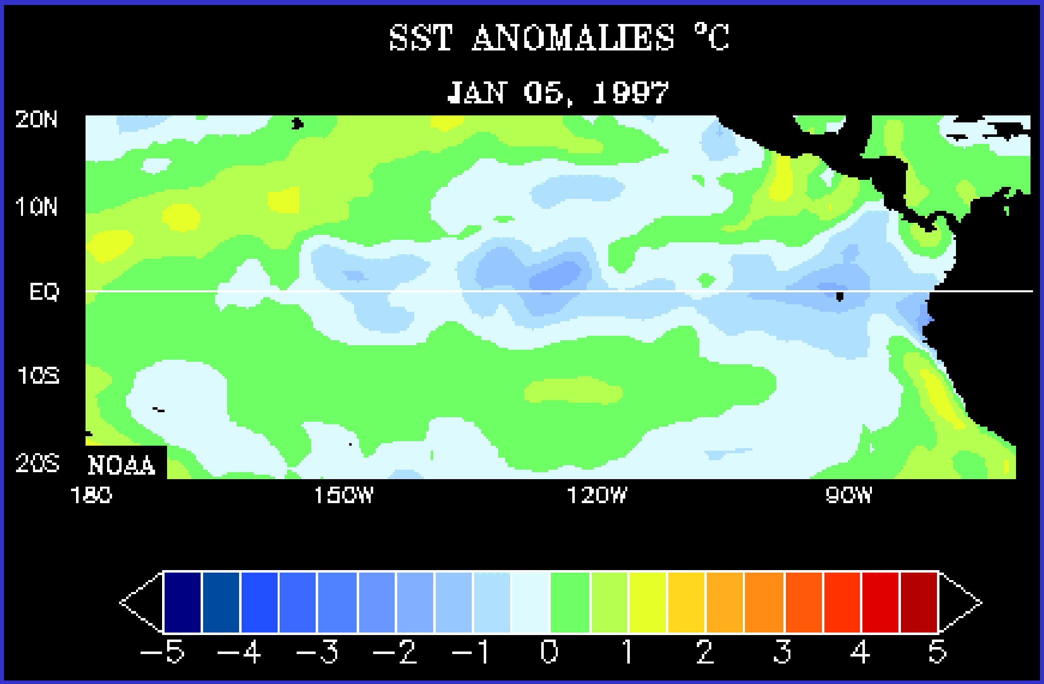
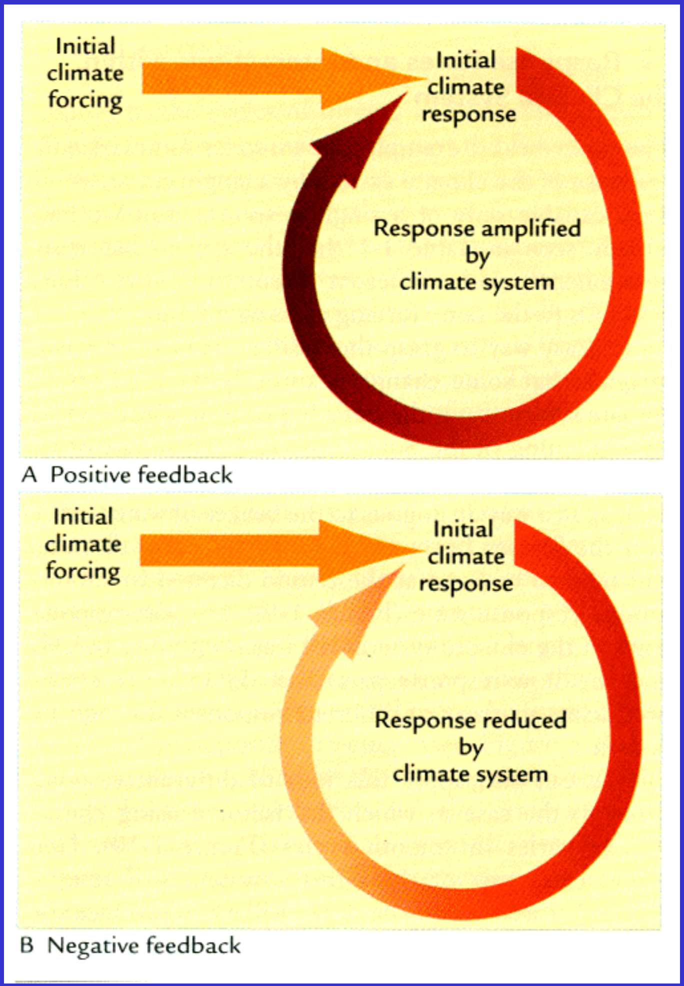
Lecture 5: Climate Changes and Variations



- Climate Sensitivity and Feedback
- El Nino Southern Oscillation
- Pacific Decadal Oscillation
- North Atlantic Oscillation (Arctic Oscillation)

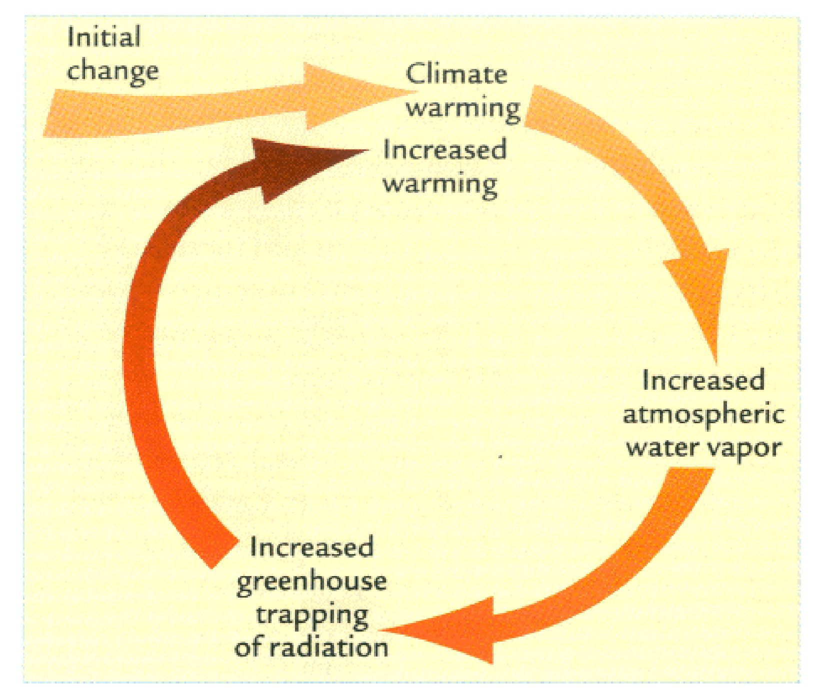
ESS200A
Prof. Jin-Yi Yu

Major Climate Feedback Processes



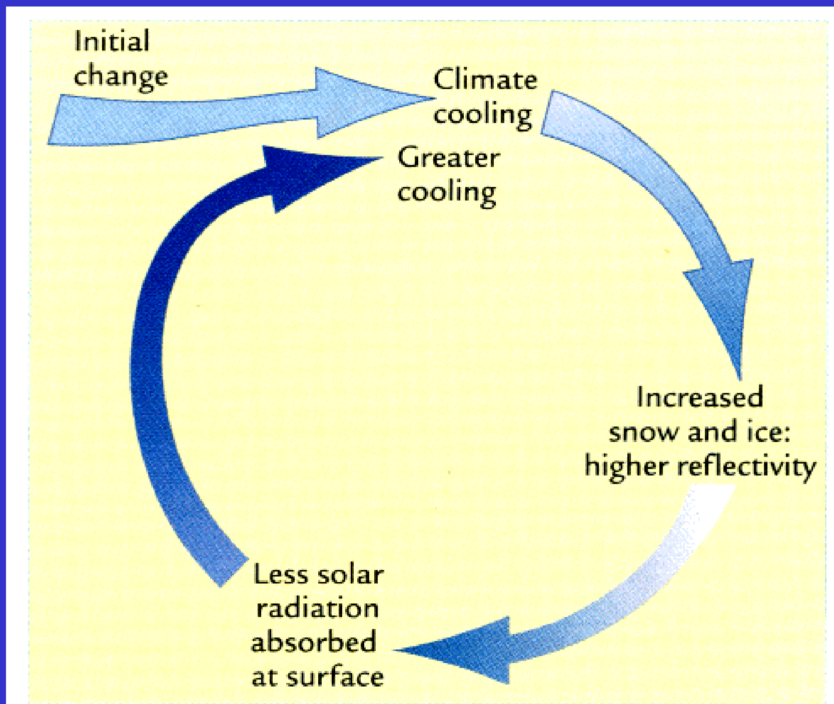
- **Water Vapor Feedback** - Positive
- **Snow/Ice Albedo Feedback** - Positive
- **Longwave Radiation Feedback** - Negative
- **Vegetation-Climate Feedback** - Positive
- **Cloud Feedback** - Uncertain

Water Vapor Feedback



- **Mixing Ratio** = the dimensionless ratio of the mass of water vapor to the mass of dry air.
- **Saturated Mixing Ratio** tells you the maximum amount of water vapor an air parcel can carry.
- The saturated mixing ratio is a function of air temperature: the warmer the temperature the larger the saturated mixing ration.
  - → a warmer atmosphere can carry more water vapor
  - → stronger greenhouse effect
  - → amplify the initial warming
  - → one of the most powerful positive feedback

Snow/Ice Albedo Feedback



- The snow/ice albedo feedback is associated with the higher albedo of ice and snow than all other surface covering.
- This positive feedback has often been offered as one possible explanation for how the very different conditions of the ice ages could have been maintained.

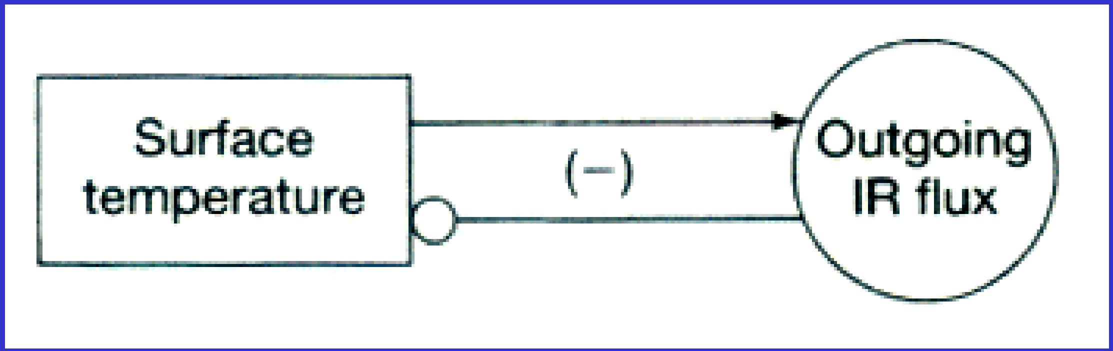
TABLE 2-1 Average Albedo Range of Earth's Surfaces

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

Adapted from W. D. Sellers, Physical Climatology *(Chicago: University of Chicago Press, 1965), and from R. G. Barry and R. J. Chorley,* Atmosphere, Weather, and Climate, *4th ed. (New York: Methuen, 1982).*

(from *Earth's Climate: Past and Future*)

Longwave Radiation Feedback



- The outgoing longwave radiation emitted by the Earth depends on surface temperature, due to the Stefan-Boltzmann Law: $F = \sigma(T_s)^4$.

→ warmer the global temperature

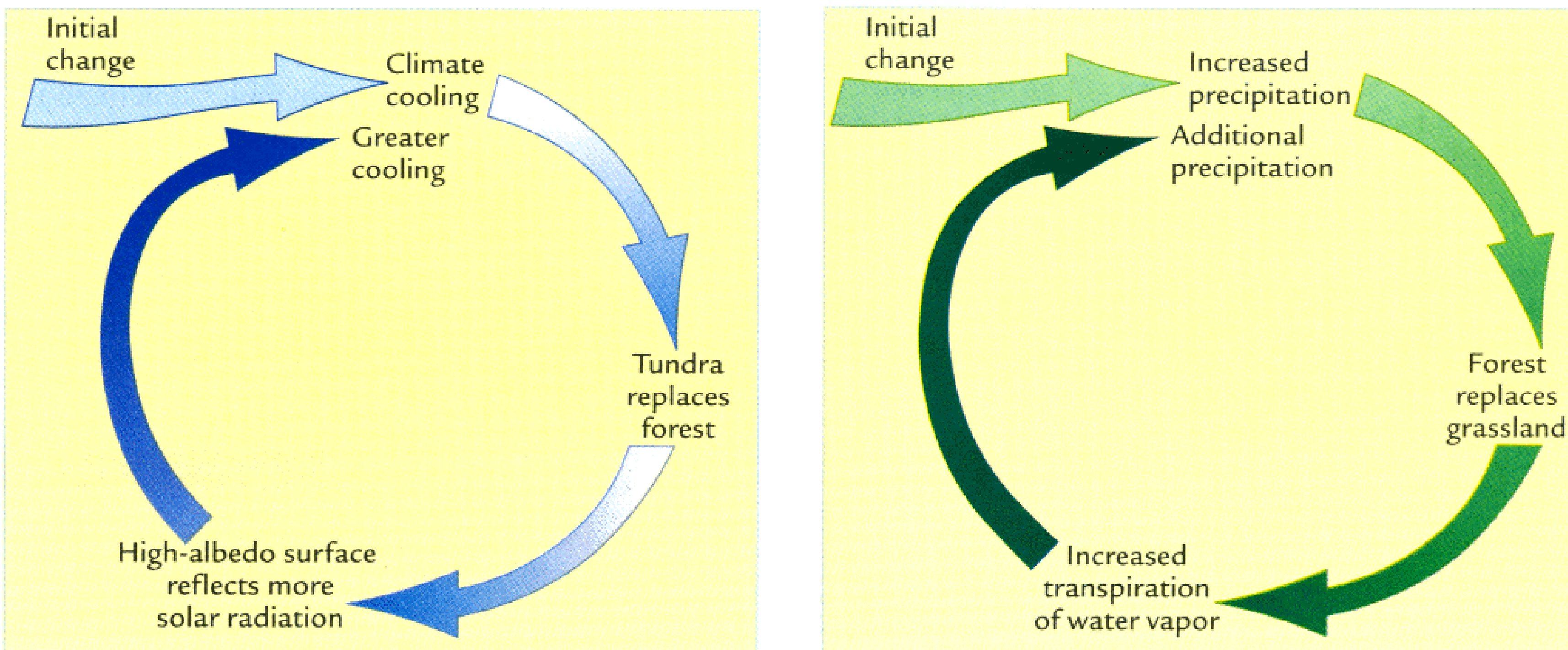
→ larger outgoing longwave radiation been emitted by the Earth

→ reduces net energy heating to the Earth system

→ cools down the global temperature

→ a negative feedback

Vegetation-Climate Feedbacks



A Vegetation–albedo feedback

B Vegetation–precipitation feedback

(from *Earth' Climate: Past and Future*)

Cloud Feedback

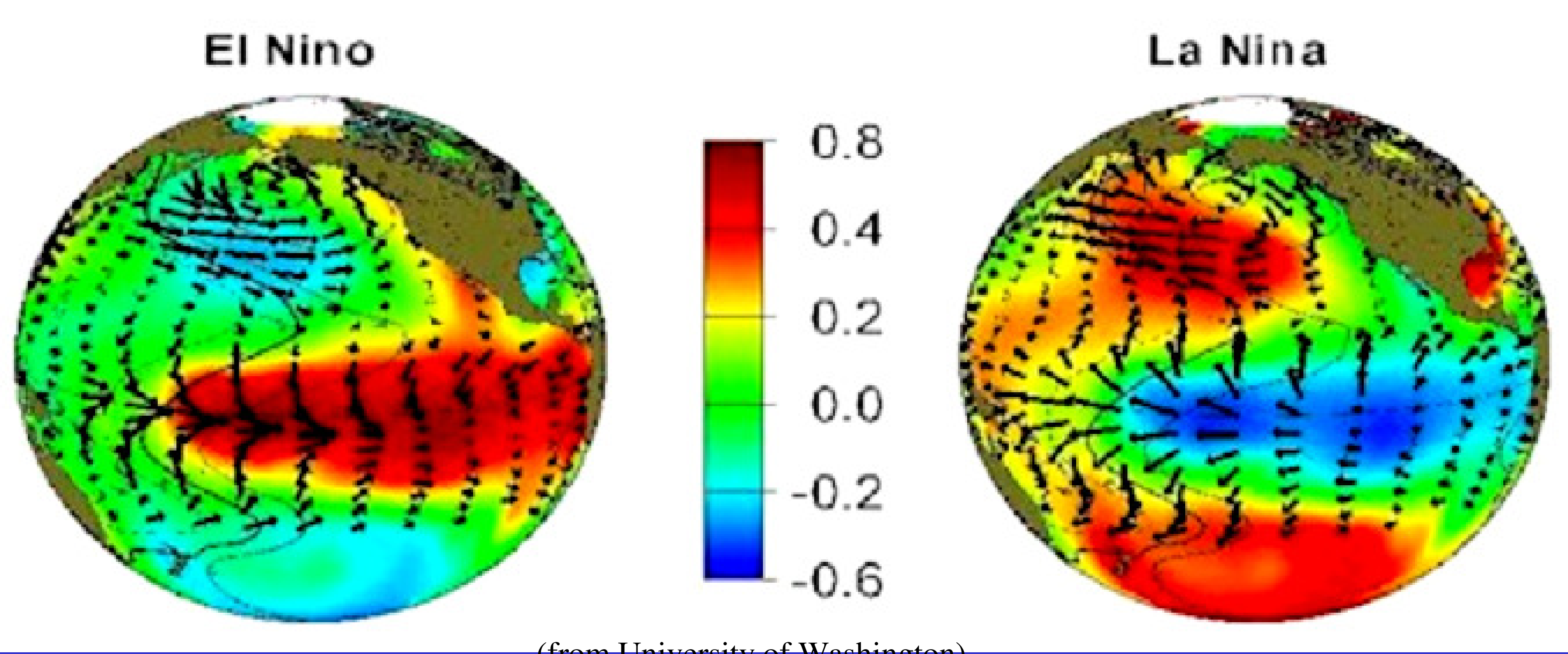
Cloud Radiative Forcing as Estimated from Satellite Measurements

	Average	Cloud-free	Cloud forcing
OLR	234	266	+31
Absorbed solar radiation	239	288	−48
Net radiation	+5	+22	−17
Albedo	30%	15%	+15%

Radiative flux densities are given in W m^{-2} and albedo in percent. [From Harrison *et al.* (1990), © American Geophysical Union.]

- Clouds affect both solar radiation and terrestrial (longwave) radiation.
- Typically, clouds increase albedo → a cooling effect (negative feedback)
  clouds reduce outgoing longwave radiation → a heating effect (positive feedback)
- The net effect of clouds on climate depends cloud types and their optical properties, the insolation, and the characteristics of the underlying surface.
- In general, high clouds tend to produce a heating (positive) feedback. Low clouds tend to produce a cooling (negative) feedback.

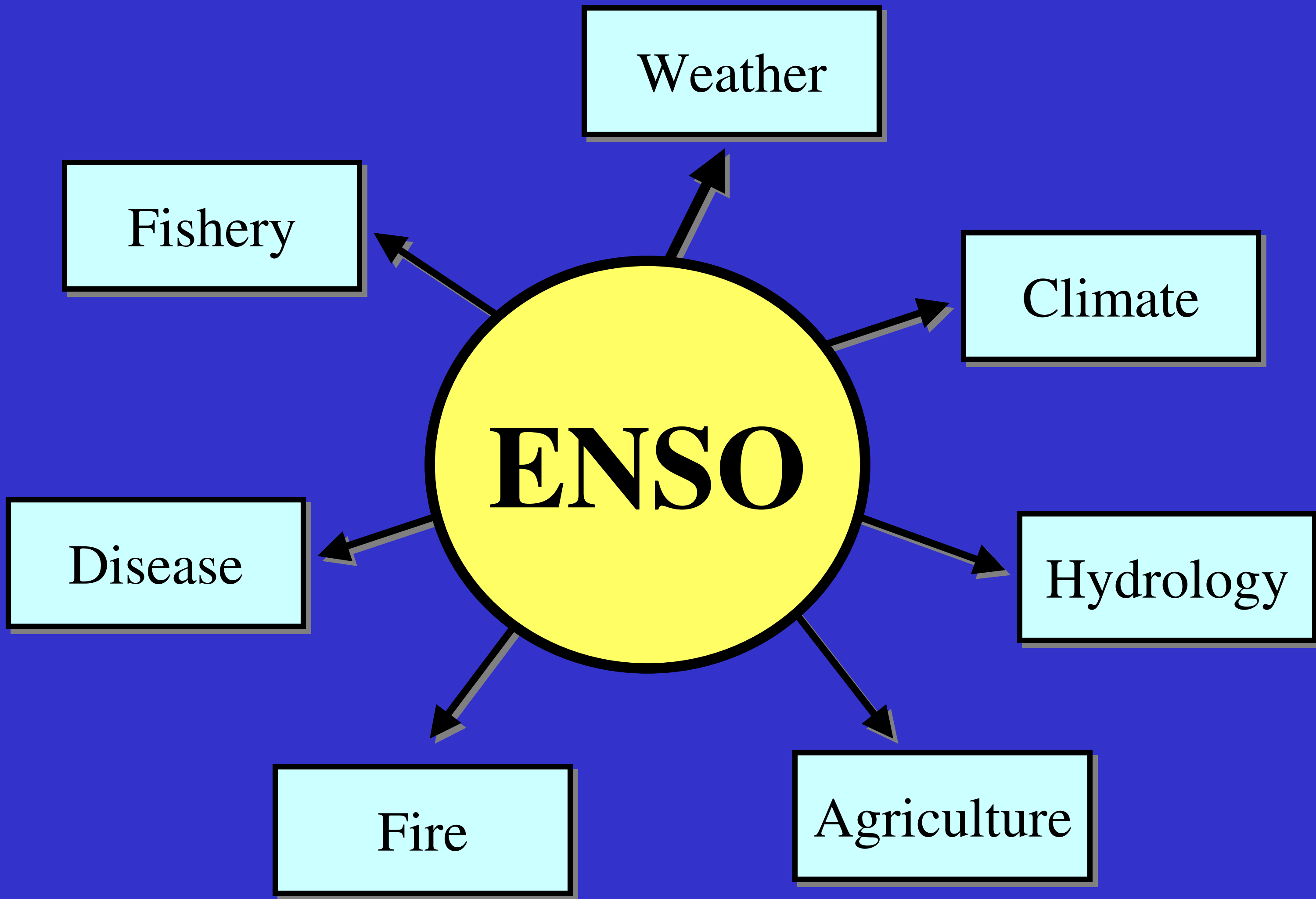
El Nino-Southern Oscillation



(from University of Washington)

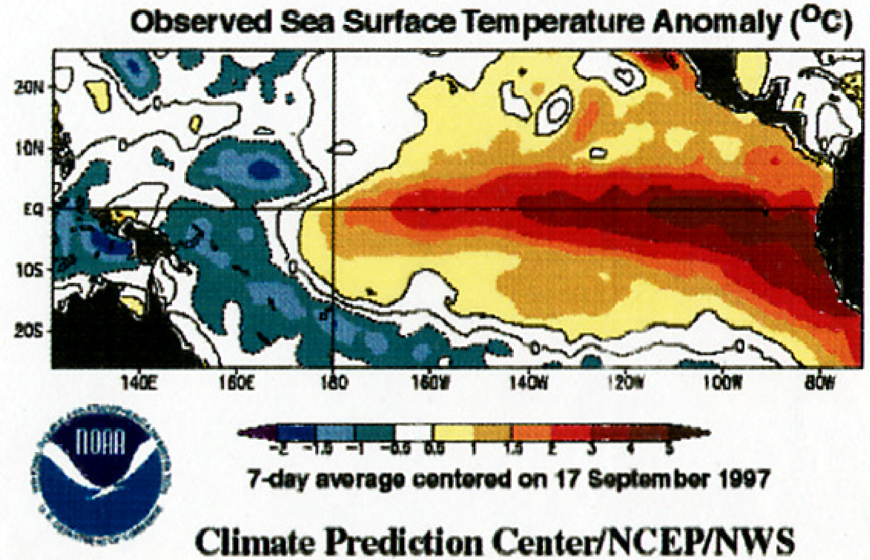
❑ ENSO is the largest interannual (year-to-year) climate variation signal in the coupled atmosphere-ocean system that has profound impacts on global climate.

ENSO-Related Research



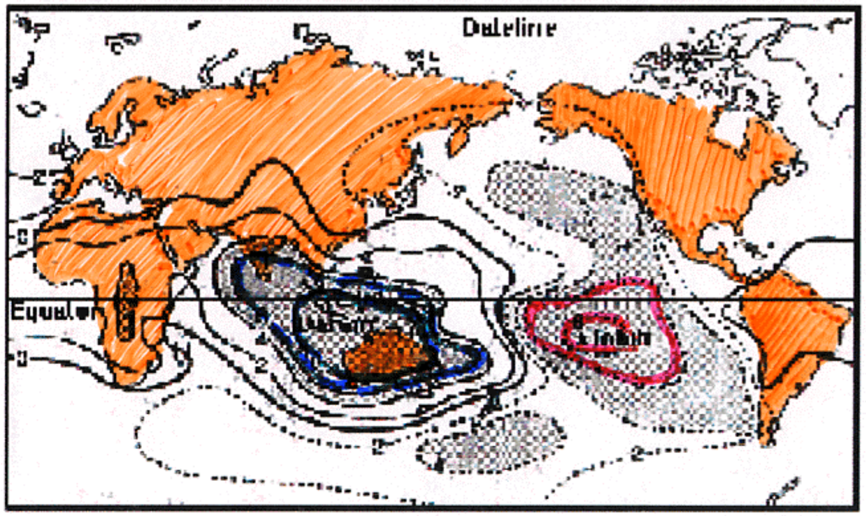
El Niño: originally, an oceanic phenomenon

- Every two to seven years, the waters warm up along the western-most shores of South America.
- Peruvian sailors who fished in this region, were the first to notice and to give a name to this phenomenon.
- Because the phenomenon would usually begin to peak around the Christian Christmas holiday, the sailors named the odd phenomenon "El Niño" meaning "the Christ Child."

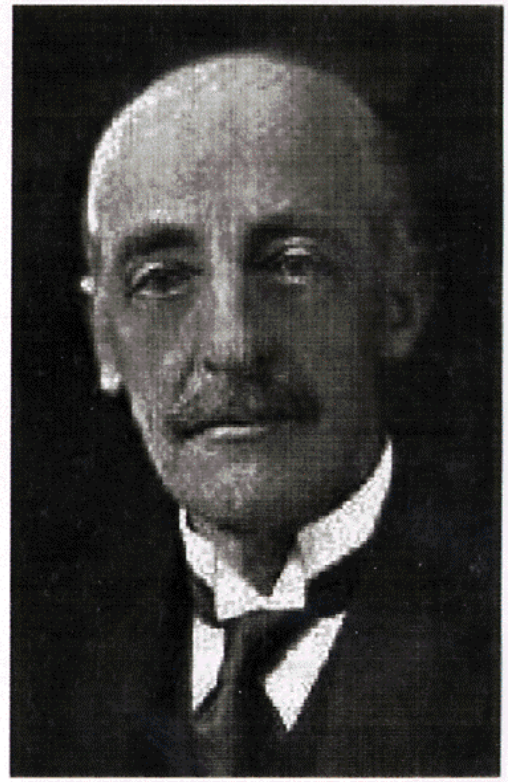


Southern Oscillation: an atmospheric phenomenon

In 1910s, Walker found a connection between barometer readings at stations on the eastern and western sides of the Pacific (Tahiti and Darwin). He coined the term **Southern Oscillation** to dramatize the ups and downs in this east-west seesaw effect.



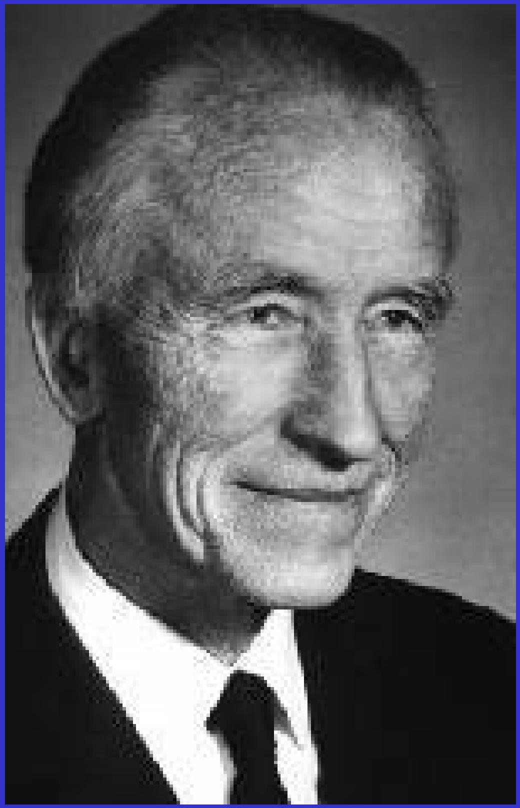
(from Rasmusson 1984)



Sir Gilbert Walker

El Nino and Southern Oscillation

- Jacob Bjerknes was the first one to recognizes that El Nino is not just an oceanic phenomenon (in his 1969 paper).
- In stead, he hypothesized that the warm waters of El Nino and the pressure seasaw of Walker's Southern Oscillation are part and parcel of the same phenomenon: the ENSO.
- Bjerknes's hypothesis of coupled atmosphere-ocean instability laid the foundation for ENSO research.



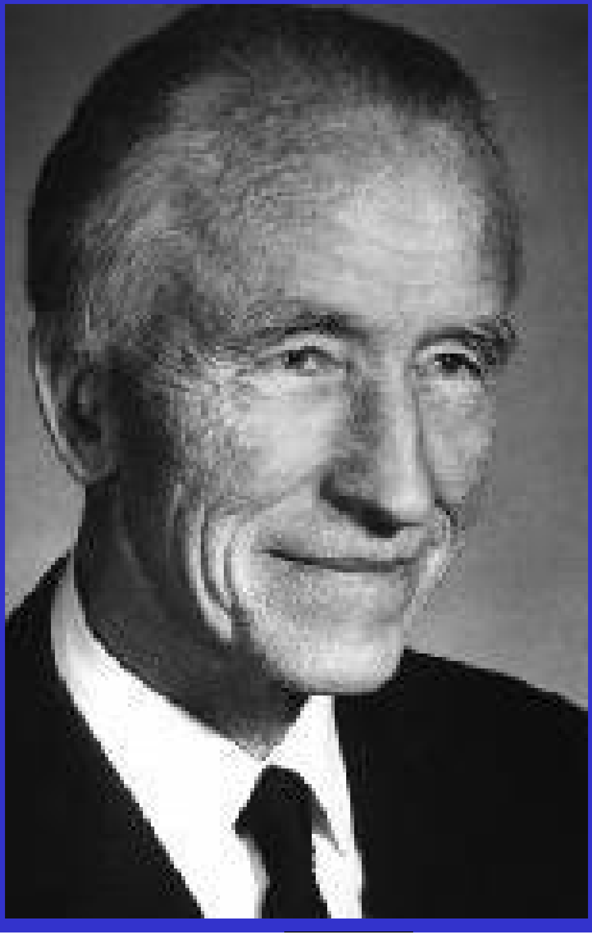
Jacob Bjerknes

Pioneers in Modern Meteorology & Climatology

Weather: Polar Front Theory

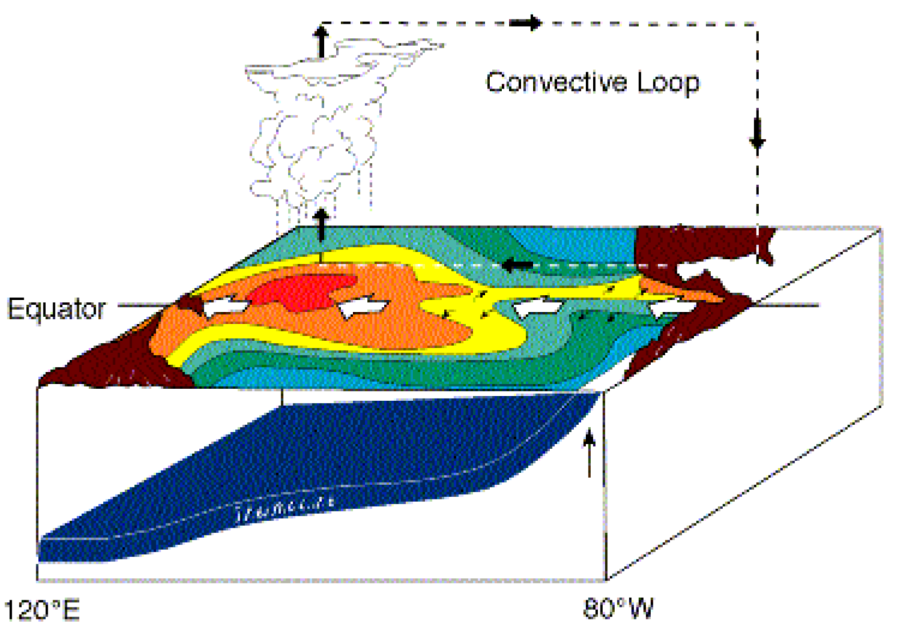
Vilhelm Bjerknes (1862-1951)

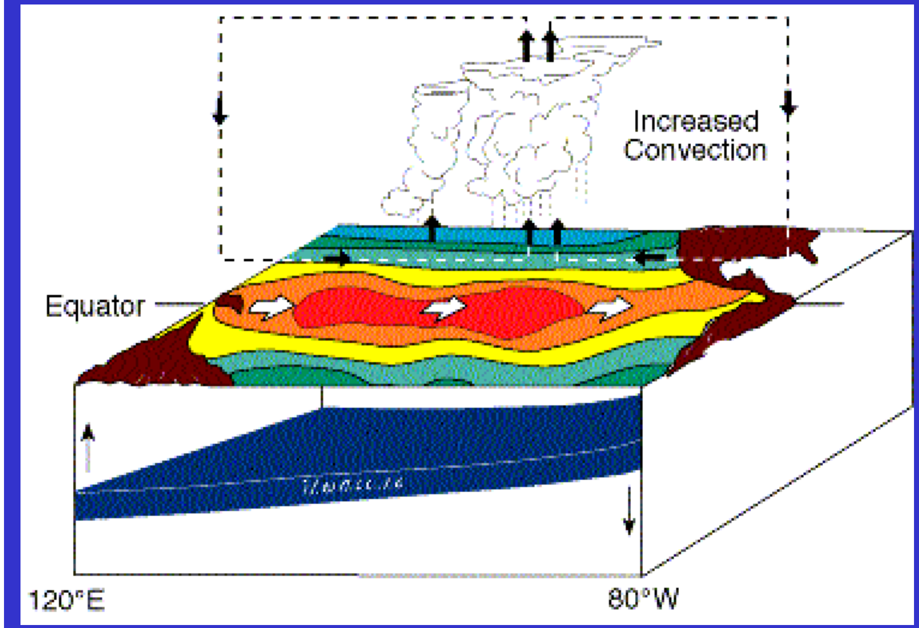
Climate: El Nino-Southern Osci.



Jacob Bjerknes (1897-1975)

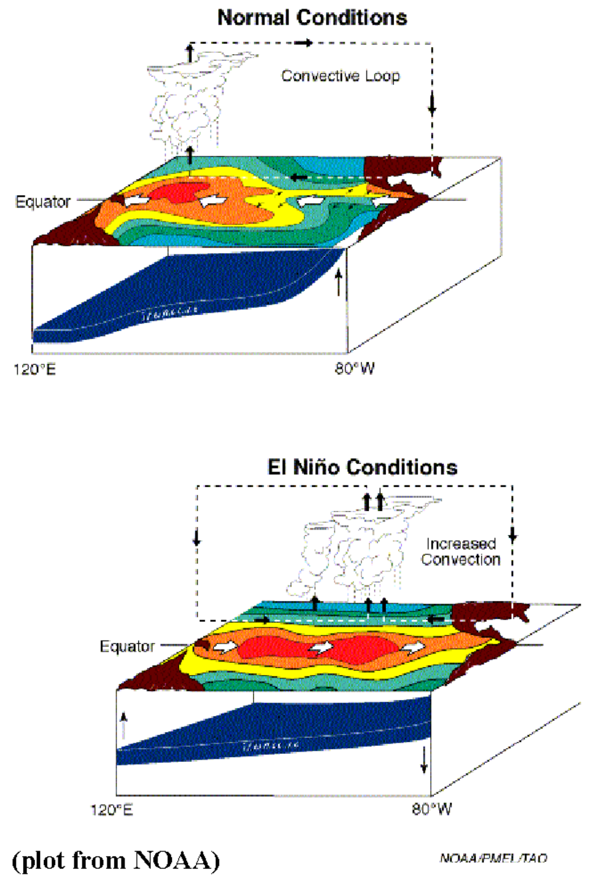
Coupled Atmosphere-Ocean System





(from NOAA)

Growth Mechanism



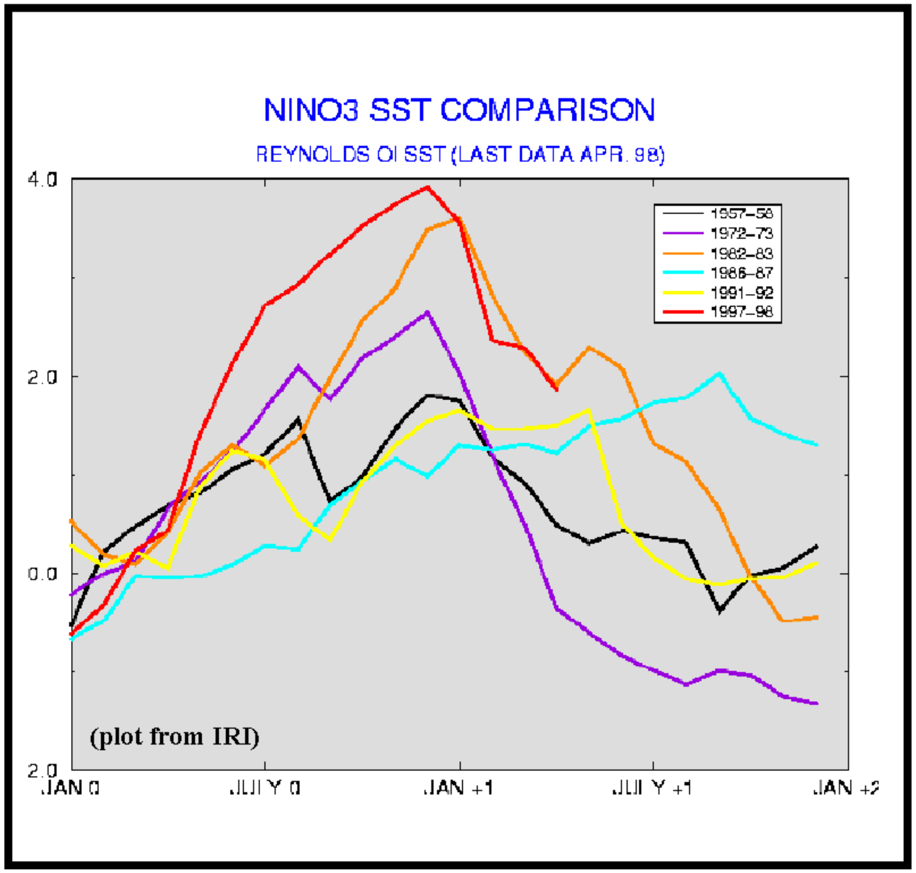
(plot from NOAA)

The growth mechanism is responsible for amplifying SST anomalies during both the warm and cold phases of the ENSO cycle.

- Positive feedbacks from the interaction between the atmosphere and ocean provide a mechanism for SST anomalies to grow in the tropical Pacific during ENSO events.

- This coupled instability mechanism was first proposed by Bjerknes (1966, 1969) based on statistical correlations and was later demonstrated by many modeling studies.

ENSO's Phase-Lock to the Annual Cycle



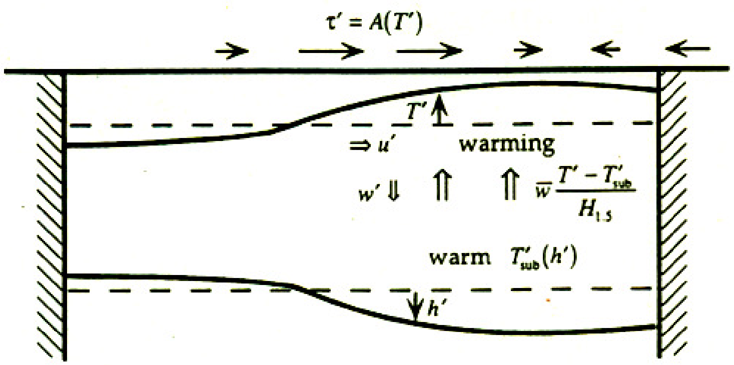
- Composition analyses have shown that ENSO events tend to onset, grow, and decay at certain seasons of the year (Rasmusson and Carpenter 1982).

Phase-Transition Mechanism

Any successful theory for the phase-transition mechanism has to be able to (1) provide a negative feedback to reverse the phase of the ENSO cycle, and (2) account for the long period associated with the cycle.

- **Delay Oscillator Theory** (Schopf and Suarez 1988; Battisti and Hirst 1989)
  - Ocean memory is carried by thermocline depth through reflection and propagation (i.e., the delay) of ocean waves (i.e., subsurface ocean dynamics dominants).
  - ENSO period is determined by the wave propagation and reflection time.
- **Slow SST-Fast Wave theory** (Neelin 1991; Neelin and Jin 1993; Jin and Neelin 1993a,b)
  - ocean memory is provided by SST through heat storage in the mixed layer (i.e., surface thermodynamics dominants).
  - ENSO period is determined by air-sea interaction and surface ocean advections.
- **Recharge Oscillator Theory** (Wyrkti 1975, 1985; Cane et al. 1986; Zebiak 1989; Jin 1997)
  - ocean memory is carried by the zonal-mean ocean thermocline depth, which is constantly in non-equilibrium with equatorial wind stress on ENSO timescales (i.e., subsurface ocean dynamics dominants).
  - ENSO period depends on the time needed to adjust the non-equilibrium mean thermocline depth at the equator throughout the tropical Pacific basin-wide.

SSTA Tendency Equation



(from Neelin et al. 1998)

- SSTA tendency =
  surface thermodynamical processes
  \+ subsurface thermocline process

Surface thermodynamical processes

- thermal feedback from the atmosphere ($-cT'$)
- wind-forced horizontal advection ($-u'*\overline{T}_x$ or $b\tau$)
- wind-induced vertical advection ($-w'*\overline{T}_z$ or $c\tau$)

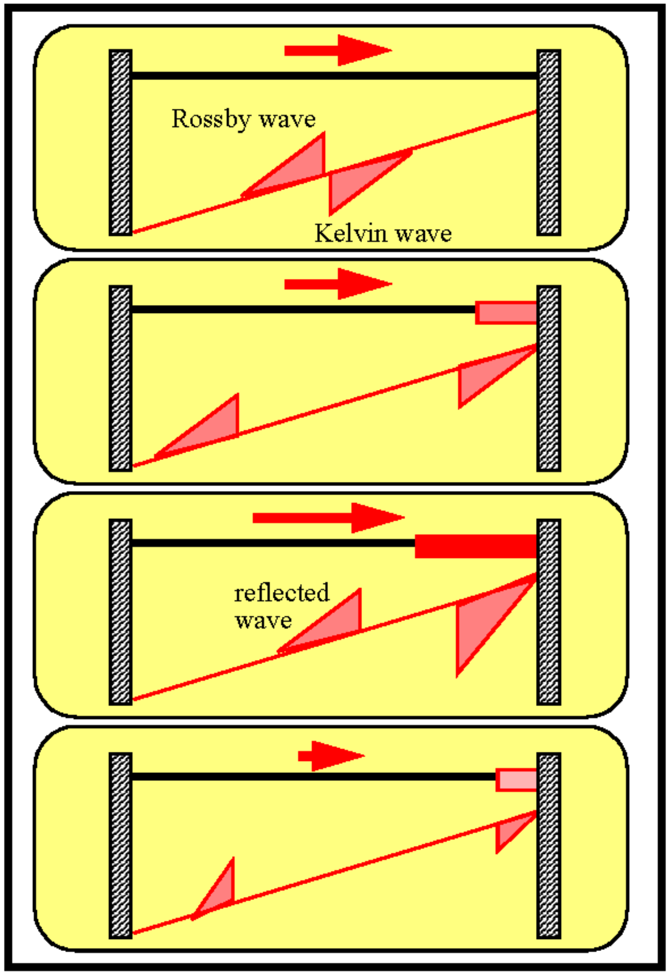
Subsurface thermocline process

- upwelling associated with thermocline depth anomaly ($-w*\Delta T/\Delta z$ or Ah')

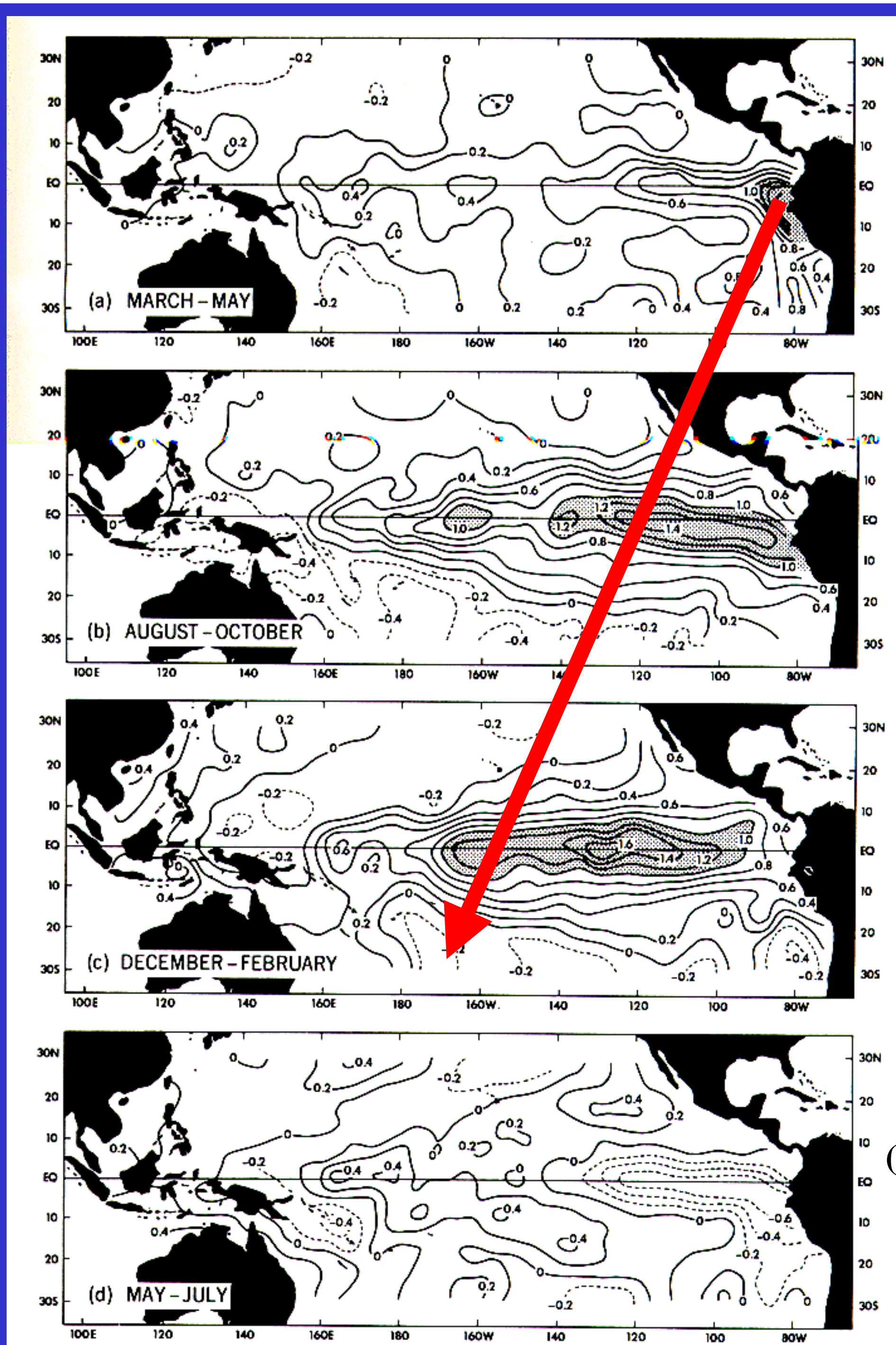
- $$\frac{\partial T'}{\partial t} = -cT' + (b+c)\tau + Ah'$$

(Jin-Yi Yu 1999)

Delayed Oscillator Theory



- Wind forcing at the central Pacific: produces a downwelling Kevin wave propagating eastward and a upwelling Rossby wave propagating westward.
- wave propagation: the fast kelvin wave causes SST warming at the eastern basin, while slow Rossby wave is reflected at the western boundary.
- wave reflection: Rossby wave is reflected as a upwelling Kelvin wave and propagates back to the eastern basin to reverse the phase of the ENSO cycle.
- ENSO period: is determined by the propagation time of the waves.



Onset Phase

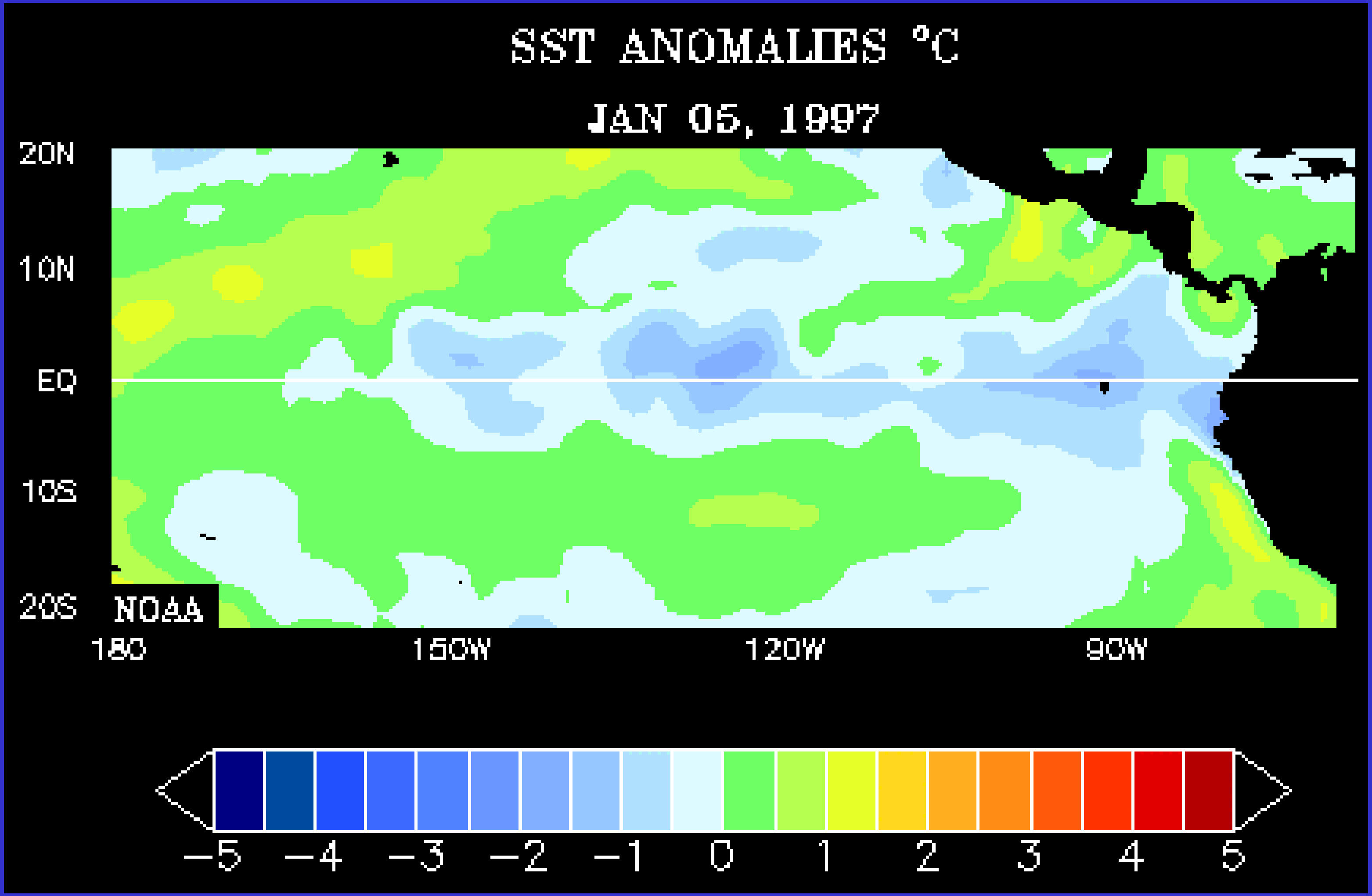
Growing Phase

Mature Phase

(from Rasmusson and Carpenter 1982)

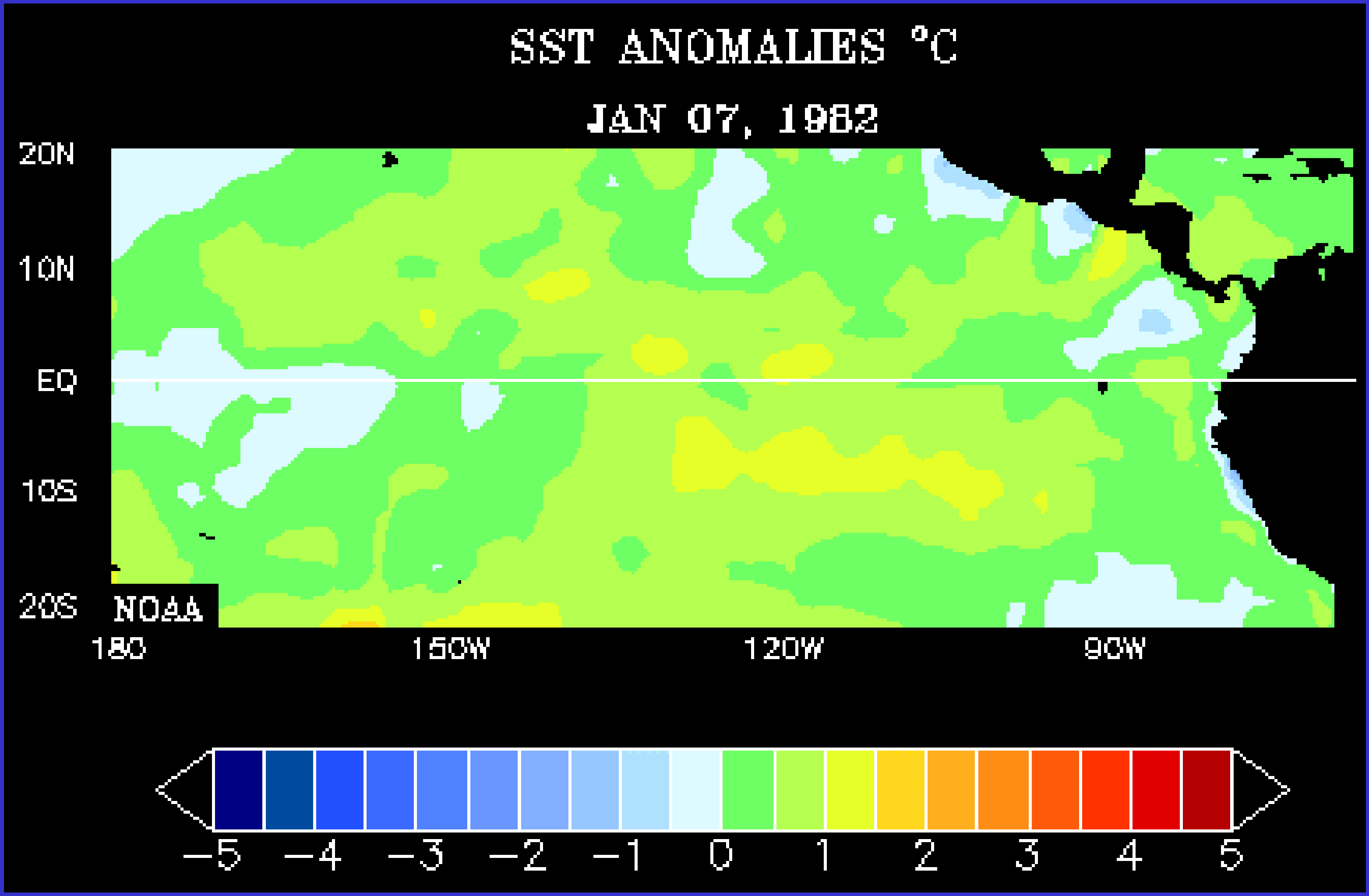
ESS200A
Prof. Jin-Yi Yu

1997-98 El Nino



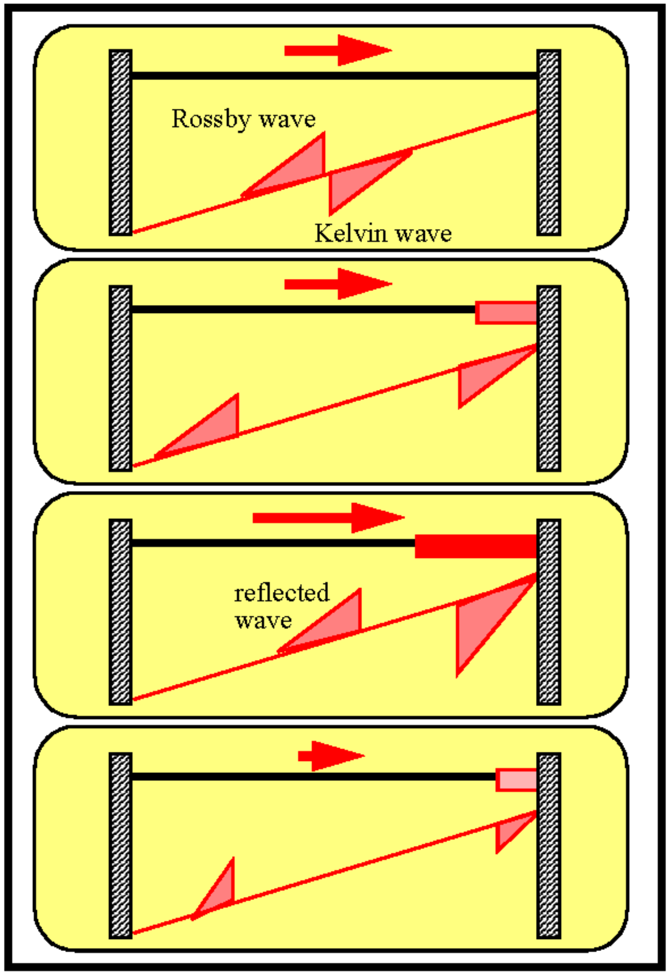
ESS200A
Prof. Jin-Yi Yu

1982-83 El Nino



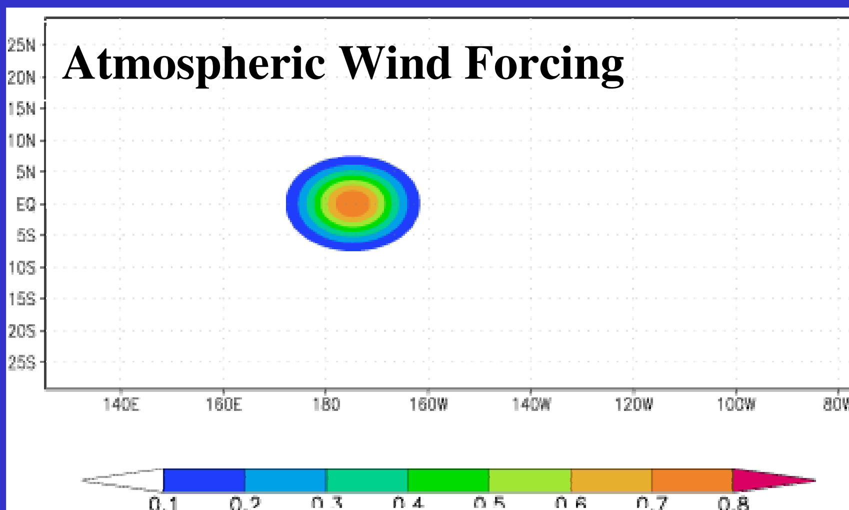
ESS200A
Prof. Jin-Yi Yu

Delayed Oscillator Theory

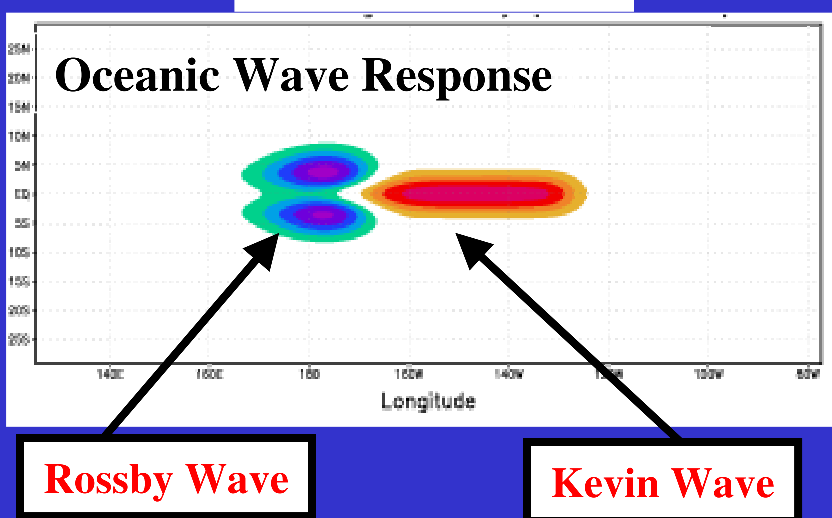


- Wind forcing at the central Pacific: produces a downwelling Kevin wave propagating eastward and a upwelling Rossby wave propagating westward.
- wave propagation: the fast kelvin wave causes SST warming at the eastern basin, while slow Rossby wave is reflected at the western boundary.
- wave reflection: Rossby wave is reflected as a upwelling Kelvin wave and propagates back to the eastern basin to reverse the phase of the ENSO cycle.
- ENSO period: is determined by the propagation time of the waves.

Delayed Oscillator: Wind Forcing

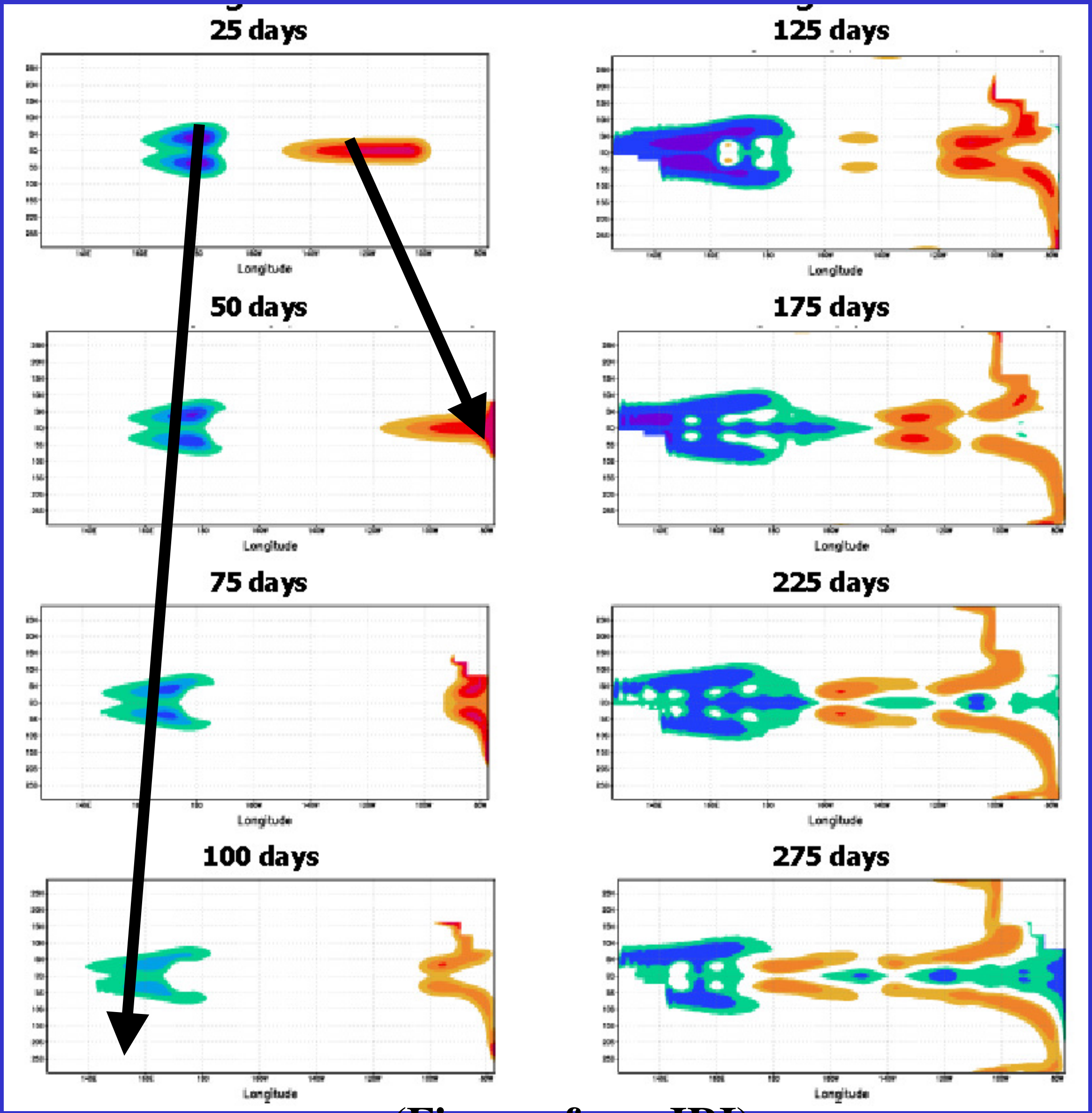


(Figures from IRI)



- The delayed oscillator suggested that oceanic Rossby and Kevin waves forced by atmospheric wind stress in the central Pacific provide the phase-transition mechanism (I.e. memory) for the ENSO cycle.
- The propagation and reflection of waves, together with local air-sea coupling, determine the period of the cycle.

Wave Propagation and Reflection



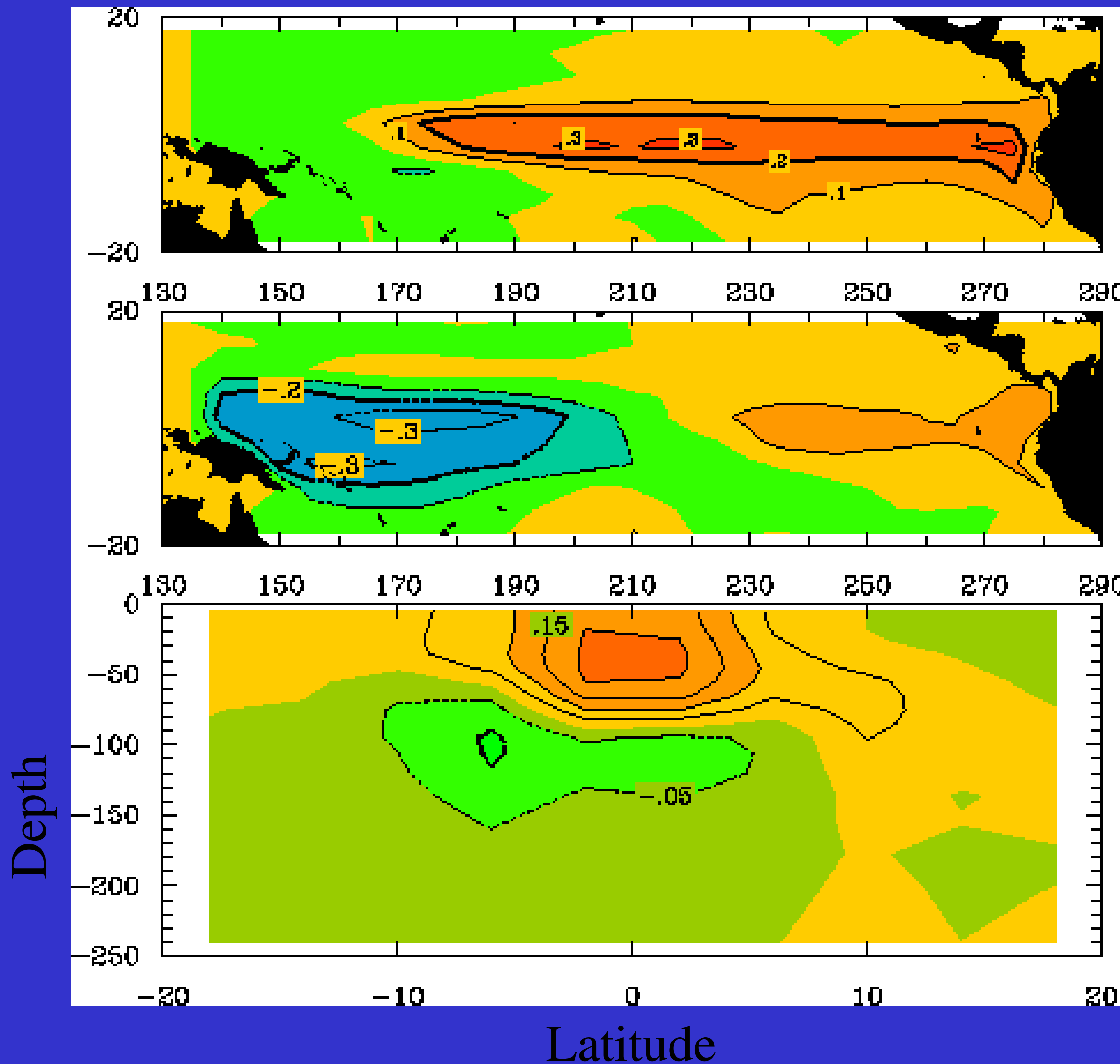
(Figures from IRI)

- It takes Kevin wave (phase speed = 2.9 m/s) about 70 days to cross the Pacific basin (17,760km).
- It takes Rossby wave about 200 days (phase speed = 0.93 m/s) to cross the Pacific basin.

Why Only Pacific Has ENSO?

- Based on the delayed oscillator theory of ENSO, the ocean basin has to be big enough to produce the "delayed" from ocean wave propagation and reflection.
- It can be shown that only the Pacific Ocean is "big" (wide) enough to produce such delayed for the ENSO cycle.
- It is generally believed that the Atlantic Ocean may produce ENSO-like oscillation if external forcing are applied to the Atlantic Ocean.
- The Indian Ocean is considered too small to produce ENSO.

ENSO Simulation by ESS CGCM

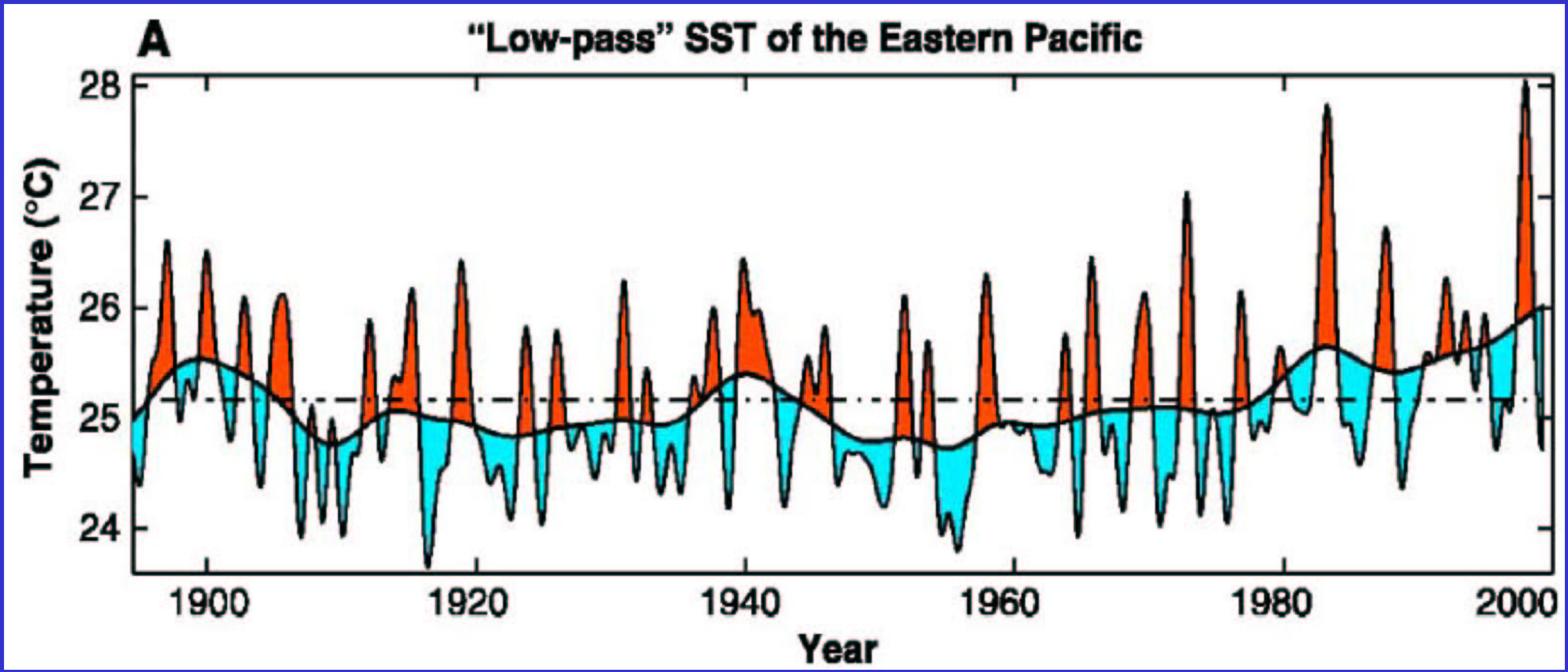


Sea Surface Temperature

Subsurface (-100m) Temp.

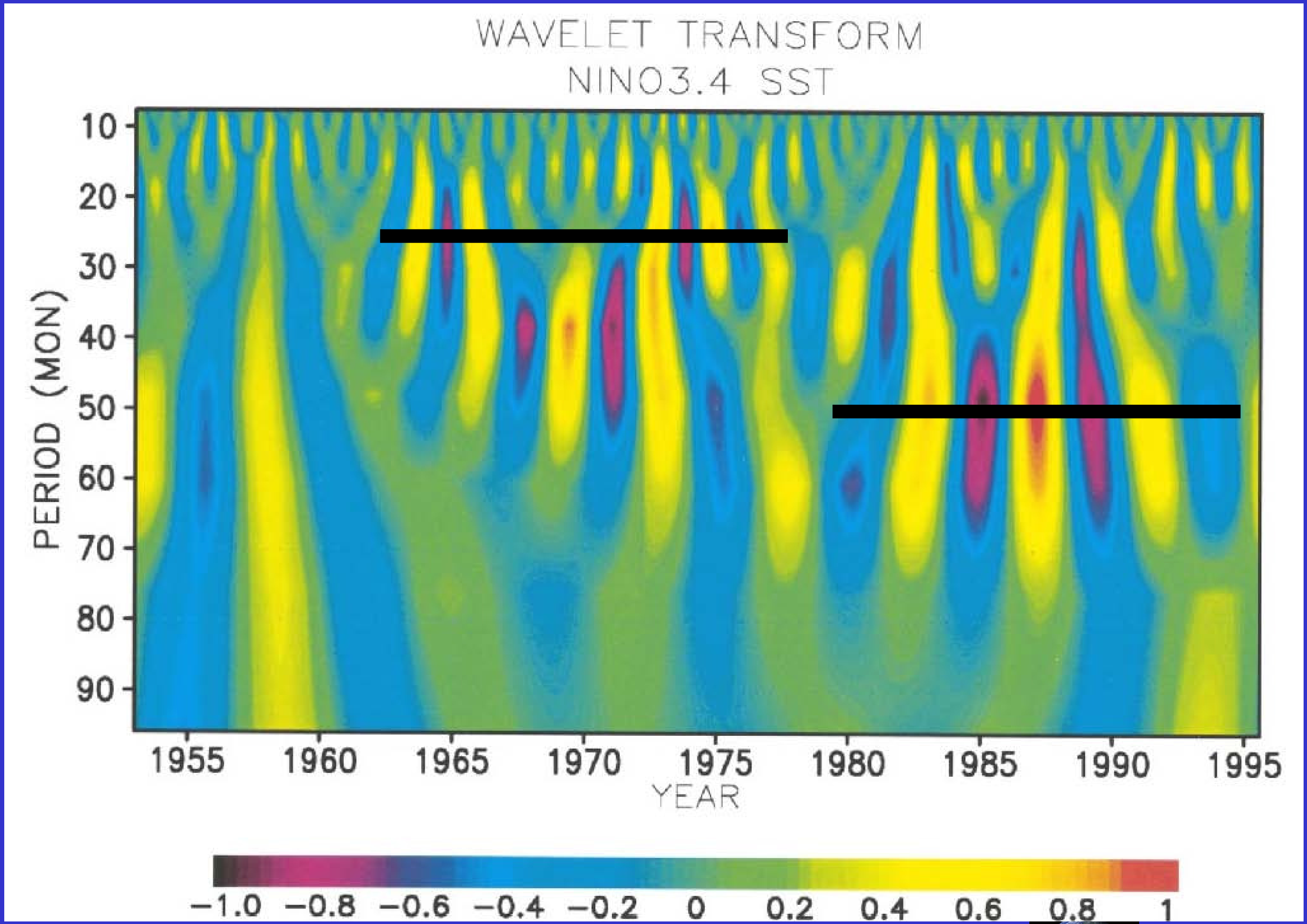
Vertical Cross-section

Decadal Changes of ENSO



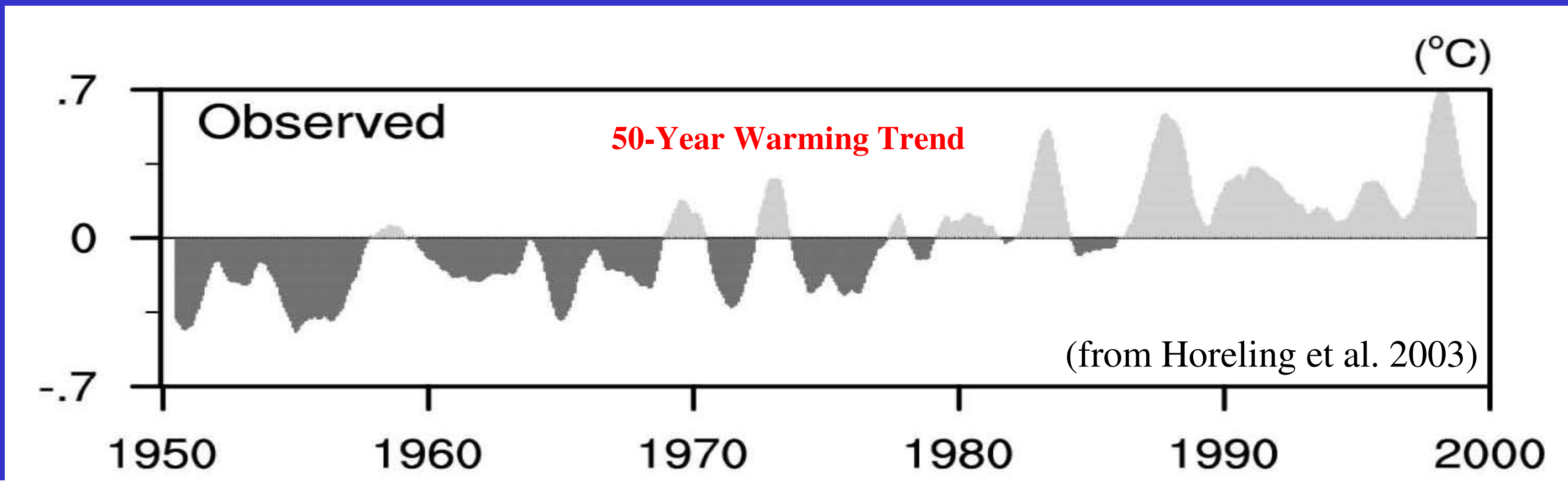
(Figure from Fedorov and Philander 2000)

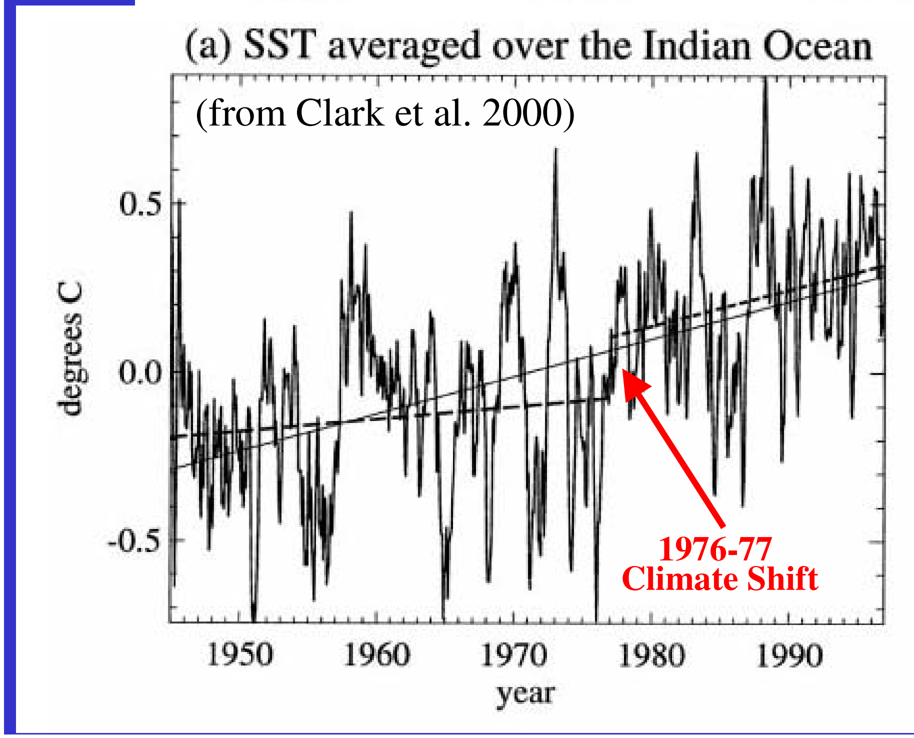
Decadal Changes in ENSO Period

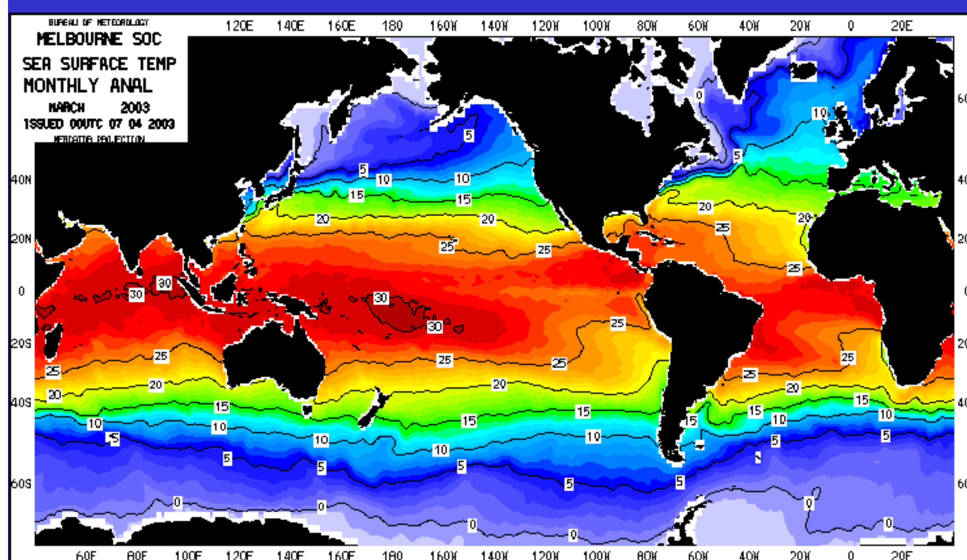


(from An and Wang 2000)

Changing Role of Indian Ocean in the Tropical Climate System



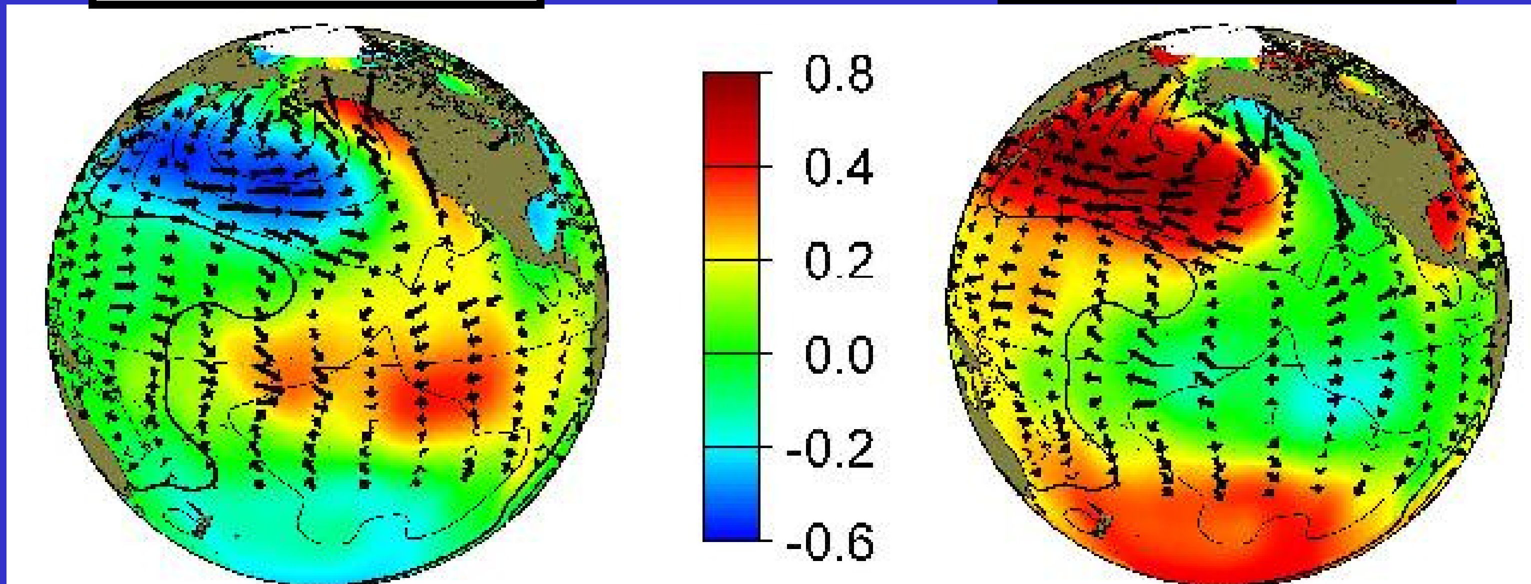




Pacific Decadal Oscillation

Positive PDO

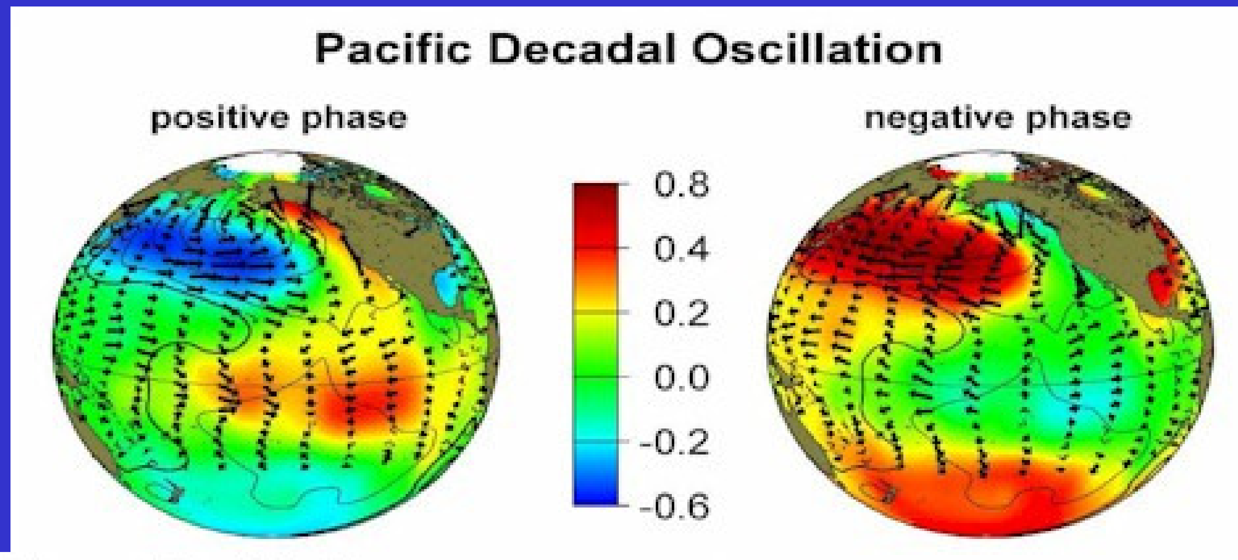
Negative PDO

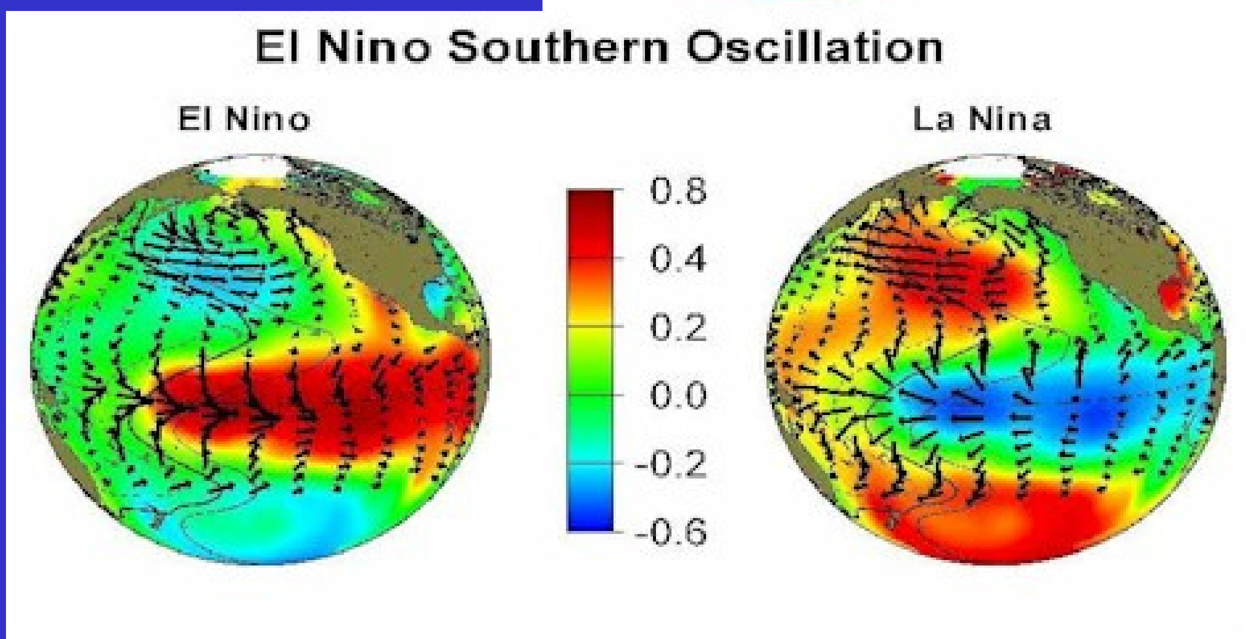


(from University of Washington)

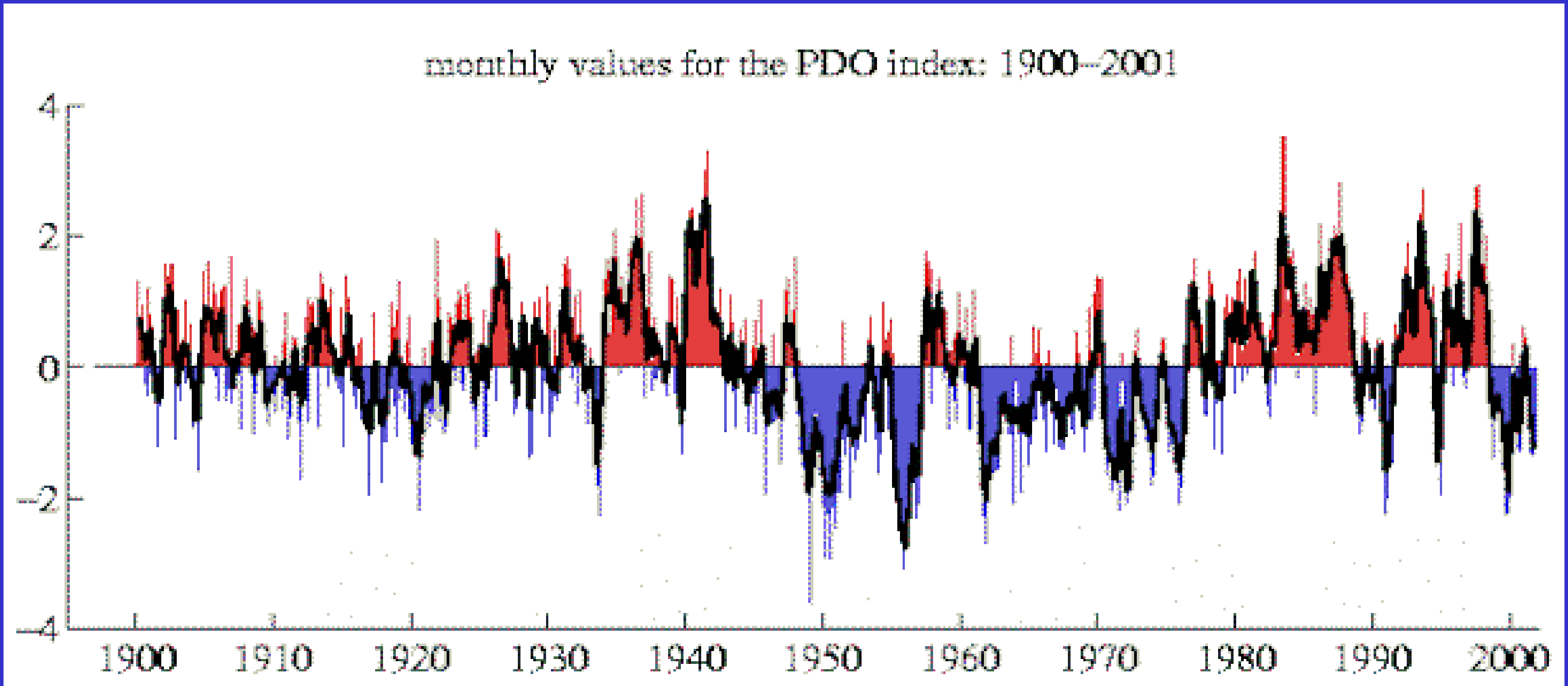
- "Pacific Decadal Oscillation" (PDO) is a decadal-scale climate variability that describe an oscillation in northern Pacific sea surface temperatures (SSTs).
- PDO is found to link to the decadal variations of ENSO intensity.

ENSO and PDO

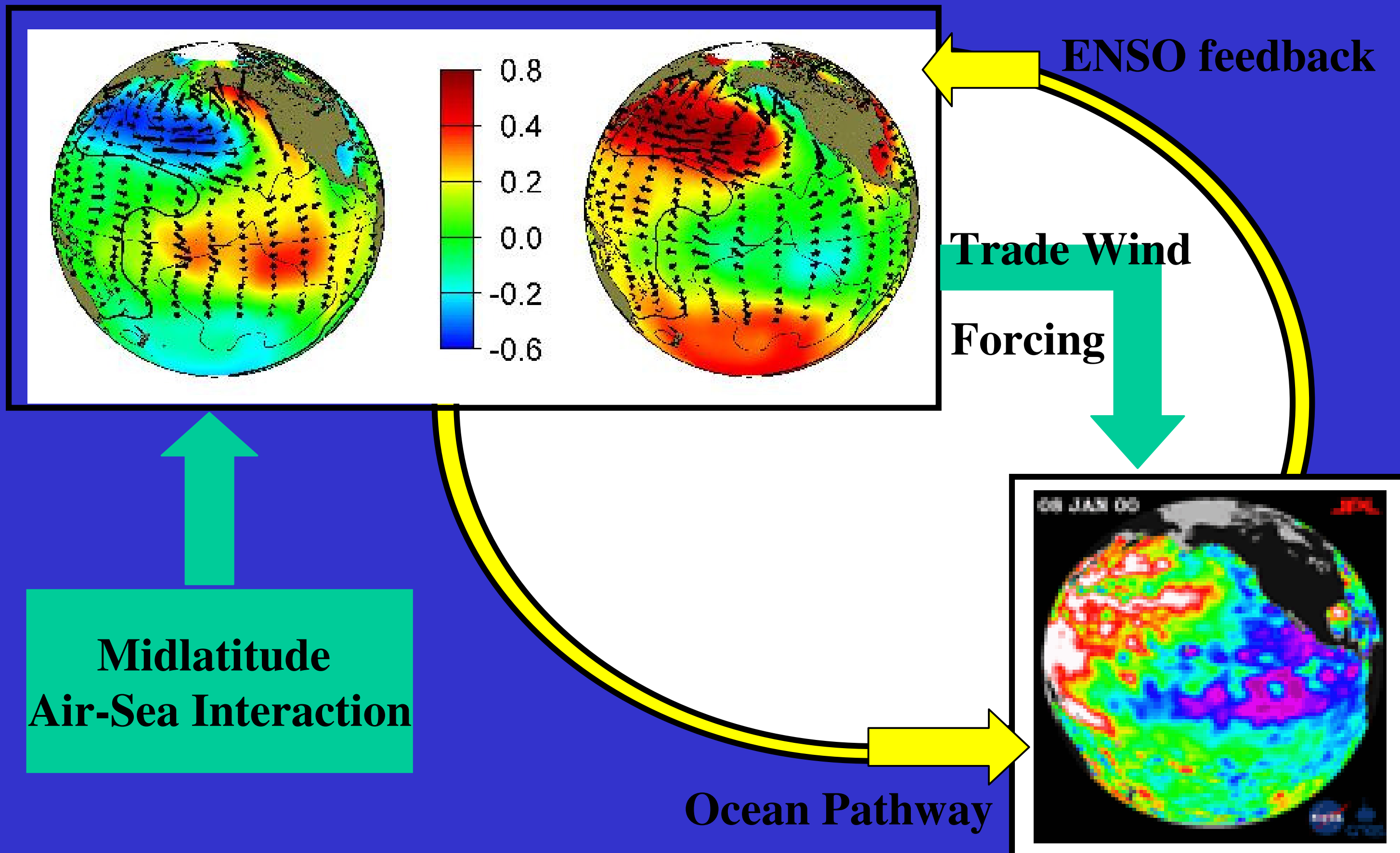

Pacific Decadal Oscillation
positive phase
negative phase
0.8
0.4
0.2
0.0
-0.2
-0.6


El Nino Southern Oscillation
El Nino
La Nina
0.8
0.4
0.2
0.0
-0.2
-0.6

PDO Index


monthly values for the PDO index: 1900–2001
4
2
0
–2
–4
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000

PDO-ENSO Relationship



Subduction

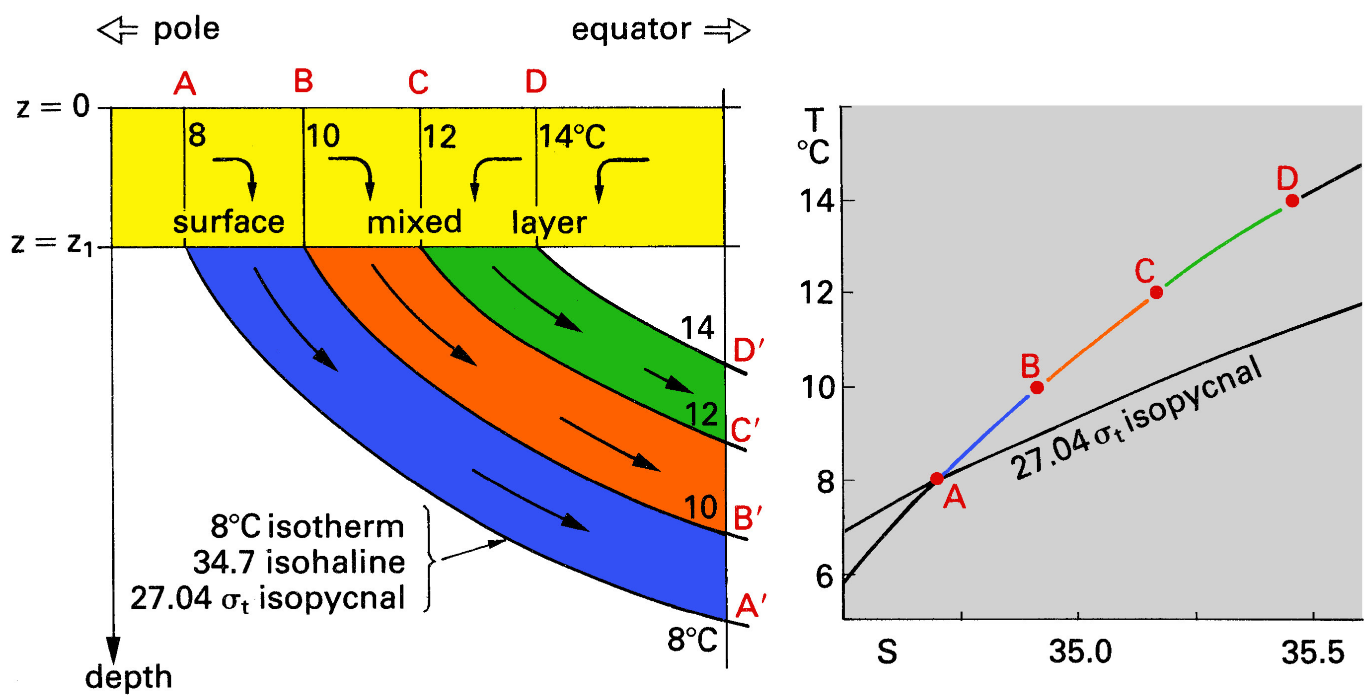
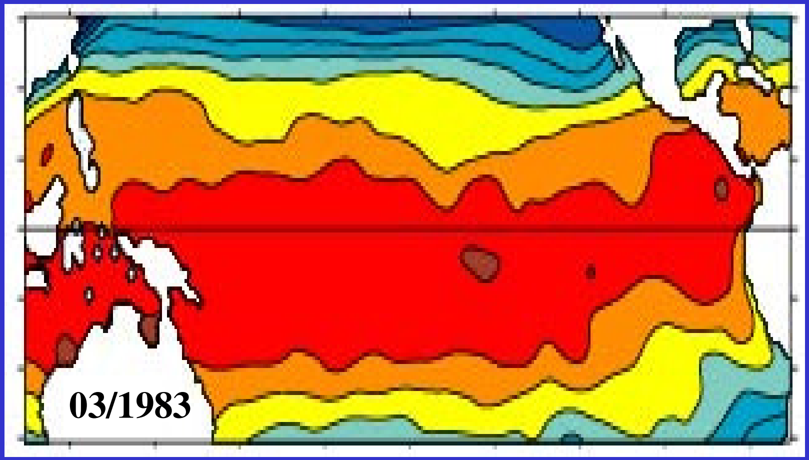
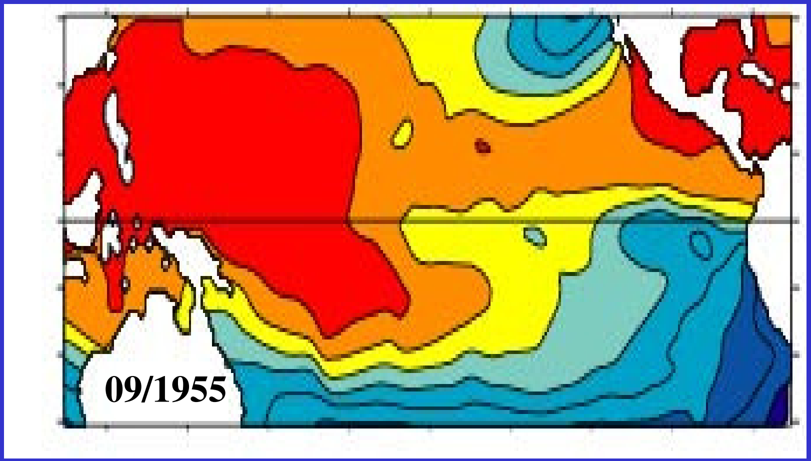


Fig. 5.3. Sketch of water mass formation by subduction in the Subtropical Convergence. The T-S diagram shows both the meridional variation of temperature and salinity between stations *A* and *D*, and the vertical variation equatorward of station *D* from the surface down along the line *A'B'C'D'*. For more detail, see text.

(from Regional Oceanography)

How El Nino Changes When Climate Warms?





- **Hypothesis 1: Permanent El Nino**

  (Philander 2003)

  When global climate warms

  → El Nino / La Nina alternations disappear

  → El Nino forever.

- **Hypothesis 2: Stronger ENSO Activity**

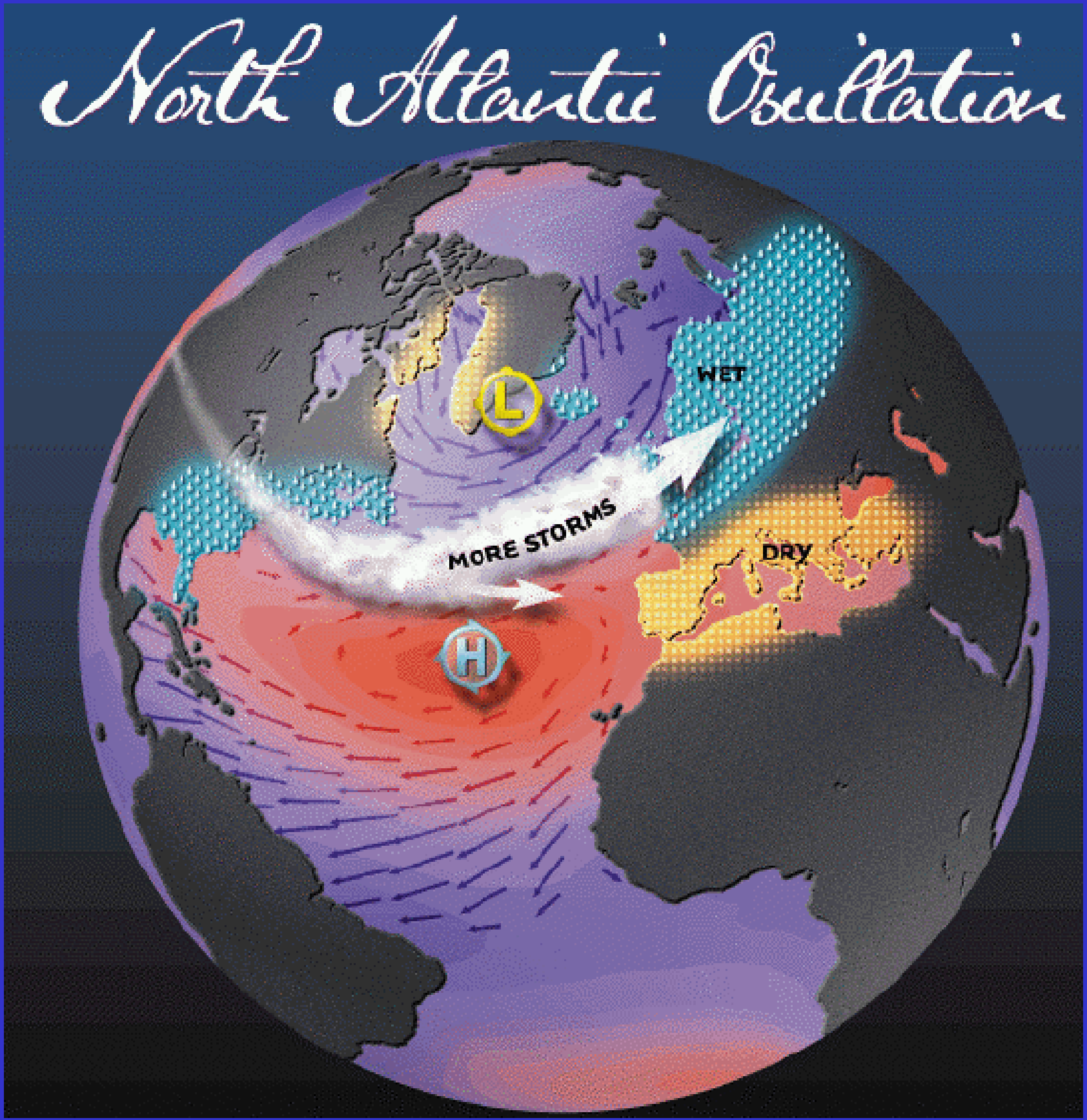
  (Huber and Gaballero 2003)

  When global climate warms

  → Stronger El Nino / La Nina lternations

  → Stronger ENSO events.

North Atlantic Oscillation

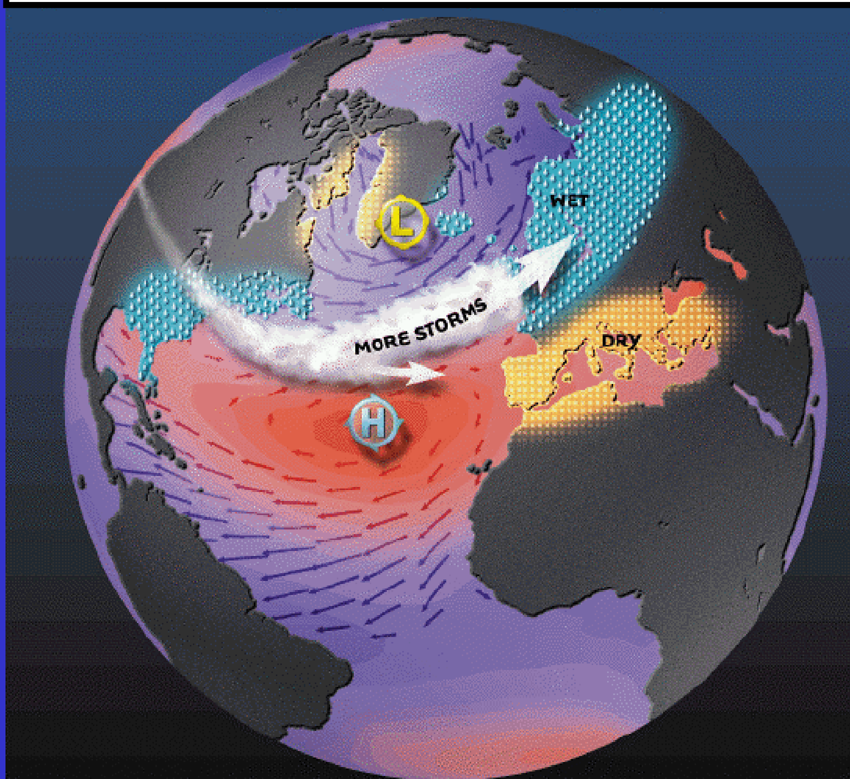


(from http://www.ldeo.columbia.edu/res/pi/NAO/)

- The NAO is the dominant mode of winter climate variability in the North Atlantic region ranging from central North America to Europe and much into Northern Asia.
- The NAO is a large scale seesaw in atmospheric mass between the subtropical high and the polar low.
- The corresponding index varies from year to year, but also exhibits a tendency to remain in one phase for intervals lasting several years.

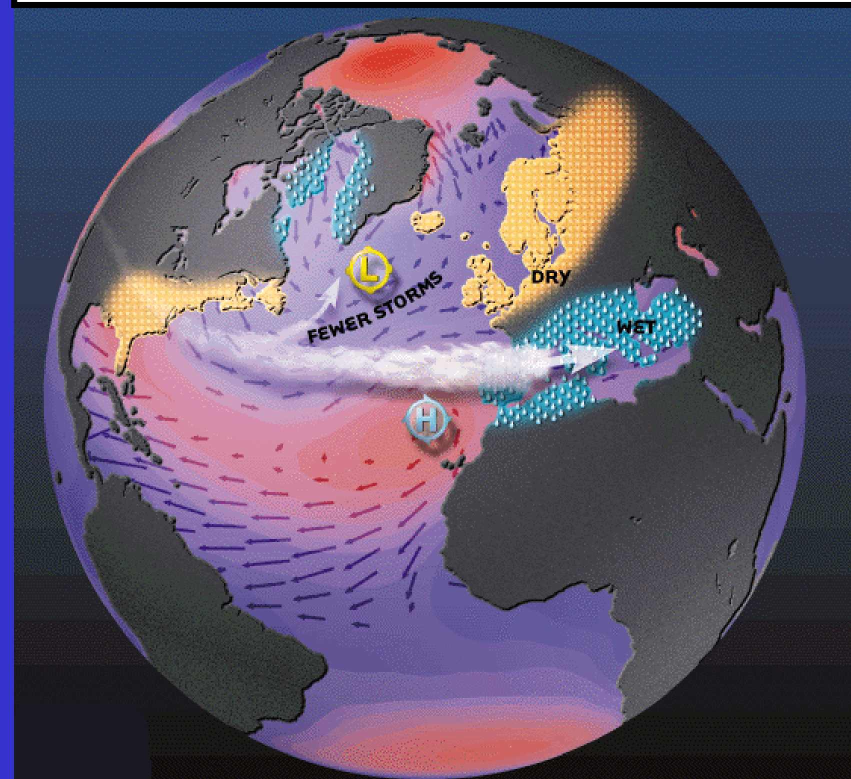
Positive and Negative Phases of NAO

Positive Phase



- A stronger and more northward storm track.

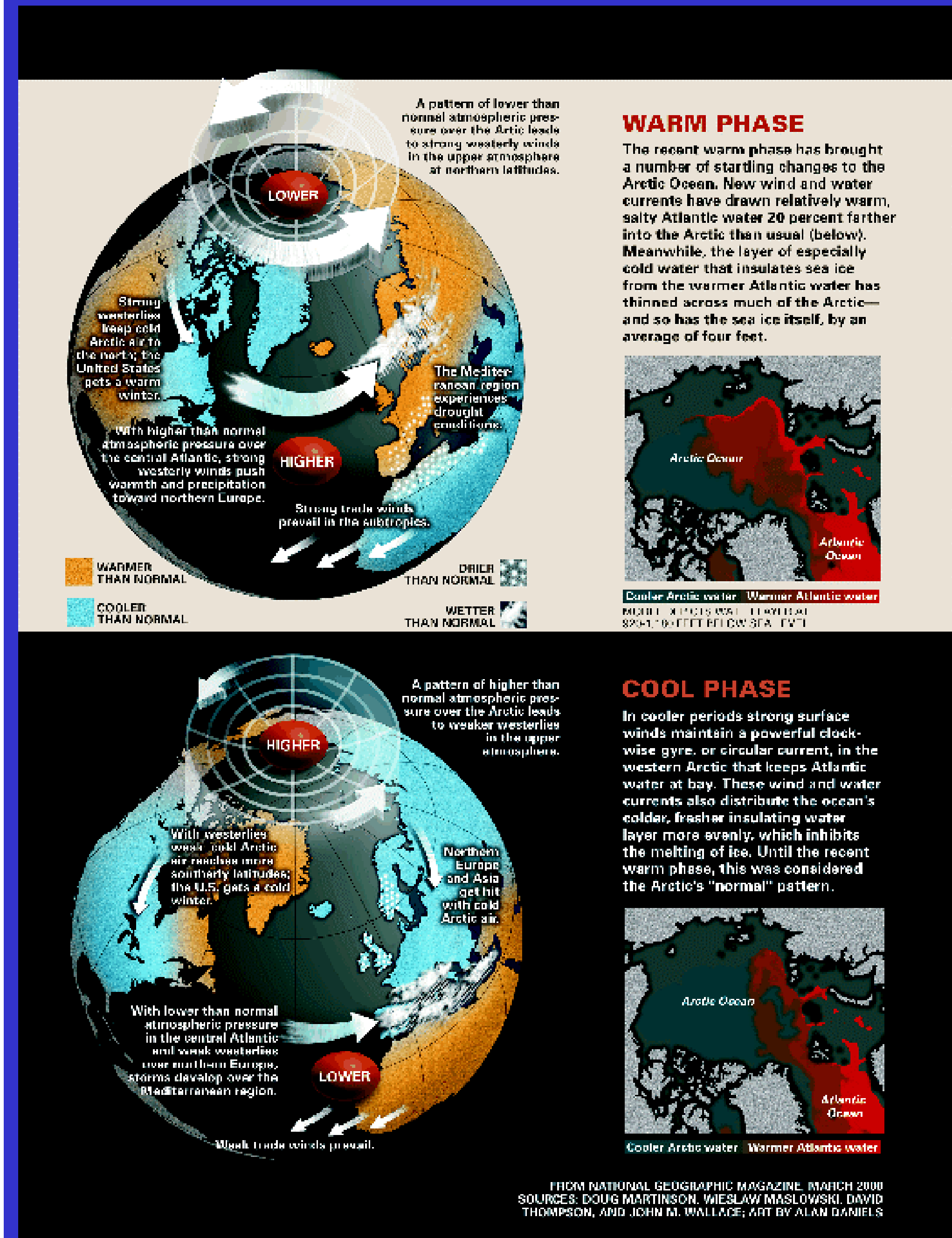
Negative Phase



- A weaker and more zonal storm track.

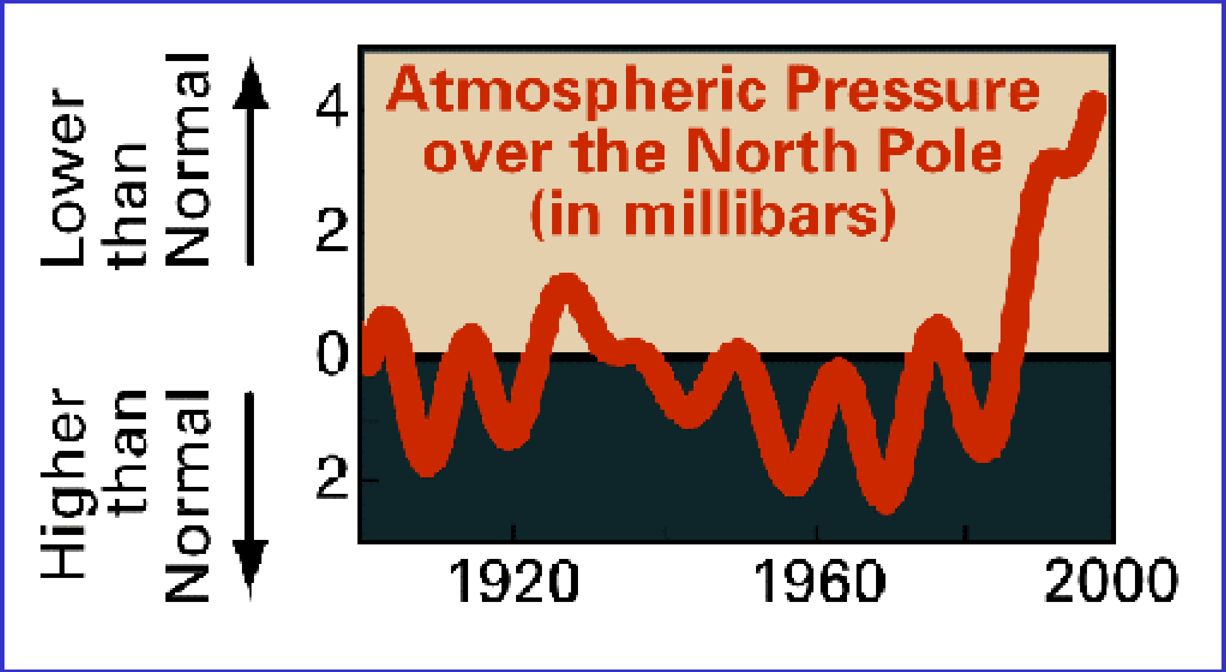
Dynamics Behind NAO

- The North Atlantic Oscillation is considered as a natural variability of the atmosphere.
- However, processes in the ocean and stratosphere and even the anthropogenic activity can affect its amplitude and phase.
- Surface winds of the NAO can force sea surface temperature variability in the Atlantic Ocean.
- Feedbacks from the ocean further affect NAO variability.



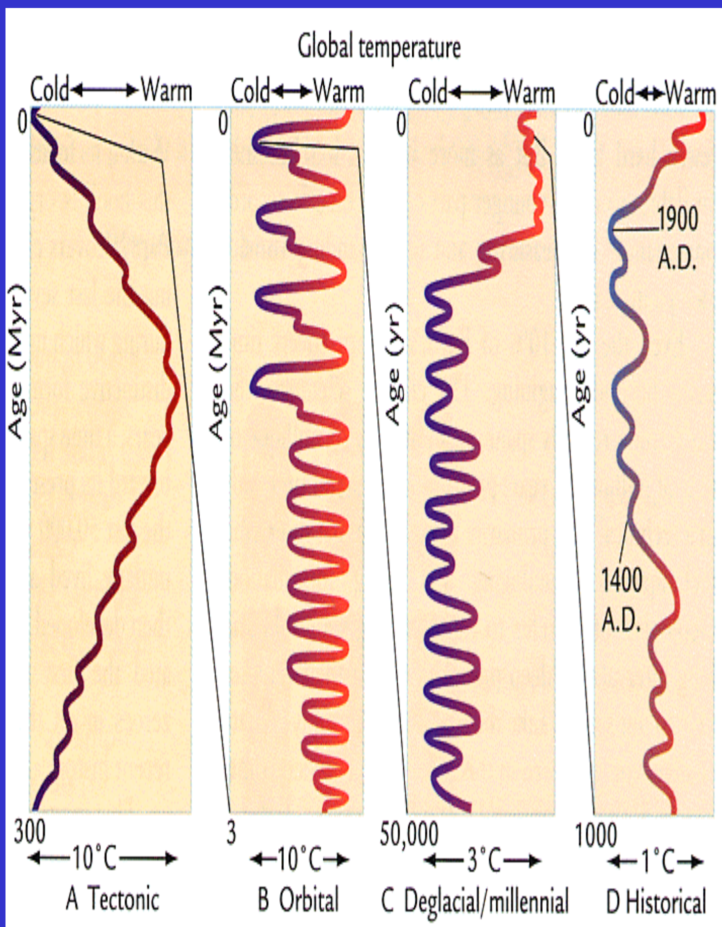
North Atlantic Oscillation
= Arctic Oscillation
= Annular Mode

Decadal Timescale of Arctic Oscillation



- The Arctic Oscillation switches phase irregularly, roughly on a time scale of decades.
- There has been an unusually warm phase in the last 20 years or so, exceeding anything observed in the last century.

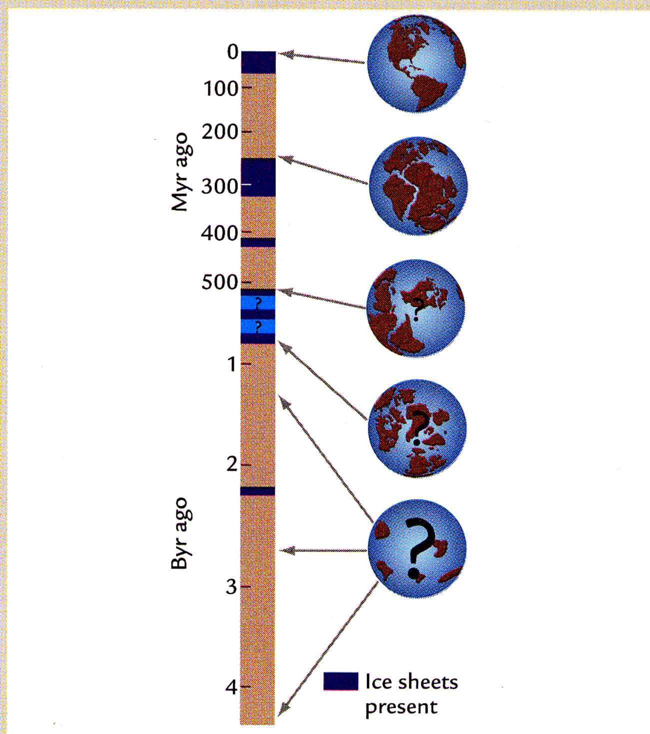
Climate *Changes*



(from *Earth's Climate: Past and Future*)

- Tectonic-Scale Climate Changes
- Orbital-Scale Climate Changes
- Deglacial and Millennial Climate Changes
- Historical Climate Change
- Anthropogenic Climate Changes

Tectonic Scale

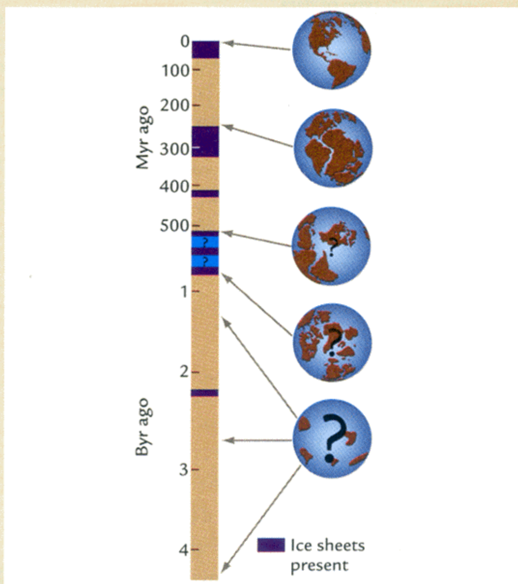


Past glaciations and continental positions. During Earth's 4.55-billion-year history, intervals when large continental ice sheets were present alternated with times when they were not (left). The earliest history of these changes is poorly defined because few ancient records are preserved. The movements of continents in relation to ocean basins are well known only for the last several hundred million years (right). (Globes adapted from D. Merritts et al., *Environmental Geology*, © 1997 by W. H. Freeman and Company.)

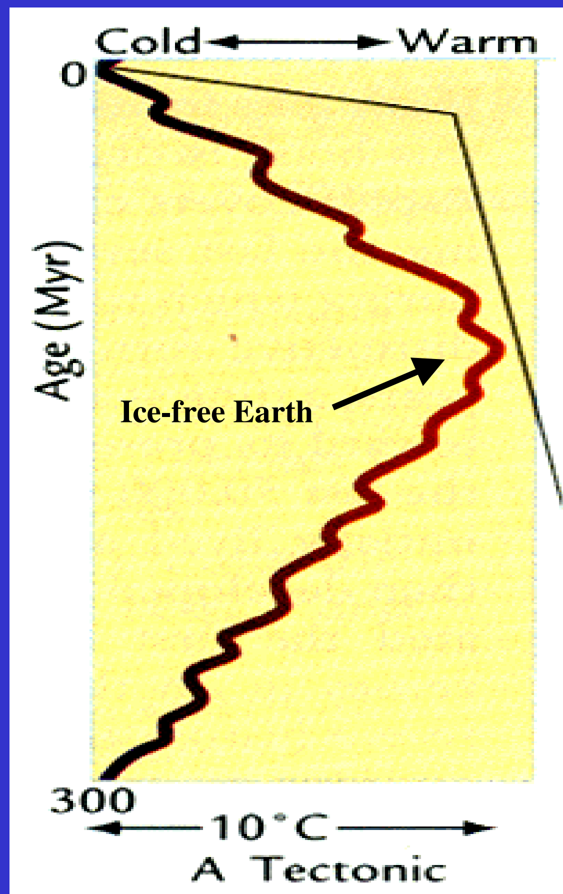
- Tectonic Scale: the longest time scale of climate change on Earth, which encompasses most of Earth's 4.55-billion years of history.
- Tectonic processes driven by Earth's internal heat alter Earth's geography and affect climate over intervals of millions of years.
- On this time scale, Earth's climate has oscillated between times when ice sheets were presented somewhere on Earth (such as today) and times when no ice sheets were presented.

(from *Earth's Climate: Past and Future*)

Tectonic-Scale Climate Change



Past glaciations and continental positions. During Earth's 4.55-billion-year history, intervals when large continental ice sheets were present alternated with times when they were not (left). The earliest history of these changes is poorly defined because few ancient records are preserved. The movements of continents in relation to ocean basins are well known only for the last several hundred million years (right). (Globes adapted from D. Merritts et al., *Environmental Geology*, © 1997 by W. H. Freeman and Company.)



(from *Earth's Climate: Past and Future*)

- The faint young Sun paradox and its possible explanation.
- Why was Earth ice-free even at the poles 100 Myr ago (the Mesozoic Era)?
- What are the causes and climate effects of changes in sea level through time?
- What caused Earth's climate to cool over the last 55 Myr (the Cenozoic Era)?

Faint Young Sun Paradox

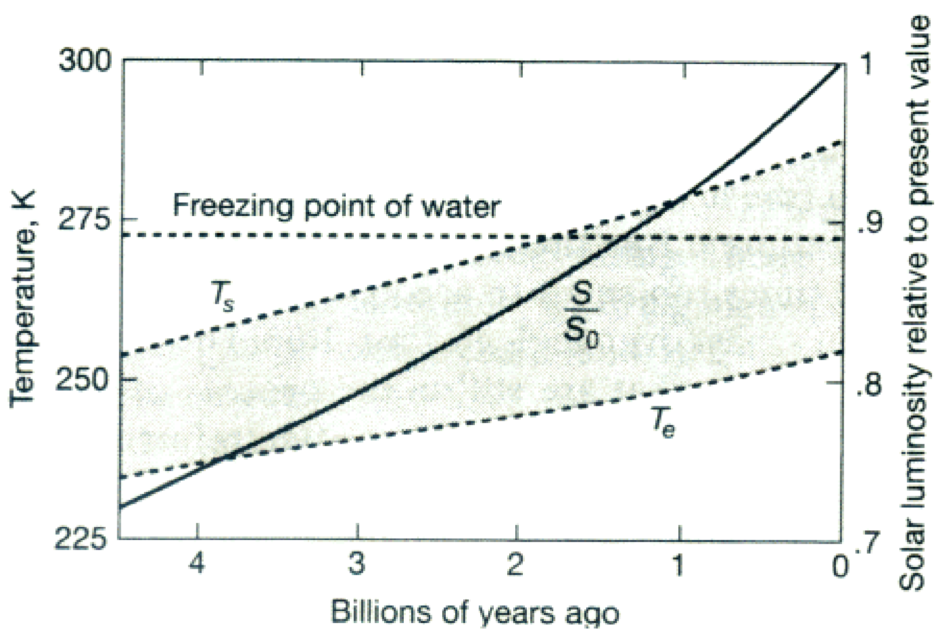


FIGURE 8-8

The faint young Sun paradox. The scale on the right applies to the solar luminosity curve, labeled S/S_0; the scale on the left applies to temperature curves. The shaded area represents the magnitude of the atmospheric greenhouse effect. (From J.F. Kasting et al., How Climate Evolved on the Terrestrial Planets, Scientific American 256(2): 90–97, 1988. Used with permission. © George V. Kelvin/Scientific American.

(from *The Earth System*)

- Solar luminosity was much weaker (~30%) in the early part of Earth's history (a faint young Sun).
- If Earth's albedo and greenhouse effect remained unchanged at that time, Earth's mean surface temperature would be well below the freezing point of water during a large portion of its 4.5 Byr history.
- That would result in a "snowball" Earth, which was not evident in geologic record.

Three Possible Solutions

- **Solution 1: Additional heat sources must have been presented**

  Unlikely: The geothermal heat from the early Earth is sometimes suggested one such additional heat source to warm Earth. However, the geothermal heat flux is not big enough to supply the required energy.

- **Solution 2: The planetary albedo must have been lower in the past**

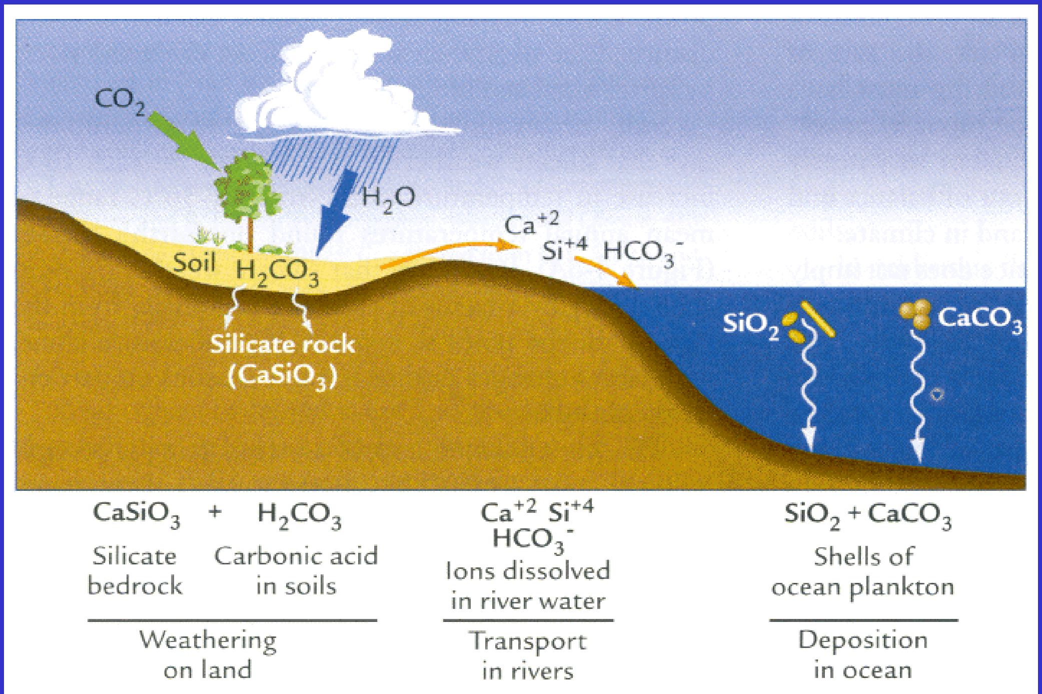
  Unlikely: It would require a ***zero albedo*** to keep the present-day surface temperature with the 30% weaker solar luminosity in the early Earth.

- **Solution 3: Greenhouse effect must have been larger**

  Most Likely: The most likely solution to the faint young Sun paradox is that Earth's greenhouse effect was larger in the past.

  But (1) why and (2) why that stronger greenhouse effect reduced to the present-day strength?

Chemical Weathering

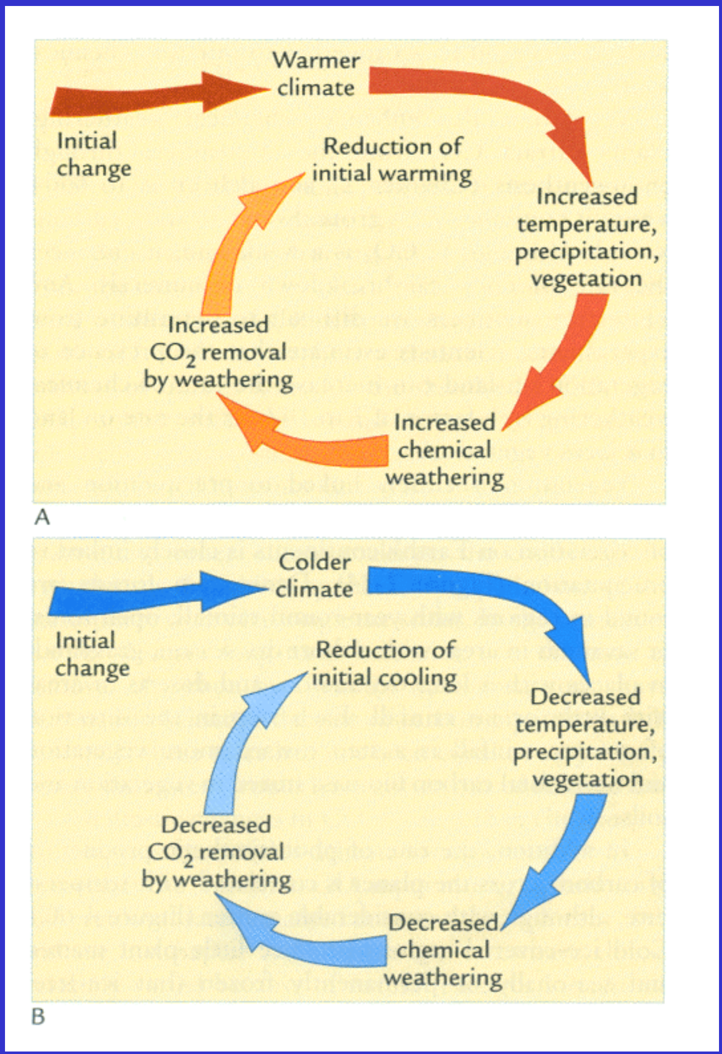


(from *Earth's Climate: Past and Future*)

- The precipitation process in the atmosphere dissolve and remove CO_2 from the atmosphere.
- Rocks exposed at Earth's surface undergo chemical attack from this rain of dilute acid.
- This whole process is known as ***chemical weathering***.
- The rate of chemical weathering tend to increase as temperature increases.
- Weathering requires water as a medium both for the dissolution of minerals and for the transport of the dissolved materials to the ocean

➔ The rate of chemical weathering increases as precipitation increases.

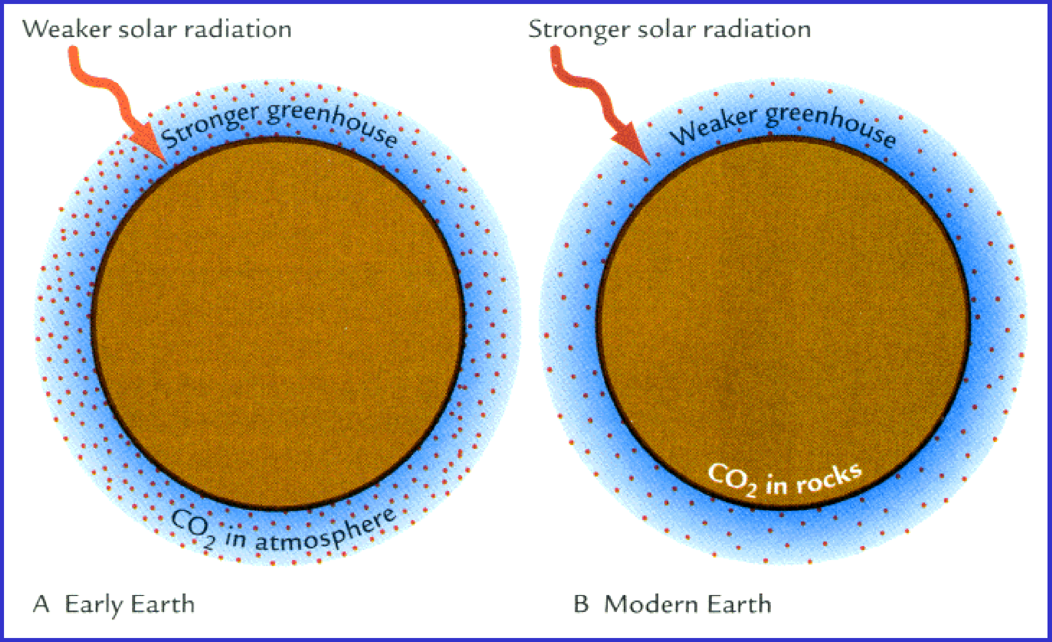
Negative Feedback From Chemical Weathering



(from *Earth's Climate: Past and Future*)

- ❑ The chemical weathering works as a negative feedback that moderates long-term climate change.
- ❑ This negative feedback mechanism links CO_2 level in the atmosphere to the temperature and precipitation of the atmosphere.
- ❑ A warm and moist climate produces stronger chemical weathering to remove CO_2 out of the atmosphere ➔ smaller greenhouse effect and colder climate.

Earth's Thermostat – Chemical Weathering



(from *Earth's Climate: Past and Future*)

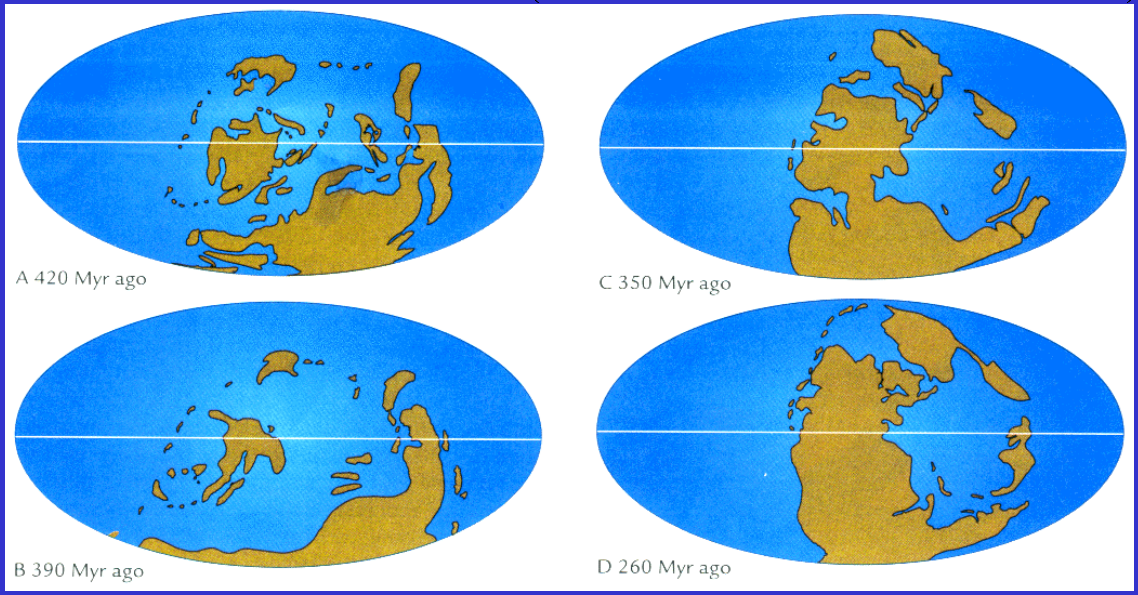
- Chemical weathering acts as Earth's thermostat and regulate its long-term climate.
- This thermostat mechanism lies in two facts:

  (1) the average global rate of chemical weathering depends on the state of Earth's climate,

  (2) weathering also has the capacity to alter that state by regulating the rate which CO_2 is removed from the atmosphere.

Plate Tectonics and Climate

(from *Earth's Climate: Past and Future*)

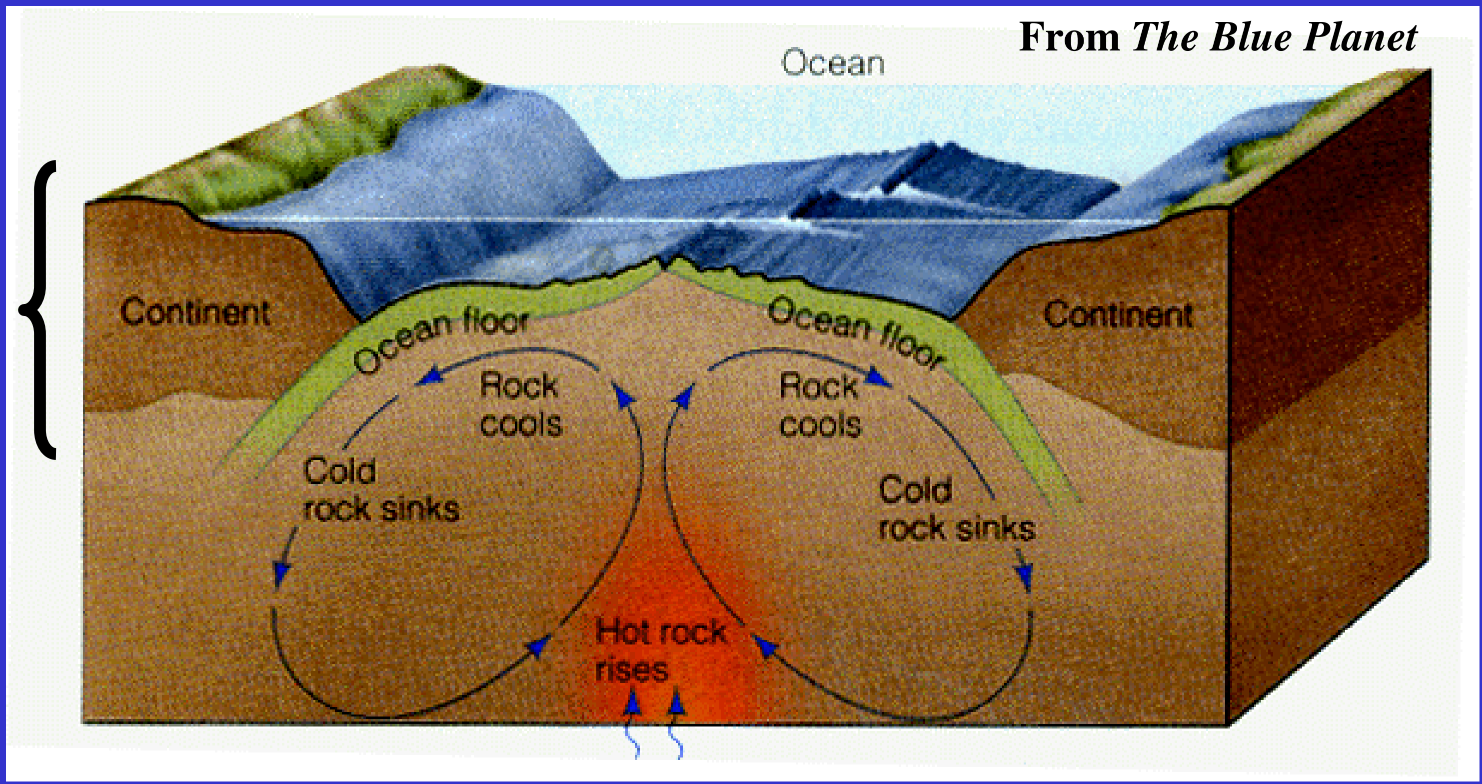


- How can one account for the alternating periods of climatic warmth and coolness observed in the geologic record?

  ➔ Part of the answer must lie in the tectonic activity and the positions of the continents.

Circulation of the Solid Earth

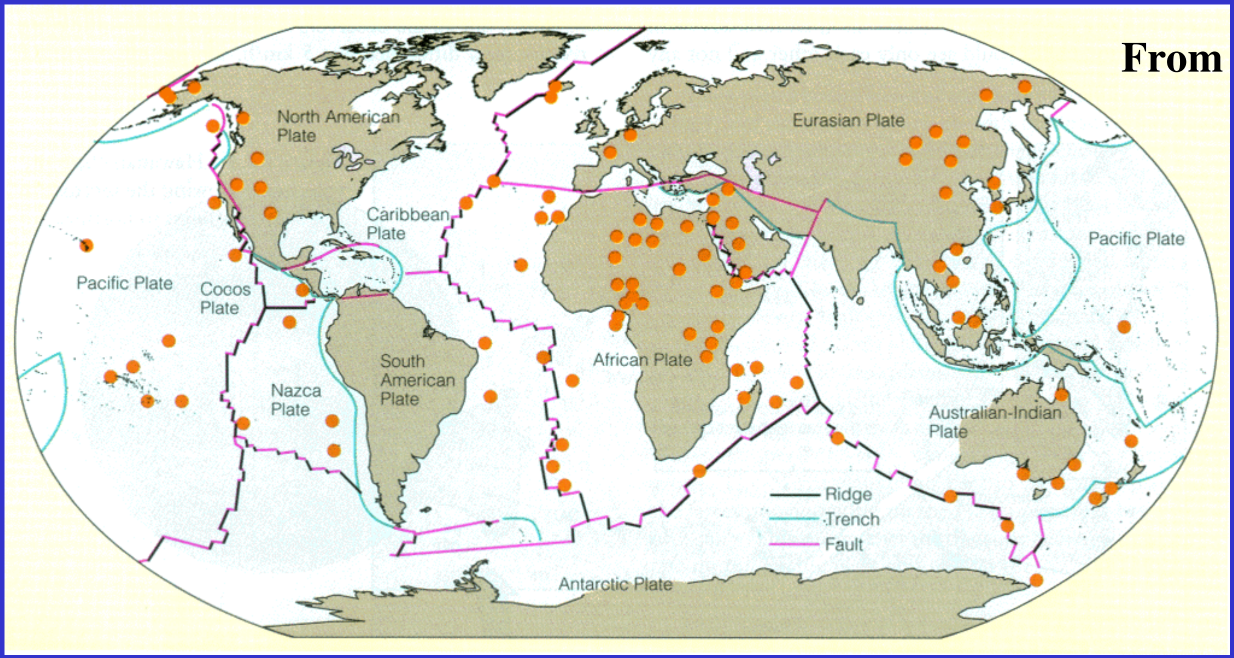
Cold Lithosphere



❑ The rising hot rocks and slid-away flows are thought to be the factor that control the positions of ocean basins and continents.

➔ The convection determines the shape of the Earth.

Twenty Rigid Plates



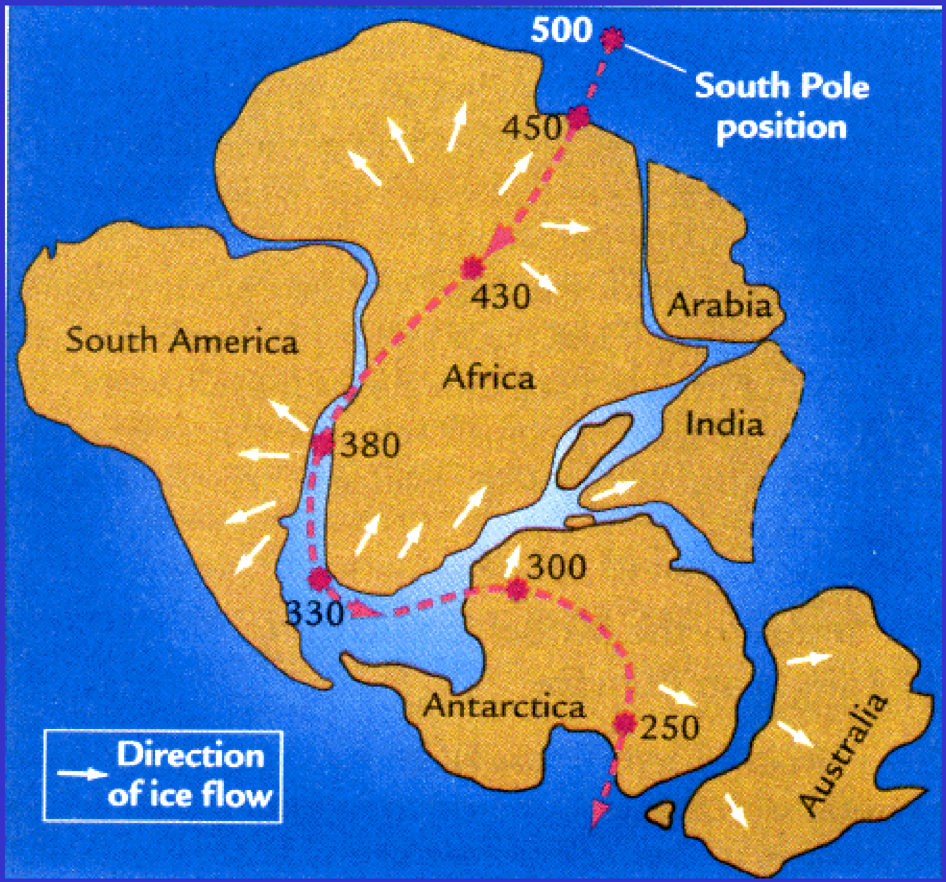
From *The Blue Planet*

- ❑ What can happen to the cold boundary?
- ➔ The lithosphere has broken into a number of rocky pieces, called plates.
- ❑ There are a few large plates plus a number of smaller one comprise the Earth’s surface (a total of 20 plates).
- ❑ The plates range from several hundred to several thousand kilometers in width.

Three Ways for Solid Earth to Affect Climate

- Polar position hypothesis
- Chemical Weathering Hypothesis
- Seafloor Spreading Hypothesis

The Polar Position Hypothesis



(from *Earth's Climate: Past and Future*)

- The polar position hypothesis focused on latitudinal position as a cause of glaciation of continents.
- This hypothesis suggested that ice sheets should appear on continents when they are located at polar or near-polar latitudes.
- To explain the occurrence of icehouse intervals, this hypothesis calls not on worldwide climate changes but simply on the movements of continents on tectonic plates.
- This hypothesis can not explain the climate of the Late Proterozoic Era, when both continents and glaciers appear to have been situated at relatively low latitudes.
- It can not explain the warm Mesozoic Era when high-latitude continents were present but were almost completely ice-free.

Climate Changes in the Last 500 Myr

TABLE 5-1 Evaluation of the Polar Position Hypothesis of Glaciation

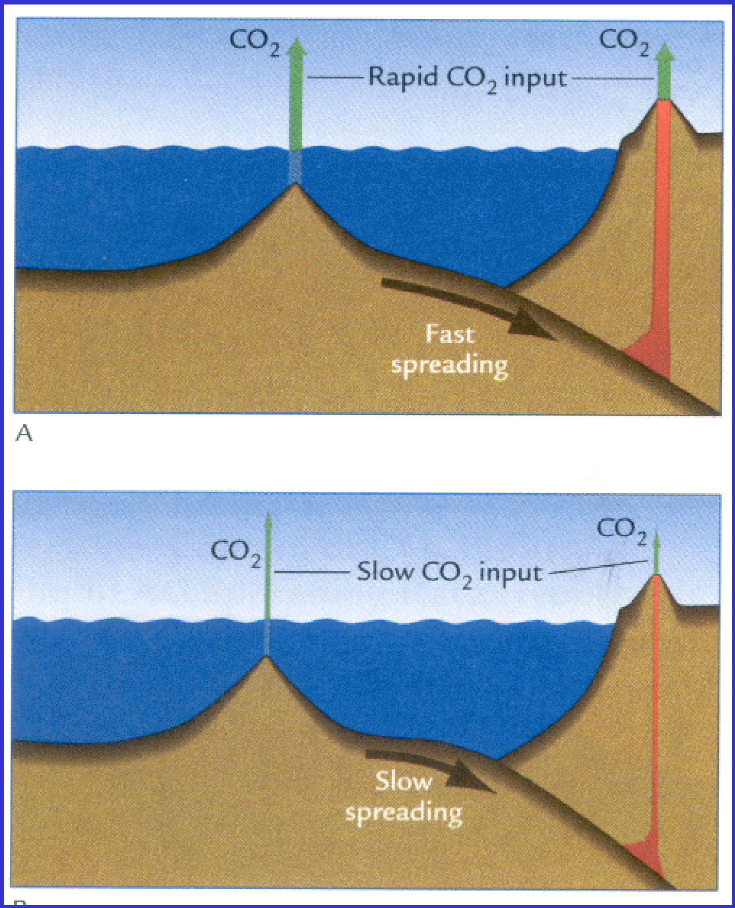
Time (Myr ago)	Ice sheets present?	Continents in polar position?	Hypothesis supported?
430	Yes	Yes	Yes
425–325	No	Yes	No
325–240	Yes	Yes	Yes
240–125	No	No	Yes
125–35	No	Yes	No
35–0	Yes	Yes	Yes

- Climate in the past 500 million years have alternated between long periods of warm climate and short periods of cold climate.

- During the last 500 million years, major continent-size ice sheets existed on Earth during three icehouse ear: (1) a brief interval near 430 Myr ago, (2) a much longer interval from 325 to 240 Myr ago, and (3) the current icehouse era of the last 35 million year.

(from *Earth's Climate: Past and Future*)

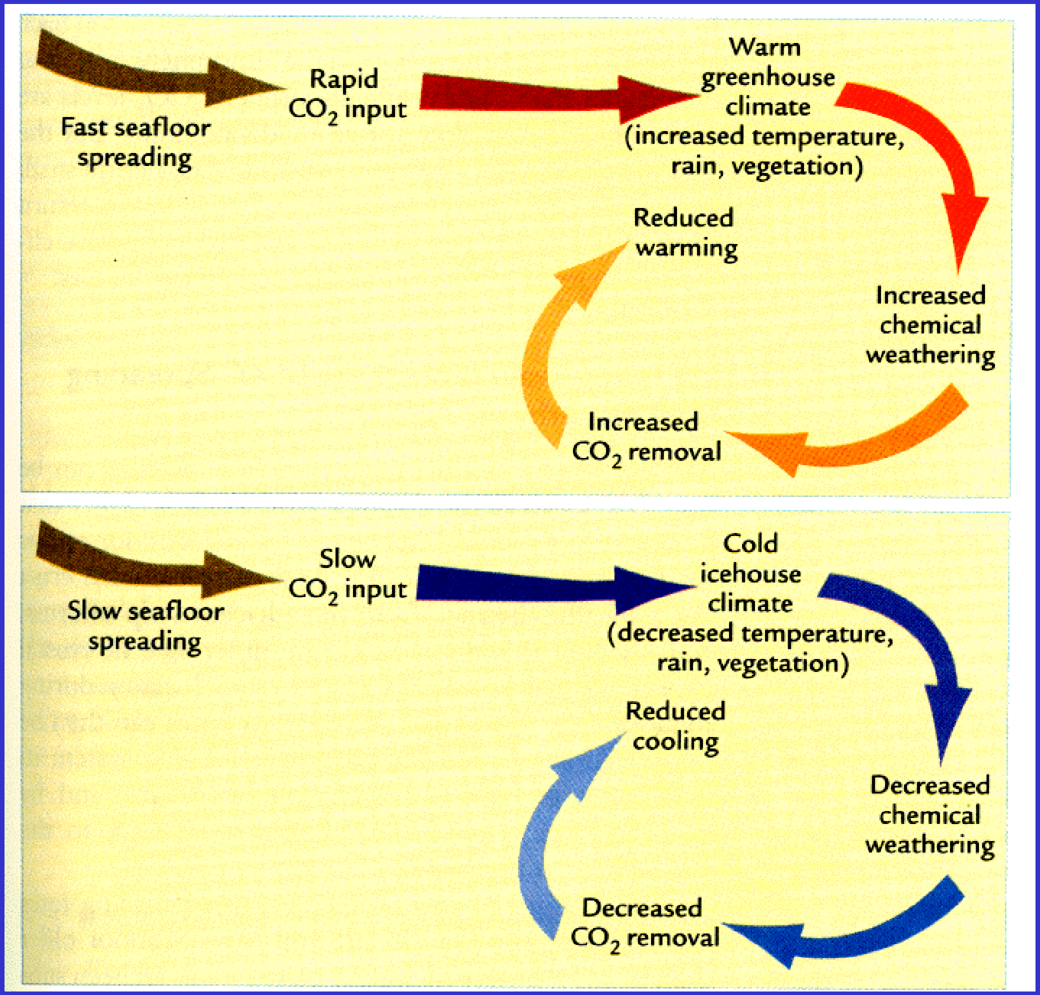
Tectonic Control of CO_2 *Input* – The Seafloor Spreading Rate Hypothesis



(from *Earth's Climate: Past and Future*)

- During active plate tectonic processes, carbon cycles constantly between Earth's interior and its surface.
- The carbon moves from deep rock reservoirs to the surface mainly as CO_2 gas associated with volcanic activity along the margins of Earth's tectonic plates.
- The centerpiece of the seafloor spreading hypothesis is the concept that changes in the rate of seafloor spreading over millions of years control the rate of delivery of CO_2 to the atmosphere from the large rock reservoir of carbon, with the resulting changes in atmospheric CO_2 concentrations controlling Earth's climate.

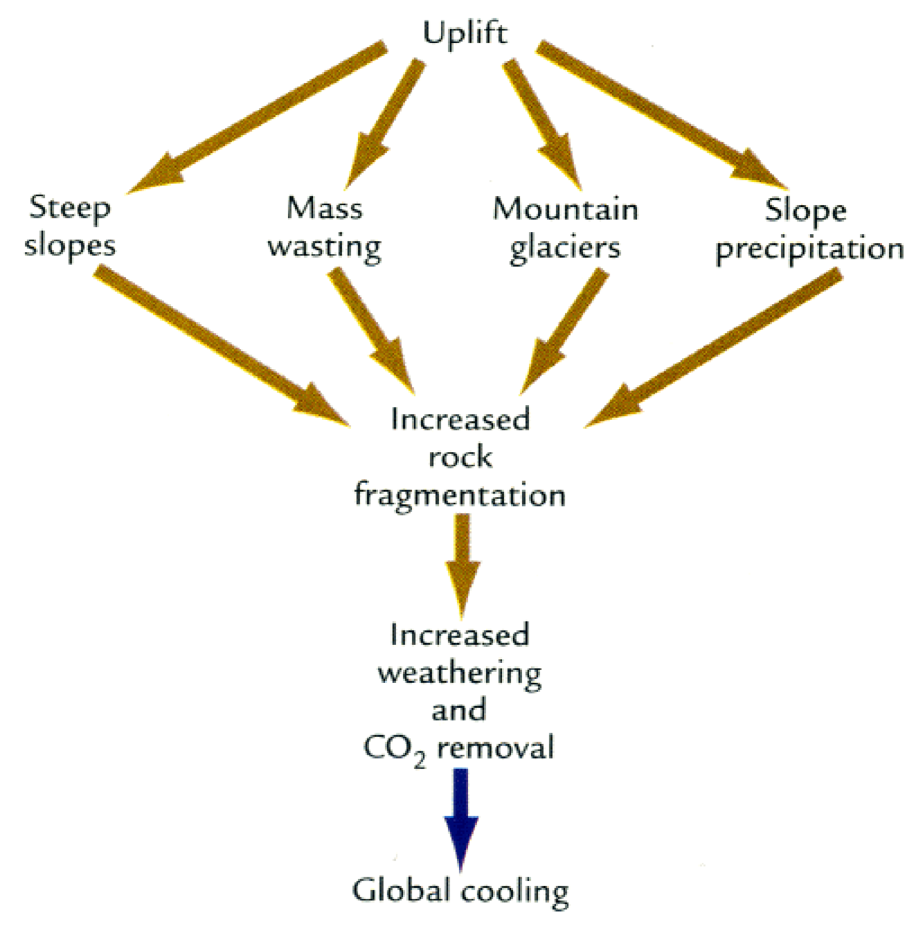
Negative Feedback in Seafloor Spreading Hypothesis



(from *Earth's Climate: Past and Future*)

- The seafloor spreading hypothesis invokes chemical weathering as a negative feedback that partially counters the changes in atmospheric CO_2 and global climate driven by changes in rates of seafloor spreading.

Tectonic Control of CO_2 *Removal* – The Uplift Weathering Hypothesis



(from *Earth's Climate: Past and Future*)

- The uplifting weathering hypothesis asserts that the global mean rate of chemical weathering is heavily affected by the availability of fresh rock and mineral surfaces that the weathering process can attack.
- This hypothesis suggests that tectonic uplifting enhances the exposure of freshly fragmented rock which is an important factor in the intensity of chemical weathering.
- This hypothesis looks at chemical weathering as the active driver of climate change, rather than as a negative feedback that moderates climate changes.

Can These Two Hypotheses Explain Tectonic-Scale Climate Changes?

TABLE 5-2 Evaluation of the BLAG Spreading Rate (CO_2 Input) Hypothesis

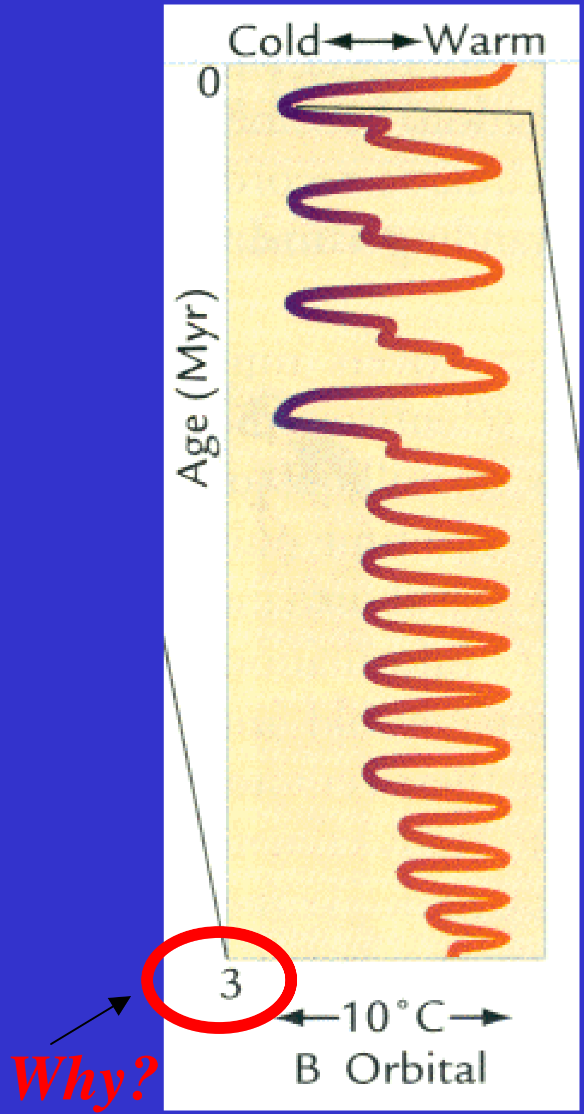
Time (Myr ago)	Ice sheets present?	Spreading rates	Hypothesis supported?
100	No	Fast	Yes (high CO_2)
0	Yes	Slow	Yes (low CO_2)

TABLE 5-3 Evaluation of the Uplift Weathering (CO_2 Removal) Hypothesis

Time (Myr ago)	Ice sheets present?	Continents colliding?	Hypothesis supported?
325–240	Yes	Yes	Yes (low CO_2)
240–35	No	No	Yes (high CO_2)
35–0	Yes	Yes	Yes (low CO_2)

(from *Earth's Climate: Past and Future*)

Orbital-Scale Climate Change

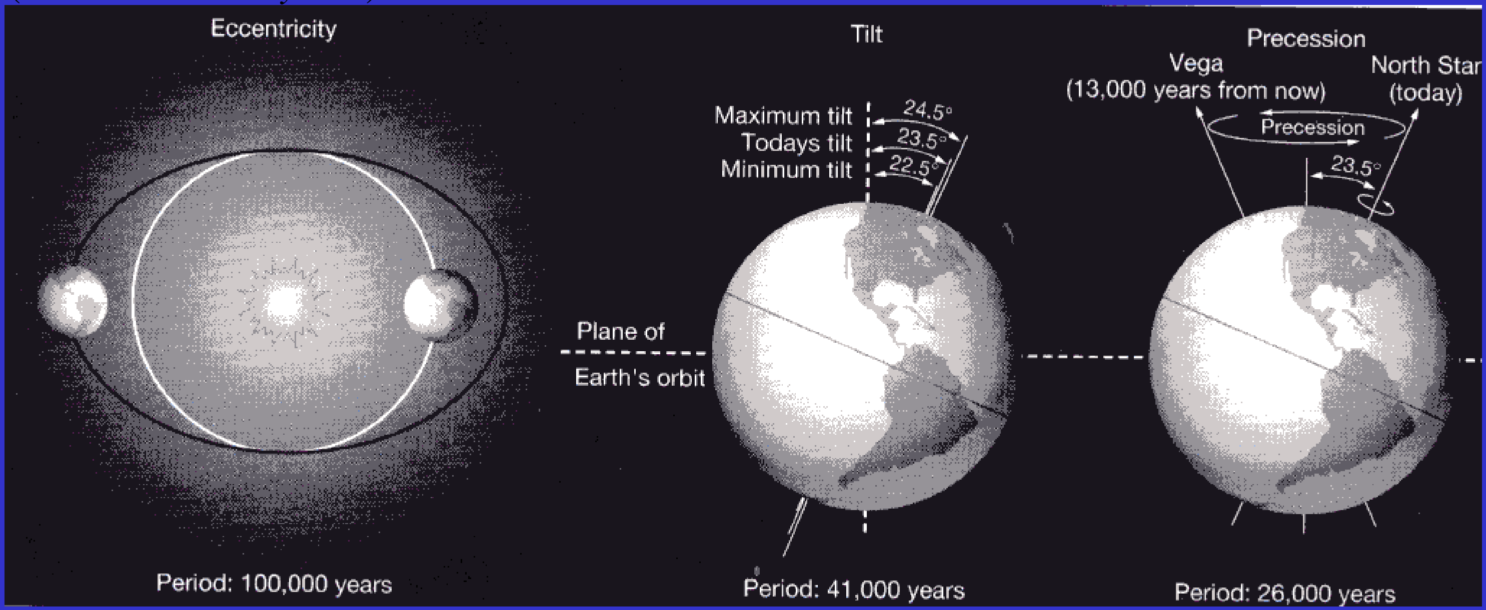


- **Changes in solar heating driven by changes in Earth's orbit are the major cause of cyclic climate changes over time scales of tens to hundreds of thousands of years (23k years, 41k years, and 100k years) .**
- Earth's orbit and its cyclic variations: tilt variations, eccentricity variations, and precession of the orbit.
- How do orbital variations drive the strength of tropical monsoons?
- How do orbital variations control the size of northern hemisphere ice sheets?
- What controls orbital-scale fluctuations of atmospheric greenhouse gases?
- What is the origin of the 100,000-year climate cycle of the last 0.9 Myr (ice sheets melt rapidly every 100,000 years)?

(from *Earth's Climate: Past and Future*)

Orbital Scale

(from *The Earth System*)



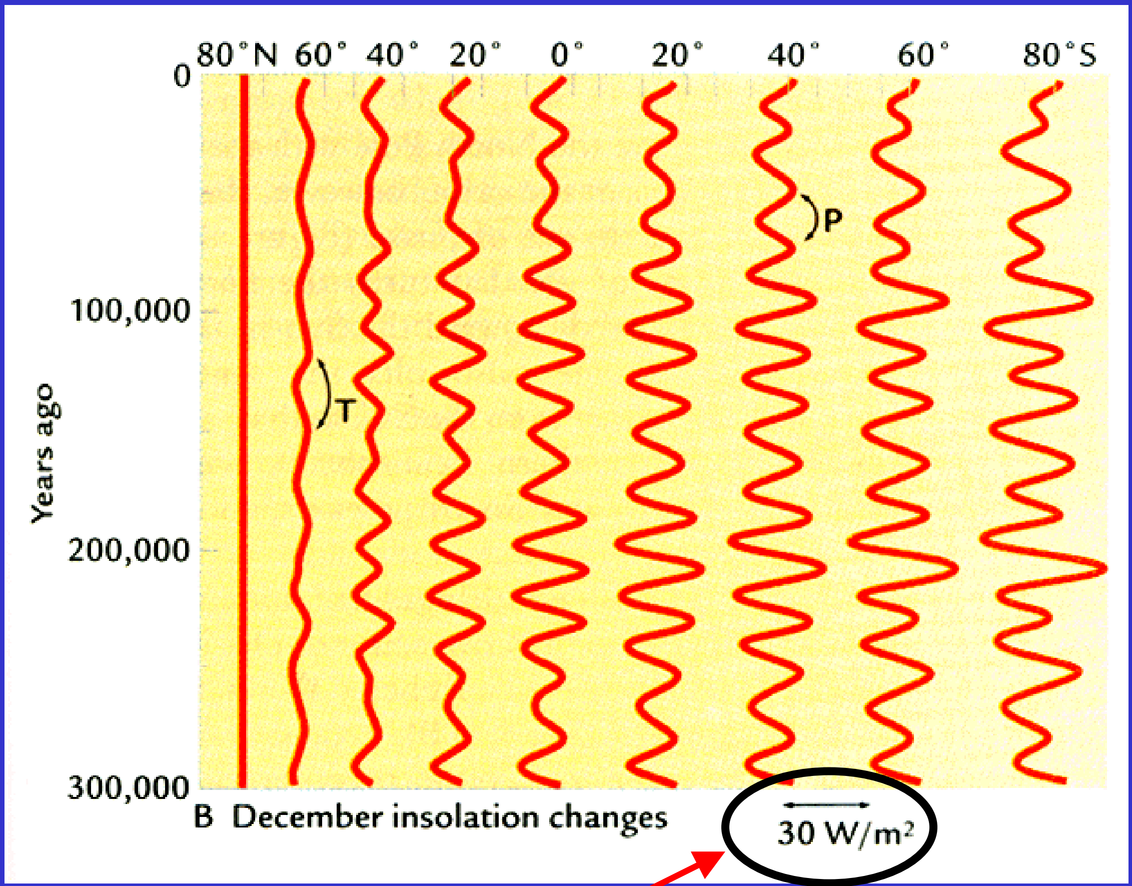
- ❑ Orbital-scale climate changes are caused by subtle shifts in Earth's orbit.

- ❑ Three features of Earth's orbit around the Sun have changed over time:
  (1) the tilt of Earth's axis,
  (2) the shape of its yearly path of revolution around the Sun
  (3) the changing positions of the seasons along the path.

- ❑ Orbital-scale climate changes have typical cycles from 20,000 to 400,000 years.

Seasonal Insolation Changes

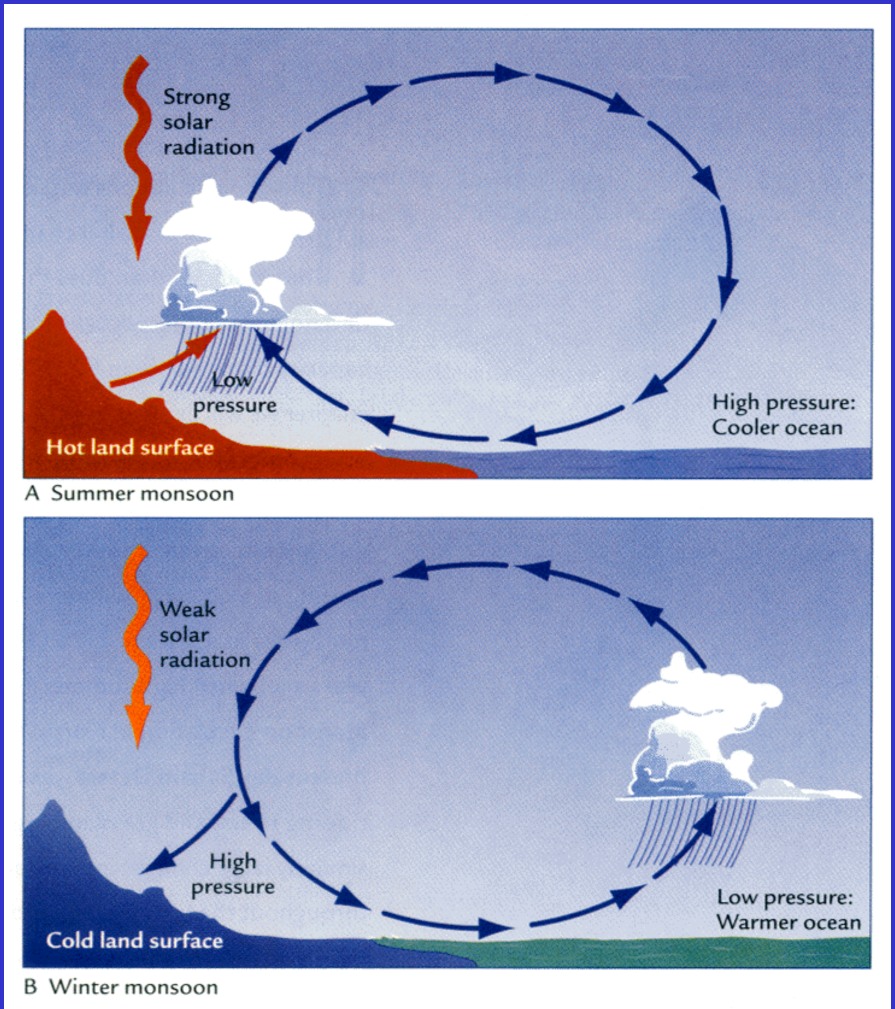
(from Earth's Climate: Past and Future)



Mean isolation value = 340 W/m²

- The 23,000-year cycle of precissional change dominants the insolation changes at low and middle latitudes.
- The 41,000-year cycle of tilt change dominants the insolation changes at higher latitudes.
- Eccentricity changes (the 1000,000 or 413,000-year cycles) is not a significant influence on seasonal insolation chanes.

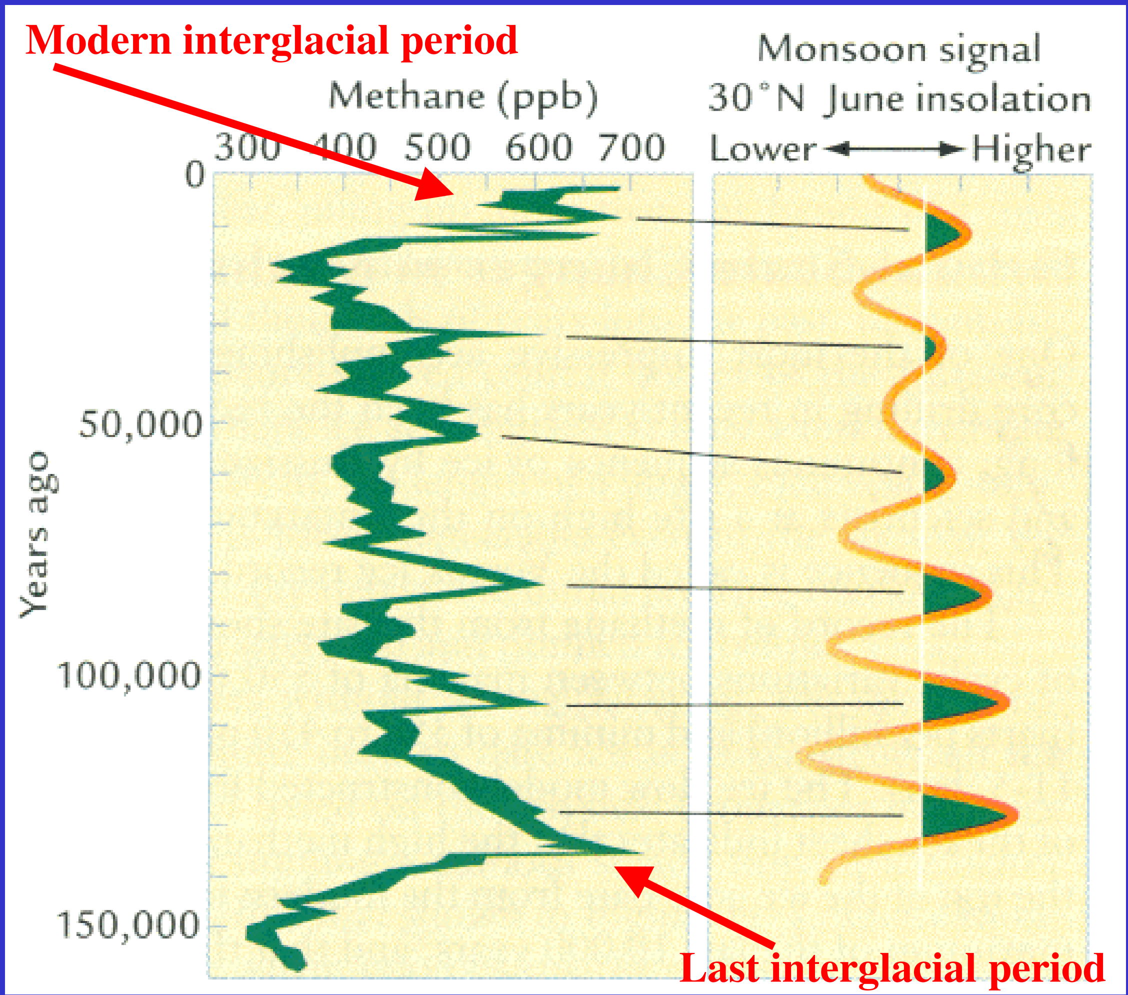
Insolation Control of Monsoons



(from Earth's Climate: Past and Future)

- Monsoon circulations exit on Earth because the land responds to seasonal changes in solar radiation more quickly than does the ocean.
- Changes in insolation over orbital time scales have driven major changes in the strength of the summer monsoons.
- Changes of 12% in the amount of insolation received at low latitudes have caused large changes in heating of tropical landmass and in the strength of summer monsoons at a cycle near 23,000 years in length.

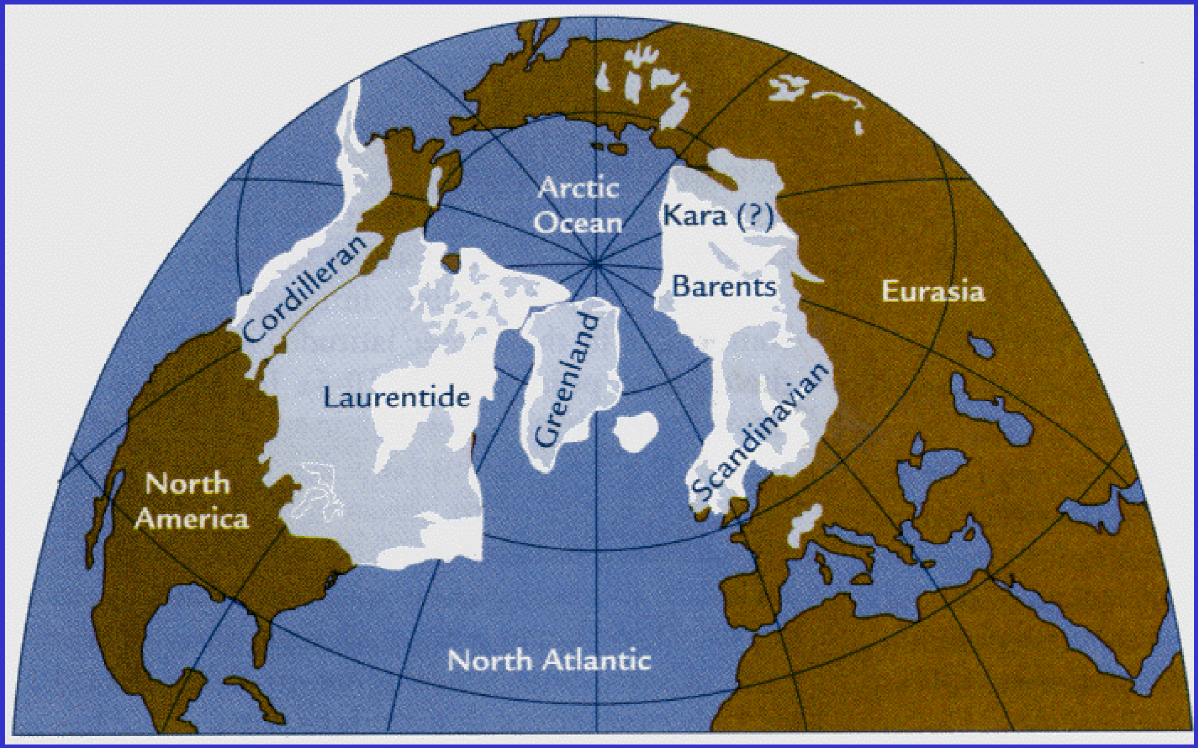
Orbital-Scale Changes in Methane



(from *Earth's Climate: Past and Future*)

- The Vostok ice record shows a series of cyclic variations in methane concentration, ranging between 350 to 700 ppb (part per billion).
- Each Ch4 cycle takes about 23,000 years.
- This cycle length points to a likely connection with changes in orbital procession.
- The orbital procession dominates insolation changes at ***lower latitudes***.

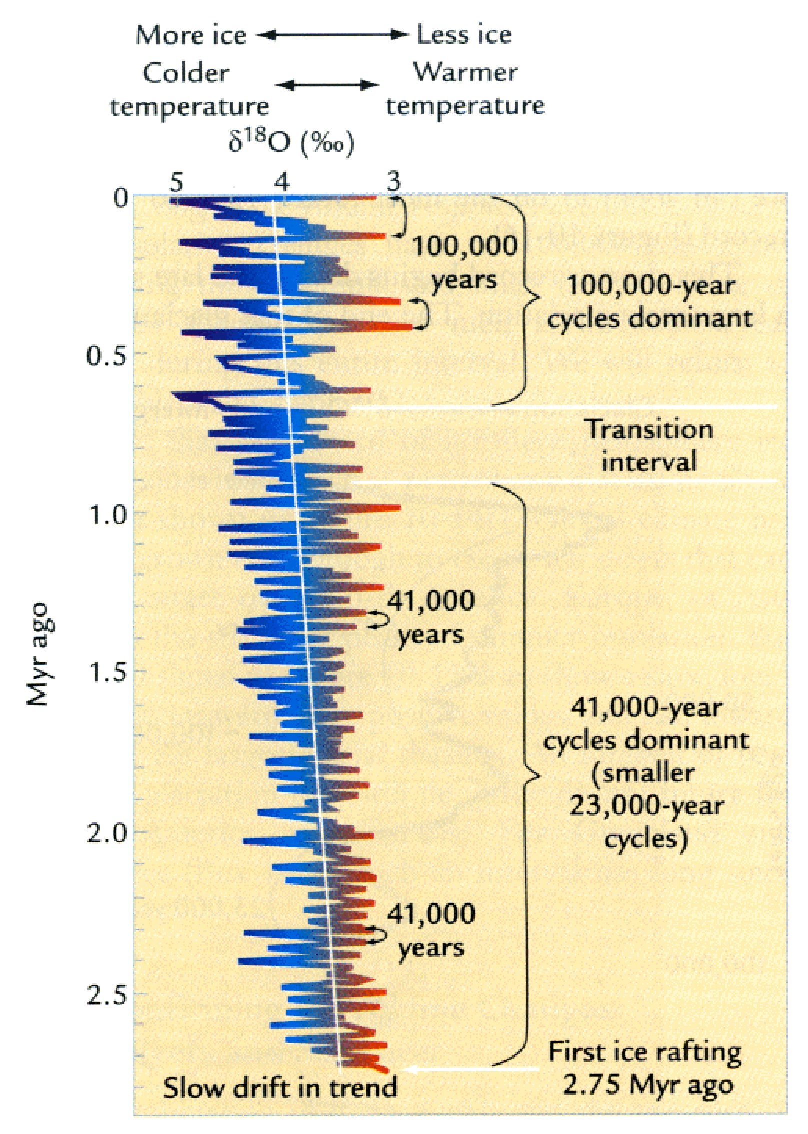
Insolation Control of Ice Sheets



(from Earth's Climate: Past and Future)

- Ice sheets reacted strongly to insolation changes.
- ***Summer*** insolation control the size of ice sheet by fixing the rate of ice melting.

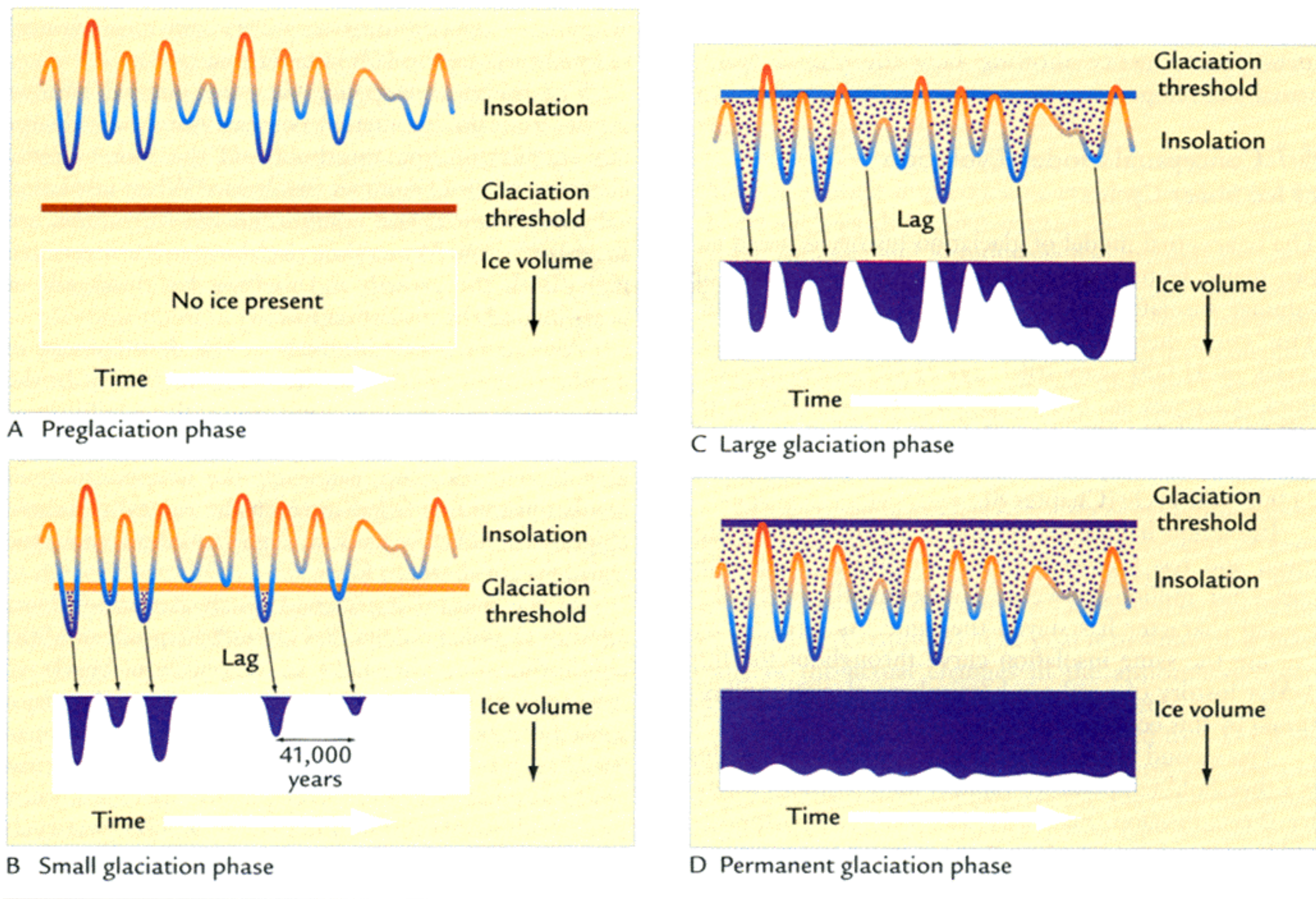
Evidence of Ice Sheet Evolution



(from *Earth's Climate: Past and Future*)

- This figures shows a North Atlantic Ocean sediment core holds a 3 Myr $\delta^{18}O$ record of ice volume and deep-water temperature changes.
- There were no major ice sheets before 2.75 Myr ago.
- After that, small ice sheets grew and melted at cycles of 41,000 and 23,000 years until 0.9 Myr ago.
- After 0.9 Myr ago, large ice sheet grew and melted at a cycle of 100,000 years.

Conceptual Phases of Ice Sheet Evolution



(from Earth's Climate: Past and Future)