How we know that human activities are driving climate change

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EMISSIONS ARE OVERWHELMING NATURAL PROCESSES

Atmospheric CO$_2$ at Mauna Loa Observatory

Scripps Institution of Oceanography
NOAA Earth System Research Laboratory

PARTS PER MILLION


YEAR

www.esrl.noaa.gov/gmd/ccgg/trends/
TODAY’S CO2 IS HIGHLY ANOMALOUS

800,000 year history of atmospheric carbon dioxide

Mauna Loa

central Antarctica

Antarctic coast

ice core

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Today’s CO2 is highly anomalous.

CO2 at the end of last ice age

- 6300 years

Mauna Loa CO2

- 70 years
- 2.0 ppm/yr
- 0.7 ppm/yr
**Isotopic Evidence for the Sources of Today’s Increase**

\[
\delta^{13}C \equiv \frac{^{13}C/^{12}C_{\text{sample}} - ^{13}C/^{12}C_{\text{reference}}}{^{13}C/^{12}C_{\text{reference}}}
\]

**δ**

<table>
<thead>
<tr>
<th>Source</th>
<th>δ(^{13}C)</th>
<th>(approximate)</th>
<th>(^{13}C/^{12}C) ratio</th>
<th>(approximate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonate rock</td>
<td>0 ‰</td>
<td>0.011237</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>−8 ‰</td>
<td>0.011147</td>
<td>1.04</td>
<td></td>
</tr>
<tr>
<td>From oceans</td>
<td>−8 ‰</td>
<td>0.011147</td>
<td>1.06</td>
<td></td>
</tr>
<tr>
<td>Terrestrial biosphere</td>
<td>−26 ‰</td>
<td>0.010945</td>
<td>1.07</td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>−24 ‰</td>
<td>0.010967</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Oil</td>
<td>−28 ‰</td>
<td>0.010923</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Natural gas</td>
<td>−45 ‰</td>
<td>0.010732</td>
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<td>0</td>
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</tbody>
</table>
Observations: the added CO2 is depleted in $^{13}$C
The CO2 added to the atmosphere is of organic origin

This would have been observed if the extra CO2 had come from volcanoes or from the oceans....

Observations: the added CO2 is depleted in $^{13}\text{C}$

Sources: CSIRO, ESRL, INSTAAR
The organic material is very old

$^{14}\text{C}$ in atmosphere and surface oceans

- **atmosphere**
- **surface waters of mid-ocean gyres**

**permil**

Cumulative fossil fuel emissions (Jan. 2010)  
(source: CDIAC)  
Gton C  
355 ± 25

Observed atmospheric increase (Jan. 2010)  
(source: ESRL)  
231 ± 10

Observed ocean increase through 1994  
(Sabine et al., Science 2004)  
118 ± 19

Modeled oceans, extrapolated through 2009  
145

mass balance:  

\[
\text{fossil fuel emissions} = \text{atmos increase} + \text{ocean increase} + \text{terrestrial biosphere}
\]
ATMOSPHERIC NORTH-SOUTH GRADIENT PROPORTIONAL TO GLOBAL EMISSIONS

Mauna Loa minus South Pole

CO₂ annual mean difference (ppm)

Outgoing infrared radiation (clear skies) from Earth to space as a function of wavelength over the Sahara desert. Measured by Nimbus 4 satellite in 1970.

THE GREENHOUSE EFFECT IS WELL UNDERSTOOD, AND OBSERVED

- CO2
- O3
- H2O
- CH4

IR "window" regions
Climate forcing by long lived GHGs  (Watt m⁻²)

<table>
<thead>
<tr>
<th>Year</th>
<th>CO2</th>
<th>CH4</th>
<th>N2O</th>
<th>F-12</th>
<th>F-11</th>
<th>minor</th>
<th>TOTAL</th>
<th>%solar</th>
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<tbody>
<tr>
<td>1950</td>
<td>0.572</td>
<td>0.244</td>
<td>0.059</td>
<td></td>
<td></td>
<td></td>
<td>0.875</td>
<td>0.348</td>
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<tr>
<td>1980</td>
<td>1.058</td>
<td>0.413</td>
<td>0.104</td>
<td>0.097</td>
<td>0.042</td>
<td>0.034</td>
<td>1.747</td>
<td>0.728</td>
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<tr>
<td>2000</td>
<td>1.512</td>
<td>0.481</td>
<td>0.151</td>
<td>0.173</td>
<td>0.066</td>
<td>0.083</td>
<td>2.467</td>
<td>1.028</td>
</tr>
<tr>
<td>2013</td>
<td>1.882</td>
<td>0.496</td>
<td>0.184</td>
<td>0.167</td>
<td>0.059</td>
<td>0.114</td>
<td>2.901</td>
<td>1.209</td>
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<tr>
<td>2014</td>
<td>1.908</td>
<td>0.499</td>
<td>0.187</td>
<td>0.166</td>
<td>0.058</td>
<td>0.116</td>
<td>2.935</td>
<td>1.223</td>
</tr>
<tr>
<td>2015</td>
<td>1.939</td>
<td>0.504</td>
<td>0.190</td>
<td>0.165</td>
<td>0.058</td>
<td>0.118</td>
<td>2.974</td>
<td>1.293</td>
</tr>
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Annual Greenhouse Gas Index:  [www.esrl.noaa.gov/gmd/aggi/](http://www.esrl.noaa.gov/gmd/aggi/)
WHAT DO WE OBSERVE?  INDEED, THE EARTH IS WARMING, AS EXPECTED
INTO THE FAR FUTURE, THOUSANDS OF YEARS

![Graph showing carbon cycle mass balance over time. The graph compares cumulative emissions and carbon reservoir changes for fossil, oceans, atmosphere, and terrestrial reservoirs. The observed trend is highlighted with an arrow.](image-url)
Total retained energy by enhanced CO$_2$ alone, 1750-2500, would be enough to raise the temperature of the upper 1000 m of the oceans by 12 degree C.

Total retained energy by all GHGs, 1750-2100, raises T by 5 degree C.

Not considered: negative climate forcings (cooling) such as fine particles (haze, also called aerosols) and their effects on clouds. Increased aerosols are also due to human activities.

Earth’s observed heat budget 1950-2004 (D. Murphy, JGR 2009):

(Excess retained heat by GHGs ~half of one solar radiation-year)

- 12% for heating of oceans
- 21% for increased IR radiation to space (cooling from warmed surface)
- 18% compensating cooling from stratospheric aerosols (volcanoes)
- ~50% compensating residual cooling, mostly by human-caused aerosols

INTO THE FAR FUTURE, THOUSANDS OF YEARS
Based on observations and well understood physics and chemistry, human actions have committed the Earth to significant climate change for thousands of years.

Additional commitment is growing at a record pace.

Modeled predictions of climate change span a large range but do not negate the above conclusions in any way.