Atmospheric Composition and the Greenhouse

12.340 Global Warming Science
February 23, 2012
Dan Cziczo
A Little About Myself...
Today’s Class

• Why are atmospheres important?
  - Bare rocks and blankets (the greenhouse concept)

• What are the Earth’s greenhouse gases? Where are they from?

• Paleo versus modern greenhouse levels
Early Atmosphere
Probably H₂, He
- Likely lost to space early

Later Atmosphere
- Volcanic out gassing + impacts
  : H₂O, CO₂, SO₂, CO, S₂, Cl₂, N₂, H₂, NH₃, and CH₄

O₂ ?

Ocean Formation ?
Planetary Temperature

Let’s start by assuming the Earth is a rock heated by the sun with no greenhouse gases.

Unless otherwise specified: Archer, Global Warming

Image by MIT OpenCourseWare.
‘Bare Rock’

Energy in = energy out
\[ F_{\text{in}} = F_{\text{out}} \text{ (Watts)} \]

From Archer: Intensity = \( W/m^2 \)

\[ F_{\text{in}}[W] = I[W \text{ m}^{-2}] \times (1-\alpha) \times \text{Area}[m^2] \]

What is \( I \)? What is albedo?
This image has been removed due to copyright restrictions. Please see the image on page https://commons.wikimedia.org/wiki/File:Albedo-e_hg.svg.
Area = $\pi r^2$ (why not $4\pi r^2$?)

$$F_{in} = I_{in} \times (1 - \alpha) \times \text{Area}$$

$$F_{in} = I_{in} \times (1 - \alpha) \times \pi r^2$$

Image by MIT OpenCourseWare.
Stephan-Boltzmann Equation

\[ F_{out} = I_{out} \times \text{Area} \]

\[ I_{out} = \varepsilon \sigma T^4 \]

Area = \( 4\pi r^2 \) (why not \( \pi r^2 \)?)

\( \varepsilon = '\text{emissivity}' , \ 0<\varepsilon<1 \)
‘Bare Rock’

\[ 4\pi r_{\text{earth}}^2 \varepsilon \sigma T_{\text{earth}}^4 = \pi r_{\text{earth}}^2 (1-\alpha) l_{\text{in}} \]

\[ T_{\text{earth}} = [(1-\alpha) l_{\text{in}} / 4\varepsilon \sigma]^{1/4} \]
\[
\frac{(1 - \alpha)I_{\text{solar}}}{4} = \varepsilon \sigma T_{\text{earth}}^4
\]

<table>
<thead>
<tr>
<th>Planet</th>
<th>$\alpha$ (%)</th>
<th>$T$ (K)</th>
<th>$I_{\text{solar}}$ (Wm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Venus</td>
<td>71</td>
<td>240</td>
<td>2600</td>
</tr>
<tr>
<td>Earth</td>
<td>33</td>
<td>251</td>
<td>1350</td>
</tr>
<tr>
<td>Mars</td>
<td>17</td>
<td>216</td>
<td>600</td>
</tr>
</tbody>
</table>

Image by MIT OpenCourseWare.
Let’s Add an Atmosphere

\[ F_{\text{out}} = 4\pi r_{\text{earth}}^2 \varepsilon \sigma T_{\text{earth}}^4 \]

Define \( I_{\text{out}} = \varepsilon \sigma T_{\text{earth}}^4 \) [W m\(^{-2}\)]

\[ F_{\text{in}} = \pi r_{\text{earth}}^2 (1-\alpha) I_{\text{in}} \]

Define \( I_{\text{in}} = (1-\alpha) I_{\text{in}}/4 \)

Image by MIT OpenCourseWare.
The Balance:

\[ I_{\text{in, solar}} = \frac{(1 - \alpha)I_{\text{in}}}{4} \]

\[ I_{\text{up, ground}} = \varepsilon \sigma T_{\text{grnd}}^4 \]

\[ I_{\text{up, atmosphere}} = \varepsilon \sigma T_{\text{atm}}^4 \]

What is \( T_{\text{grnd}} \)?
1 Layer

The atmosphere is like the bare rock:

\[
\frac{(1 - \alpha)I_{solar}}{4} = \frac{I_{\text{up, atmosphere}}}{4}
\]

\[
\varepsilon \sigma T_{atm}^4 = (1-\alpha)I_{\text{solar}}/4
\]

\[
T_{atm} = [(1-\alpha)I_{\text{in}}/4\varepsilon \sigma]^{1/4}
\]
1 Layer

And the ground is now warmer:

$$I_{up, atm} + I_{down, atm} = I_{up, grnd}$$

$$2\varepsilon\sigma T_{atm}^4 = \varepsilon\sigma T_{grd}^4$$

$$T_{grd} = [2]^{1/4} T_{atm} \sim 1.2 T_{atm}$$

$$T_{grd} = [(1-\alpha)I_{solar}/2\varepsilon\sigma]^{1/4}$$
What about Venus and Mars?

<table>
<thead>
<tr>
<th>Planet</th>
<th>$\alpha$ (%)</th>
<th>$T$ (K)</th>
<th>$T_{\text{observed}}$ (K)</th>
<th>$T_{\bot}$ layer (K)</th>
<th>$I_{\text{solar}}$ (Wm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Venus</td>
<td>71</td>
<td>240</td>
<td>700</td>
<td>285</td>
<td>2600</td>
</tr>
<tr>
<td>Earth</td>
<td>33</td>
<td>251</td>
<td>295</td>
<td>303</td>
<td>1350</td>
</tr>
<tr>
<td>Mars</td>
<td>17</td>
<td>216</td>
<td>240</td>
<td>259</td>
<td>600</td>
</tr>
</tbody>
</table>

Image by MIT OpenCourseWare.
If It Wasn’t For Greenhouse Gases We Wouldn’t Be Here!

(or we’d look a lot different)
Earth’s Atmosphere

The Earth’s atmosphere can be mimicked by a 1 layer atmosphere but is much more complex.

Figure by MIT OpenCourseWare.
Greenhouse Gases

Carbon dioxide, methane and nitrous oxide are natural (as well as anthropogenic)

More on CO$_2$ in a moment.

Methane (CH$_4$) – from wetlands, grazing animals, termites, and other sources

Nitrous Oxide (N$_2$O) – from denitrifying bacteria
Where Do Greenhouse Gases Come From (and go)?

\[ \text{H}_2\text{O} + \text{CO}_2 \rightarrow \text{H}_2\text{CO}_3 \text{ (soil)} \]

\[ \text{H}_2\text{CO}_3 + \text{CaSiO}_3 \rightarrow \text{CaCO}_3 + \text{SiO}_2 + \text{H}_2\text{O} \]

Image by MIT OpenCourseWare.

Ruddiman, 2001
Greenhouse Gases

What if volcanoes stopped?

Concept of lifetime:

Abundance (Gton) / Emission (Gton/yr) = Lifetime (yr)

A Major carbon reservoirs (gigatons; 1 gigaton = $10^{15}$ grams)

Image by MIT OpenCourseWare.
Greenhouse Gases Record


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Please see the image on page http://www.nature.com/ngeo/journal/v4/n7/fig_tab/ngeo1186_F1.html
Paleo Changes in GGs

Greenhouse Gases

Table: Principal gases of dry air

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Percent by volume</th>
<th>Concentration in Parts Per Million (PPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argon (Ar)</td>
<td>0.934</td>
<td>9,340.0</td>
</tr>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>0.036</td>
<td>360.0</td>
</tr>
<tr>
<td>Helium (He)</td>
<td>0.000524</td>
<td>5.24</td>
</tr>
<tr>
<td>Hydrogen (H₂)</td>
<td>0.00005</td>
<td>0.5</td>
</tr>
<tr>
<td>Krypton (Kr)</td>
<td>0.000114</td>
<td>1.14</td>
</tr>
<tr>
<td>Methane (CH₄)</td>
<td>0.00015</td>
<td>1.5</td>
</tr>
<tr>
<td>Neon (Ne)</td>
<td>0.00182</td>
<td>18.2</td>
</tr>
<tr>
<td>Nitrogen (N₂)</td>
<td>78.084</td>
<td>780,840.0</td>
</tr>
<tr>
<td>Oxygen (O₂)</td>
<td>20.946</td>
<td>209,460.0</td>
</tr>
</tbody>
</table>

Figure and table from Lutgens and Tarbuck, The Atmosphere, 8th edition.

Table 2.1. Present-day concentrations and RF for the measured LLGHGs. The changes since 1998 (the time of the TAR estimates) are also shown.

<table>
<thead>
<tr>
<th>Species</th>
<th>Concentrations(^b) and their changes(^c)</th>
<th>Radiative Forcing(^d)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2005</td>
<td>Change since 1998</td>
</tr>
<tr>
<td>CO₂</td>
<td>379 ± 0.65 ppm</td>
<td>+13 ppm</td>
</tr>
<tr>
<td>CH₄</td>
<td>1,774 ± 1.8 ppb</td>
<td>+11 ppb</td>
</tr>
<tr>
<td>N₂O</td>
<td>319 ± 0.12 ppb</td>
<td>+5 ppb</td>
</tr>
</tbody>
</table>

Modern CO2

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1 Tg = 1 million metric tons = $10^9$ Kg = $10^{12}$ g

Added CO$_2$ per year (man made) is $\sim$9000 Tg (9 Gigatons)

This is out of 700 Gtons of CO$_2$ in the atmosphere at any given time

Methane is about 60% / 40% anthropogenic / natural

N$_2$O is about 40 / 60%
Greenhouse Gases

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CH$_4$ and Nitrous Oxide Global Emissions - IPCC

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The Other Greenhouse Gases

(more in Lecture 13)

<table>
<thead>
<tr>
<th>Gas</th>
<th>Global Warming Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide</td>
<td>1</td>
</tr>
<tr>
<td>Methane</td>
<td>72</td>
</tr>
<tr>
<td>Nitrous Oxide</td>
<td>289</td>
</tr>
<tr>
<td>CFC-12</td>
<td>11000</td>
</tr>
<tr>
<td>HCFC-22</td>
<td>5160</td>
</tr>
<tr>
<td>Sulphur Hexafluoride</td>
<td>16300</td>
</tr>
</tbody>
</table>

Implication?
The Earth’s Energy Balance

Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, FAQ 1.1, Figure 1. Cambridge University Press. Used with permission.
Solar Irradiance ~ 1350 W/m²

(more in Lecture 15)
No Models! (ok, a little modeling)

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Please see Figure 6 on page http://onlinelibrary.wiley.com/doi/10.1029/2009JD012105/full

(more in Lecture 15,17,18)
Anthropogenic CO$_2$ and a Delayed Ice Age?

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Please see the images on pages
http://digitaljournal.com/article/317605 and
http://www.ibtimes.com/next-ice-age-1500-years-prevented-carbon-dioxide-emissions-393160
Anthropogenic CO2 and a Delayed Ice Age?

Problems?

- Adaptation (extinction)?
- Increase drought
- Increasingly severe storms
- Sea level rise / lost land
- Increased disease
- Increased conflict over resources

Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 6.3 and Figure 6.4. Cambridge University Press. Used with permission.
Recap

• The concept of greenhouse gases and why they are important (necessary!)

• The important natural and anthropogenic greenhouse gases

• Paleo versus modern greenhouse levels
References


