Lecture 5: Climate Changes and Variations

- Climate Sensitivity and Feedback
- El Nino Southern Oscillation
- Pacific Decadal Oscillation
- North Atlantic Oscillation (Arctic Oscillation)
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 ratio.
  - a warmer atmosphere can carry more water vapor
  - stronger greenhouse effect
  - amplify the initial warming
  - one of the most powerful positive 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

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


(from Earth’s Climate: Past and Future)
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

1. Initial change
2. Climate cooling
3. Greater cooling
4. Tundra replaces forest
5. High-albedo surface reflects more solar radiation

B Vegetation-precipitation feedback

1. Initial change
2. Increased precipitation
3. Additional precipitation
4. Forest replaces grassland
5. Increased transpiration of water vapor

(from Earth’ Climate: Past and Future)
Cloud Feedback

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 on 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.

Cloud Radiative Forcing as Estimated from Satellite Measurements

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Cloud-free</th>
<th>Cloud forcing</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLR</td>
<td>234</td>
<td>266</td>
<td>+31</td>
</tr>
<tr>
<td>Absorbed solar radiation</td>
<td>239</td>
<td>288</td>
<td>-48</td>
</tr>
<tr>
<td>Net radiation</td>
<td>+5</td>
<td>+22</td>
<td>-17</td>
</tr>
<tr>
<td>Albedo</td>
<td>30%</td>
<td>15%</td>
<td>+15%</td>
</tr>
</tbody>
</table>

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

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

(from University of Washington)
ENSO-Related Research

- Weather
- Climate
- Hydrology
- Agriculture
- Fire
- Disease
- Fishery

ENSO
El Niño: originally, an oceanic phenomenon

- Every two to seven years, the waters warm up along the westernmost 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 recognize that El Nino is not just an oceanic phenomenon (in his 1969 paper).
- Instead, 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.
Pioneers in Modern Meteorology & Climatology

Weather: Polar Front Theory

Climate: El Nino-Southern Oscillations

Vilhelm Bjerknes (1862-1951)

Jacob Bjerknes (1897-1975)
Coupled Atmosphere-Ocean System

(from NOAA)
Growth Mechanism

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.

  - 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

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

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

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

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

(from Neelin et al. 1998)

(Jin-Yi Yu 1999)
Delayed Oscillator Theory

- **Wind forcing at the central Pacific:** produces a downwelling Kelvin 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)
1997-98 El Nino

SST Anomalies °C

JAN 05, 1997

NOAA

ESS200A
Prof. Jin-Yi Yu
1982-83 El Nino

SST ANOMALIES °C
JAN 07, 1982
**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.
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

- 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.

(Figures from IRI)
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

- **50-Year Warming Trend**
- **1976-77 Climate Shift**

(from Horeling et al. 2003)

(from Clark et al. 2000)
“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

El Nino Southern Oscillation
- El Nino
- La Nina
PDO Index

monthly values for the PDO index: 1900–2001
PDO-ENSO Relationship

Midlatitude Air-Sea Interaction

Ocean Pathway

Trade Wind Forcing

ENSO feedback
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 alternations
  ➔ Stronger ENSO events.
North Atlantic Oscillation

- 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.

(from http://www.ldeo.columbia.edu/res/pi/NAO/)
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
The Arctic Oscillation switches phase irregularly, roughly on a timescale 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

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

(from Earth’s Climate: Past and Future)
Tectonic Scale

- **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

- 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)?

(from Earth’s Climate: Past and Future)
Faint Young Sun Paradox

- 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.

**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)
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

- The precipitation process in the atmosphere dissolve and remove CO\textsubscript{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.

(from *Earth’s Climate: Past and Future*)
Negative Feedback From Chemical Weathering

- 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.

(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 CO₂ is removed from the atmosphere.

(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.
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.
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 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.

(from Earth’s Climate: Past and Future)
Climate Changes in the Last 500 Myr

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 era: (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

- 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.

(from Earth’s Climate: Past and Future)
Negative Feedback in Seafloor Spreading Hypothesis

- 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.

(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.

(from *Earth’s Climate: Past and Future*)
Can These Two Hypotheses Explain Tectonic-Scale Climate Changes?

### TABLE 5-2 Evaluation of the BLAG Spreading Rate (CO₂ Input) Hypothesis

<table>
<thead>
<tr>
<th>Time (Myr ago)</th>
<th>Ice sheets present?</th>
<th>Spreading rates</th>
<th>Hypothesis supported?</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>No</td>
<td>Fast</td>
<td>Yes (high CO₂)</td>
</tr>
<tr>
<td>0</td>
<td>Yes</td>
<td>Slow</td>
<td>Yes (low CO₂)</td>
</tr>
</tbody>
</table>

### TABLE 5-3 Evaluation of the Uplift Weathering (CO₂ Removal) Hypothesis

<table>
<thead>
<tr>
<th>Time (Myr ago)</th>
<th>Ice sheets present?</th>
<th>Continents colliding?</th>
<th>Hypothesis supported?</th>
</tr>
</thead>
<tbody>
<tr>
<td>325–240</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes (low CO₂)</td>
</tr>
<tr>
<td>240–35</td>
<td>No</td>
<td>No</td>
<td>Yes (high CO₂)</td>
</tr>
<tr>
<td>35–0</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes (low CO₂)</td>
</tr>
</tbody>
</table>

(from Earth’s Climate: Past and Future)
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

The 23,000-year cycle of precessional 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 changes.

Mean isolation value = 340 W/m²
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.

(from Earth’s Climate: Past and Future)
Orbital-Scale Changes in Methane

- 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.

(from Earth’s Climate: Past and Future)

ESS200A
Prof. Jin-Yi Yu
Insolation Control of Ice Sheets

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

(from Earth’s Climate: Past and Future)
Evidence of Ice Sheet Evolution

(from Earth’s Climate: Past and Future)

- This figure 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)