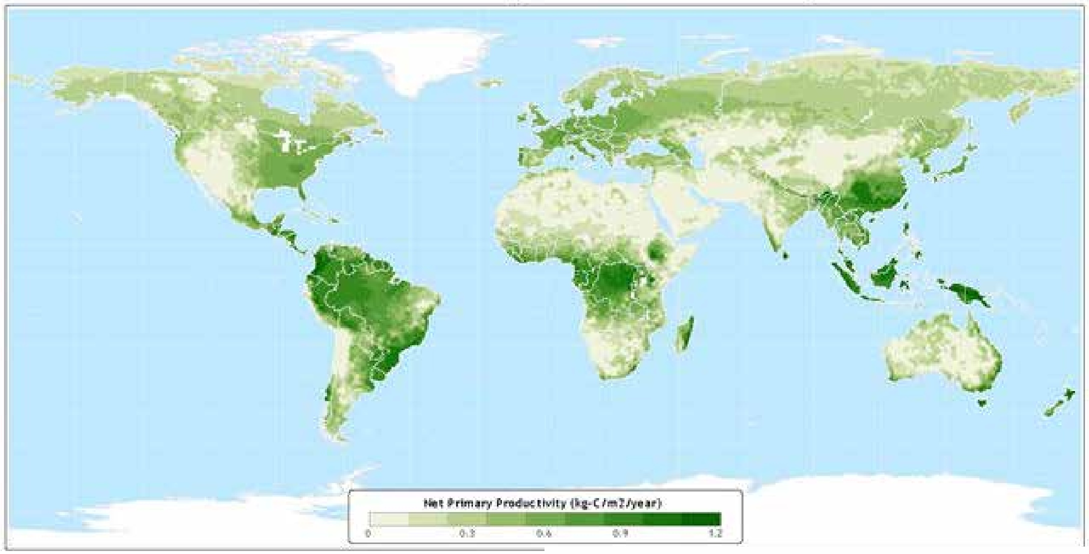


Annual Total Precipitation

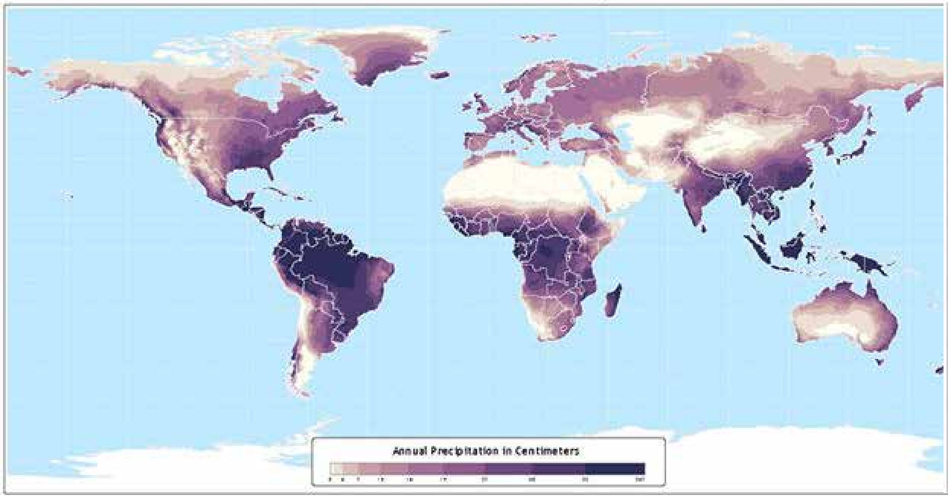


Is temperature or precipitation a better predictor of NPP?

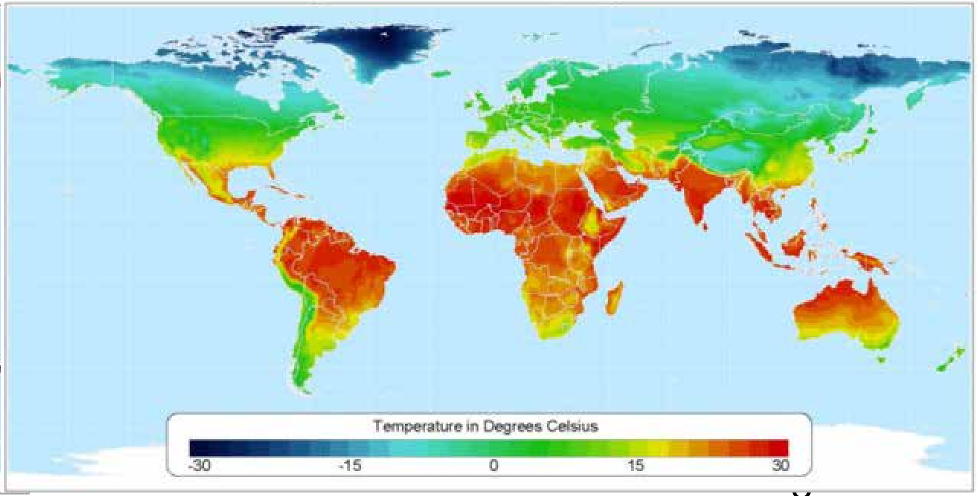
Net Primary Productivity



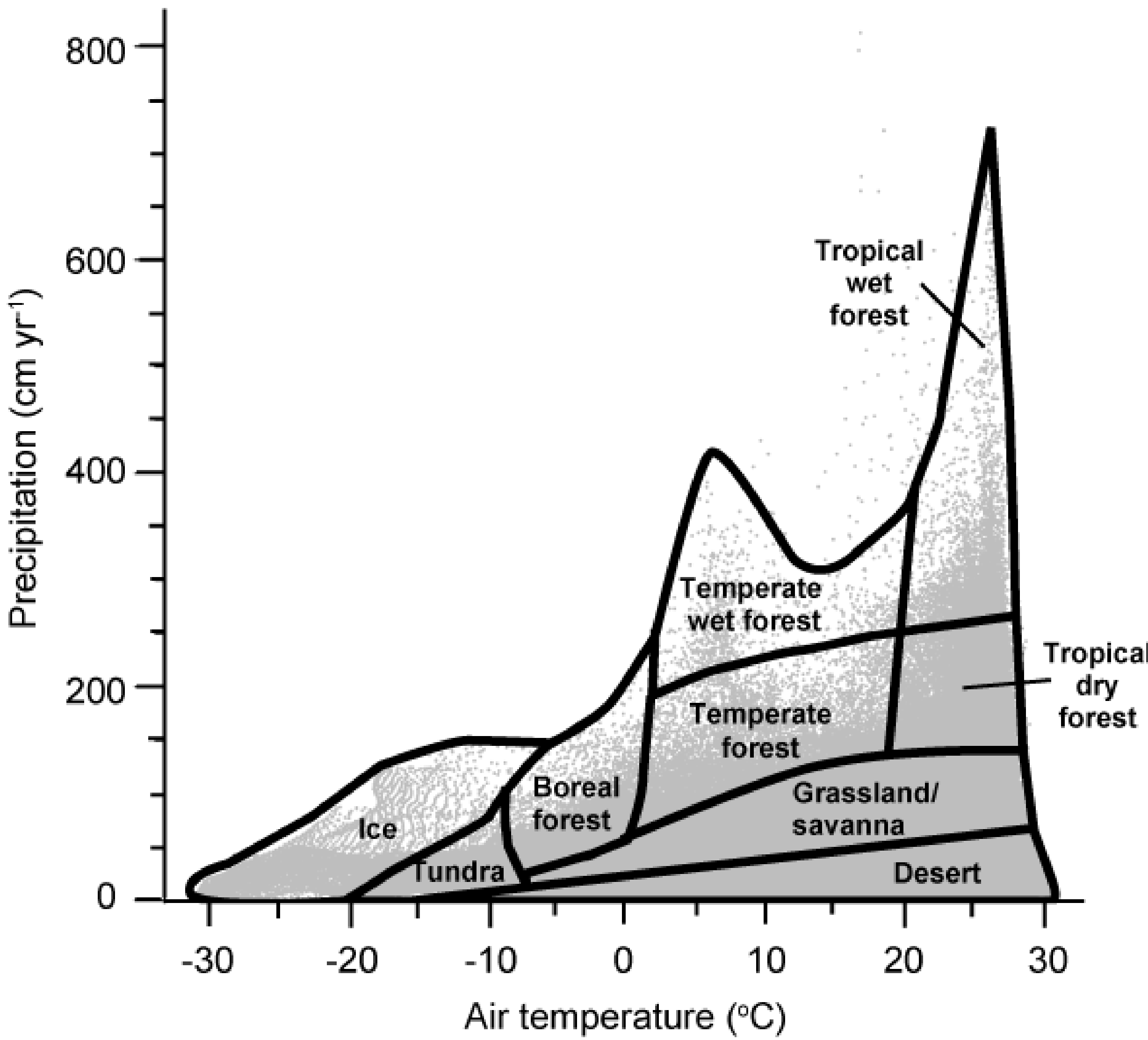
Annual Total Precipitation



Average Annual Temperature

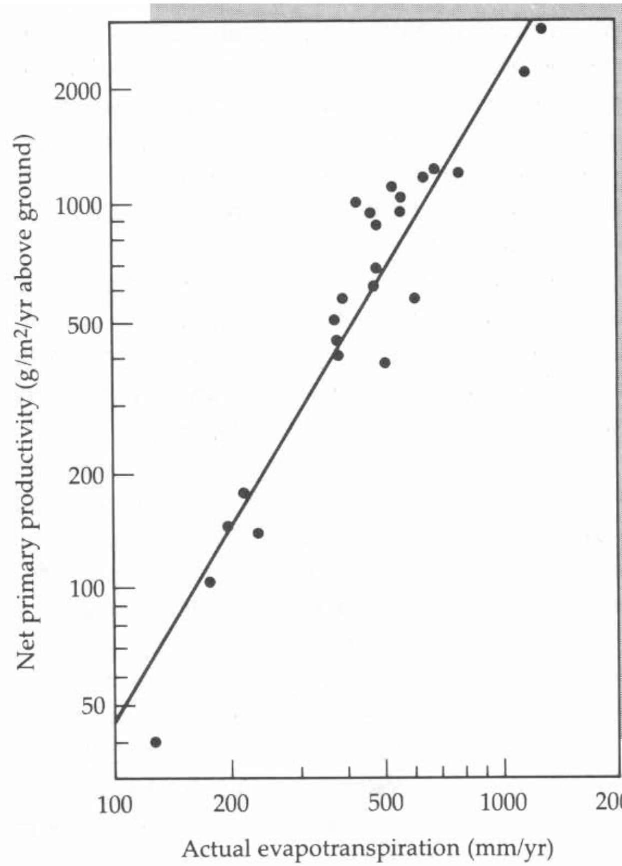


Relationship of ecosystem type to climate



Earth's Climate System

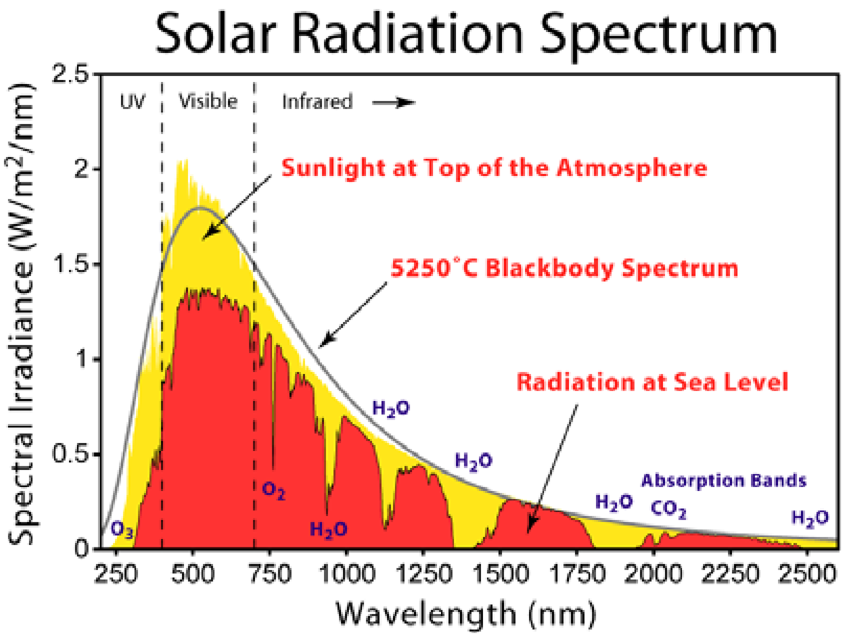
- Climate (MAT & MAP) also correlates very well with ecosystem processes. Why?
  - Temperature and precipitation:
    - Largely determine rates at which chemical & biological reactions occur
    - Rates of chemical & biological reactions, in turn, control ecosystem processes
  - AET, for example, is a function of both precipitation (water supply) and temperature (largely drives both transpiration and evaporation)
- What drives Earth's climate?



Aber & Melillo (1991)

Earth's Climate System

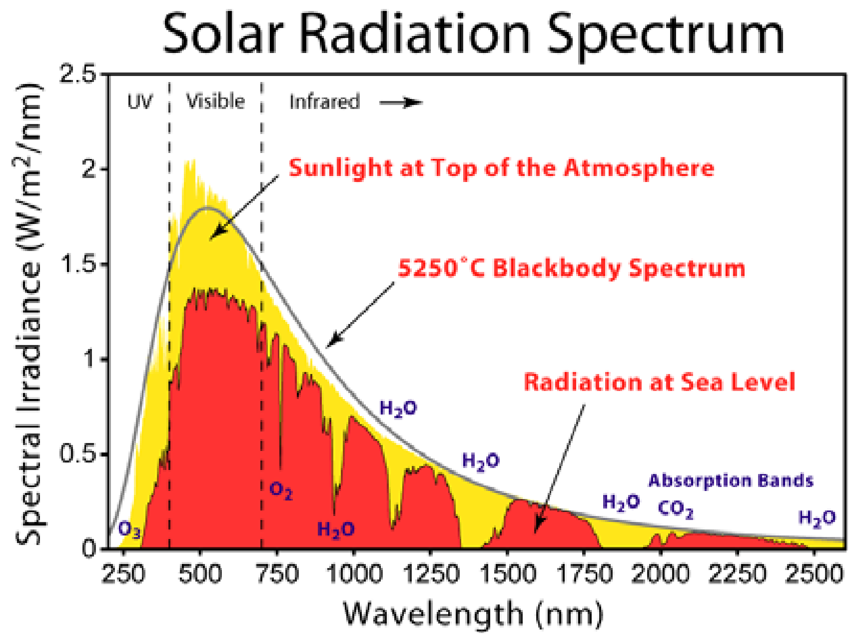
- Solar energy (solar radiation) drives Earth's climate system
  - Incoming solar radiation is primarily shortwave (0.3 - 3 mm)
    - High energy radiation
  - UV (8%); <0.4 mm
    - Absorbed by O_3 in atmosphere
  - Visible (39%); 0.4-0.7 mm
    - Also know as PAR; drives photoautotrophic production
  - Near-IR (53%); 0.7-3 mm



1 micron (mm) = 1000 nanometers (nm)

Earth's Climate System

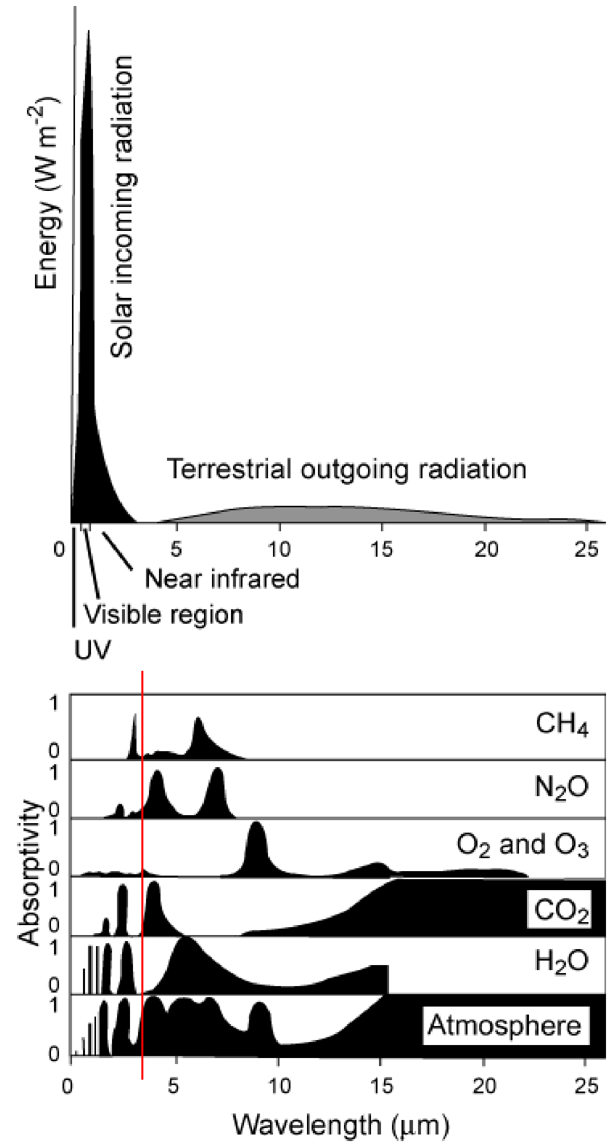
- Solar energy (solar radiation) drives Earth's climate system
  - Outgoing radiation is primarily longwave (>3 mm; ~70%)
    - Low energy radiation
    - Energy that has been absorbed and reemitted (Far IR)
  - Radiation absorbed by the surface is reradiated back to the atmosphere, absorbed by gases and reradiated back to Earth, etc.
    - "Greenhouse effect"
  - **Balance of incoming & outgoing radiation → Available energy**



1 micron (mm) = 1000 nanometers (nm)

Earth's Climate System

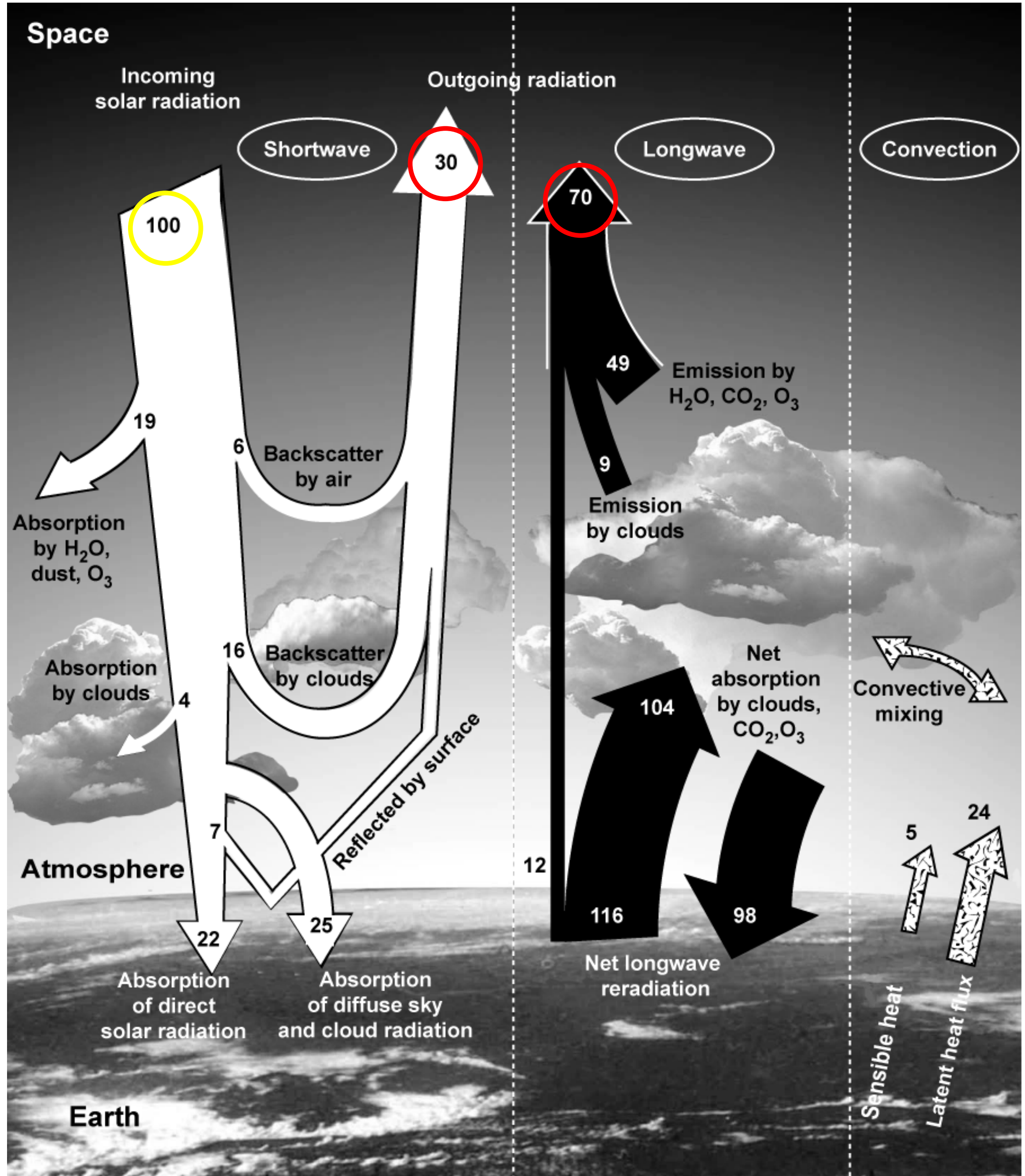
- Not all radiation makes it through the Earth's atmosphere
  - Shortwave
    - ~23% absorbed by atmosphere
  - Longwave
    - ~90% absorbed by atmosphere
  - Absorbed radiation is reradiated in all directions as longwave radiation
    - That directed back towards Earth → "Greenhouse effect"



Earth’s Climate System

- What happens to incoming solar radiation?
  - **Keys are that**
    1. Incoming solar radiation is relatively constant
    2. On a long-term global average, the solar radiation budget is in balance (i.e., what comes in goes out)
  - Of incoming shortwave solar radiation:
    - ~30% is reflected as shortwave (albedo)
    - ~70% is absorbed
      - 20% by atmosphere (including clouds) and 49% by the surface
      - All of this is eventually reemitted as longwave radiation
  - If the solar radiation budget is in balance, then what is absorbed must be reemitted
    - Function of Reflection (albedo), Absorption, & Emission

- As a long-term global average, Earth is in a state of radiative equilibrium
- in = out
- 100 = 30 + 70
  - Numbers are % of energy received as incoming solar radiation
  - 100% is ~341 watts/m^2

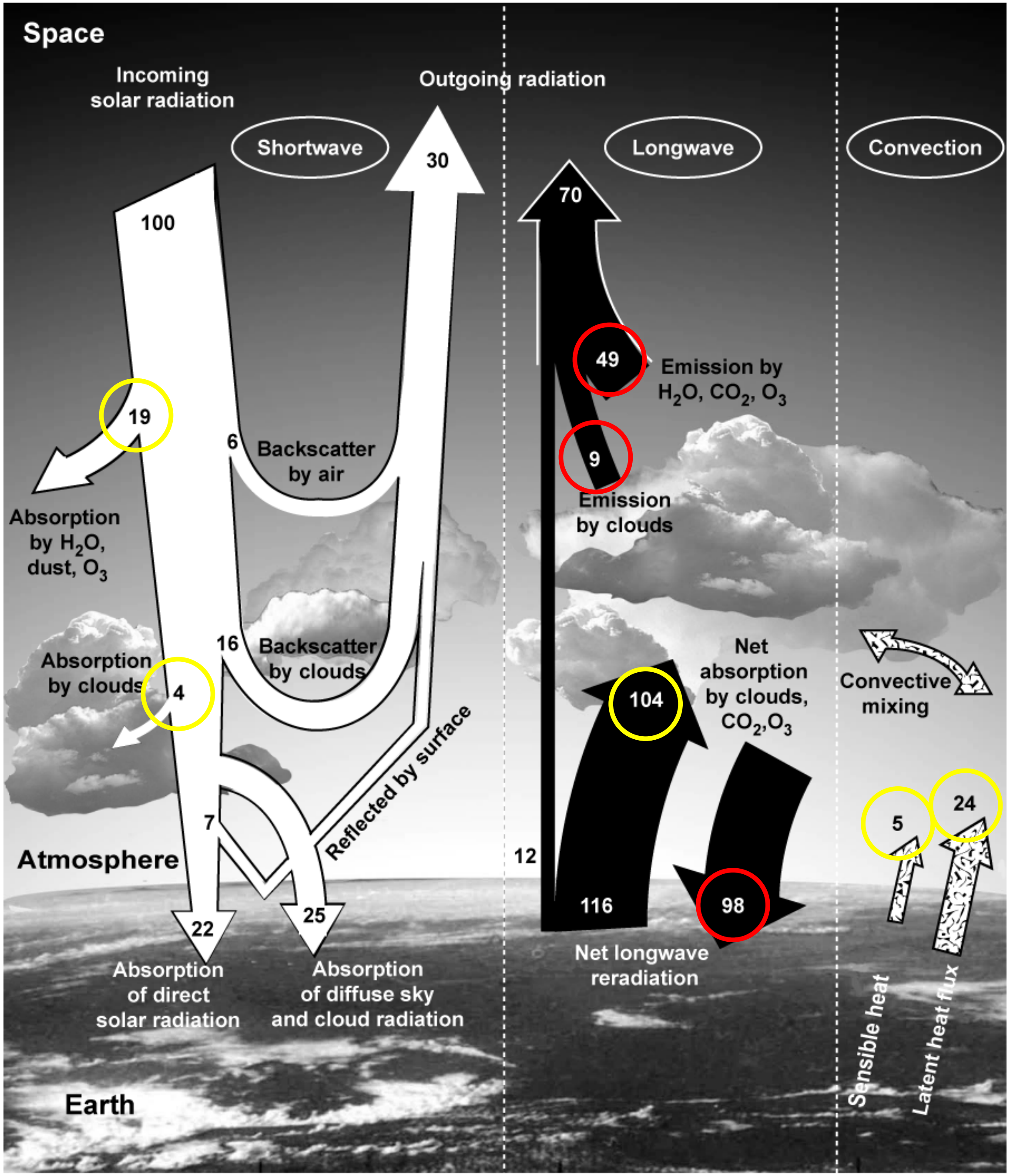


Within the atmosphere:

Absorbed = emitted

19+4+104+5+24 = 49+9+98

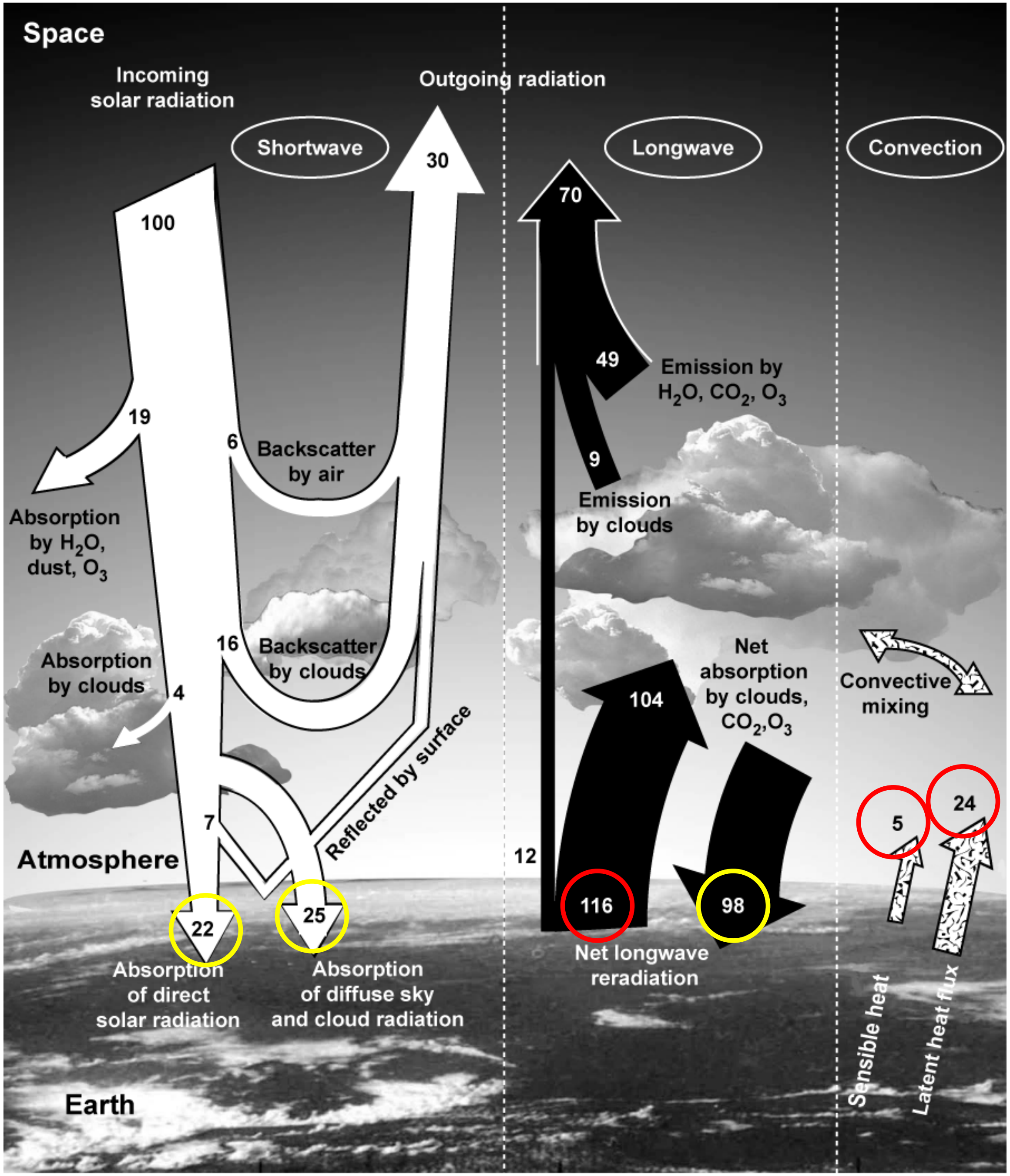
"Lost" radiation: most reflection of incoming shortwave & emission of outgoing longwave radiation happens in the atmosphere



At Earth's surface:

Absorbed = emitted

22+25+98 = 116+5+24



Earth's Climate System

- Three processes are responsible for transferring energy/heat from the surface to the atmosphere
    1. Longwave reradiation from Earth's surface (~78%)
    2. Sensible heat flux (~4%)
        - **Conduction**: heat transferred from the warmer ground and sea surface to the cooler atmosphere
        - **Convection**: heated air rises and is replaced by sinking cooler air
    3. Latent heat flux (~18%)
        - Evaporation and condensation of H_2O
            - H_2O evaporates at the surface (absorbs heat), is transported to the atmosphere via convection, and condenses in the atmosphere (releases heat)

Earth's Climate System

- Atmosphere is very important to Earth's climate because it:
  1. Reflects solar radiation
  2. Absorbs both short- and longwave radiation
  3. Emits longwave radiation
  – What is the atmosphere composed of?

Table 3.1 Global Average Concentration of Well-Mixed Atmospheric Constituents[a]

Compounds	Formula	% by volume Concentration (volumetric)	Total mass (g)
Major constituents (%)			
Nitrogen	N_2	78.084	3.87×10^{21}
Oxygen	O_2	20.946	1.19×10^{21}
Argon	Ar	0.934	6.59×10^{19}
Parts-per-million constituents (ppm = 10^{-6})			
Carbon dioxide	CO_2	360	2.80×10^{18}
Neon	Ne	18.2	6.49×10^{16}
Helium	He	5.24	3.70×10^{15}
Methane	CH_4	1.75	4.96×10^{15}
Krypton	Kr	1.14	1.69×10^{16}
Parts-per-billion constituents (ppb = 10^{-9})			
Hydrogen	H_2	510	1.82×10^{14}
Nitrous oxide	N_2O	311	2.42×10^{15}
Xenon	Xe	87	2.02×10^{15}
Parts-per-trillion constituents (ppt = 10^{-12})			
Carbonyl sulfide	COS	500	5.30×10^{12}
Chlorofluorocarbons			
CFC 11	CCl_3F	280	6.79×10^{12}
CFC 12	CCl_2F_2	550	3.12×10^{13}
Methylchloride	CH_3Cl	620	5.53×10^{12}
Methylbromide	CH_3Br	11	1.84×10^{11}

[a] Those with a mean residence time >1 year. Assuming a dry atmosphere with a molecular weight of 28.97. The overall mass of the atmosphere sums to 514×10^{19} g (Trenberth and Guillemot 1994).

>99.9%

▪ 0.0367%

Schlesinger (1997)

Earth's Climate System

- What determines atmospheric composition?
  - Mean residence time
    - MRT = total mass / flux
      - N_2 = 13,000,000 yrs
      - O_2 = 10,000 yrs
      - CO_2 = 4-5 yrs
      - CH_4 = 10 yrs
      - H_2O = 10 days
    - Aerosols also very important
      - Small solid or liquid particles
      - Reflect & absorb solar radiation
      - Act as condensation nuclei for formation of cloud droplets

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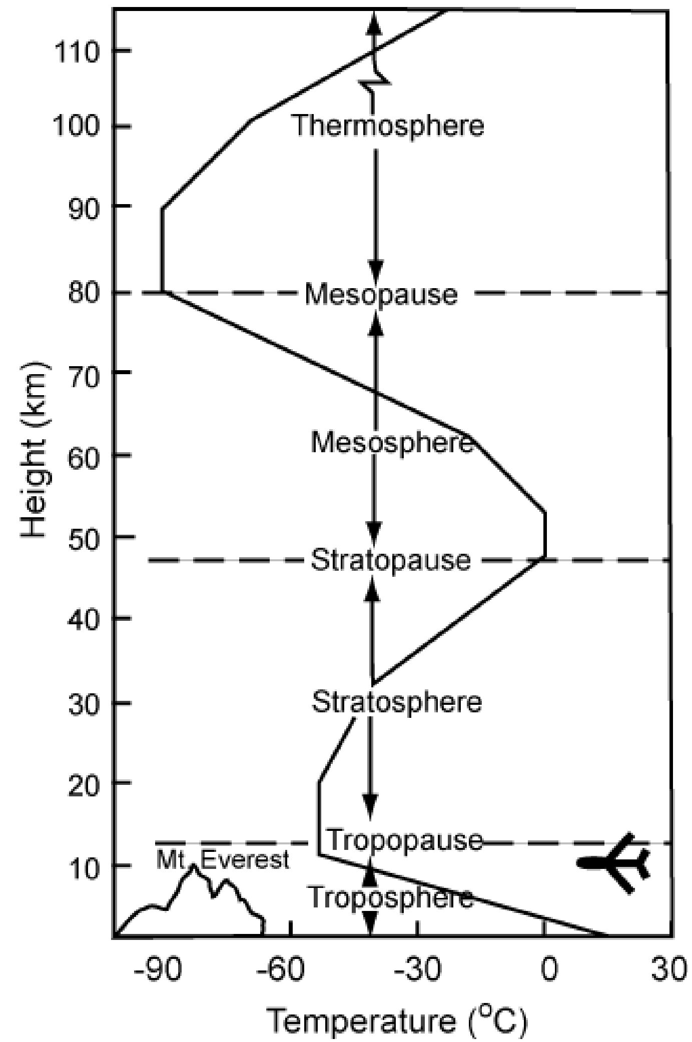
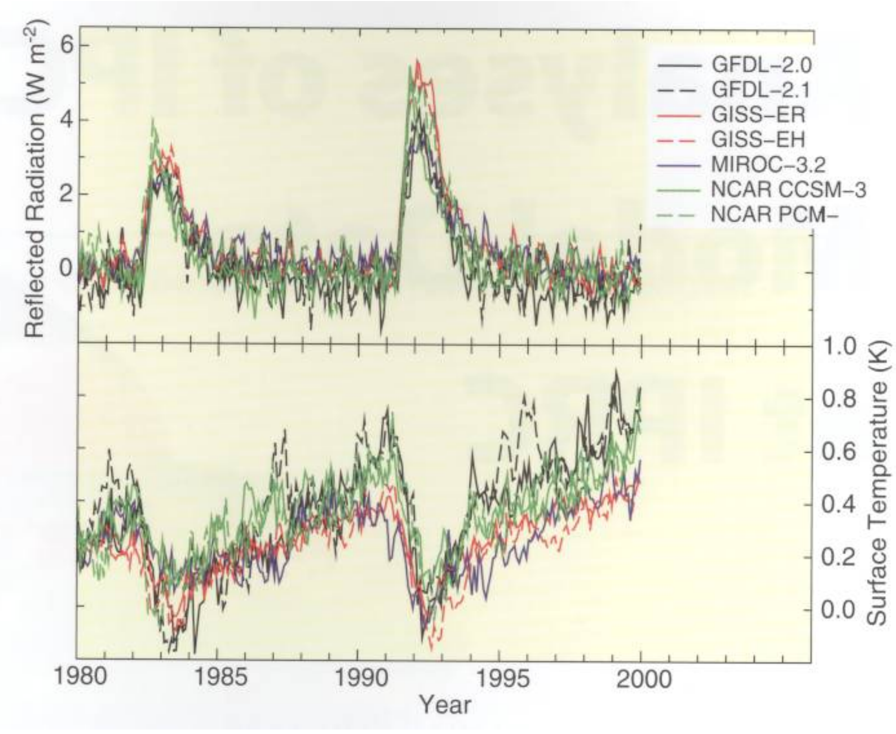
Earth's Climate System

- Atmospheric structure
  - 2 atmospheric layers are most important for biological activity
    - Stratosphere
      - Absorption of UV radiation by O_3 causes the stratosphere to be heated from the top down
    - Ozone hole: Breakdown of O_3 by Cl-containing gases (CFCs)
      - In the troposphere O_3 is a pollutant (smog) and is detrimental (e.g., to photosynthesis)

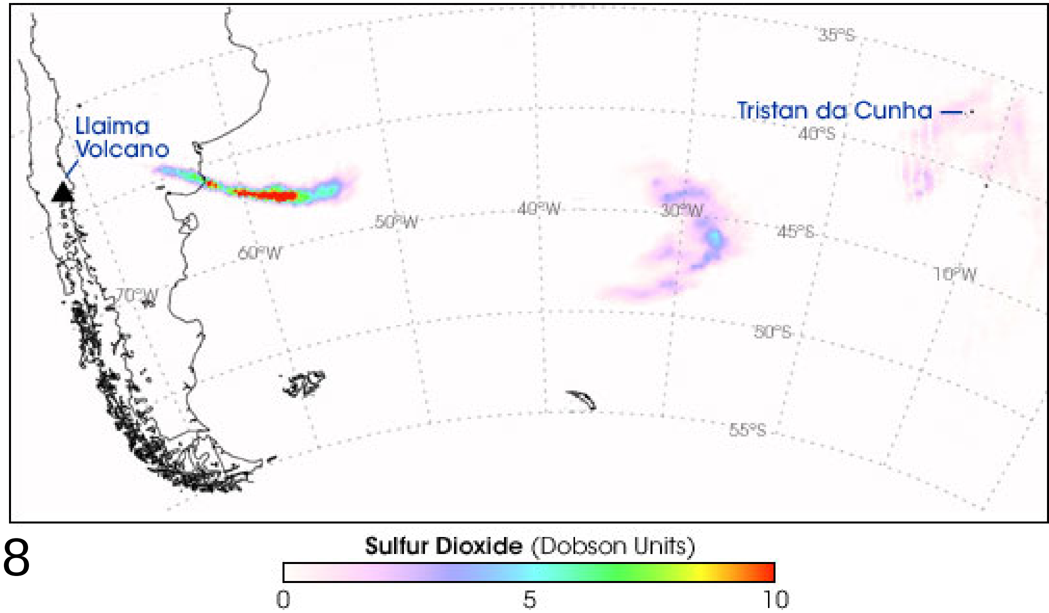


Earth's Climate System

- Stratospheric influence on climate
  - Periods where reflectance of shortwave radiation ↑ and surface temperature ↓
  - Volcanic Activity
    - Mt. Saint Helens (1980), El Chichón (1982), Mt. Pinatubo (1992)
      - Large quantities of sulfur dioxide → sulfate aerosols in the stratosphere
      - Ash particles in the stratosphere (to a lesser extent)



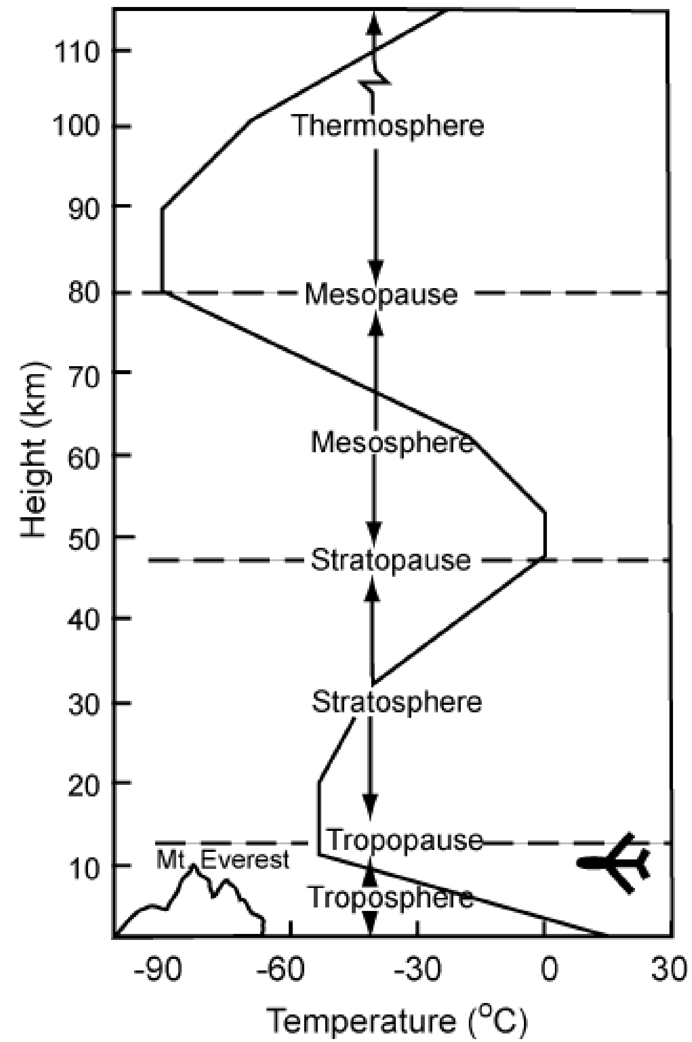
Volcán Llaima, Chile



Erupted 1/1/08
Image 1/2-1/4/08

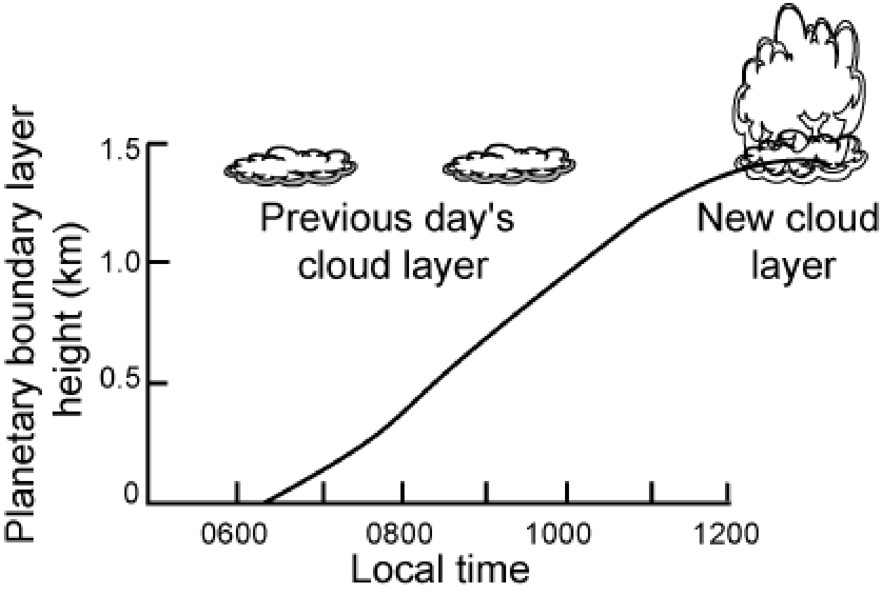
Earth’s Climate System

- Atmospheric structure
  - 2 atmospheric layers are most important for biological activity
    - Troposphere (weather layer)
      - Portion of the atmosphere that directly influences, and is influenced by, ecosystems
      - ~16 km in tropics & ~9 km at poles; lower in winter than summer
      - 75% of atmospheric mass
      - Heated from bottom up
        - Longwave radiation, sensible heat flux, and latent heat flux from Earth’s surface



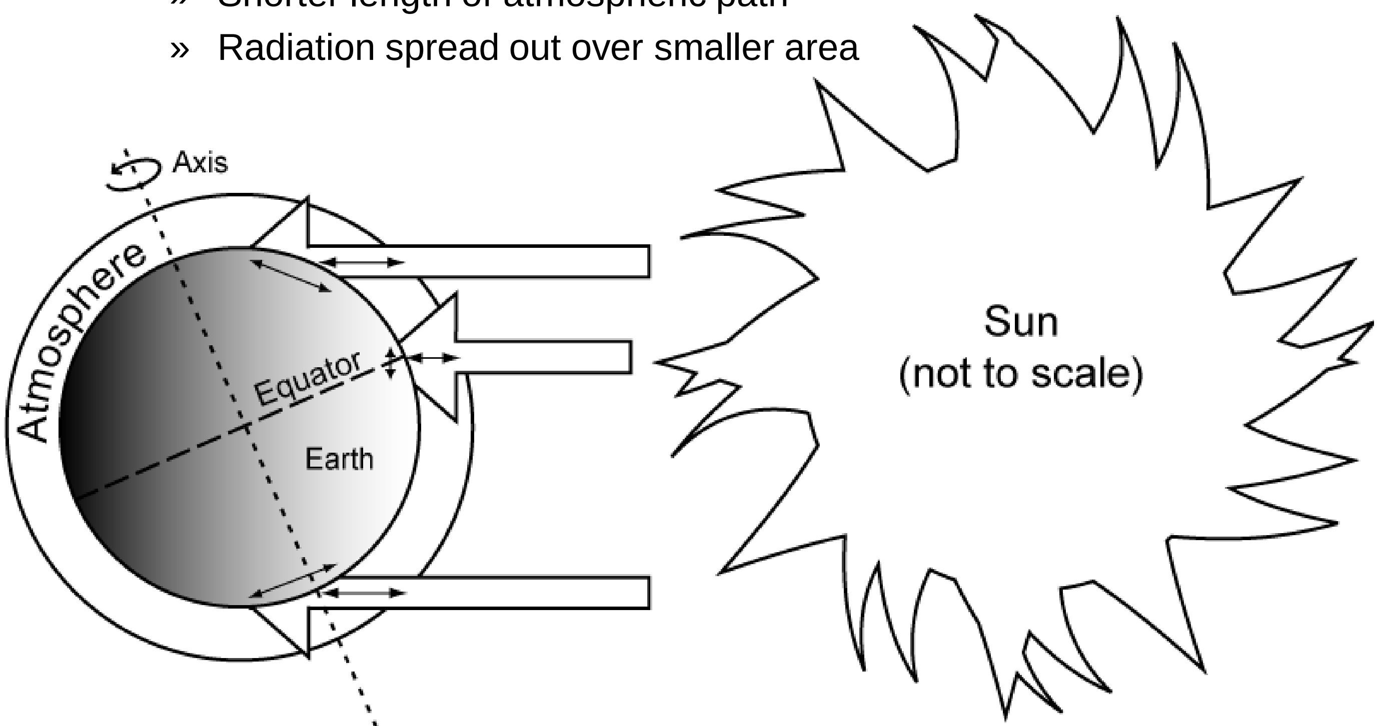
Earth's Climate System

- Planetary Boundary Layer
  - Lower portion of troposphere that interacts directly with Earth's surface via mixing
  - Mixing occurs due to
    1. Convective turbulence (surface heating → warm air is less dense and rises)
    2. Mechanical turbulence (friction of air moving across the Earth's surface)
  - Height of PBL increases during the day due to convective turbulence



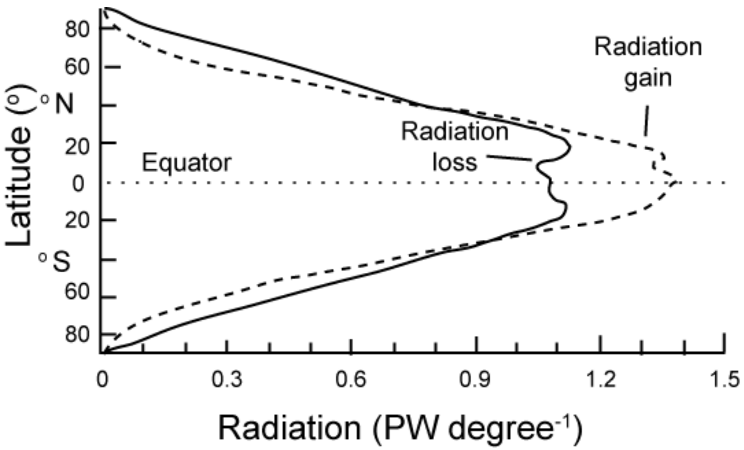
Earth’s Climate System

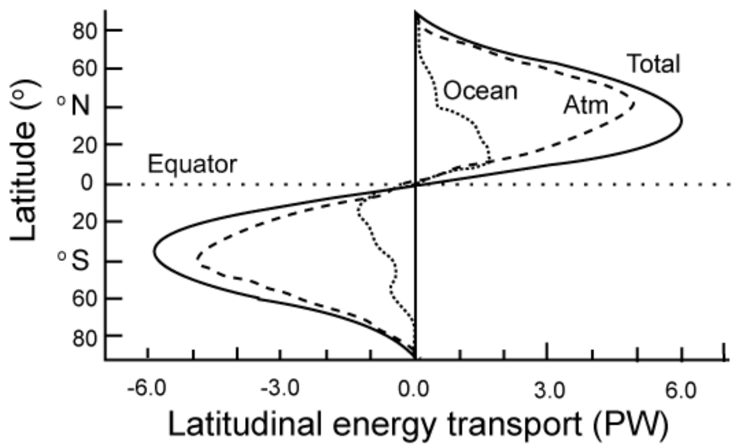
- Global atmospheric circulation
  - Driven by uneven heating of Earth’s surface (& troposphere) by solar radiation
    - Suns rays are perpendicular between 23.5° N & S latitudes (the tropics)
      - More energy is absorbed per unit surface area in the tropics:
        - » Shorter length of atmospheric path
        - » Radiation spread out over smaller area



Earth's Climate System

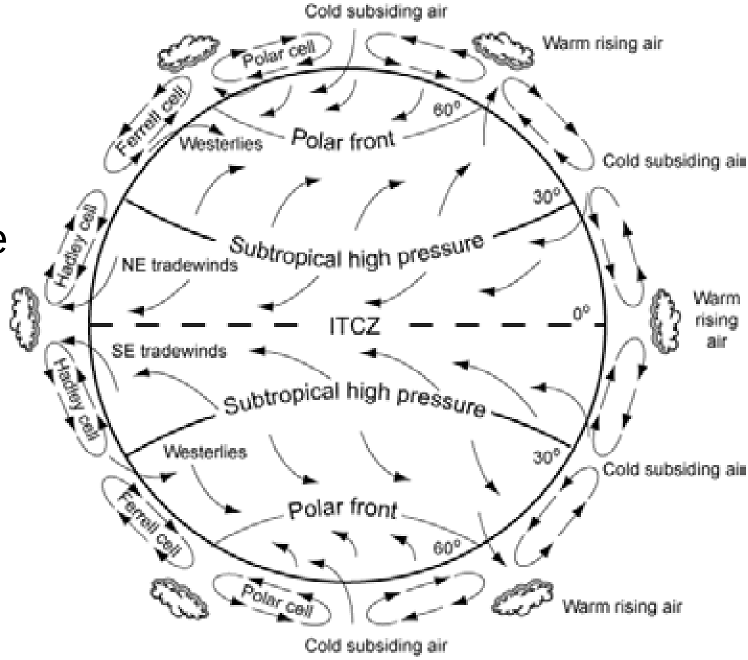
- Global atmospheric circulation
  - Because energy in = energy out globally, heat is driven from equator to poles
    - Globally, ~60% of poleward transfer of heat from equator due to atmospheric circulation
      - Other 40% due to ocean circulation
    - Latitudes <35° N & S → net radiation surplus (more enters than leaves)
      - Shortwave (↓) > Longwave (↑)
    - Latitudes >35°N & S → net deficit of radiation (more leaves than enters)
      - Shortwave (↓) < Longwave (↑)





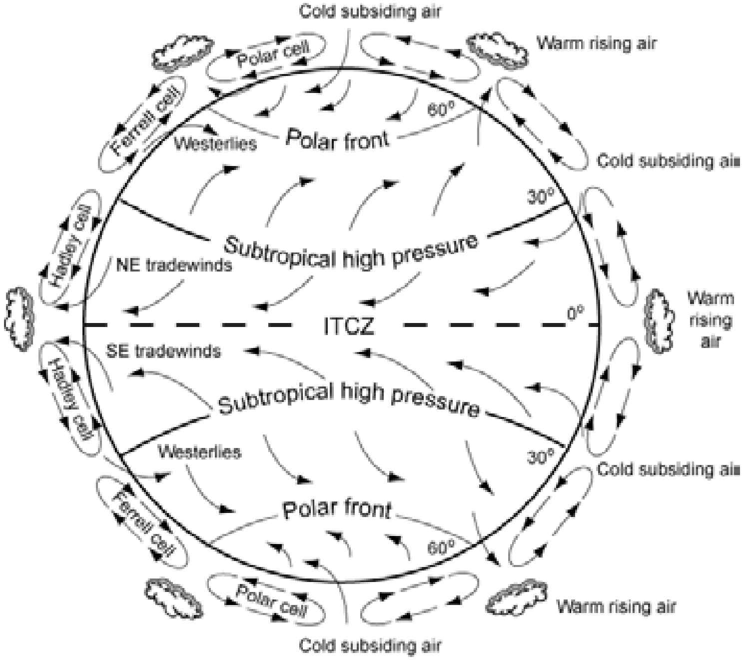
Earth’s Climate System

- Atmospheric circulation
  - Hadley cells
    - Hot moist air ↑ at equator; moisture condenses and releases precipitation (and heat) to atmosphere
      - High precipitation in tropics; warm atmosphere
    - Warm dry air flows N & S, cools, & ↓ at ~30°
      - As dry air ↓, compressed & heats; → intense evaporation & a belt of deserts at ~30° N & S = HORSE LATITUDES
    - Air flows towards equator, picks up moisture over oceans, deflected by Coriolis force to W → moist surface flow = TRADE WINDS.
      - NE & SE trades converge at the Equator = INTERTROPICAL CONVERGENCE ZONE
      » Zone of low pressure, light winds = DOLDRUMS



Earth's Climate System

- Atmospheric circulation
  - Polar Cells
    - Subsidence of cold converging air at poles
    - Deflected to the W causing EASTERLIES
  - Ferrell Cells
    - At 30°N & S, surface air flows poleward → Ferrel Cells (indirect cell)
      - Deflection by Coriolis force → prevailing WESTERLIES
    - Ferrell Cell encounters cold air moving from poles at ~60° N&S
      - POLAR FRONT: unstable air, lots of precipitation and storm systems
    - Warm air rises over polar air & circulates back to complete Ferrel Cell

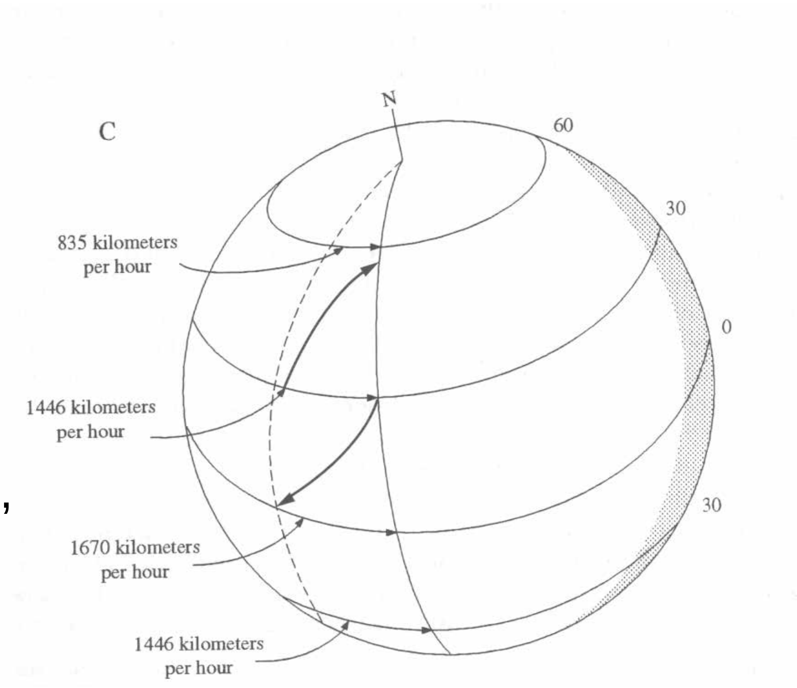


ITCZ – Intertropical Conversion Zone

- Is the ITCZ always located at the equator? Why?
  – No. Location of the circulation cells shifts due to tilt of the Earth (seasonal changes in surface heating by the sun)

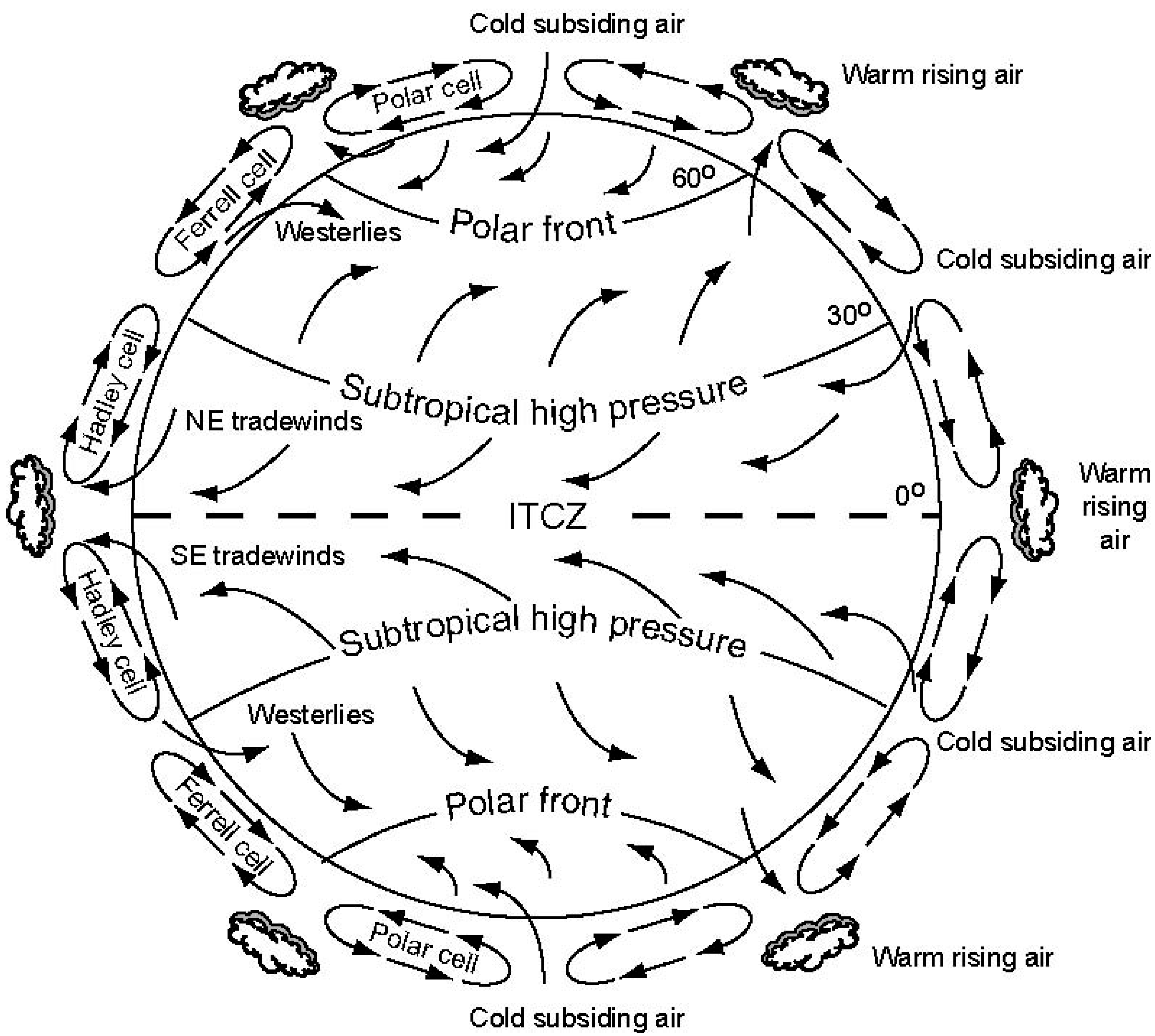
Earth’s Climate System

- Coriolis Force
  - At different latitudes, Earth rotates at different speeds in relation to the atmosphere
    - Earth rotates from W to E and atmospheric cells move N or S
    - Atmosphere maintains momentum relative to Earth’s surface
    - Key is understanding atmospheric cells, specifically surface movement
      - Poleward air encounters less surface and increases speed → Westerly surface winds (winds move W → E)
      - Equatorward air encounters more surface and reduces speed → Easterly surface winds (winds move E → W)



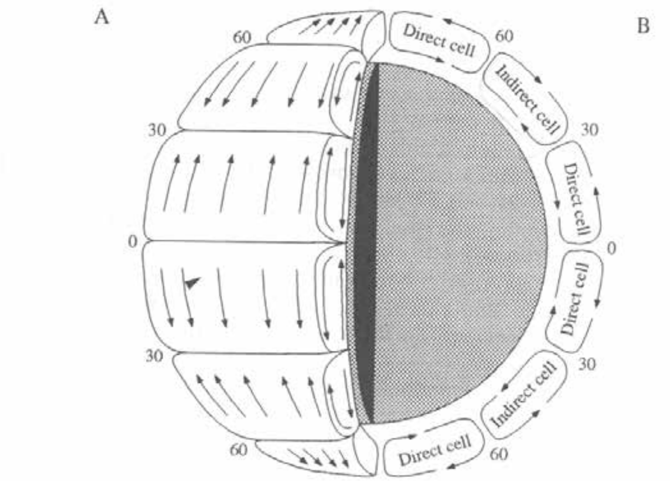
Schlesinger (1997)

Earth’s Climate System



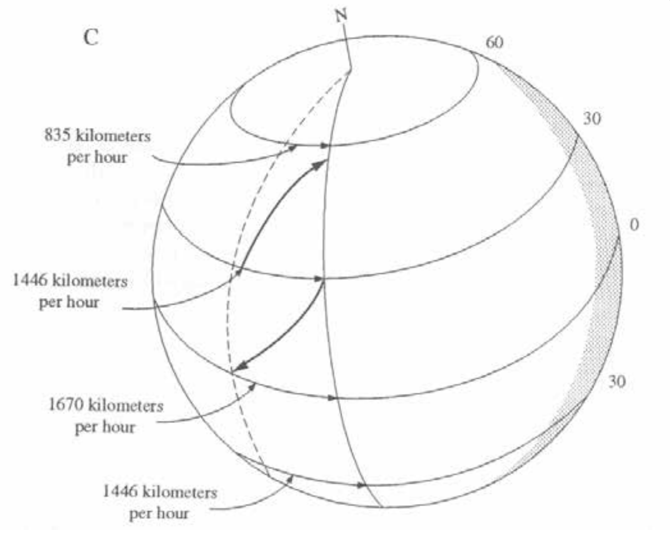
Earth's Climate System

Vertical mixing drives circulation cells



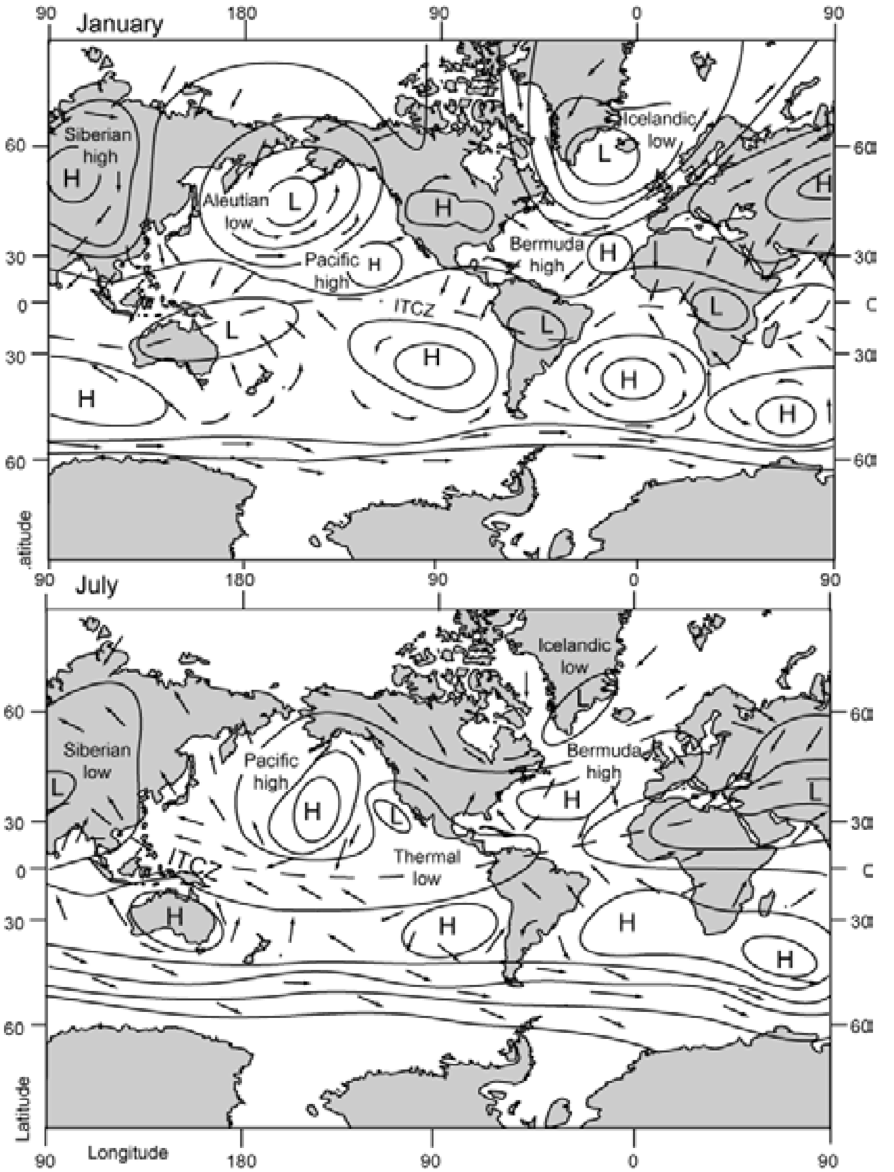
Schlesinger (1997)

Coriolis forces drive wind directions (<u>and</u> shallow ocean circulation)



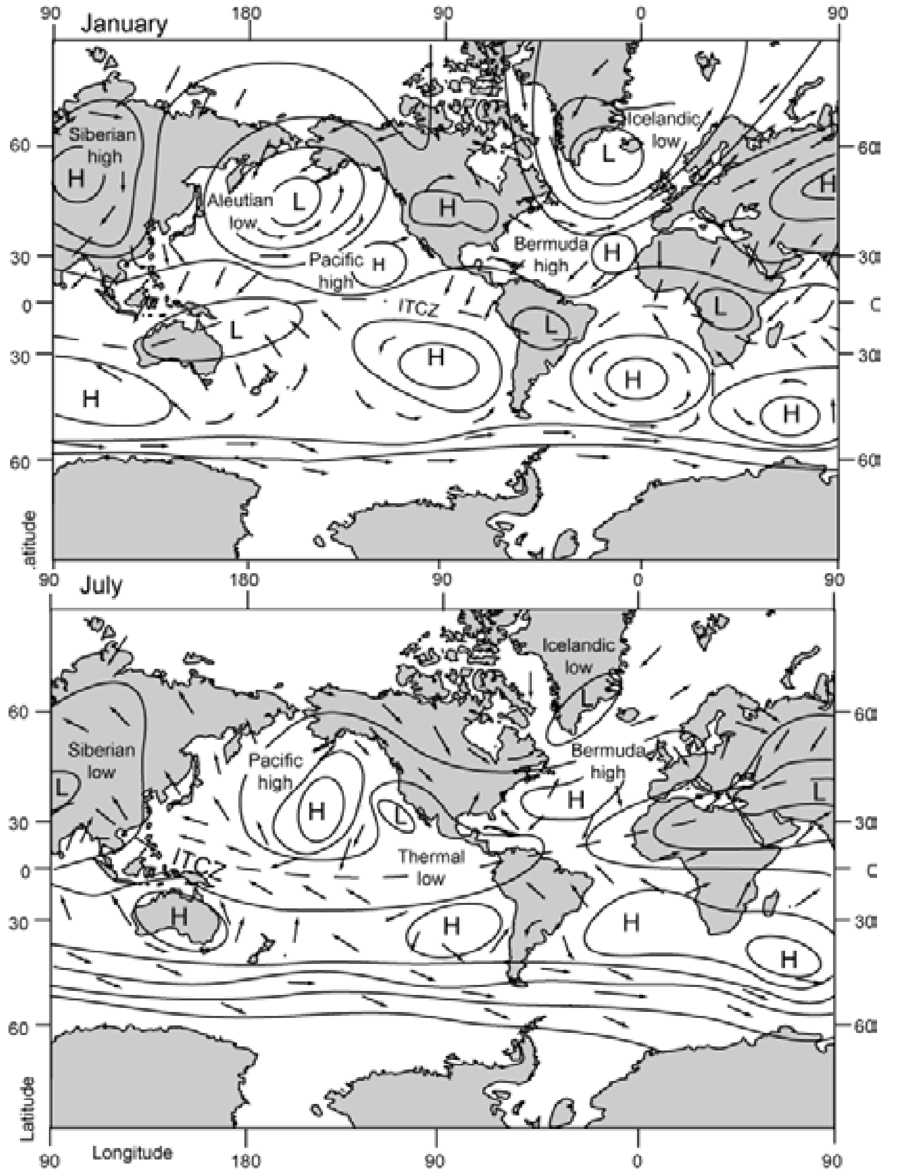
Earth’s Climate System

- Continental/Ocean Effects
  - Uneven distribution of land & ocean modifies general latitudinal trends in climate:
    - Rising & sinking of air creates low and high pressure centers, resp.
      - Air ↓ more strongly over cool ocean, resulting in high pressure zones over oceans at 30° N and S
        - High pressure circulates clockwise in N. hemi. & counterclockwise in S. hemi.
      - Rising air at 60° N and S creates low pressure zones (time averages)
        - Low pressure circulates counter-clockwise in N. hemi.
        - Lack of land in S. hemi. leads to broad trough of low pressure



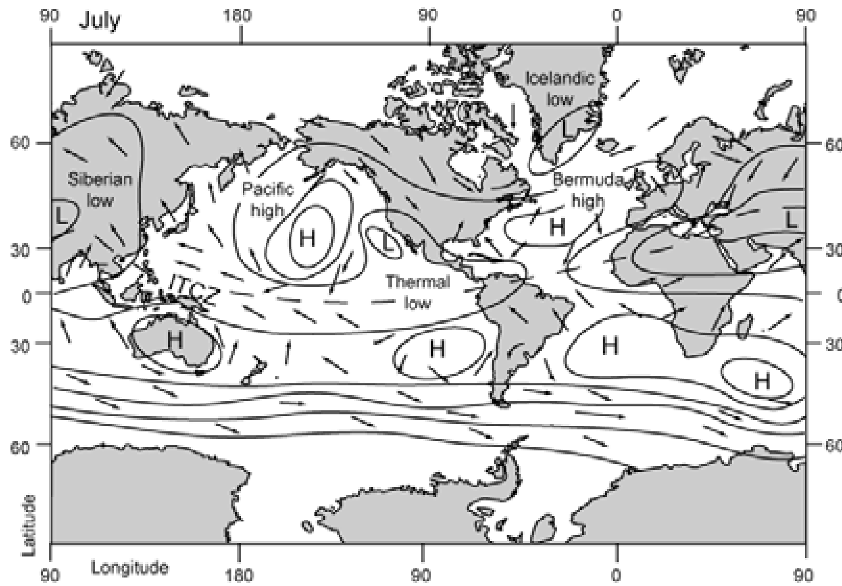
Earth's Climate System

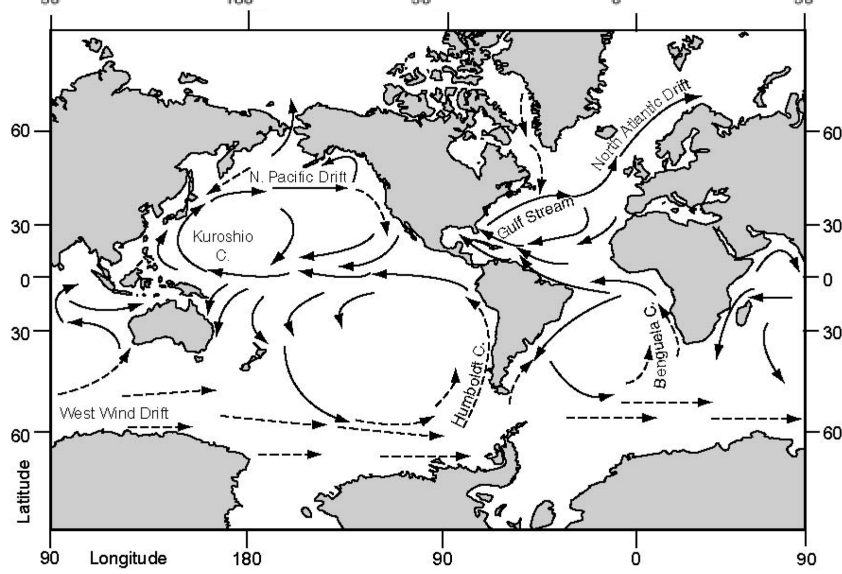
- Continental/Ocean Effects
  - Planetary waves
    - Deviations from expected wind directions on a planetary scale
      - Most pronounced in N hemisphere
      - Influenced by:
        - Coriolis effect
        - Land-ocean heating contrasts
        - Large mountain ranges



Earth's Climate System

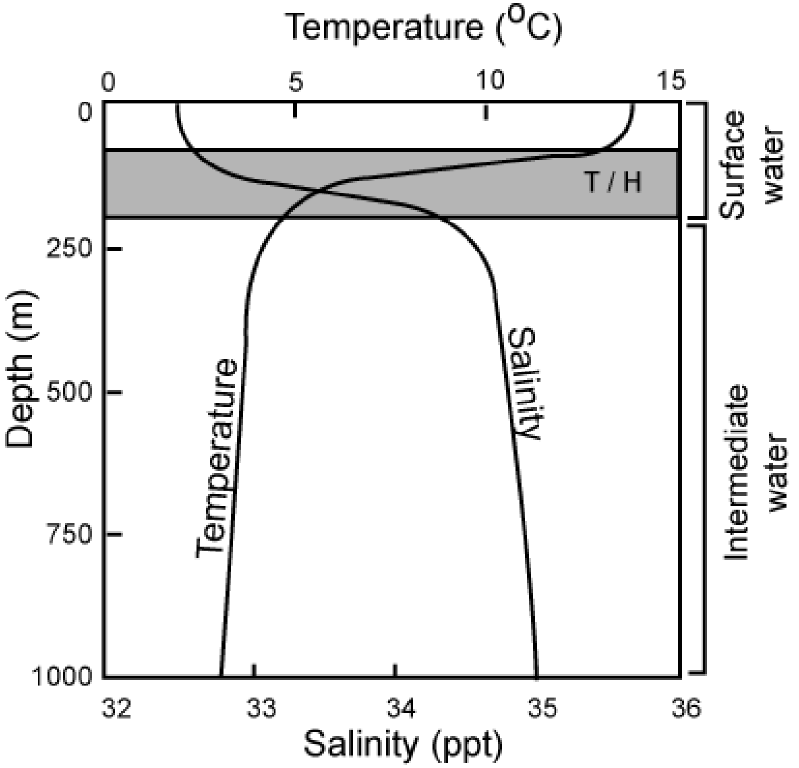
- Ocean Circulation
  - Responsible for other 40% of poleward movement of heat
    - Has strong moderating effects on regional climate
  - Two processes at work:
  1. Surface (shallow) circulation
     - Driven by surface wind patterns that result from the Coriolis effect
     - Deflected by continents to form 'gyres'





Earth’s Climate System

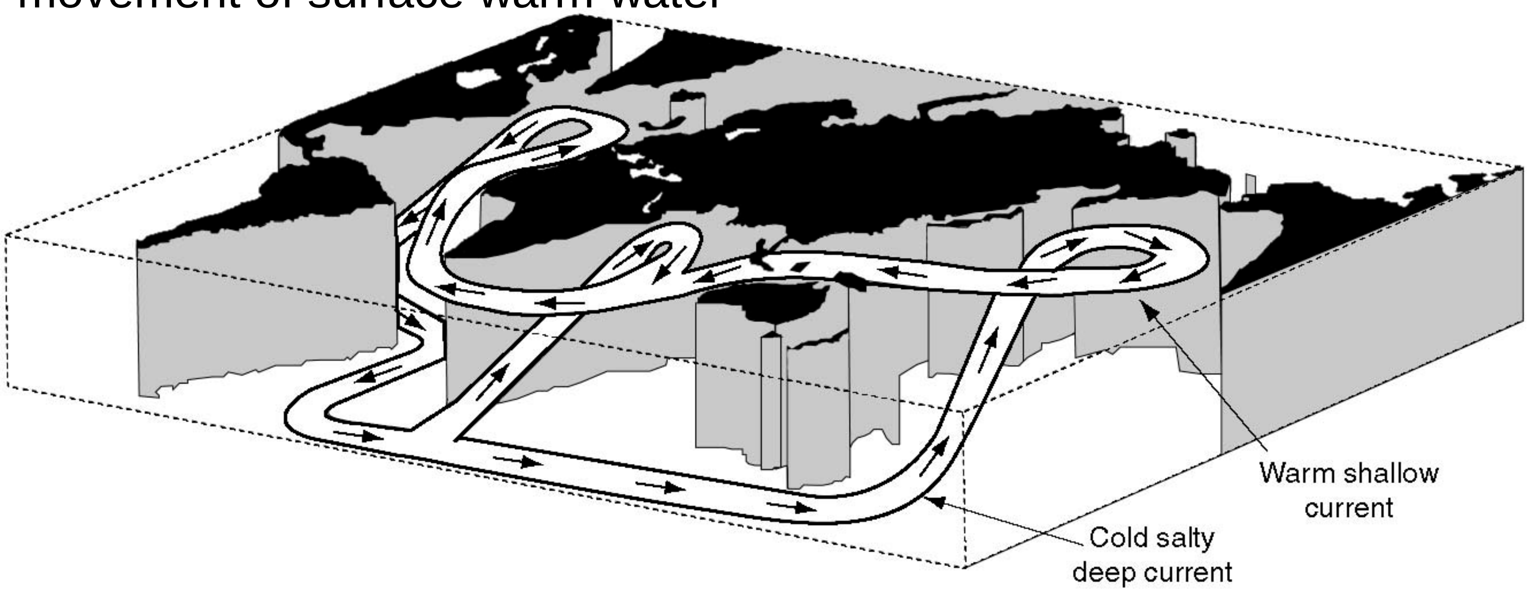
- Ocean Circulation
  2. Thermohaline (deep) circulation
     - Result of temperature & salinity gradients
     - Ocean heated from the top → warm water stays at the top → more stable and less mixing than in atmosphere
       - Warm water at surface, cool water at depth
         - Stable vertical stratification of low density surface water over denser deep water
         - Mixes over 100s to 1,000s of years
       - “Thermohaline” circulation refers to importance of both temperature & salinity
         - Warm water will sink if saline enough



Earth’s Climate System

- Ocean Circulation

  2. Thermohaline (deep) circulation
     - Driven by water downwelling at poles
       - Cold air cools water to form ice → ice formation excludes salt → colder and more saline sinks strongly at poles
     - Mixes water between ocean basins
     - Balanced by upwellings on the East margins of ocean basins at low latitudes
       - Drives nutrient transport to shallow waters and high productivity → fisheries
     - Movement of deep cold water towards equator is balanced by poleward movement of surface warm water



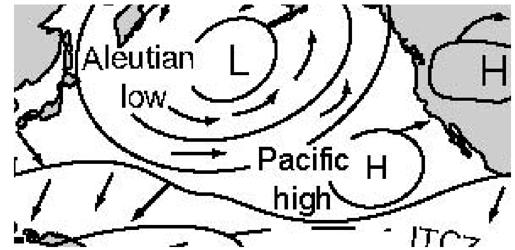
Earth’s Climate System

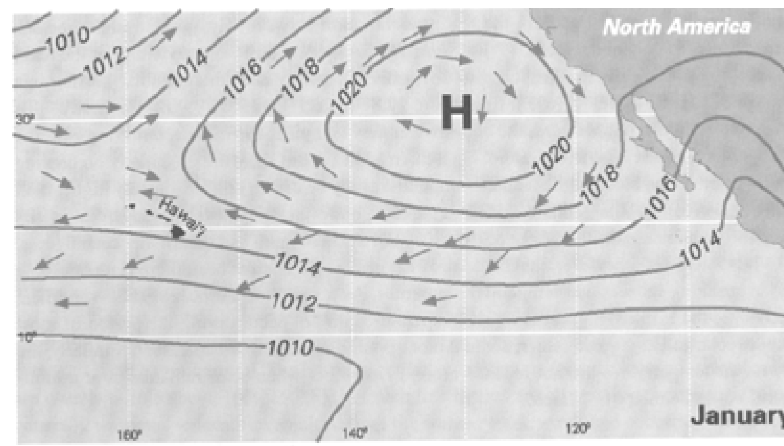
- Hawai‘i Climate
  - Dominated by global climatic patterns
    - Proximity to equator (Hadley Cell), NE tradewinds, cold fronts, and Kona Lows
  - Influenced by important landform effects
    - Orographic effect, inversion layer, and convective uplift (land/sea breezes)

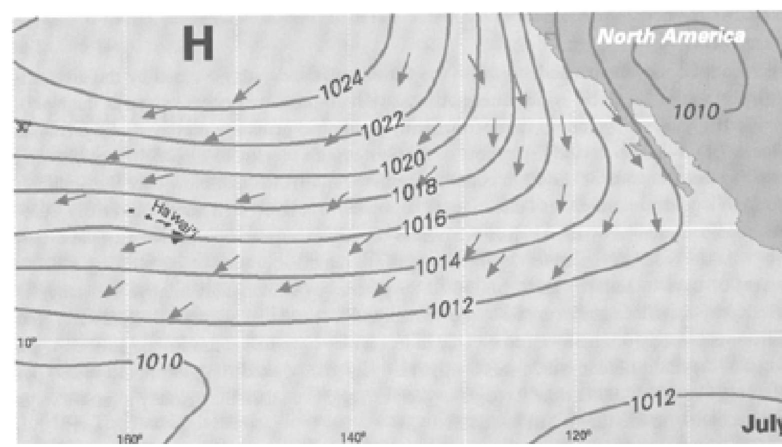
Earth's Climate System

- Hawai‘i Climate
  - Tradewind Weather
    - NE Tradewinds from Coriolis effect and the North Pacific High
      - 80% in summer and 50-80% in winter

    - North Pacific High & Aleutian Low shift seasonally
      - In, winter, allows the Aleutian Low to approach the islands → Kona Lows and Cold-Fronts (Low pressure systems)

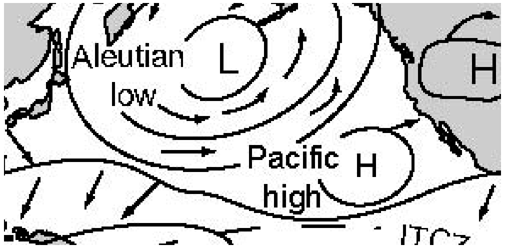


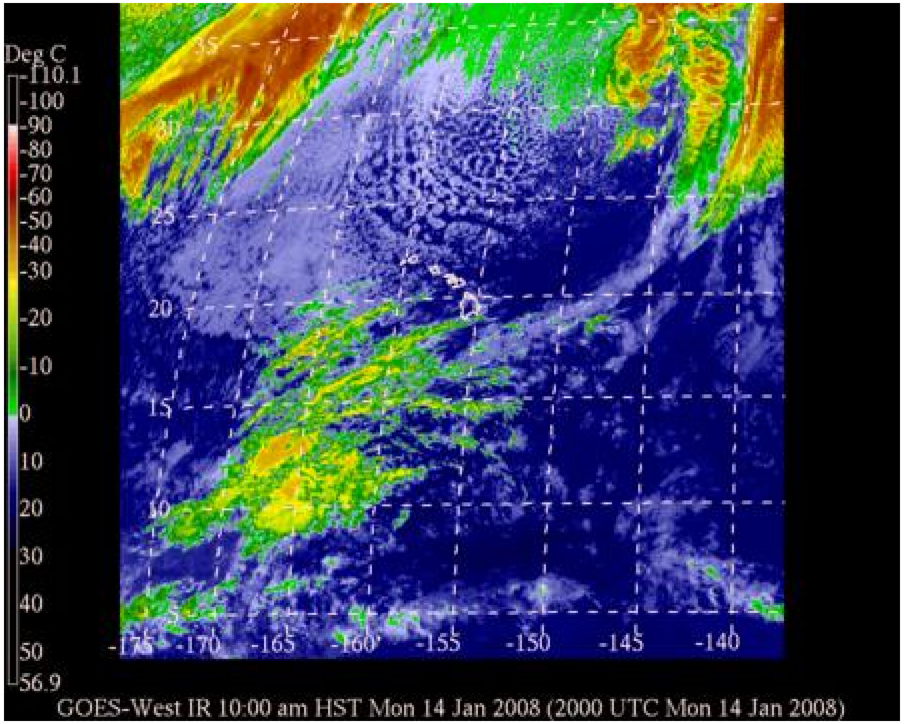




Earth's Climate System

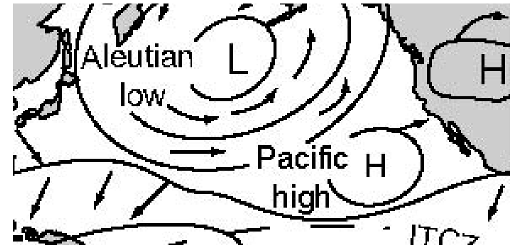
- Hawai‘i Climate
  - Tradewind Weather

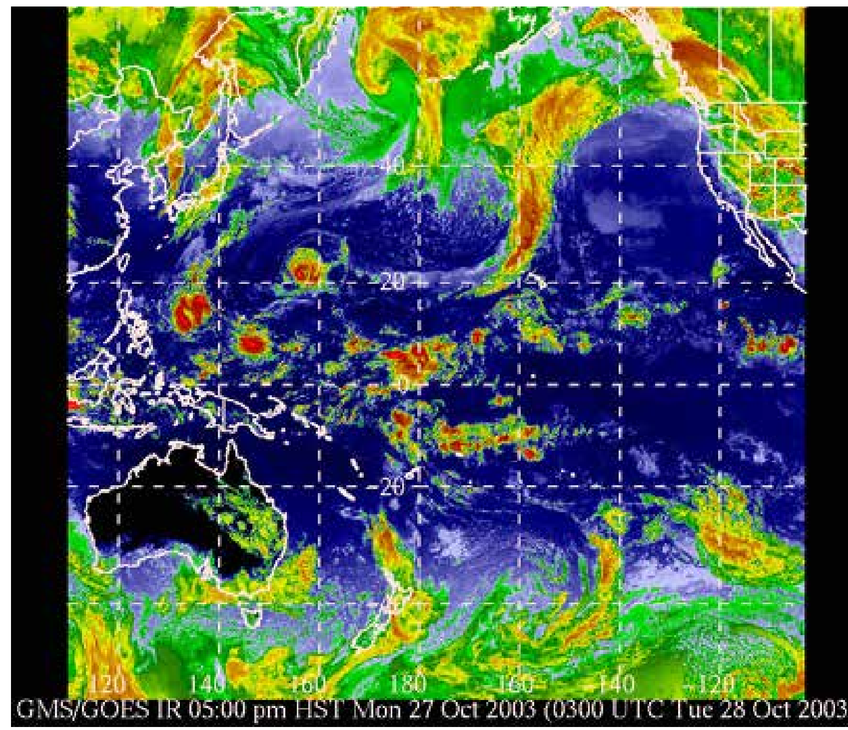




Earth's Climate System

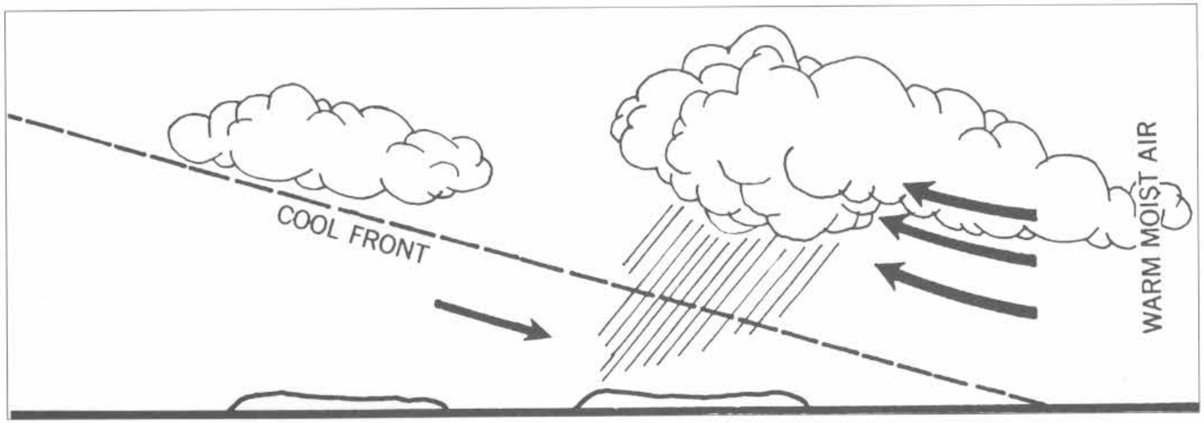
- Hawai'i Climate
  - Kona Lows
    - Cyclones from the N tropics or subtropics
    - Deep trough of cold low pressure from the north protrudes south near Hawaii
    - ~2-3x yr^{-1}
    - Slow moving with widespread precipitation (≥1 week)
    - Seasonal (in the winter)

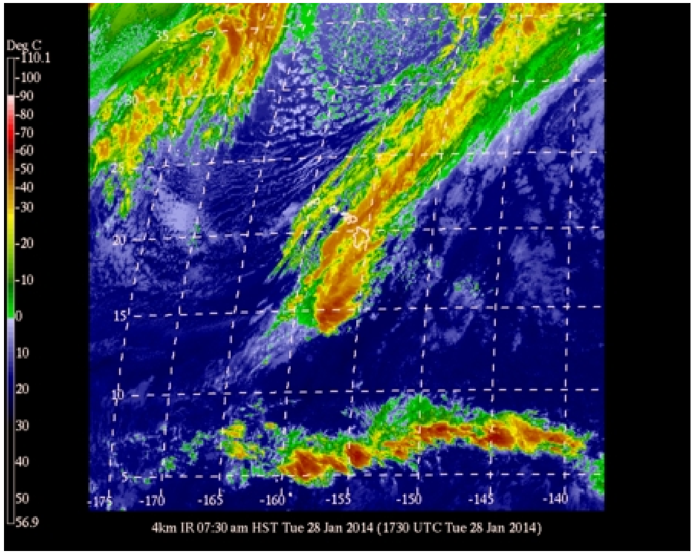




Earth's Climate System

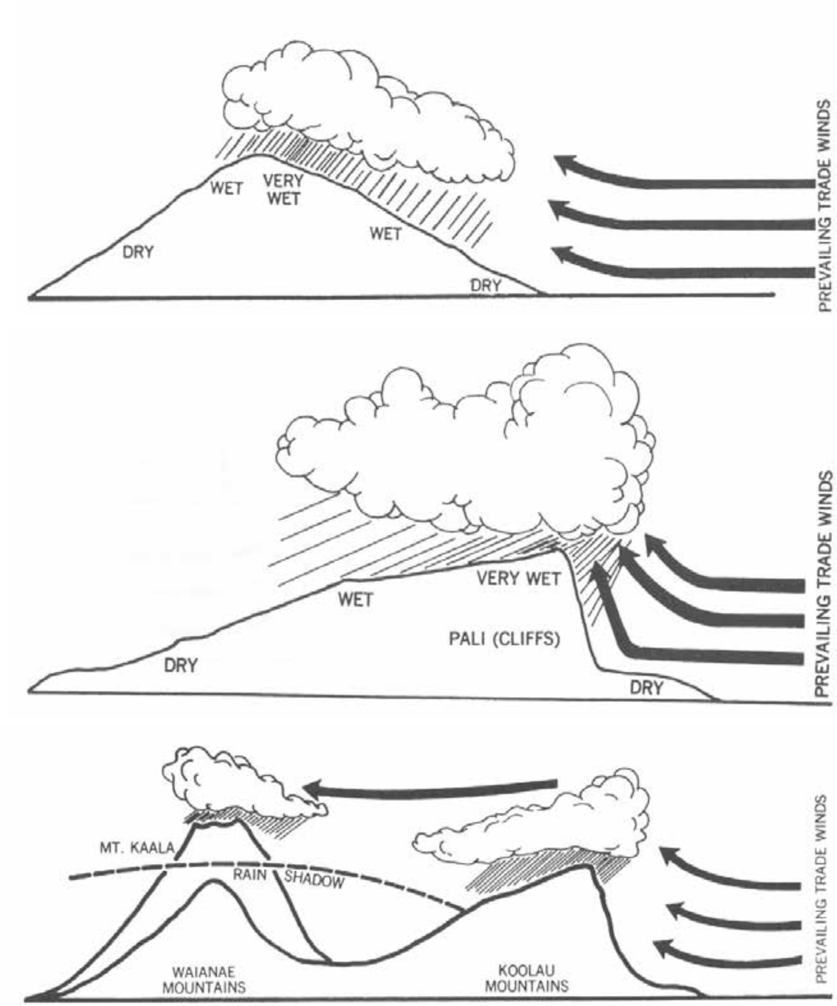
- Hawai‘i Climate
  - Cold-front storms
    - Result when Aleutian Low Pressure system approaches the Islands
      - ~2-12x yr^{-1}
    - Storm-track has cool dense air
    - Pushes warm, moist air up causing unstable atmosphere, widespread precipitation and strong winds





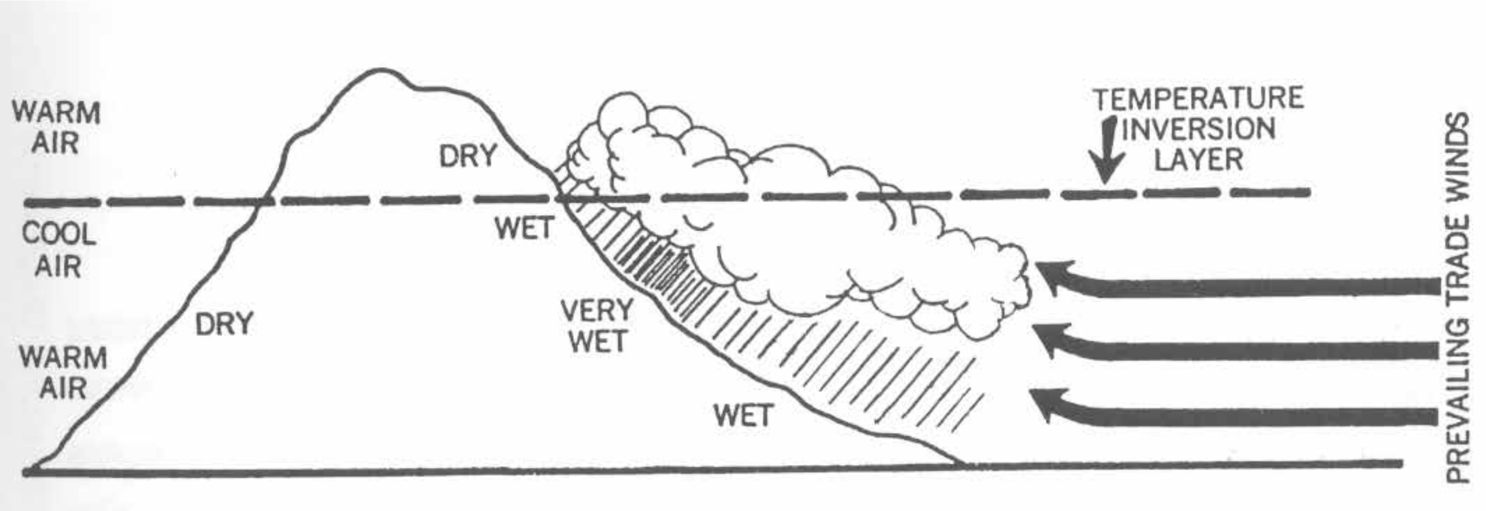
Earth's Climate System

- Hawai'i Climate
  - Also driven by a number of "landform" effects
  - Orographic Effect
    - •Dominant wind patterns (tradewinds) results in rainy windward and dry leeward conditions
    - •Variability related to topography of landforms



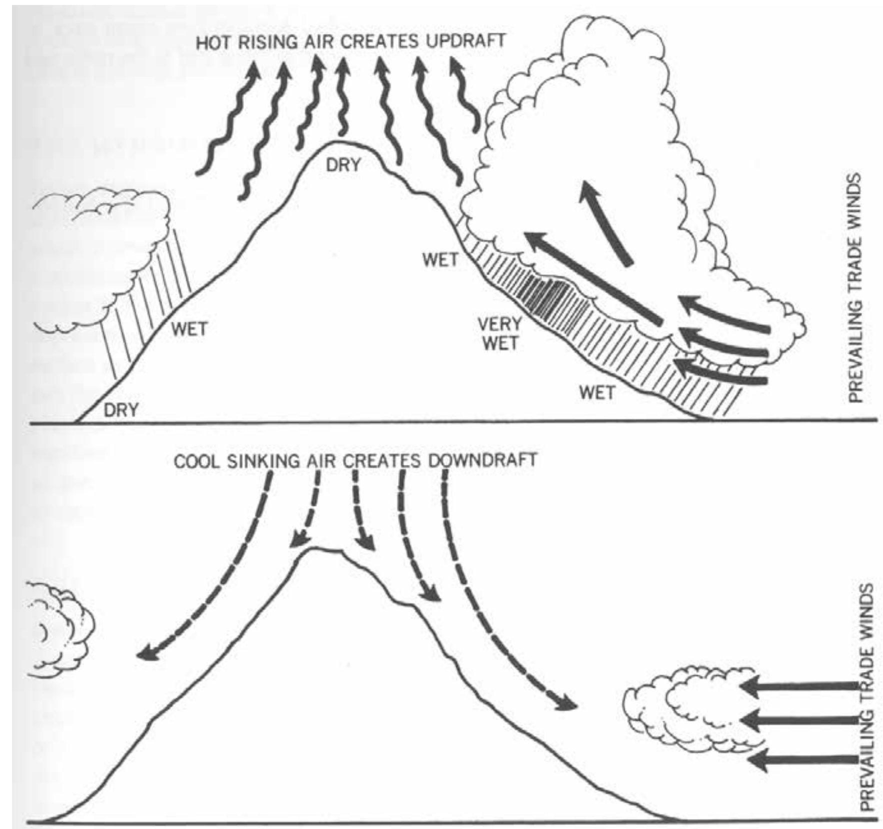
Earth’s Climate System

- Hawai‘i Climate
  - Inversion Layer
    - Typically air mass rises, cools, and releases moisture
    - Very dry air descends from above (Hadley cell), heats by compression, and suppresses the cold air from rising
      - Temperature inversion layer with warmer air over colder air
      - ~1,500-2,100 m.a.s.l
      - Present ~½ to ¾ of the time (only on larger/taller islands)



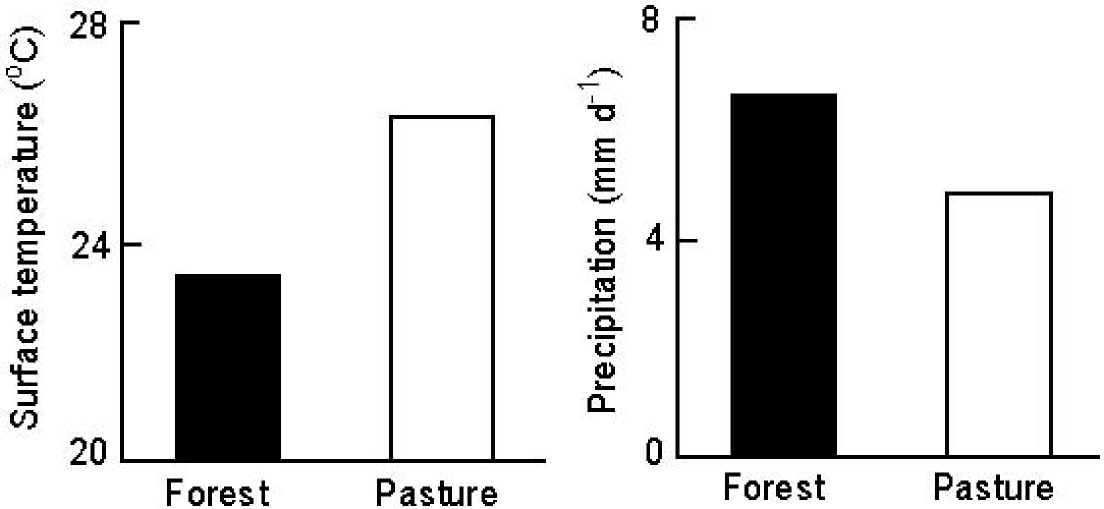
Earth's Climate System

- Hawai‘i Climate
  - Convective Patterns
    - Differential heating of land / ocean
      - Sea breezes in the day
      - Land breezes at night
  - Vegetation also influences climate locally and regionally
    - Primarily through effects on surface energy budgets
      - Albedo, sensible heat flux, and latent heat flux

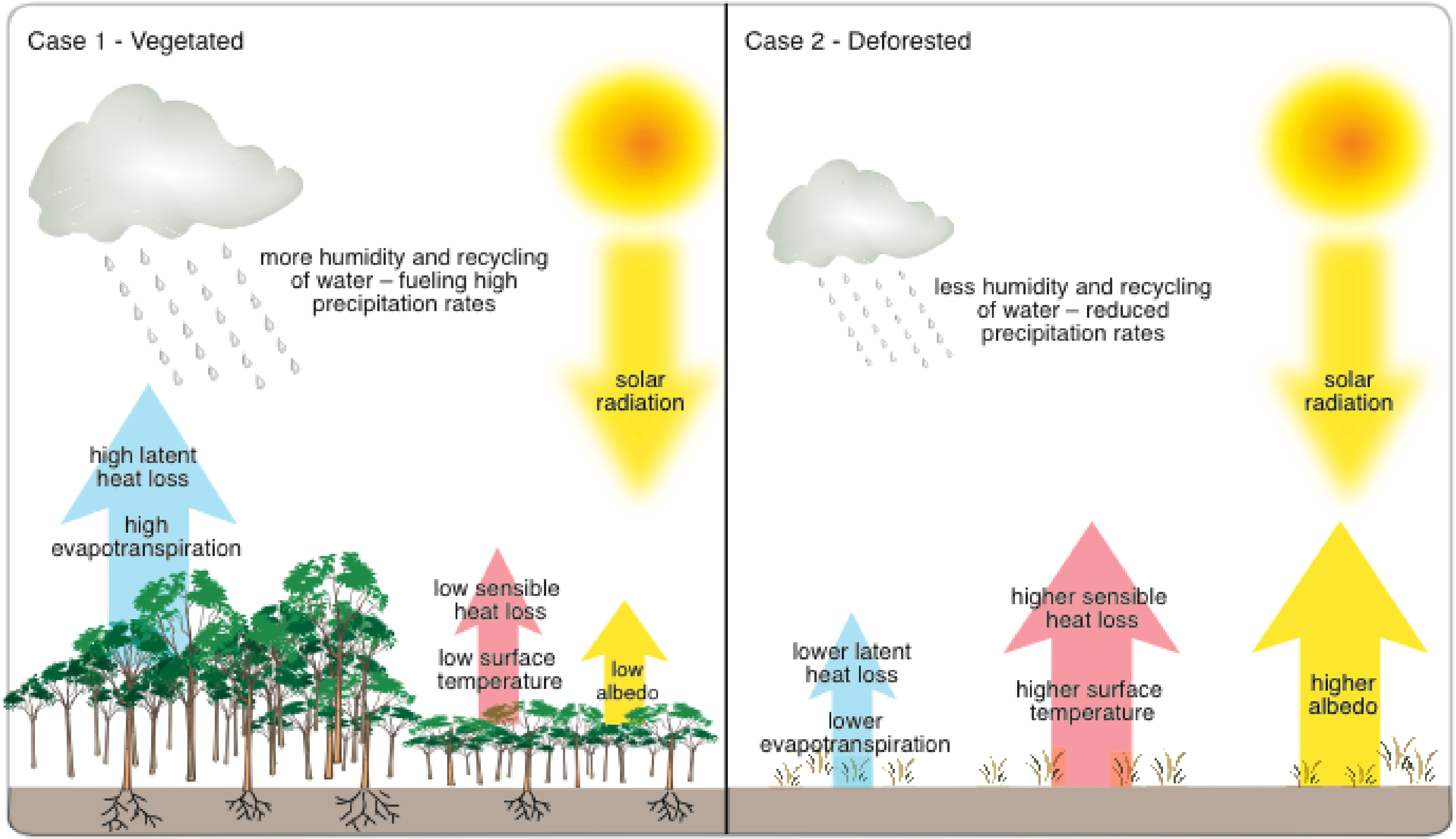


•Climatic consequences of tropical deforestation (computer simulation model for entire Amazon basin)

- Results in warmer drier climate
- Why?



- Vegetation alters surface energy budget
  - •Impacts reflectivity (albedo), sensible heat flux, and latent heat flux



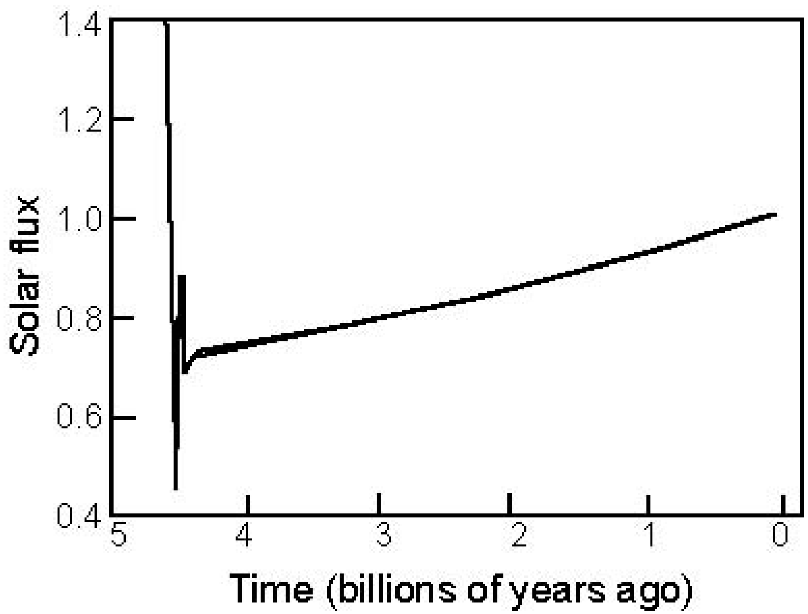
- Low Albedo → high energy absorption
- High transpiration cools surface
- Supplies abundant moisture to atmos.

- High Albedo → low energy absorption
- Low transpiration results in warm surface
- Low moisture supply to atmos.

Foley et al. (2003)

Earth's Climate System

- Long-term climate variability (100,000s to millions of years) is driven primarily by changes in solar input
  - Evolution of the sun (the sun is a relatively young star)
  - Changes in Earth's atmospheric composition
  - Milankovitch Cycles



Earth's Climate System

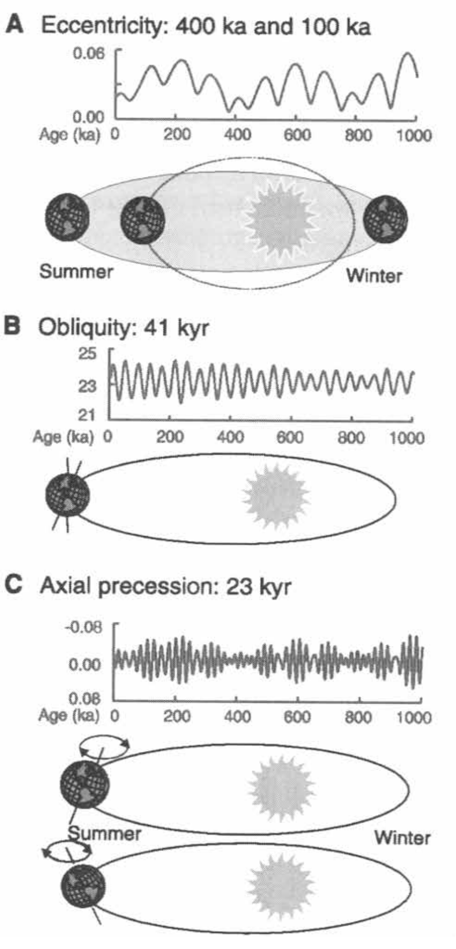
Long-term climate variability

"Milankovitch cycles" - 1941

A. ° of ellipticity of orbit; eccentricity (100,000 & 400,000 years)

B. Change in tilt of Earth's axis; obliquity or "wobbling" (41,000 yrs)

C. Change in time of year of perihelion (23,000 yrs)



Millar & Brubaker (2006)

Earth's Climate System

- Nobody was around then, so how do we know that climate was so variable in the past?
  - Ice cores
  - Pollen profile (vegetation reconstructions)

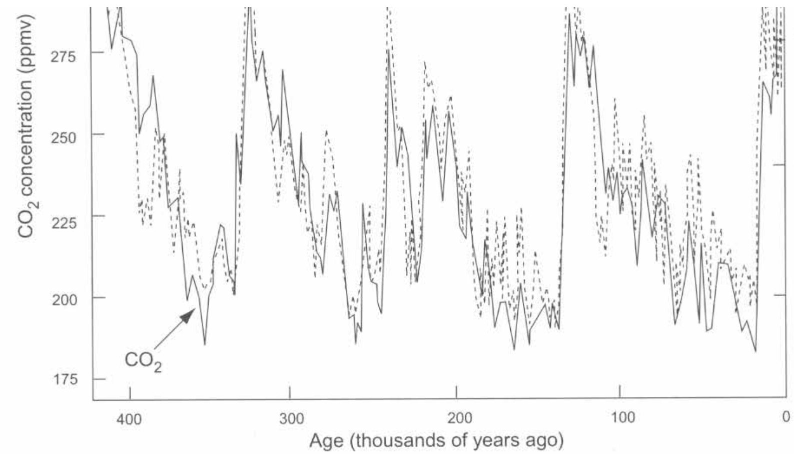
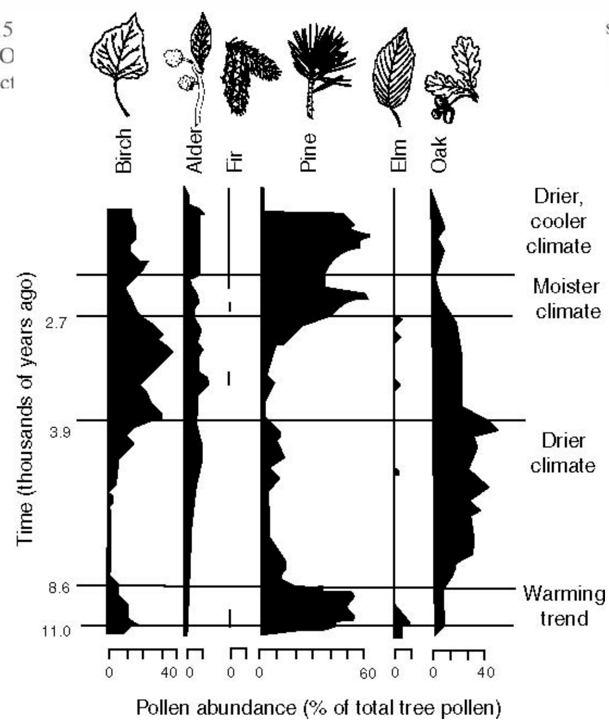


FIGURE 15 pheric CO in Antarct

sment Report 2001;

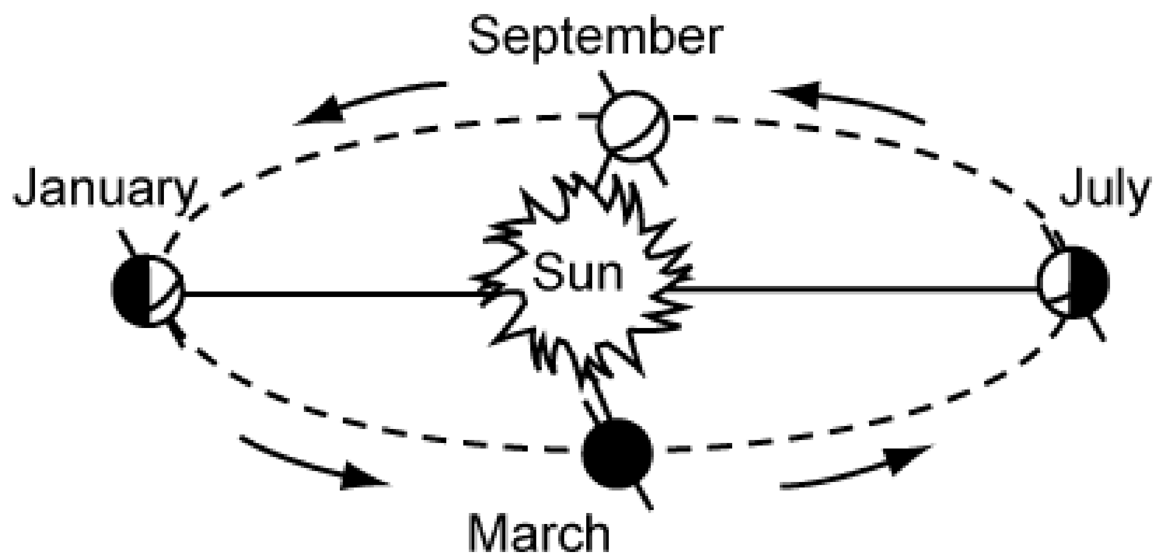


Earth's Climate System

- Short-term climate variability
  - Diurnal and Seasonal cycles (intraannual)
  - ENSO (interannual)
  - PDO (decadal)
  - Volcanic activity (decades to millenia)
  - Changes in surface properties and atmospheric composition
    - Largely from human activities today, but has resulted in geologic past for largely unknown reasons

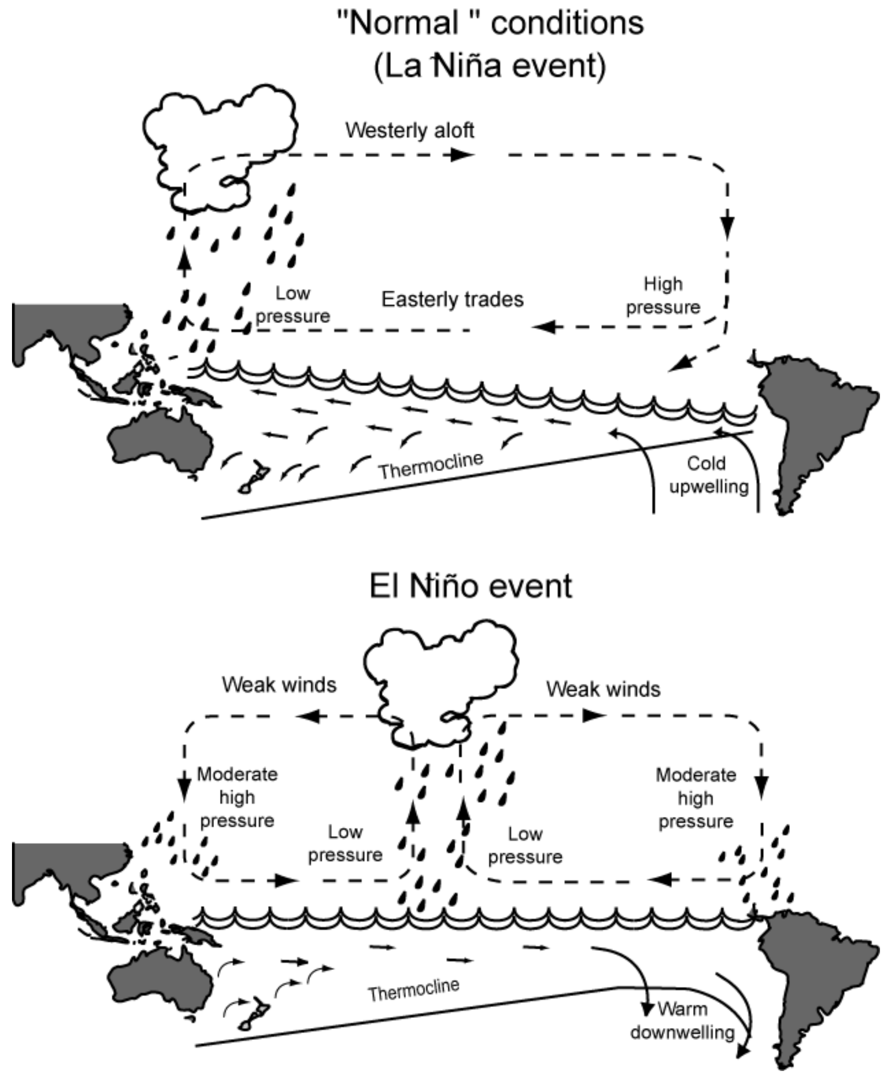
Earth's Climate System

- Short-term climate variability
  - Diurnal and Seasonal cycles
    - Variation in solar input
      - Diurnal (diel) cycles due to rotation of the Earth around its axis
      - Seasonal cycles due to tilt of the Earth and rotation of Earth around the sun



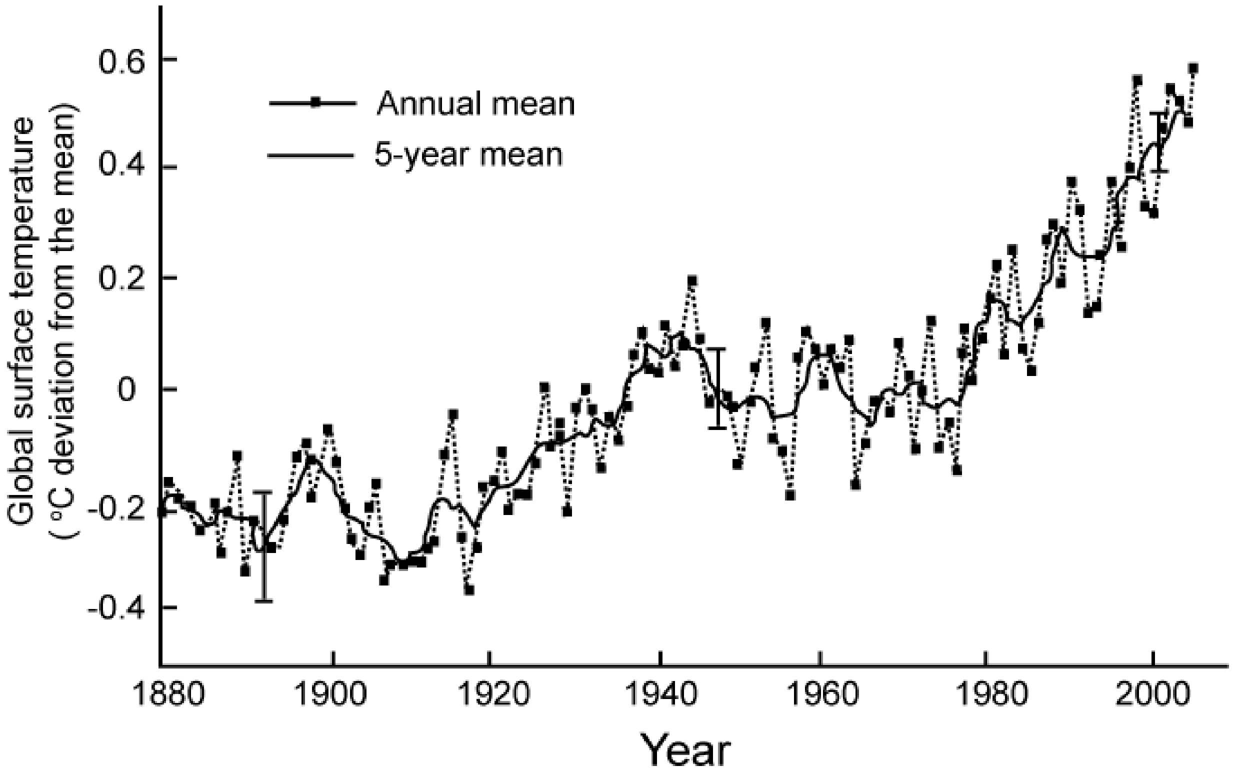
Earth’s Climate System

- ENSO
  - Cycles: El Niño – La Niña
    - ~3-7 yrs
  - El Niño is primarily driven by a breakdown in the tradewinds
  - Impacts for Hawai‘i
    - El Niño results in drought (Pineapple Express takes moisture from the Western Pacific)
    - La Nina results in moister conditions

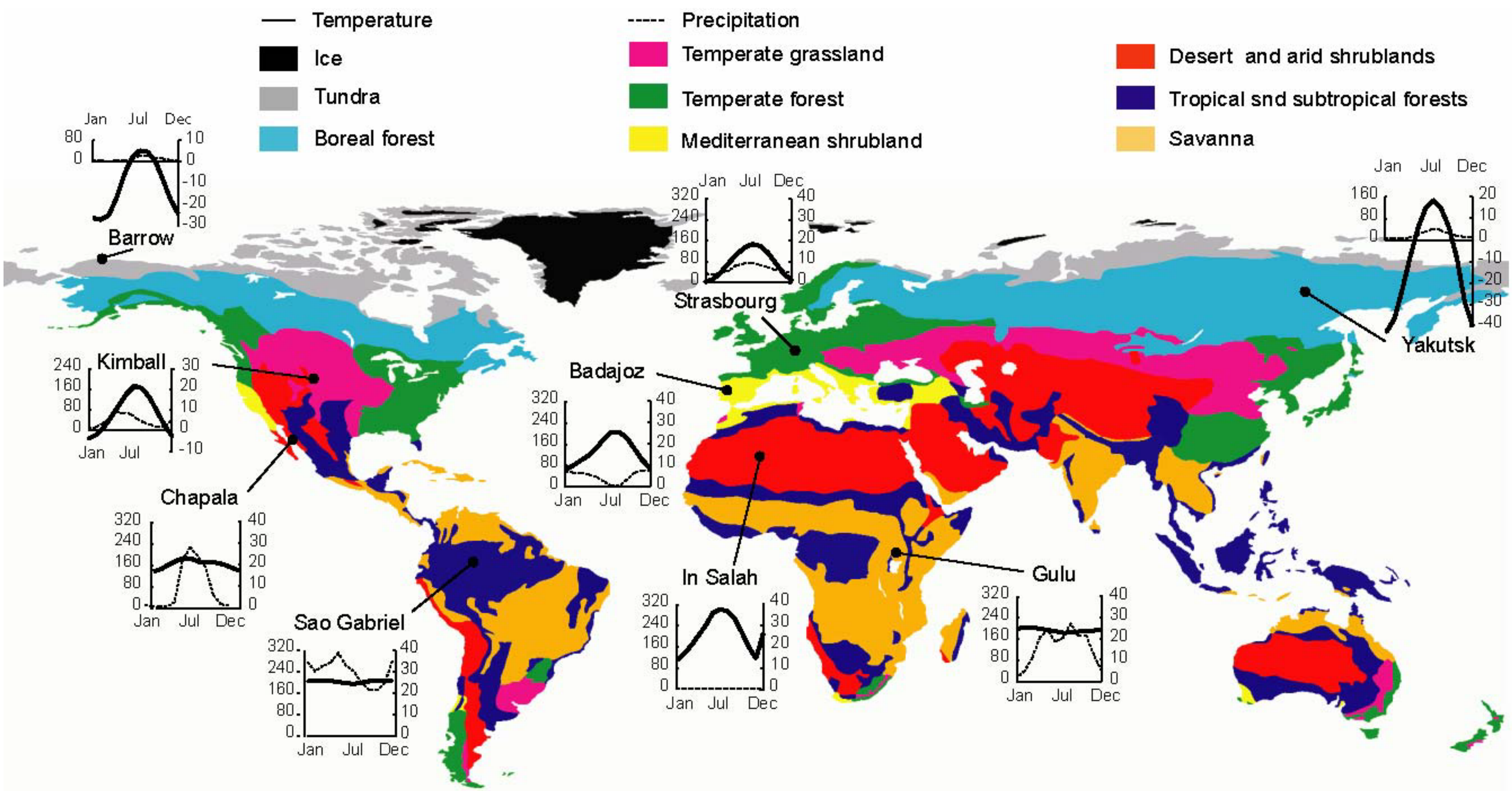


Earth's Climate System

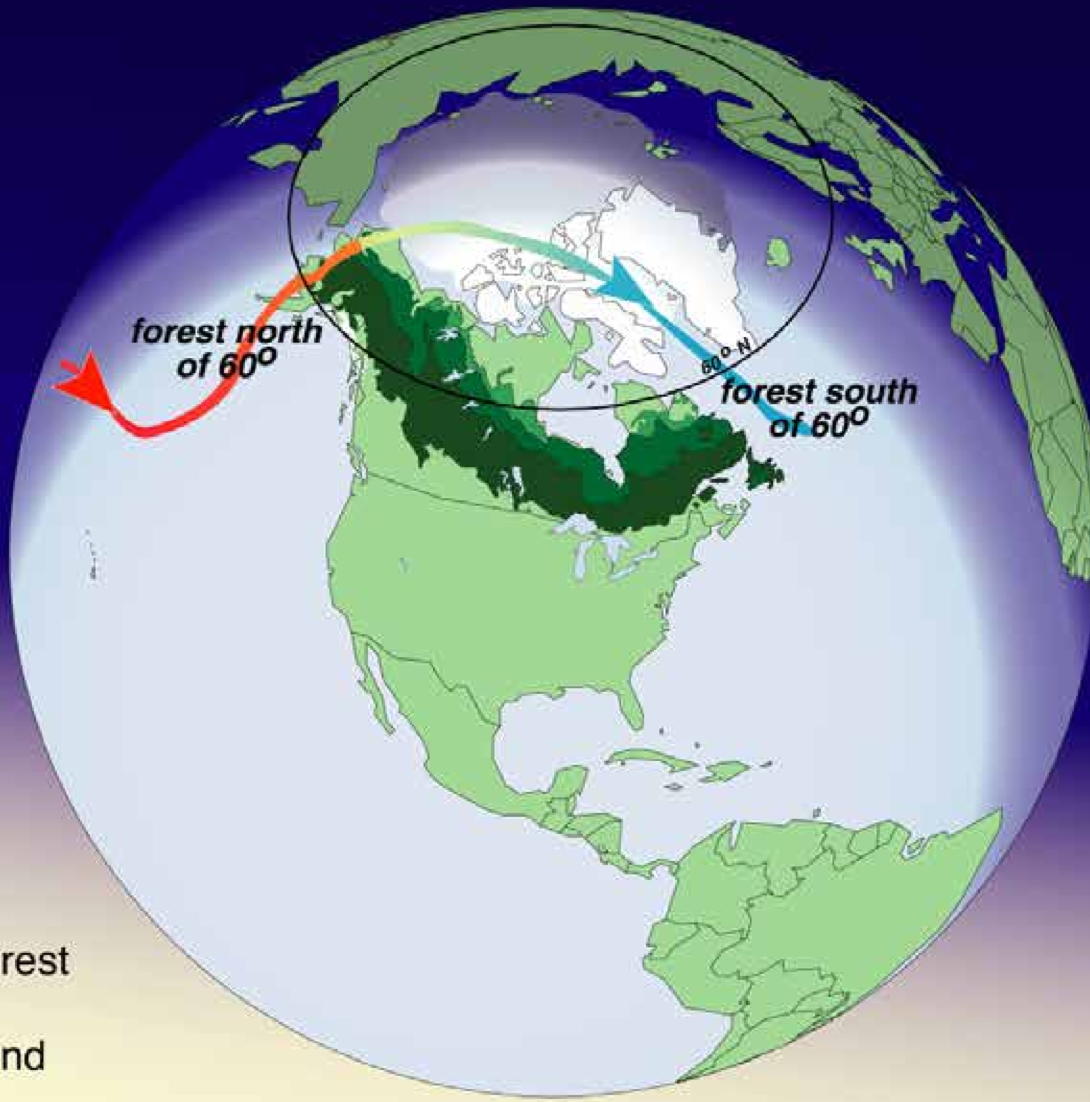
- Short (or long?) -term climate variability
  - Human impacts on atmospheric composition are leading to increased atmospheric temperatures



Why do boreal forests in N. Am. occur farther to the N in the West and farther to the S in the East?



Distribution of Boreal Forest in North America



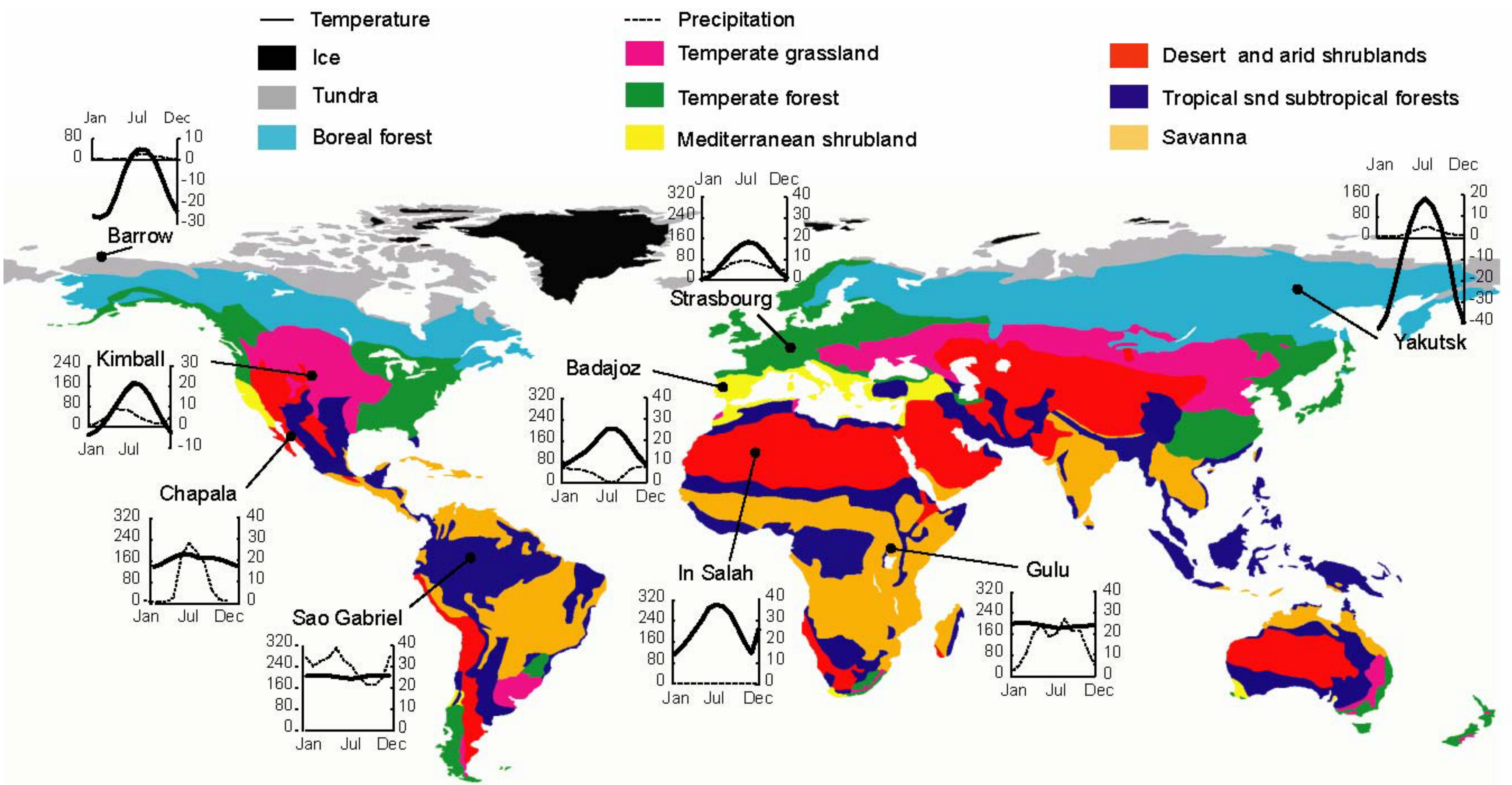
forest tundra

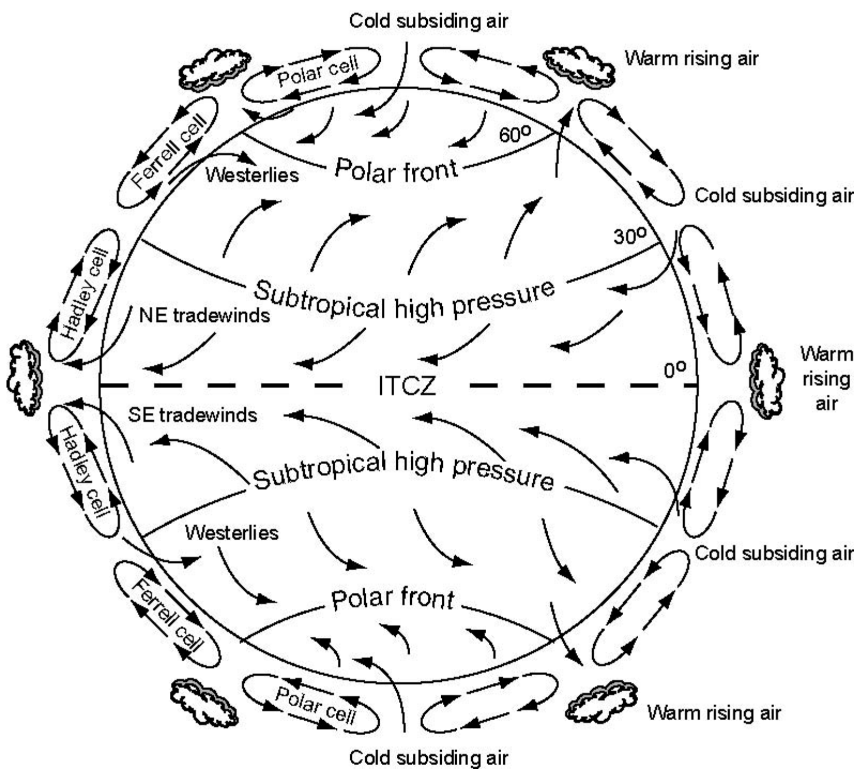
full-canopy forest

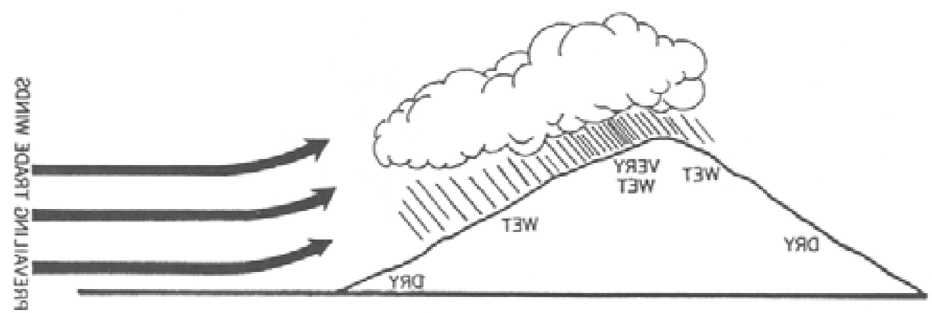
lichen woodland

sources:
Elliott-Fisk (1988), North American Terrestrial Vegetation
Viereck (1971), USDA Ag. Handbook No.410
Kuchler (1969), National Atlas of the United States, Potential Natural Vegetation of Alaska
(adapted by G. Juday)

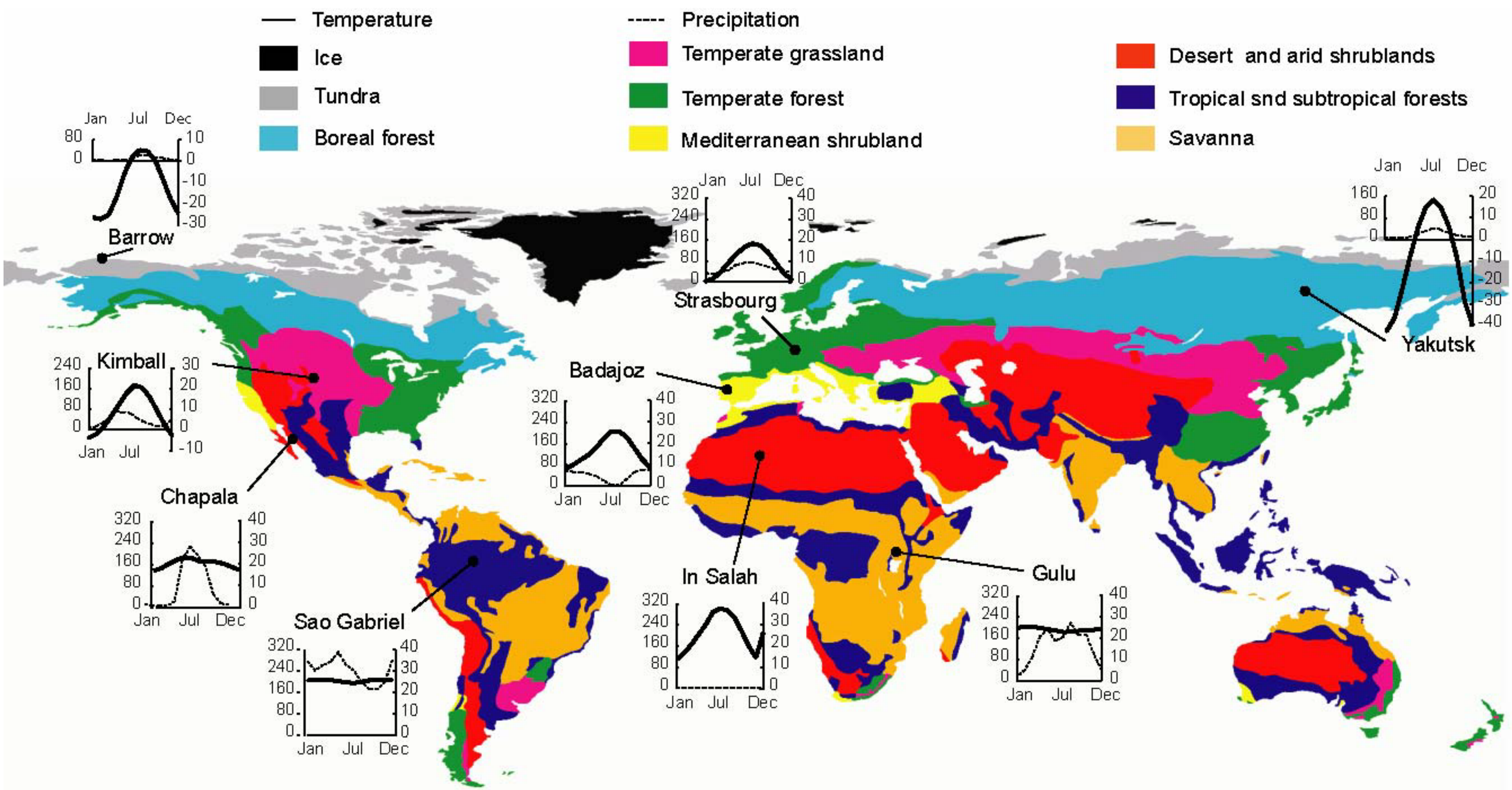
In southern S. Am., why do temperate forests occur to the W. and deserts to the E. in the Southern Cone?

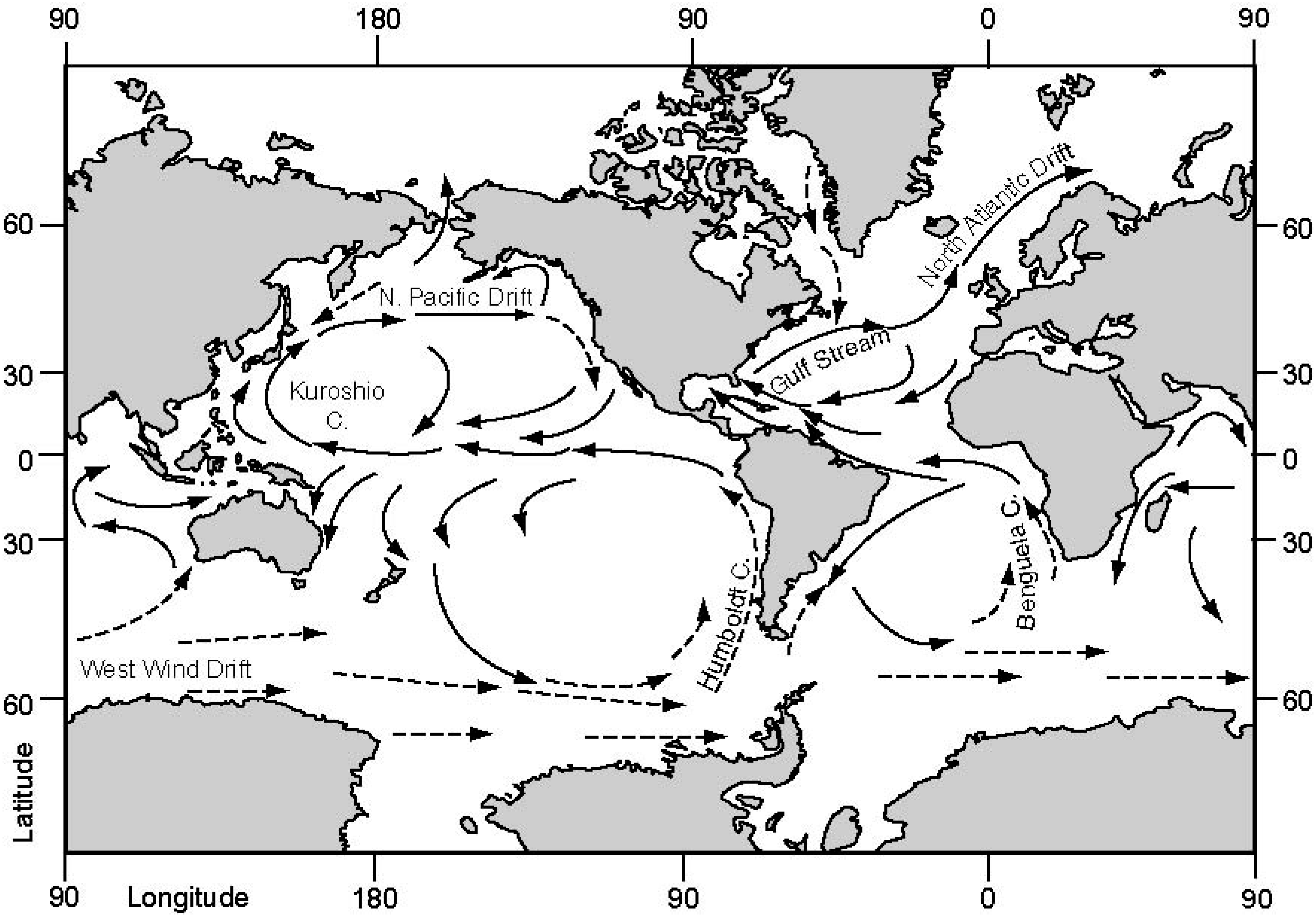



Cold subsiding air
Warm rising air
Polar cell
Ferrell cell
60o
Westerlies
Polar front
Cold subsiding air
30o
Hadley cell
Subtropical high pressure
NE tradewinds
0o
ITCZ
Warm
rising
air
SE tradewinds
Hadley cell
Subtropical high pressure
Westerlies
Cold subsiding air
Polar front
Ferrell cell
Polar cell
Warm rising air
Cold subsiding air

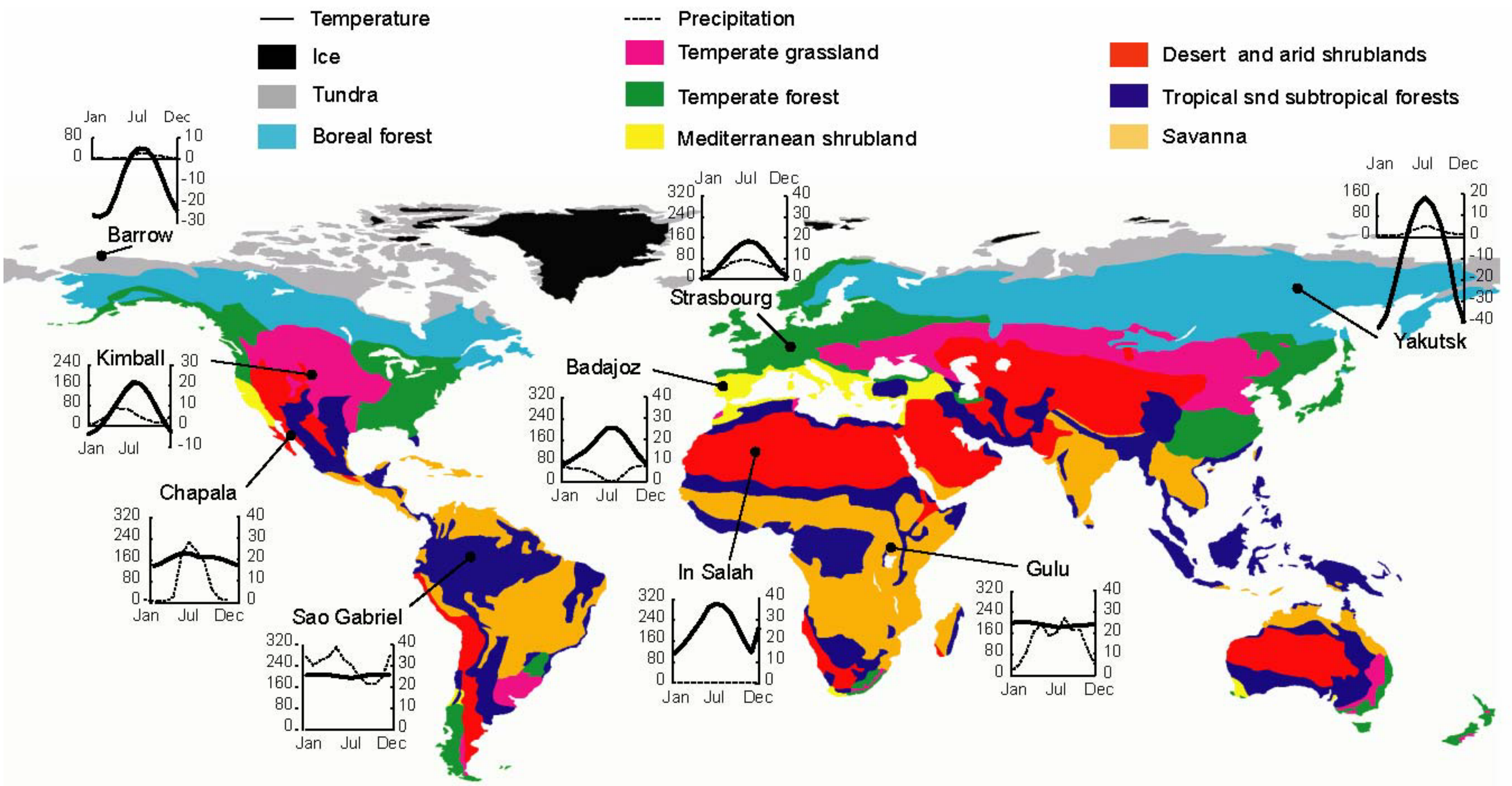

PREVAILING TRADE WINDS
VERY WET
WET
WET
DRY
DRY

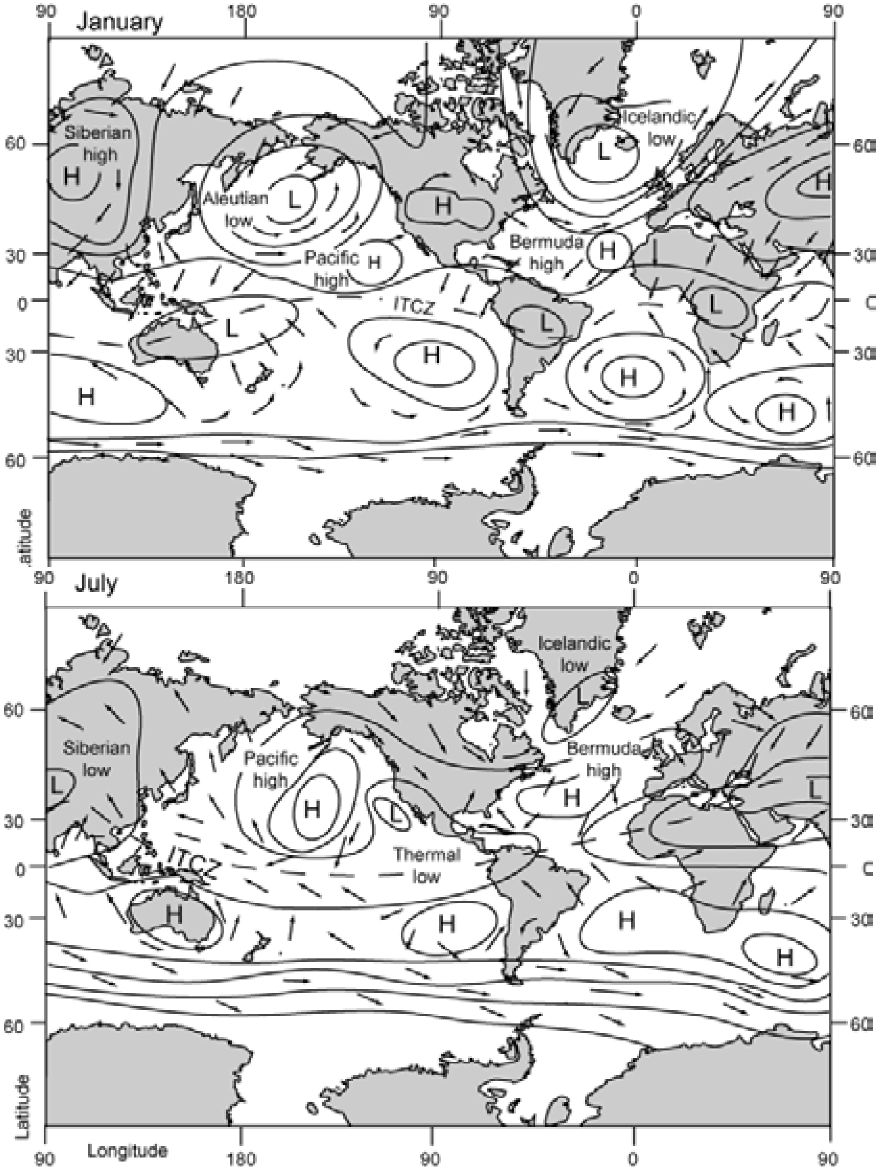
Why do temperate forests occur much farther to the N. in eastern Eurasia than Eastern North America?

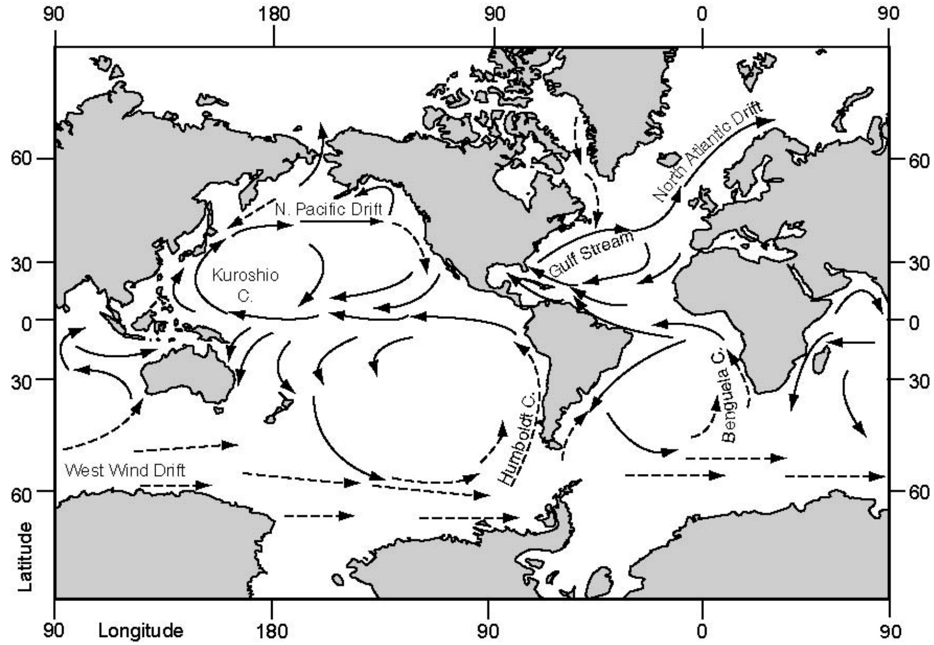



90
180
90
0
90
60
30
0
30
60
Latitude
Longitude
N. Pacific Drift
Kuroshio C.
Gulf Stream
North Atlantic Drift
Humboldt C.
Benguela C.
West Wind Drift

Why do you get Mediterranean ecosystems outside of The Mediterranean?




January
Siberian high
Aleutian low
Icelandic low
Pacific high
Bermuda high
ITCZ
July
Siberian low
Pacific high
Icelandic low
Bermuda high
Thermal low
ITCZ
Latitude
Longitude


N. Pacific Drift
Kuroshio C.
Gulf Stream
North Atlantic Drift
Humboldt C.
Benguela C.
West Wind Drift
Latitude
Longitude