a) Defining “climate change”
b) Patterns of past climate change
c) Causes of past climate change

Climatology = Climate

Statistical properties of the atmosphere: means, variability, max, min., etc.

Hypothetical climate data: mean annual temperature

![Graph](image)
(a) Defining Climate Change

Boundary Conditions

Configuration of variables *external to Earth*

- Change in boundary conditions $\rightarrow$ climate change. e.g., hypothetical increase in solar radiation:

Hypothetical climate data: mean annual temperature

![Graph showing mean annual temperature anomaly over time](image)
(a) Defining Climate Change

Statistical properties contain random variability *(these are random values)*:

Hypothetical climate data: mean annual temperature

http://www.random.org/coins/

http://www.betweenwaters.com/probab/flip/coinmainD.html
(1) Nearly impossible to link an individual event with “climate change”
(a) Defining Climate Change

(2) Climate “change” must be referenced to a specific spatial and temporal scale:

[Map showing temperature change over 1970-2004]

(3) When does a pattern indicate a “change”?

1.6% chance of getting 6 “loonies” in a row from a fair coin.

http://www.random.org/coins/
(3) When does a pattern indicate a “change”? 

a) Defining “climate change”
b) Patterns of past climate change
c) Causes of past climate change

(c) Current and future climate change

IPCC:

- Established in 1988 by the United Nations Environmental Program (UNEP) and the World Meteorological Organization (WMO)

- Goal: “to assess on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation”

- http://www.ipcc.ch/
(c) Current and future climate change

IPCC Assessments:

IPCC Report (AR4)

Assessment Reports

IPCC Fourth Assessment Report: Climate Change 2007 (AR4)

- Working Group I Report "The Physical Science Basis"
  - CLICK HERE
- Working Group II Report "Impacts, Adaptation and Vulnerability"
  - CLICK HERE
- Working Group III Report "Mitigation of Climate Change"
  - CLICK HERE
- The AR4 Synthesis Report
  - CLICK HERE

IPCC Third Assessment Report: Climate Change 2001 (TAR)

- Working Group I:
- Working Group II:
- Working Group III:
- Synthesis Report

IPCC 4th Assessment, Fig. 6.3: http://www.ipcc.ch/graphics/gr-ar4-wg1.htm
(b) Patterns of Past Climate Change

Warm and cool periods strongly linked to levels of CO²

IPCC 4th Assessment, Fig. 6.3: http://www.ipcc.ch/graphics/gr-ar4-wg1.htm
(b) Patterns of Past Climate Change

Warm and cool periods strongly linked to levels of CO²

IPCC 4th Assessment, Fig. 6.3: [http://www.ipcc.ch/graphics/gr-ar4-wg1.htm](http://www.ipcc.ch/graphics/gr-ar4-wg1.htm)
Earth’s history is characterized by climate change: relative warmth, punctuated by ice ages

- Relative warmth, 4.5-2.5 billion yr ago
- Ice ages, 10-20% of the time over the past 2.5 billion yr, otherwise relatively warm
  - E.g. mid-Cretaceous period (120-90 MYA):
    - 5-15° C warmer than present
    - Dinosaurs above Arctic Circle
    - Coral reefs up to 15 latitude poleward of current locations
(b) Patterns of Past Climate Change

Climate records improve in resolution as we approach present: “Quaternary” climate change covers only 0.05% of Earth’s history

- **Pleistocene Epoch**: 1.8 million to 11,000 years ago (the current ice age)
- **Holocene Epoch**: 11,000 years ago to right now
Climate varies at multiple scales

Multi-millennial – millennial: glacial / interglacial periods

IPCC 4th Assessment, Fig. 6.3: http://www.ipcc.ch/graphics/gr-ar4-wg1.htm
(b) Patterns of Past Climate Change

Glacial-interglacial cycles:

- \( \approx 100,000 \text{-yr cycles} \)
- 30 cycles in past 2 million yr
- Global temp. changes \( \approx 5 \, ^\circ C \)
- \( \approx 3\% \) change in NH ice volume
- Altered greenhouse gas concentrations

- *Gradual cooling, abrupt warming*

Short warm periods \( \sim 10-30 \text{ ka yr} \)

Longer cool periods \( \sim 70-90 \text{ ka yr} \)

IPCC 4th Assessment, Fig. 6.3: [http://www.ipcc.ch/graphics/gr-ar4-wg1.htm](http://www.ipcc.ch/graphics/gr-ar4-wg1.htm)
(b) Patterns of Past Climate Change

Last Glacial Maximum (≈ 20,000 yr ago)

- Global temp. ≈ 5 °C cooler, also drier
- Ice sheets over most of NA and Europe

Textbook Fig. 16-4.
(b) Patterns of Past Climate Change

Climate varies at multiple scales

Millennial to centennial: glacial-Holocene transition

Ice core temperature record from the Greenland Ice Sheet

Data: Greenland Ice Sheet Project II (GISP II) [http://www.ngdc.noaa.gov/paleo/icecore/icecore-varlist.html](http://www.ngdc.noaa.gov/paleo/icecore/icecore-varlist.html)
(b) Patterns of Past Climate Change

Glacial-Holocene transition

- Younger Dryas (YD; 13,000-11,800 yr ago)
- Abrupt cooling, lasting 1200 yr

Ice core temperature record from the Greenland Ice Sheet

Data: Greenland Ice Sheet Project II (GISP II) [http://www.ngdc.noaa.gov/paleo/icecore/icecore-varlist.html]
(b) Patterns of Past Climate Change

**Glacial-Holocene transition**

- **Younger Dryas (YD; 13,000-11,800 yr ago)**
  - Abrupt cooling, lasting 1200 yr
  - **Mechanism:** change in salinity and shutdown of North Atlantic ocean circulation

http://svs.gsfc.nasa.gov/vis/a000000/a003600/a003658/index.html
(b) Patterns of Past Climate Change

Glacial-Holocene transition

- "8.2 event" (8200 yr ago)
  - Abrupt cooling (up to 8°C) in N Atlantic, lasting 300-400 yr.

Data: Greenland Ice Sheet Project II (GISPII) [http://www.ngdc.noaa.gov/paleo/icecore/icecore-varlist.html](http://www.ngdc.noaa.gov/paleo/icecore/icecore-varlist.html)
(b) Patterns of Past Climate Change

Climate varies at multiple scales

Centennial-decadal: past 1000 years

IPCC 4th Assessment, Fig. 6.13: http://www.ipcc.ch/graphics/gr-ar4-wg1.htm
(b) Patterns of Past Climate Change

Medieval Warm Period ("Medieval Climate Anomaly")

- 900-1200 AD: Viking settlement of Greenland

IPCC 4th Assessment, Fig. 6.13: http://www.ipcc.ch/graphics/gr-ar4-wg1.htm
(b) Patterns of Past Climate Change

**Little Ice Age**

- **1400-1850 AD: local temp. ↓ of 1.5-2.0 °C**

IPCC 4th Assessment, Fig. 6.13: [http://www.ipcc.ch/graphics/gr-ar4-wg1.htm](http://www.ipcc.ch/graphics/gr-ar4-wg1.htm)
(b) Patterns of Past Climate Change

20th-century warming

- $\uparrow > 0.8 \, ^\circ C$ globally (from instrumental record)

IPCC 4th Assessment, Fig. 6.13: http://www.ipcc.ch/graphics/gr-ar4-wg1.htm
(b) Patterns of Past Climate Change

20th–century warming
- Varies between ocean and land...why?

Textbook Fig., pg. 487
a) Defining “climate change”
b) Patterns of past climate change
c) Causes of past climate change

(c) Causes of Past Climate Change

Mechanisms:

Millennial time scale, global spatial scales:
1. Changes in Earth’s orbital parameters
2. Changes in land configuration
3. Feedbacks

Annual to centennial time scales, local to global spatial scales:
1. Variations in solar output (e.g., sunspots)
2. Changes in atmospheric aerosols
3. Changes in radiation-absorbing gases
4. Feedbacks
(c) Causes of Past Climate Change

1. Changes in Earth’s orbital parameters

Milankovitch Cycles:
Changes Sun-Earth geometry that alter the distribution of insolation over millennial time scales; caused by changes in:

a. Eccentricity
b. Obliquity
c. Precession (of the equinox)
(c) Causes of Past Climate Change

**Eccentricity:** Changes in Earth’s orbit, over a ≈100,000- and 400,000-yr cycle, 1-11% difference in Earth-Sun distance (compared to 3% today).
Obliquity: Changes in Earth’s axial tilt, over ≈ 41,000-yr cycle; varies between 22.1-24.5°; 15% variation in available solar radiation in high latitudes.
(c) Causes of Past Climate Change

Precession (of the equinox): “Wobble” of Earth’s axis over 27,000-yr cycle, so poles point in different directions.
(c) Causes of Past Climate Change

Precession (of the equinox):
- *Interacts with eccentricity*
(a) Causes of Past Climate Change

Net effect of eccentricity, obliquity, and precession:

IPCC 4th Assessment, Chap. 6, FAQ 6.1: [http://www.ipcc.ch/graphics/gr-ar4-wg1.htm](http://www.ipcc.ch/graphics/gr-ar4-wg1.htm)

(a) Causes of Past Climate Change

Mechanisms:
Millennial time scale, global spatial scales:

2. Changes in land configuration
   Distribution of continents
   Mountain building: e.g. Rockies, Himalayas, and Andes modify Rossby waves during winter and promote monsoon circulation in the summer.
(c) Causes of Past Climate Change

Mechanisms:
Millennial time scale, global spatial scales:

3. Feedbacks:
   Ice-albedo feedbacks
(a) Causes of Past Climate Change

Mechanisms:
Annual to centennial time scales, local to global spatial scales:

1. Variations in solar output (e.g., sunspots)
   - 0.1-0.2% change in Sun’s output; 11-yr cycles
     - Maunder Minimum
(a) Causes of Past Climate Change

Variations in solar output: Maunder Minimum, minimal sunspot activity between 1645-1715, coincident with the Little Ice Age.

IPCC 4th Assessment, Fig. 6.13: [http://www.ipcc.ch/graphics/gr-ar4-wg1.htm](http://www.ipcc.ch/graphics/gr-ar4-wg1.htm)

Textbook Fig., pg. 41
C) Causes of Past Climate Change

Mechanisms:

2. Changes in atmospheric aerosols:
   - absorb incoming solar radiation, heating the atmosphere
   - increase backscattering and reduce radiation reaching the surface
   - increase absorption of outgoing, longwave radiation and increase nighttime temperatures
   - lead to more extensive, longer-lived, brighter clouds
(a) Causes of Past Climate Change

Aerosols can lead to more extensive, longer-lived, brighter clouds: e.g., stratocumulus clouds from ship exhaust (e.g. aerosols)
2. Changes in atmospheric aerosols can

**Tropospheric aerosols:**
- sea salt, soot and gasses from fires, wind-blown dust, and more
- short residence times – hours to days – so their effects vary widely across space and are short lived

**NET EFFECT = reduce surface temperatures globally**
- Thus, increased tropospheric aerosols have reduced the magnitude of greenhouse-gas induced warming
(a) Causes of Past Climate Change

2. Changes in atmospheric aerosols can

**Stratospheric aerosols:**
- volcanic eruptions (sulfur gases)
- longer residence time (weeks to months)
- \( \text{NET EFFECT} = \text{promote globally lower temperatures} \) — e.g. El Chichon (1982), Mt. Pinatubo (1991)
(a) Causes of Past Climate Change

Global aerosol content before and after Mt. Pinatubo: June 12, 1991

Textbook Fig., 16-10
(a) Causes of Past Climate Change

Annual to centennial time scales, local to global spatial scales:

3. Changes in radiation-absorbing (aka “greenhouse”) gasses

- CO$_2$, CH$_4$, N$_2$O all are effective absorbers of longwave radiation thus warm Earth’s climate.

(a) Causes of Past Climate Change

Summary:

1. Orbital parameters
2. Land configuration
3. Solar output
4. Atmospheric aerosols
5. Concentration of greenhouse gases