REFERENCES

The first textbook was always on my desk when I was preparing these lecture notes. I also list *wikipedia*, which was the source for many of the images and animations plus many useful tidbits of information.

Specific references are supplied on every slide except when the slide content is part of common mechanical engineering lore and can be found in any relevant textbook.

• Wikipedia, the free encyclopedia ([http://en.wikipedia.org/wiki/Main_Page](http://en.wikipedia.org/wiki/Main_Page))
Module 2

Global Warming - Physics
The Context

• Today, a discussion on energy futures is inextricably linked with a discussion on global warming

• The scarcity issues are still relevant but are only of second order importance
Climate Change - 1

- The 10 warmest years on record have all been since 1990. Over the last century average global temperatures have risen by 0.6°C: the most drastic temperature rise for over 1,000 years.

- Extreme events are becoming more frequent. Glaciers are melting. Sea ice and snow cover is declining. Animals and plants are responding to an earlier spring. Sea levels are rising and are forecast to rise another 88cm by 2100 threatening 100m people globally who currently live below this level.

- The number of people affected by floods worldwide has already risen from 7 million in the 1960s to 150 million today.
Climate Change - 2

- In Europe alone, the severe floods in 2002 had an estimated cost of $16b.
- These environmental changes and severe weather events are already affecting the world insurance industry. Swiss Re, the world's second largest insurer, has estimated that the economic costs of global warming could double to $150 billion each year in the next 10 years, hitting insurers with $30-40 billion in claims.
- By the middle of this century, temperatures could have risen enough to trigger irreversible melting of the Greenland ice-cap - eventually increasing sea levels by around seven metres.
- There is good evidence that 2003 European heat wave was influenced by global warming. It resulted in 26,000 premature deaths and cost $13.5 billion.
- It is calculated that such a summer is a one in about 800 year event. On the latest modelling climate change means that as soon as the 2040s at least one year in two is likely to be even warmer than 2003.
The problem

“The emission of greenhouse gases … is causing global warming at a rate that began as significant, has become alarming and is simply unsustainable in the long term.

And by long term I do not mean centuries ahead. I mean within the lifetime of my children certainly; and possibly within my own.

And by unsustainable, I do not mean a phenomenon causing problems of adjustment.

I mean a challenge so far reaching in its impact and irreversible in its destructive power; that it alters radically human existence…

There is no doubt the time to act is now.”

*Tony Blair, Address to the 10th anniversary of HRH’s Business & Environment Forum, 14 Sep 2004*

[http://www.number-10.gov.uk/output/page6333.asp](http://www.number-10.gov.uk/output/page6333.asp)
What is the Greenhouse Effect?

Basic Physics
What is a Greenhouse?

Greenhouses are used to grow commercial plants in relatively cold climates.

The sunlight can enter through the glass roof and walls. The heat inside is radiated at a higher wavelength and is trapped by the glass.

The trapped heat increases the inside temperature while the building is exposed to sun. The commercial greenhouses must have ventilation and shading controls to prevent overheating.

The mechanism is similar to the interior of a car getting hot when the car is exposed to sunlight.
Solar Spectrum

The solar radiation impinging our upper atmosphere is very close to ideal blackbody radiation at 5900 °K. A large part is in the visible spectrum.

The earth absorbs part of the incoming radiation and re-radiates it back in the infrared region (similar to ideal blackbody radiation at earth temperatures).

Greenhouse gases absorb part of this re-radiated heat.
Earth’s radiation absorbed by greenhouse gases
Without the greenhouse gases acting like a blanket on the earth keeping part of its heat in, the earth would be too cold a place at 255 °K or -18 °C. However, too much of a good thing is bad. Too thick a blanket would make earth too hot.
The earth is just right!

The earth would be too cold like Mars if the natural greenhouse effect did not warm our planet. On the other hand, the earth would be too hot like Venus if we had too much greenhouse gas. The Mars’ blanket is too thin, the Venus’ blanket is too thick. The earth is just right.

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Sun-Earth-Space Radiative Equilibrium

The numbers refer to the average numbers as given by Fay & Golomb, “Energy and the Environment”, Sec 10.2.2.
Radiative Forcing

- The change caused by extra amounts of Greenhouse Gases (GHG) is called radiative forcing.
- The CO₂ absorption band is almost saturated at the centre. Additional CO₂ does not affect this region as much but increases the absorption at the lower and higher ends of the spectrum. Therefore, only a fraction of the extra CO₂ causes warming.
- The atmosphere is relatively lean on methane. Therefore, every additional CH₄ molecule directly contributes to global warming.
Global Warming Potential (GWP)

- The Global Warming Potential (GWP) is a simplified index that can be used to estimate the potential future impacts of emissions of different gases upon the climate system in a relative sense.
- Reference values for GWP of significant greenhouse gases are published by the Intergovernmental Panel of Climate Change (IPCC).
- The calculations are based on a 100-year horizon.
- Methane has a GWP value of 23. This means that methane is 23 times more effective at trapping heat in the atmosphere when compared to CO$_2$ over a 100-year time period.
Greenhouse Gases (GHG)

*Table 4.1(a) of “Climate Change: Scientific Basis – 2001” by IPCC*

Chemically reactive greenhouse gases

<table>
<thead>
<tr>
<th>Chemical species</th>
<th>Formula</th>
<th>Lifetime (yr)</th>
<th>100-yr GWP b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>CH₄ (ppb)</td>
<td>8.4/12 c</td>
<td>23</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>N₂O (ppb)</td>
<td>120/114 c</td>
<td>296</td>
</tr>
<tr>
<td>Perfluoromethane</td>
<td>CF₄</td>
<td>&gt;50000</td>
<td>5700</td>
</tr>
<tr>
<td>Perfluoroethane</td>
<td>C₂F₆</td>
<td>10000</td>
<td>11900</td>
</tr>
<tr>
<td>Sulphur hexafluoride</td>
<td>SF₆</td>
<td>3200</td>
<td>22200</td>
</tr>
<tr>
<td>HFC-23</td>
<td>CHF₃</td>
<td>260</td>
<td>12000</td>
</tr>
<tr>
<td>HFC-134a</td>
<td>CF₃CH₂F</td>
<td>13.8</td>
<td>1300</td>
</tr>
<tr>
<td>HFC-152a</td>
<td>CH₃CHF₂</td>
<td>1.40</td>
<td>120</td>
</tr>
</tbody>
</table>

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Indicators of the human influence on the atmosphere during the Industrial era

- Carbon Dioxide concentration
- Nitrous Oxide concentration
- Methane concentration
- Sulfur aerosols deposited in Greenland ice
The rise in the greenhouse gas CO\(_2\) (produced from burning fossil fuel) to levels well beyond the range ever experienced during the entire time since humans first appeared on Earth: this is arguably the most important event of the last century and indeed of the last millennium. (The natural background in the concentration of CO\(_2\) is near 275 ppm, as seen in ice core data.)

Why is it saw tooth shaped?
The past and the future

LAST 400,000 YEARS: ATMOSPHERIC CO₂ (200-280 ppm)

ESTIMATED EFFECTS
450ppm: (1.2 - 2.3°C)
550ppm: (1.5 - 2.5°C)
650ppm: (1.7 - 3.2°C)

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CO₂ Sources

- Residential: 14%
- Transport: 24%
- Power: 35%
- Manuf: 18%
- Other: 9%

“Overview of CO2 capture”, Kelly Thambimuthu, GHGT-7, Vancouver, 5-9 September 2004

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The focus is on reducing CO2 emissions in power generation industries.

Transport is next big fraction but can probably be replaced only by direct or indirect electricity, ie more power generation.

Residential heating is important but this is mostly in undeveloped world and not easy to change.

“Overview of CO2 capture”, Kelly Thambimuthu, GHGT-7, Vancouver, 5-9 September 2004

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Past and Future CO$_2$

“IEA World Energy Investment Outlook”, Marianne Haug, Director, IEA Energy Technology, GHGT-7, Vancouver, 5-9 Sep 2004

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CO$_2$ Emissions in 2002

World Total CO2 Emission in 2002 = 24 billion tonnes (38b t projected for 2030)

“IEA World Energy Investment Outlook”, Marianne Haug, Director, IEA Energy Technology, GHGT-7, Vancouver, 5-9 September 2004

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Projected CO$_2$ Emissions in 2030

World Total CO2 Emission in 2030 = 38 billion tonnes (about 10b tonnes of Carbon)

OECD

22 b tonnes

Others

16 b tonnes

58%

42%

“IEA World Energy Investment Outlook”, Marianne Haug, Director, IEA Energy Technology, GHGT-7, Vancouver, 5-9 Sep 2004

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Australia may meet the Kyoto target of 108% of 1990 levels, largely through one-off benefits of reduced land clearing. Stationary energy sector emissions are forecast to increase to 146% of 1990 levels by 2012.
Carbon Cycle

The actual numbers are difficult to know and there is variation between sources. This chart is copied from Earth Observatory, NASA, on http://earthobservatory.nasa.gov/Library/CarbonCycle.

Compare the figures of exchange with the estimates in Figure 10.7 of Fay and Golomb. Significant differences will be observed. The main uncertainty is due to the fact that when the CO2 in the air goes up, the earth tends to absorb more through photosynthesis on land (more forests) and in oceans (plankton growth).

However, it is clear that the earth cannot absorb all of the extra CO2 released to the atmosphere by human activities.

How do we know that the earth cannot absorb all of the extra CO2 released to the atmosphere by human activities?

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Feedback Effects

• Rising temperatures will cause secondary effects called feedback effects:

\[ \Delta T_s \propto \frac{\Delta Q}{\beta} \]

- \( \Delta T_s \): Surface temp. rise
- \( \Delta Q \): Radiative forcing due to GHG alone
- \( \beta \): Feedback factor

• \( \beta < 1 \) → Positive feedback (amplifying effect)
• \( \beta > 1 \) → Negative feedback (corrective effect)
• Possible feedback effects include water vapour, cloud radiation, aerosols, ice-albedo, and ocean circulation
Water Vapour Feedback

- Water has strong absorption bands in the far-infrared region. If it were classified as a GHG, it would have a GWP higher than CO₂.
- Since water vapour continuously circulates, a given molecule does not stay in the air for decades like CO₂ or methane molecules do. Therefore, it is treated as a feedback rather than a GHG in its own right.
- Higher temperatures
  - increased evaporation from the oceans
  - more water vapour in the air
  - more absorption of the outgoing far-IR radiation
  - higher temperatures
  … and it goes on like this like any positive feedback mechanism
- Models predict water vapour feedback to increase GHG-caused global warming by about 60% (β≈0.6)
Cloud Radiation Feedback

- Clouds may have both positive and negative feedback
- Positive feedback (low-altitude cumulus-type clouds):
  - More clouds will reflect more of the incoming solar radiation
  - The earth’s albedo will increase
  - The surface temperature will decrease
- Negative feedback (high-altitude, cirrus-type clouds)
  - More clouds will reflect more of the earth’s radiation back
  - The surface temperature will increase
- Modelling of cloud feedback is very uncertain
- Fay & Golomb quote a feedback value of $\beta=0.80$, but the opinion varies
Aerosol Feedback

• Aerosols are natural or man-made small particles suspended in the air
• Particle diameters are much smaller than 1 μm. Larger particles will fall (see the terminal velocities in the next slide)
• Roughly two-thirds caused by fossil fuel combustion
• Aerosols scatter and reflect incoming solar radiation and therefore act as a negative feedback mechanism ($\beta \approx 1.1$)
• On the other hand, aerosols help cloud formation forming as condensation nuclei. Therefore, more aerosols mean more clouds. The cloud feedback effect is more uncertain.
Terminal velocity

(A Digression)

\[ V_{\text{term}} = \sqrt{\frac{2m_p g}{C_d \rho_{\text{air}} A_p}} \]
Ice-Albedo Feedback

• Ice is more reflective than land or liquid water
• Therefore, more ice on earth’s surface means that more of the incoming solar radiation is reflected back without heating the earth (in other words, more ice increases earth’s albedo)
• Global warming causes ice to melt, which reduces the albedo of the earth and hence will cause a further increase of the surface temperature as a positive feedback mechanism.
• Fay & Golomb recommend $\beta \approx 0.8$. 
Ocean Circulation Feedback

- Salinity differences drive the large ocean currents, e.g. Gulf Stream
- Global warming will melt polar ice caps and will increase rainfall at higher latitudes
- Both will reduce the seawater salinity in those regions
- Ocean circulation patterns may then be switched, e.g. the Gulf Stream may reverse its direction
- The effect on global warming is not clear and could be positive, negative or neutral.
- However, the effect on human life would be very significant
- If, for example, the Gulf Stream changes its direction, the climate in most of Europe and North America would reduce to Ice Age temperatures with a radical effect on life in these regions.
Variations of the Earth's surface temperature for...

Departure in temperature in °C (from the 1961-1990 average)

the past 140 years (global)

Direct temperatures

Departure in temperature in °C (from the 1961-1990 average)

the past 1000 years (Northern Hemisphere)

Direct temperatures
Proxy data
The global climate of the 21st century

(a) CO₂ emissions
(b) CO₂ concentrations
(c) SO₂ emissions

(d) Temperature change
(e) Sea level rise

WG1 - SPM FIGURE 5
Key questions about the climate system and its relation to human kind

What changes have occurred?
Observations:
- temperatures
- precipitation
- snow / ice cover
- sea level
- circulation
- extremes

How well are the past and present climates understood?

What changes could lie ahead?
Simulations:
- natural variation
- forcing agents
- global climate
- regional climate
- high impact events
- stabilisation

Observations vis-à-vis Simulations

Timeline:
- Palaeo & Instrumental Periods
- The Present
- The Future
Historical variations

- The average earth surface temperature has changed in the past, indicated by the geological records of glacial and inter-glacial ages. Possible causes of such temperature change:
  - Changing GHG concentrations in the atmosphere
  - Earth’s orbit around the sun (the eccentricity changes with a period of about 100,000 years
  - The ecliptic angle of the earth varies between 21.6 and 24.5° with a period of about 41000 years
  - Changes to the solar constant (possible but not definite)