Chapter 3

• The Sun
• Orbital Cycles
• The Atmosphere
• Heating the Atmosphere
• Energy Budget
• Enhanced GH Effect
• Radiative Forcing
• Climate Sensitivity

The Earth Climate System

The climate system is the sum of all exchanges of energy and mass between the atmosphere, hydrosphere, cryosphere, biosphere, and lithosphere.
Chapter 3

- The Sun
- Orbital Cycles
- The Atmosphere
- Heating the Atmosphere
- Energy Budget
- Enhanced GH Effect
- Radiative Forcing
- Climate Sensitivity

- Sun averages 150 million km away from Earth
- Total Solar Irradiance (TSI) is the amount of energy received at top of atmosphere and is 1370 W/m²
- TSI varies by as much as 3.4% due to orbital changes and by 0.5-.75 W/m² due to sunspot cycles

Web Alert:

- It’s the Sun!

- IPCC (2007) current estimates suggest that only 0.1 °C of the 0.8 °C of warming since the late 1800s is due to solar irradiance.
- More importantly, since direct satellite measurements (1980 – present) solar contribution to the observed rapid warming is negligible.
- There is no evidence that variations in the strength of the sun are the cause of the modern day climate change.
Chapter 3

• The Sun
• Orbital Cycles
• The Atmosphere
• Heating the Atmosphere
• Energy Budget
• Enhanced GH Effect
• Radiative Forcing
• Climate Sensitivity

Text Book Animation: Earth – Sun Relations

• **Summer Solstice**: NH tilted toward the sun resulting in higher sun angle. Higher angle causes more direct sun rays, passes through a thinner atmosphere, and results in more hours of daylight.

• **Winter Solstice**: NH tilted away from the sun resulting in lower sun angle. Lower angle causes less direct sun rays, passes through a thicker atmosphere, and results in fewer hours of daylight.

• Equinox: NH tilt parallel to sun and equal hours of daylight vs. night.
Sunspots are points of tightly coiled magnetic fields
Although they are “cool spots” they are surrounded by very hot faculae which increases total solar irradiance (TSI)
More sunspots = greater TSI
Sunspots are points of tightly coiled magnetic fields
Although they are “cool spots” they are surrounded by
very hot faculae which increases total solar irradiance (TSI)
More sunspots = greater TSI
Sunspots can explain much of the warming before 1978

Since 1978, global T is rising rapidly while TSI is decreasing

Sunspots cannot be the cause of warming since 1978
Chapter 3

• The Sun
• Orbital Cycles
• The Atmosphere
• Heating the Atmosphere
• Energy Budget
• Enhanced GH Effect
• Radiative Forcing
• Climate Sensitivity

Video: Solar Schmolar
Chapter 3

- The Sun
- Orbital Cycles
- The Atmosphere
- Heating the Atmosphere
- Energy Budget
- Enhanced GH Effect
- Radiative Forcing
- Climate Sensitivity

- *Milankovitch Cycles* change climate due to changes in earth’s orbit and tilt of its axis

- 41,000 year cycle due to tilt (obliquity) changes

- 100,000 year cycle due to changes in shape of orbit around sun (eccentricity)

- 23,000 year changes due to wobble of axis (precession)

**Text Book Animation: Orbital Variations and Climate Change**
Chapter 3

• The Sun
• Orbital Cycles
• The Atmosphere
• Heating the Atmosphere
• Energy Budget
• Enhanced GH Effect
• Radiative Forcing
• Climate Sensitivity

Kitchen (2013)

• Earth’s rotation axis is currently 23.4°
• Varies between 22.1° and 24.5° over 41,000 years
• More tilt means more extreme seasons
• Summer melt controls ice more than winter growth
• Higher tilt values causes less ice while lower tilt values cause more ice.
• Current angle is decreasing and will reach 22.1° in 8,000 years
Chapter 3

• The Sun
• Orbital Cycles
• The Atmosphere
• Heating the Atmosphere
• Energy Budget
• Enhanced GH Effect
• Radiative Forcing
• Climate Sensitivity

Earth’s orbit is an ellipse, not a circle

Eccentricity ($e$) is a measure of how far from a circle the shape is. $e=0$ for a circle.

e varies between 0.005 and 0.06 over 100,000 years

Currently $e=0.017$ which is still nearly circular

Perihelion – earth closest to sun

Aphelion – earth farthest from sun

Kitchen (2013)
Chapter 3

• The Sun
• Orbital Cycles
• The Atmosphere
• Heating the Atmosphere
• Energy Budget
• Enhanced GH Effect
• Radiative Forcing
• Climate Sensitivity

• Earth’s tilt wobbles around a fixed point every 23,000 years and is called *precession*.

• Precession determines if the NP or SP leans toward the sun at perihelion.
Chapter 3

- The Sun
- Orbital Cycles
- The Atmosphere
- Heating the Atmosphere
- Energy Budget
- Enhanced GH Effect
- Radiative Forcing
- Climate Sensitivity

When \( e \) is large, tilt is small, and at **summer during aphelion**, ice will grow in the NH (Fig. A)

When \( e \) is large, tilt is large, and at **summer during perihelion**, ice will decrease in the NH (Fig. B)
Chapter 3

• The Sun
• Orbital Cycles
• The Atmosphere
• Heating the Atmosphere
• Energy Budget
• Enhanced GH Effect
• Radiative Forcing
• Climate Sensitivity

Is Recent Climate Change Due to Orbital Cycles?

• Milankovitch cycles are fairly regular so are predictive

• Currently, $e$ is low (0.017)

• Should stay low for another 100,000 years

• The Earth’s tilt is getting smaller and will do so for another 8,000 years

• Orbital cycles are **cooling** the Earth right now
Air is composed of 78% nitrogen (N₂), 21% oxygen (O₂) and 1-3% water (H₂O) with trace amounts of carbon dioxide (CO₂) [390 ppm] and methane (CH₄) [2 ppm]

**Troposphere:** contains most of the atmosphere even though it is very shallow. The normal environmental lapse rate (ELR) is negative (cooling with increasing height) because the ground is the heat source and rising air always cools due to the *adiabatic process*

**Stratosphere:** above the tropopause, a layer of air that has a positive ELR due to absorption of UV rays from the sun by the ozone.
Chapter 3

• The Sun
• Orbital Cycles
• **The Atmosphere**
• Heating the Atmosphere
• Energy Budget
• Enhanced GH Effect
• Radiative Forcing
• Climate Sensitivity

- This course will primarily deal with the troposphere along with some discussion of the stratosphere
Chapter 3

• The Sun
• Orbital Cycles
• The Atmosphere
• Heating the Atmosphere
• Energy Budget
• Enhanced GH Effect
• Radiative Forcing
• Climate Sensitivity

The Greenhouse Effect (GHE)

• Greenhouse gases (GHGs) trap outgoing heat but do not impede incoming sunlight
• The GHE of various gases:
  • Water vapor: 50% - 67%
  • Clouds: 0% - 25%
  • Carbon dioxide: 19% - 24%
  • Others: 7% - 9%
• Water vapor is naturally cycled into and out of the atmosphere on a relatively short time cycle so it is not considered to be a major component of long-term climate change.
• Therefore, the concentrations of CO₂ is the main driver of greenhouse gas induced climate change.

Text Book Animation: Global Warming, Climate Change
• CO2 cycles during the year due to vegetation changes
• Warmer weather = more plants = CO2 removed
• Cooler weather = less plants = CO2 returns
Possibly highest values in the previous *millions of years*!
Chapter 3

- The Sun
- Orbital Cycles
- The Atmosphere
- Heating the Atmosphere
- Energy Budget
- Enhanced GH Effect
- Radiative Forcing
- Climate Sensitivity

Web Alert:

**Misleading: Nature Emits Much More CO2 Than Humans**
Chapter 3

• The Sun
• Orbital Cycles
• The Atmosphere
• Heating the Atmosphere
• Energy Budget
• Enhanced GH Effect
• Radiative Forcing
• Climate Sensitivity

Methane

• Natural sources: wetlands, termites, oceans

• Methane hydrates store trillions of tons of methane in deep ocean and in permafrost

• Human sources: rice paddies, cows, coal mining, natural gas production, waste dumps, biomass burning, and others

• Current level is 1.8 ppm which is 1.5 times that of pre-IR

• After a decade of stability methane is on the rise again in the past few years see: NOAA Methane Levels

Video: Permafrost: The Tipping Time Bomb
Chapter 3

- The Sun
- Orbital Cycles
- The Atmosphere
- Heating the Atmosphere
- Energy Budget
- Enhanced GH Effect
- Radiative Forcing
- Climate Sensitivity

Methane

See: Arctic Shelf Venting Methane
Chapter 3

- The Sun
- Orbital Cycles
- The Atmosphere
- Heating the Atmosphere
- Energy Budget
- Enhanced GH Effect
- Radiative Forcing
- Climate Sensitivity

- **Insolation** – the amount of incoming sunshine measured in W/m²

- Insolation varies from maximum in the tropics to minimum at the poles

- Incoming radiation is mostly *visible light*, a short wavelength (SW)

- Earth emits heat to space in the form of *infrared* radiation (IR), a long wavelength (LW)

- Temperature of the earth-atmosphere system changes when incoming and outgoing radiation at the top of the atmosphere (TOA) is unequal
• Satellites can measure radiation emitted from Earth as reflected sunlight and outgoing LW radiation

• Although GHGs are present in trace amounts they are the only gases that can absorb outgoing LW, most gases in the air cannot

• Due to GHGs, the surface is about 34°C (61°F) warmer than without these trace gases (then Earth would be -18°C)

• Radiation emitted from a body is a function of $T^4$ so a doubling of $T$ means a 16x increase in outgoing IR
If the atmosphere had no heat-trapping greenhouse gases, all of the radiation received at the surface of the Earth would be emitted back to space.

This condition would result in an average temperature of -18°C (-0.4°F) instead of the current 16°C (60.8°F)
Chapter 3

- The Sun
- Orbital Cycles
- The Atmosphere
- Heating the Atmosphere
- Energy Budget
- Enhanced GH Effect
- Radiative Forcing
- Climate Sensitivity

- GHGs are not equally distributed in the atmosphere
- Water vapor is concentrated in the lower atmosphere
- CO2 is well-mixed throughout the atmosphere
- Middle and upper tropospheric levels are more influenced by man-made GHGs
• Net incoming SW to surface is 161 W/m².

• LW radiation from GHGs adds another 342 W/m².

• 240 W/m² received by planet and 239 W/m² leaves the planet Climate is NOT in equilibrium. Excess energy!
Chapter 3

- The Sun
- Orbital Cycles
- The Atmosphere
- Heating the Atmosphere
- Energy Budget
- Enhanced GH Effect
- Radiative Forcing
- Climate Sensitivity

Wang & Liang (2009) found that daily downwelling LW increased at an average rate of 2.2 W/m² per decade from 1973 to 2008. The rising trend results from increases in air temperature, atmospheric water vapor, and CO₂ concentration.

Evans & Puckrin (2006) - an energy flux imbalance of 3.5 W/m² has been created by anthropogenic emissions of greenhouse gases since 1850. This compares favorably with a modeled prediction of 2.55 W/m².

They concluded: "This experimental data should effectively end the argument by skeptics that no experimental evidence exists for the connection between greenhouse gas increases in the atmosphere and global warming."

See: How Do We Know CO₂ is Causing Warming?
Chapter 3

- The Sun
- Orbital Cycles
- The Atmosphere
- Heating the Atmosphere
- Energy Budget
- Enhanced GH Effect
- Radiative Forcing
- Climate Sensitivity

Additional GHGs causes an enhanced greenhouse effect (EGHE)
More GHG causes more warming at higher altitudes in troposphere
Warmer air can have more water vapor which increases GHE
Level where outgoing radiation can escape to space is higher and colder
Colder air cannot emit as much outgoing radiation
Incoming solar radiation is unchanged
Net result = heat imbalance (troposphere must warm)

Kitchen (2013)
IPCC defines radiative forcing as “the change in the net, downward minus upward, irradiance at the tropopause due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide or the output of the sun.”

- Sun = +0.12 W/m²

- GHGs (Total = 2.43 W/m²):
  - Carbon Dioxide CO₂ = 1.46 W/m²
  - Methane CH₄ = 0.48 W/m²
  - Nitrous Oxide N₂O = 0.15 W/m²
  - Ozone O₃ = 0.35 W/m²

- Black carbon = 0.2 W/m², Organic carbon = -0.05 W/m²
Chapter 3

• The Sun
• Orbital Cycles
• The Atmosphere
• Heating the Atmosphere
• Energy Budget
• Enhanced GH Effect
• Radiative Forcing
• Climate Sensitivity

• Aerosols are tiny particles of solid or liquid that are suspended in the atmosphere and act to partially block the sun (global dimming)

• These particles also make more cloud droplets so clouds are more reflective

• Between 1950s and 1990s insolation decreased 1.3% per decade

• Clean air legislation has reversed this trend
Chapter 3

- The Sun
- Orbital Cycles
- The Atmosphere
- Heating the Atmosphere
- Energy Budget
- Enhanced GH Effect
- Radiative Forcing
- Climate Sensitivity

<table>
<thead>
<tr>
<th>Emitted compound</th>
<th>Resulting atmospheric drivers</th>
<th>Radiative forcing by emissions and drivers</th>
<th>Level of confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>CO₂</td>
<td>1.68 [1.33 to 2.03]</td>
<td>VH</td>
</tr>
<tr>
<td>CH₄</td>
<td>CO₂, H₂O, O₃, CH₄</td>
<td>0.97 [0.74 to 1.20]</td>
<td>H</td>
</tr>
<tr>
<td>Halo-carbons</td>
<td>O₃, CFCs, HCFCs</td>
<td>0.18 [0.01 to 0.35]</td>
<td>H</td>
</tr>
<tr>
<td>N₂O</td>
<td>N₂O</td>
<td>0.17 [0.13 to 0.21]</td>
<td>VH</td>
</tr>
<tr>
<td>CO</td>
<td>CO₂, CH₄, O₃</td>
<td>0.23 [0.16 to 0.30]</td>
<td>M</td>
</tr>
<tr>
<td>NMVOC</td>
<td>CO₂, CH₄, O₃</td>
<td>0.10 [0.05 to 0.15]</td>
<td>M</td>
</tr>
<tr>
<td>NOₓ</td>
<td>Nitrate, CH₄, O₃</td>
<td>-0.15 [-0.34 to 0.03]</td>
<td>M</td>
</tr>
<tr>
<td>Aerosols and precursors</td>
<td>Mineral dust, Sulphate, Nitrate, Organic carbon, Black carbon</td>
<td>-0.27 [-0.77 to 0.23]</td>
<td>H</td>
</tr>
<tr>
<td>Cloud adjustments due to aerosols</td>
<td></td>
<td>-0.55 [-1.33 to -0.06]</td>
<td>L</td>
</tr>
<tr>
<td>Albedo change due to land use</td>
<td></td>
<td>-0.15 [-0.25 to -0.05]</td>
<td>M</td>
</tr>
<tr>
<td>Natural</td>
<td>Changes in solar irradiance</td>
<td>0.05 [0.00 to 0.10]</td>
<td>M</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total anthropogenic RF relative to 1750</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
</tr>
<tr>
<td>1.25 [0.64 to 1.86]</td>
</tr>
<tr>
<td>1980</td>
</tr>
<tr>
<td>1.25 [0.64 to 1.86]</td>
</tr>
<tr>
<td>1950</td>
</tr>
<tr>
<td>0.57 [0.29 to 0.85]</td>
</tr>
</tbody>
</table>

IPCC (2013)
Chapter 3

- The Sun
- Orbital Cycles
- The Atmosphere
- Heating the Atmosphere
- Energy Budget
- Enhanced GH Effect
- Radiative Forcing
- Climate Sensitivity

Figure 10.5 | Assessed likely ranges (whiskers) and their mid-points (bars) for attributable warming trends over the 1951–2010 period due to well-mixed greenhouse gases, other anthropogenic forcings (OA), natural forcings (NAT), combined anthropogenic forcings (ANT) and internal variability. The Hadley Centre/Climatic Research Unit gridded surface temperature data set 4 (HadCRUT4) observations are shown in black with the 5 to 95% uncertainty range due to observational uncertainty in this record (Morice et al., 2012).
Chapter 3

- The Sun
- Orbital Cycles
- The Atmosphere
- Heating the Atmosphere
- Energy Budget
- Enhanced GH Effect
- Radiative Forcing
- Climate Sensitivity

Attribution of Surface Temperature trends since 1950

> 50% warming due to human activity

PDF derived from IPCC Fig. 10.5

Best guess ~110%

Fractional attribution to anthropogenic causes

IPCC (2013)
Chapter 3

• The Sun
• Orbital Cycles
• The Atmosphere
• Heating the Atmosphere
• Energy Budget
• Enhanced GH Effect
• Radiative Forcing
• Climate Sensitivity

• Global dimming likely caused the warming trend to stop between the years 1945 and 1978

• Some models suggest that with more legislation worldwide to clean the air, global warming could lead to a 6°F (11°F) by the year 2100
• Even as solar radiation decreased, global air temperatures were increasing due to increases in GHGs
• Large downward spikes in sunlight are due to volcanic eruptions
Chapter 3

- The Sun
- Orbital Cycles
- The Atmosphere
- Heating the Atmosphere
- Energy Budget
- Enhanced GH Effect
- Radiative Forcing
- **Climate Sensitivity**

---

**Web Alert:**

*Skeptical Science (2010)*

**Impact of Greenhouse Gases**

- *Climate sensitivity* is defined as the expected increase in global average T due to a doubling of pre-IR CO₂ from 280 ppm to 560 ppm.

- The IPCC concludes “*climate sensitivity is likely to be in the range 2 to 4.5°C with a best estimate of about 3°C*, and is very unlikely to be less than 1.5°C. Values substantially higher than 4.5°C cannot be excluded, but agreement of models with observations is not as good for those values”
Chapter 3

- The Sun
- Orbital Cycles
- The Atmosphere
- Heating the Atmosphere
- Energy Budget
- Enhanced GH Effect
- Radiative Forcing
- Climate Sensitivity

It’s us

Video: 13 Misconceptions About Global Warming
Chapter 3

• The Sun
• Orbital Cycles
• The Atmosphere
• Heating the Atmosphere
• Energy Budget
• Enhanced GH Effect
• Radiative Forcing
• Climate Sensitivity

Summary

• Up until the past 30 years, volcanic eruptions and solar variance can explain most of the global warming and cooling

• In the last 30 years temperatures of the oceans, surface, and air are rising even though solar activity is declining

• Climate models can only match modern warming if increases in GHGs are included.

• Natural forcing would result in global cooling in the past 30 years

• Models predict global temps will rise between 1°C and 6°C with 3°C the most likely by the year 2100.