Lecture 6: Climate Changes

- Tectonic-Scale Climate Changes
- Orbital-Scale Climate Changes
- Deglacial and Millennial Climate Changes
- Historical Climate Changes
- Global Warming

(from Earth’s Climate: Past and Future)
The global average surface temperature has increased over the 20th century by about 0.6°C.
Both the earlier period of warming (1910 to 1945) and the more recent one (1976 to 1999) saw rates of warming about twice as great in the Northern Hemisphere than in the Southern Hemisphere.
Faster Warming Trend Over Lands

Annual temperature trends: 1976 to 1999
Climate Change on Various Time Scales

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

(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)
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
Tectonic Control of CO₂ *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 CO₂ 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 CO₂ to the atmosphere from the large rock reservoir of carbon, with the resulting changes in atmospheric CO₂ concentrations controlling Earth’s climate.

(from *Earth’s Climate: Past and Future* )
Why the Cooling over the Last 50 Myr?

- The collision of Indian and Asia happened around 40 Myr ago.
- The collision produced the Himalayas and a huge area of uplifted terrain called the Tibetan Plateau.
- The Himalayas Mountains provided fresh, readily erodable surfaces on which chemical weathering could proceed rapidly.
- At the same time, the uplifting of the Tibetan Plateau create seasonal monsoon rainfalls, which provided the water needed for chemical weathering.
- Therefore, the collision of India and Asia enhanced the chemical weathering process and brought down the atmospheric CO2 level to the relatively low values that prevail today.
- This reduced the greenhouse effect and cooled down the climate over the last 50 Myr.

(from The Earth System)
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)
Earth’s Orbit and Its Variations

- First, Earth spins around on its axis once every day ➔ The *Tilt*.
- Second, Earth revolves around the Sun once a year ➔ The shape of the *Orbit*.
- Both the tilt and the shape of the orbit have changed over time and produce three types of orbital variations:
  - (1) obliquity variations
  - (2) eccentricity variations
  - (3) precession of the spin axis.
How Does the Tilt Affect Climate?

- At present-day, the axis is tilted at an angle of 23.5°, referred to as Earth’s “obliquity”, or “tilt”.
- The Sun moves back and forth through the year between 23.5°N and 23.5°S.
- Earth’s 23.5° tilt also defines the 66.5° latitude of the Artic and Antarctic circles. No sunlight reaches latitudes higher than this in winter day.
- The tilt produces *seasons*!!

(from *Earth’s Climate: Past and Future*)
Precession

Polaris (current pole star)

Vega (pole star in 14,000 A.D.)

Thuban (pole star in 3000 B.C.)

Earth’s axis of rotation

Ecliptic plane
Milankovitch suggested that the critical factor for Northern Hemisphere continental glaciation was the amount of summertime insolation at high northern latitudes.

- Low summer insolation occurs during times when Earth’s orbital tilt is small.
- Low summer insolation also results from the fact that the northern hemisphere’s summer solstice occurs when Earth is farthest from the Sun and when the orbit is highly eccentric.

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

- 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.

(from Earth’s Climate: Past and Future)
Deglacial and Millennial Scales

- Climate changes of these scales in the past several tens of thousands of years occurred within the time span of recorded human civilization.

(from Earth’s Climate: Past and Future)
The Last Glacial Maximum (21,000 Years Ago)

- Seasonal insolation levels 21,000 years ago were nearly identical to those today.

- The only factors that can explain the colder and drier glacial maximum climate 21,000 years ago are:
  1. the large ice sheets
  2. the lower values of greenhouse gases.

(from Earth’s Climate: Past and Future)
Ice extent during the last glacial
Historical Climate Changes

- Climate changes over the last 1000 years have been smaller than those over tectonic, orbital, and glacial-age millennial time scales, never exceeding 1°C on a global basis.

- Climate changes over the last several thousand years have been highly variable in pattern from region to region.

(from Earth’s Climate: Past and Future)
The Little Ice Age

- Medieval Warming: A relatively warm climate near 1000 to 1300.
- Little Ice Age: The cooling during 1400-1900 that seriously affect Europe.
- Twentieth-Century Warming
IPCC AR4
Ch. 10: Global Climate Projections
IPCC Special Report on Emission Scenarios (SRES)
A1 Scenario

- The A1 story line is split into 4 scenarios which each are modeled in different ways.

- There is an energy intensive A1 group called \( A1T \), an oil and gas resource focused A1 called \( A1G \), a coal based A1 resource \( A1C \), or a mix of resources which was called \( A1B \).
The AR4 scenarios were bases on three scenarios: $A2$ (high emission), $A1B$ (medium emission), and $B1$ (low emission).
CO2 Emission for All Scenarios

Global carbon dioxide emissions (GtC/yr)

Energy & Industry

- A1B AIM
- A1B ASF
- A1B IMAGE
- A1B MESSAGE
- A1B MINCAMA
- A1B MARIA
- A1C AIM
- A1C MESSAGE
- A1C MINCAMA
- A1G AIM
- A1G MESSAGE
- A1G MINCAMA
- A1T AIM
- A1T MESSAGE
- A1T MARIA
- A2 AIM
- A2 IMAGE
- A2 MESSAGE
- A2 MINCAMA
- A2 MINCAME
- A2/3 AIM
- A2/3 IMAGE
- A2/3 MESSAGE
- A2/3 MINCAMA
- B1 AIM
- B1 IMAGE
- B1 MESSAGE
- B1 MINCAMA
- B1/2 AIM
- B1/2 IMAGE
- B1/2 MESSAGE
- B1/2 MINCAMA
- B1/3 AIM
- B1/3 IMAGE
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- B1/3 MINCAMA
- B2 AIM
- B2 IMAGE
- B2 MESSAGE
- B2 MINCAM
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- B3/3 MINCAMA
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- C1 IMAGE
- C1 MESSAGE
- C1 MINCAMA
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- Middes MINCAMA
- 50% AIM
- 50% IMAGE
- 50% MESSAGE
- 50% MINCAMA
- 95% AIM
- 95% IMAGE
- 95% MESSAGE
- 95% MINCAMA
Multi-model (23 AOGCMs) ensembles

Section 10.2

CO2, CH4, N2O, CFC, SO4
Projected Surface Warming
(relative to 1980-1999)

![Graph showing projected surface warming](image)

<table>
<thead>
<tr>
<th>Global mean warming (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2</td>
</tr>
<tr>
<td>A1B</td>
</tr>
<tr>
<td>B1</td>
</tr>
<tr>
<td>Commit</td>
</tr>
</tbody>
</table>
Warming Pattern / Ocean vs. Land
(during 2080-2099)
Vertical Distribution of Warming

- Stratospheric cooling
- Tropospheric warming
Projected Temperature Extreme

- It is very likely that heat waves will be more intense, more frequent and longer lasting in a future warmer climate. Cold episodes are projected to decrease significantly.

- Almost everywhere, daily minimum temperatures are projected to increase faster than daily maximum temperatures, leading to a decrease in diurnal temperature range.
Projected Changes in Cloud Cover

- more high clouds
- less middle clouds
- decrease cloud cover
Projected Precipitation Changes

- Precipitation generally increases in the areas of regional tropical precipitation maxima (such as the monsoon regimes) and over the tropical Pacific.

- Precipitation generally decreases in the subtropics and increases at high latitudes due to the poleward shift of the storm track due to the expansion of the Hadley circulation.
Projected Monsoon Precipitation Changes

North America Monsoon \textit{(decrease)}

Asian Monsoon \textit{(increase)}

Australian Monsoon \textit{(increase)}

Weaker monsoon circulation + more water vapor available = increase monsoon rainfalls
Projected Precipitation Extreme

- Intensity of precipitation events is projected to increase, particularly in tropical and high latitude areas that experience increases in mean precipitation.

- The number of dry days increases between precipitation events in the subtropics and lower mid-latitudes.

- There is a tendency for drying of the mid-continental areas during summer, indicating a greater risk of droughts in those regions.
Projected Hurricane Activities

- Most recent published modelling studies projected a decrease in the overall number of storms.
- Although less confidence, studies projected decrease of relatively weak storms in most basins, with an increase in the numbers of the most intense tropical cyclones.
Projected Extratropical Storms

- For a future warmer climate, a poleward shift of storm tracks in both hemispheres that is particularly evident in the SH, with greater storm activity at higher latitudes.

- A future tendency for more intense extratropical storms, although the number of storms could be less.
Projected ENSO Activity

- No conclusion: different AOGCMs project different results.
- Mean state in the Pacific will become more El Nino-like.
Projected Sea Ice Cover

- Sea Ice cover will reduce in both the Arctic and Antarctic.
- The decline will be faster in summer than in winter.
- The decline will be larger in the Arctic than the Antarctic.
- Sea ice volume decreases more quickly than sea ice cover.
Projected Change in Atlantic Meridional Overturning Circulation (MOC)

- The MOC is an indicator of ocean circulation changes in response to global warming.
- The MOC is projected to slow down in the future.
- It is due to the warming and increased precipitation at higher latitudes.
- The weakened MOC will help to reduce global warming at higher latitude, because less heat will be transported there.
Positive Climate-Carbon Cycle Feedback

- Future climate change would reduce the efficiency of the Earth system (land and ocean) to absorb anthropogenic CO2.
- As a result, an increasingly large fraction of anthropogenic CO2 would stay airborne in the atmosphere under a warmer climate.
During 2090 to 2099 under A1B, the central estimate of the rate of rise is 3.8 mm yr⁻¹.

In all scenarios, the average rate of rise during the 21st century very likely exceeds the 1961 to 2003 average rate (1.8 ± 0.5 mm yr⁻¹).
Global Warming and Sea-Level Change

Global Warming (2.65°C by 2099; A1B)

- Thermal Expansion (0.22m)
- Glacier and Ice Caps (0.11m)
- Greenland Ice Sheet (0.04m)
- Antarctic Ice Sheet (-0.07m)

Sea Level Rise (0.30m by 2099)
IPCC AR4
Ch. 11: Regional Climate Projections
How to Make Regional Projections?

Regional climate change projections presented here are assessed drawing on information from four potential sources:

(1) AOGCM simulations;

(2) Downscaling of AOGCM-simulated data using techniques to enhance regional detail;

(3) Physical understanding of the processes governing regional responses;

(4) Recent historical climate change.
Table 11.1

The time takes for the projected climate response (to the CO2 increase) to be 95% significant, compared to the internal variability.

<table>
<thead>
<tr>
<th>Region</th>
<th>Temperature Response (°C)</th>
<th>Precipitation Response (%)</th>
<th>Extreme Seasons (%)</th>
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<td></td>
<td>Season</td>
<td>Min</td>
<td>25</td>
</tr>
<tr>
<td>POLAR REGIONS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ARC^b</td>
<td>DJF</td>
<td>4.3</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>MAM</td>
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<td>3.7</td>
</tr>
<tr>
<td></td>
<td>JJA</td>
<td>1.2</td>
<td>1.6</td>
</tr>
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<td></td>
<td>SON</td>
<td>2.9</td>
<td>4.8</td>
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<td></td>
<td></td>
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<td></td>
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<tr>
<td>60N,180E</td>
<td>Annual</td>
<td>2.8</td>
<td>4.0</td>
</tr>
<tr>
<td>to</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90N,180W</td>
<td>Annual</td>
<td>1.4</td>
<td>2.3</td>
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<td>ANT^c</td>
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<td></td>
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<tr>
<td></td>
<td>SON</td>
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<tr>
<td></td>
<td>Annual</td>
<td>1.4</td>
<td>2.3</td>
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### Table 11.1

The percentage of the number of seasons/years that the simulated Temp./Precip. in the projected simulations during 2080-2099 are greater than the extreme T/P value during the control simulation of 1980-1999.

<table>
<thead>
<tr>
<th>Region</th>
<th>Season</th>
<th>Min</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>Max</th>
<th>T yrs</th>
<th>Min</th>
<th>25</th>
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<th>Dry</th>
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<td>9</td>
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<td>16</td>
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<td>21</td>
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<td>100</td>
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<td>35</td>
<td>25</td>
<td>99</td>
<td>81</td>
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</tbody>
</table>

Polar Regions
Summary of Regional Responses - Temperature

N.H. regions warm more than the S.H. regions
Summary of Regional Responses - Precipitation (from global projections)

June–July–August (JJA)

December–January–February (DJF)

Based on regional studies assessed in chapter 11:

- Precipitation increase ≥90% of simulations
- Precipitation increase ≥66% of simulations
- Precipitation increase ≥50% of simulations
- Precipitation decrease very likely
- Precipitation decrease likely
- Precipitation extreme increase likely
- Increased drought likely
- Less snow very likely

(mm day⁻¹)
Projected Precipitation Changes

- Precipitation generally increases in the areas of regional tropical precipitation maxima (such as the monsoon regimes) and over the tropical Pacific.

- Precipitation generally decreases in the subtropics and increases at high latitudes due to the poleward shift of the storm track due to the expansion of the Hadley circulation.
Africa

- Drying in most of the subtropical African.
- Increased (or no change) rainfalls in the tropical African.
Key Processes to African Rainfalls

(from IRI)

Mean Jan GPCP Precipitation (79–03)

ITCZ

Midlatitude stormtrack

Tropical cyclone

Midlatitude stormtrack

Prof. Jin-Yi Yu
Hurricane Distribution

- June-November (lull in August)
- June-December
- August-October
- January-March

Typhoons, cyclones, and hurricanes
Hurricane zones
Europe and Mediterranean

- Annual precipitation is very likely to increase in most of northern Europe and decrease in most of the Mediterranean area.
The North Atlantic Oscillation (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/)
Most of the Asia will receive increased rainfall, except Central Asia in summer.

Key climate factors for rainfalls: (1) monsoon, (2) ENSO, (3) tropical cyclone, and (4) Tibetan Plateau.
Projected Monsoon Precipitation Changes

North America Monsoon (decrease)

Asian Monsoon (increase)

Australian Monsoon (increase)

Weaker monsoon circulation + more water vapor available = increase monsoon rainfalls
Rainfalls increased in Canada and northeast USA but decrease in southwest USA and Mexico.

Major climate features that affect the rainfalls: (1) mid-latitude storms, (2) tropical cyclone, (3) North American monsoon.

Projections: (1) more positive AO (i.e., northward shift of storm track), (2) weaker N.-A. monsoon, (3) intensified subtropical high in the eastern Pacific.

In California: (1) increase in extreme hot events, (2) larger diurnal temperature range, (3) increase precipitation extreme in cold seasons.
Central and South America

- Rainfalls decrease in Central America and southern Andes,
- Rainfalls increase in Tierra and Fuego during winter and in south-eastern South America during summer.
- In northern South America, rainfalls increase in Ecuador and northern Peru but decrease in southern northeast Brazil and northern tip of the continent.
- Rainfall changes are uncertain in the Amazon forest.
Central America Climate

Topography (meter)

Caribbean Subtropical High

E. Pacific Warm Pool

ESS200A
Prof. Jin-Yi Yu
Key Processes to South America Rainfalls

(from IRI)
Australia and New Zealand

- Rainfalls decrease in southern Australia (due to poleward shift of the storm track) but increase in the west of the South Island of New Zealand.
- Rainfall changes uncertain in other parts of the region.
- It is uncertain how ENSO and Australian monsoon will respond in the future climate change.
Arctic and Antarctic

- Precipitations increase in both Arctic and Antarctic.
- Polar climate in complex, involving atmosphere-land-cryosphere-ocean-ecosystem interactions.
- Not enough observations to valid and improve climate models.
Antarctic Temperature Changes

- Antarctic climate is affected by Southern Annual Mode, ENSO, and ozone hole.
- In recent decades, Arctic climate has been affected by a trend toward the positive phase of Southern Annual Mode, which is characterized by warm anomalies in the Antarctic Peninsula but cold anomalies in the rest of the continent.
- This temperature change pattern is not projected to continue in the 21st century, although the SAM is predicted to be in a more positive phase, indicating the need to consider the role of ozone hole in the present-day peninsula warming.
ENSO and Antarctic Climate

El Nino

La Nina

(from Yuan 2003)