Outline

1. The water cycle

2. Climate and climate-change
   • Atmosphere radiation balance
   • CO₂ and other greenhouse gases
   • Aerosol effects
   • Cloud effects

3. Climate change implications
   • Sea-level rise
   • Sea ice loss
   • Storm intensification

4. Climate change mitigation
The Water Cycle

“The annual circulation of H₂O is the largest movement of a chemical substance at the surface of the Earth”

The distribution of water at the Earth's surface:

<table>
<thead>
<tr>
<th>Description</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceans</td>
<td>97.2</td>
</tr>
<tr>
<td>Ice caps and glaciers</td>
<td>2.15</td>
</tr>
<tr>
<td>Groundwater</td>
<td>0.63</td>
</tr>
<tr>
<td>Lakes &amp; streams</td>
<td>0.016</td>
</tr>
<tr>
<td>Soils</td>
<td>0.005</td>
</tr>
<tr>
<td>Atmosphere (as vapor)</td>
<td>0.001</td>
</tr>
<tr>
<td>Rivers</td>
<td>0.0001</td>
</tr>
<tr>
<td>Biosphere</td>
<td>0.00004</td>
</tr>
</tbody>
</table>
70% of the sun’s energy is absorbed at the Earth’s surface, where it drives the hydrologic cycle.

### Solar Energy Budget

<table>
<thead>
<tr>
<th>Description</th>
<th>Kilocalories/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total energy from sun to earth</td>
<td>$1.3 \times 10^{21}$</td>
</tr>
<tr>
<td>30% reflected</td>
<td>$3.9 \times 10^{20}$</td>
</tr>
<tr>
<td>47% to heating atmosphere and earth's surface</td>
<td>$6.1 \times 10^{20}$</td>
</tr>
<tr>
<td>23% used in evaporation</td>
<td>$3.0 \times 10^{20}$</td>
</tr>
<tr>
<td>0.2% used in generating winds, waves and currents</td>
<td>$2.6 \times 10^{18}$</td>
</tr>
<tr>
<td>0.0023% used in photosynthesis</td>
<td>$3 \times 10^{17}$</td>
</tr>
</tbody>
</table>
Three-cell Model of Atmospheric Circulation

(1) Polar cells
(2) Midlatitude cells
(3) Hadley cells
Movement of H$_2$O through the atmosphere determines the distribution of rainfall.

Global average precip $\approx$ 943mm/yr
Net evaporation from the surface ocean

• Affects surface water salinity in the ocean
• Increases surface water density
• Controls thermohaline circulation of ocean
Surface Seawater Salinity

The maxima in evaporation-precipitation results in the highest surface water salinities in the mid-latitudes around 30N and 20S.
What does “Climate” mean?

Dictionary:

“Climate: the average condition of the weather at a place over a period of years, as exhibited by temperature, wind velocity, and precipitation”

So “climate” refers not to the weather today or this week or this year, but rather to the range of weather (including hot and cold years, wet and dry years) that is typical of each region.
Global mean surface temp has increased >0.5°C in this time. Is this natural variability or anthropogenic climate change?
How does climate change work?

The Earth’s temperature is set by a *Radiation Balance*: If more heat arrives from the sun than can escape as infrared (IR) rays, the Earth gets warmer.
The average Albedo (reflectivity) of Earth is 0.3. The majority of outgoing IR comes from gases.

**Figure 6.3.** Schematic diagram of the global radiation budget in the climatic system. A value of 100 units is assigned to the incoming flux of solar energy.
CO₂ is the most important greenhouse gas (one that prevents the escape of IR, a process that would normally cool the Earth).

Mauna Loa Monthly Carbon Dioxide Record

Keeling Record 1958 - 2008

1900 – 293 ppmv  1940 – 307 ppmv
Ocean CO₂ Increase Tracks Atmosphere
“Ocean Acidification”

Time series of atmospheric CO₂ at Mauna Loa and surface ocean pH and pCO₂ at Ocean Station Aloha in the subtropical North Pacific Ocean. Mauna Loa data: Dr. Pieter Tans, NOAA/ESRL; HOTS/Aloha data: Dr. David Karl, University of Hawaii (modified after Feely, 2008).
Our fuel burning is converting fossilized carbon (coal, oil, and natural gas) into CO₂, and 45% of it stays in the air.
We can look at ice cores to see that CO$_2$ was pretty constant for the last thousand years. The rapid increase began about the time of the industrial revolution.
Global Temperatures Are Linked to Atmospheric CO₂

Vostok Ice Core CO₂ Concentration and Temperature Variation Record

Ceiling at ~290 ppm
Floor at ~190 ppm

Source: Barnola, et.al.; Petit et.al. (PAGES / IGBP)
The Earth is now in a NO-ANALOG zone!

The inhabited Earth has never before dealt with these conditions

Therefore, paleo records cannot be 100% reliable tests of climate models

Source: C. D. Keeling and T. P. Whorf; Etheridge et.al.; Barnola et.al.; (PAGES / IGBP); IPCC
Model predictions from IPCC:

“Global temperature will rise from 1.4-5.8°C over this century unless greenhouse gas emissions are greatly reduced”
Aerosol Radiative Forcing of Climate

Climate Models didn’t do a very good job of reproducing temperature trends in the last 150 years when they did not include aerosol impacts.
The primary effects of atmospheric aerosols on global climate:

- **Direct reflection and scattering** of incoming solar radiation by clouds and particulates - warming or cooling, depending on altitude:
  - Low clouds and particulates can increase the Earth’s albedo but have little effect on IR transmission, leading to surface cooling
  - High clouds and particulates can reduce longwave (IR) emission to space, leading to surface warming
  - **Nucleation of clouds** - warming or cooling, depending on cloud altitude
Direct Indirect

Clouds double Earth’s albedo (15% → 30%)
Models do much better when they include aerosols, even using crudely understood aerosol effects.
Not every place is warming, though - the blue spots are areas that have been cooling.

How could that be?

Each of these areas is polluted with aerosols.
Aerosol Forcings Cause the Largest Uncertainty in the Earth’s Radiation Budget

Radiative Forcing Components

<table>
<thead>
<tr>
<th>RF Terms</th>
<th>RF values (W m⁻²)</th>
<th>Spatial scale</th>
<th>LOSU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-lived greenhouse gases</td>
<td>-0.05 [-0.15 to 0.05]</td>
<td>Continental to global</td>
<td>Med</td>
</tr>
<tr>
<td></td>
<td>0.35 [0.25 to 0.65]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>0.48 [0.43 to 0.53]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>1.66 [1.49 to 1.83]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>Ozone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stratospheric</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tropospheric</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH₄</td>
<td>0.16 [0.14 to 0.16]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>Halocarbons</td>
<td>0.34 [0.31 to 0.37]</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>Anthropogenic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stratospheric water vapour from CH₄</td>
<td>0.07 [0.02 to 0.12]</td>
<td>Global</td>
<td>Low</td>
</tr>
<tr>
<td>Surface albedo</td>
<td>-0.2 [-0.4 to 0.0]</td>
<td>Local to continental</td>
<td>Med - Low</td>
</tr>
<tr>
<td>Black carbon on snow</td>
<td>0.1 [0.0 to 0.2]</td>
<td>Local to continental</td>
<td>Med - Low</td>
</tr>
<tr>
<td>Total Aerosol</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct effect</td>
<td>-0.7 [-1.8 to -0.3]</td>
<td>Continental to global</td>
<td>Low</td>
</tr>
<tr>
<td>Cloud albedo effect</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear contrails</td>
<td>0.01 [0.003 to 0.03]</td>
<td>Continental to global</td>
<td>Low</td>
</tr>
<tr>
<td>Natural</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar irradiance</td>
<td>0.12 [0.06 to 0.30]</td>
<td>Global</td>
<td>Low</td>
</tr>
<tr>
<td>Total net anthropogenic</td>
<td>1.6 [0.6 to 2.4]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Dust can have a huge impact on climate, both by \textit{scattering} light to space and by \textit{absorbing} light

Where this Saharan dust plume is, there is more light reflected back to space than over the dark ocean:
Smoke and Dust Both Affect Climate

The whitest things (most reflective of sunlight) in this SeaWiFS image are clouds.

Changing the extent or density of clouds is called the radiative indirect effect on climate.
Ship tracks in the Atlantic. These are strong evidence of the **Indirect Effect** of aerosols on clouds: **More aerosol nuclei make clouds whiter (more reflective of sunlight)**
A warmer climate would melt glaciers and thermally expand the ocean...which will submerge many Polynesian islands!

Temperature Rise
1 to 3°C

Sea Level Rise
10 to 90 cm (5 to 37”)

Note complications of wave effects and groundwater contamination (handout)
Arctic Sea-Ice Extent is Shrinking Rapidly
Arctic Sea-Ice is Also Thinning Rapidly

End of February Arctic Sea Ice Age

1981-2000 Median  

2009

First year ice  
(< 1 Year Old)  

Second year ice  
(1-2 Years Old)  

Older ice  
(>2 Years Old)  

http://www.indybay.org
Positive Feedback: Warming Causes *More* Warming!

1. Light colored ice reflects back the Sun’s energy efficiently.
2. Exposed land is darker and absorbs more energy; warming.
3. As the ice melts, more land is exposed. This absorbs more heat, melting more ice, and causing further warming.
4. The altitude of the melting ice is reduced so it becomes harder for new ice to form (esp for Greenland).

Melt water flows to the base of the Greenland ice sheet.

Ice is melting MUCH faster than glaciologists had forecast.

Positive Feedback can cause Runaway Warming, by darkening originally-light surfaces.

The climate system is full of feedbacks.
Ice core data show that the summer ice melt has been 10 times more intense over the past 50 years compared with 600 years ago (handout)
The number of Category 4 and 5 hurricanes worldwide has nearly doubled over the past 35 years, even though the total number of hurricanes has dropped since the 1990s. The shift occurred as global sea surface temperatures have increased over the same period. This is compelling evidence that *global climate change is making tropical storms more powerful and more damaging.*
Climate change is expected to increase the range of diseases like malaria
Some of the unexpected cold winter weather is due to a (natural) Arctic Oscillation in weather patterns.

Such oscillations can obscure longer-term trends.
How Can Climate be Stabilized?

Must Restore Planet’s Energy Balance

  Modeled Imbalance:  $+0.75 \pm 0.25 \text{ W/m}^2$

Requirement Might be Met Via:

  - Reducing atm CO$_2$ to 350 ppm or less
  - and -
  - Reducing non-CO$_2$ forcing by $\sim 0.25 \text{ W/m}^2$
Are Needed Actions Feasible?

Coal must be phased out & Unconventional Fossil Fuels avoided

One possibility: Carbon tax & dividend
‘Cap & Trade’ has not worked effectively

Also important: non-CO$_2$ pollutants

Methane + Ozone most important (reduction feasible as fossil fuel use declines)

Emphasize black carbon reductions among aerosols
“Want to Slow Sea Level Rise? Curb Four Pollutants” (handout)

The four pollutants — black carbon, methane, ozone and hydrofluorocarbons — all cycle through the atmosphere more quickly than carbon dioxide (weeks – decades vs. centuries)

Cutting these air pollutants worldwide by 30 to 60% over the next several decades would lower predicted sea level rise by 22 to 42% by 2100

Do we have the will to make these changes????