Math 5490
Topics in Applied Mathematics
Introduction to the Mathematics of Climate

Fall 2023
1:25 - 3:20 Tuesdays and Thursdays
Amundson Hall 162

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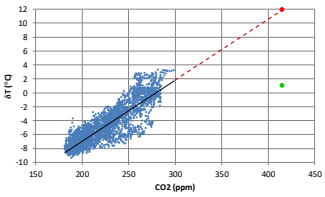
course website
www-users.cse.umn.edu/~mcgehee/teaching/Math5490/

Earth's Carbon Cycle

Why do we think that atmospheric CO_2 has anything to do with surface temperature?

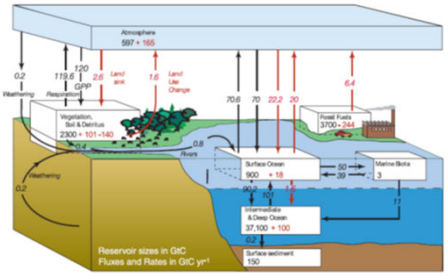
1. Theory of greenhouse gasses.
2. Strong correlation between atmospheric CO_2 concentration and surface temperature during the last million years.



Earth's Carbon Cycle

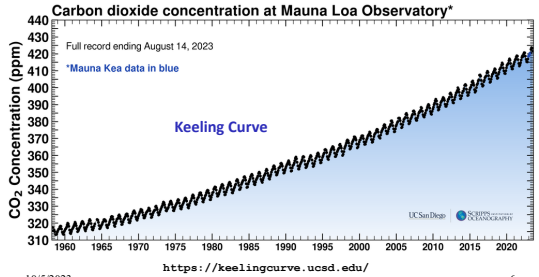
Why do we think that the increase in atmospheric CO_2 has anything to do with human activity?

The Short-Term Carbon Cycle

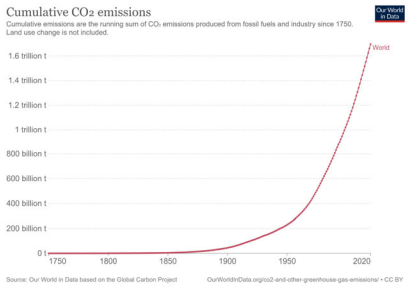


Couplings Between Changes in the Climate System and Biogeochemistry, IPCC AR4, p.513
http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Print_CH07.pdf

Why do we think that the Keeling curve has anything to do with human activity? It could just be an unknown natural source of carbon.



https://keelingcurve.ucsd.edu/



The cumulative carbon emission are going up. This graph resembles the Keeling curve.

https://www.weforum.org/agenda/2022/11/visualizing-changes-carbon-dioxide-emissions-since-1900/

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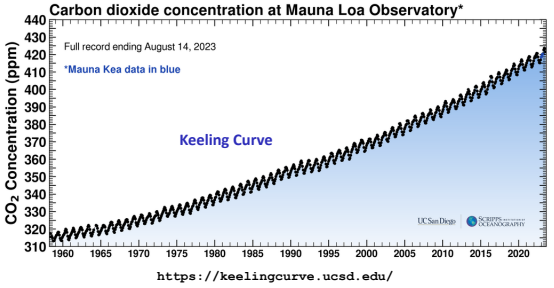
Looks like the emissions curve!



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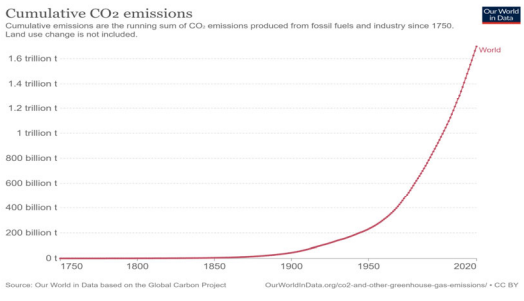

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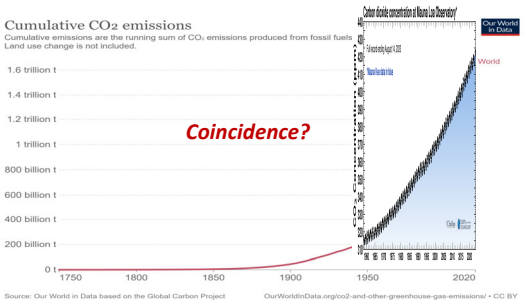

Coincidence?

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No big deal. Both the accumulated emissions and the atmospheric CO2 are increasing.

Is that all you got?

Nope.

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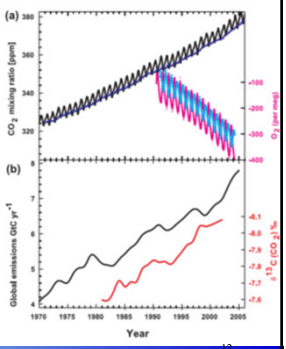
Carbon isotope ratios and atmospheric oxygen depletion indicate that the increase in atmospheric CO_2 comes from burning fossil fuels.



Changes in Atmospheric Constituents and in Radiative Forcing, IPCC AR4, Chap. 2, p.138
https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-chapter2-1.pdf

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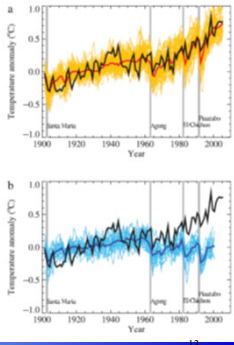
Models with and without human activity.



Understanding and Attributing Climate Change, IPCC AR4, Chap. 9, p.684
https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-chapter9-1.pdf

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Scientific Conclusion

The scientific data are consistent with the hypothesis that the burning of fossil fuels is causing changes in the Earth's climate.

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Reasonable Human Reaction

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Scientific Conclusion

The scientific data are consistent with the hypothesis that the burning of fossil fuels is causing changes in the Earth's climate.

Reasonable Human Reaction

WTF! We gotta stop burning fossil fuels!

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https://www.lemonde.fr/en/environment/article/2023/01/01/uk-climate-group-extinction-rebellion-suspends-public-disruption-tactics_6009966_114.html

https://newrepublic.com/article/166821/climate-delay-discourse-denial

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Earth's Heat Imbalance

What determines the Earth's surface temperature?

Conservation of Energy
Heat is a form of energy.
Temperature measures heat.

temperature change ~ energy in – energy out

short wave energy from the Sun

long wave energy from the Earth

Everything else is detail.

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Earth's Heat Imbalance

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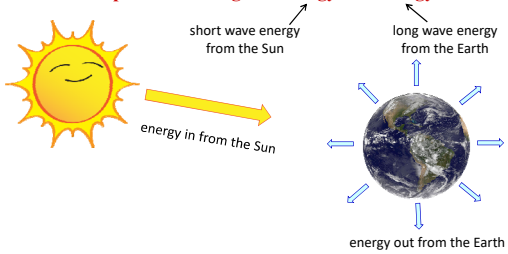

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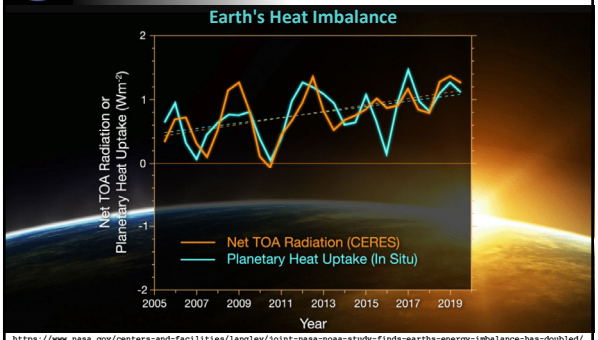
Earth's Heat Imbalance



https://www.nasa.gov/centers-and-facilities/langley/joint-nasa-noaa-study-finds-earths-energy-imbalance-has-doubled/

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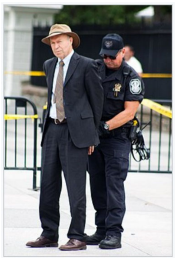
Earth's Heat Imbalance

James Hansen



James Hansen arrested at a demonstration outside the White House, August 29, 2011

Hansen giving testimony before the United States Congress in 1988.

https://en.wikipedia.org/wiki/James_Hansen

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Earth's Heat Imbalance

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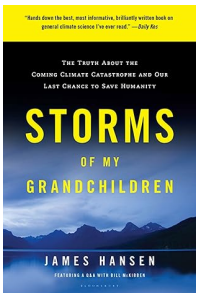

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Earth's Heat Imbalance

www.sciencemag.org SCIENCE VOL 308 3 JUNE 2005

RESEARCH ARTICLES

Earth's Energy Imbalance: Confirmation and Implications

James Hansen,[1,2*] Larissa Nazarenko,[1,2] Reto Ruedy,[3] Makiko Sato,[1,2] Josh Willis,[4] Anthony Del Genio,[1,5] Dorothy Koch,[1,2] Andrew Lacis,[1,2] Ken Lo,[3] Surabi Menon,[6] Tica Novakov,[6] Judith Perlwitz,[1,2] Gary Russell,[1] Gavin A. Schmidt,[1,2] Nicholas Tausnev[3]

Our climate model, driven mainly by increasing human-made greenhouse gases and aerosols, among other forcings, calculates that Earth is now absorbing 0.85 ± 0.15 watts per square meter more energy from the Sun than it is emitting to space. This imbalance is confirmed by precise measurements of increasing ocean heat content over the past 10 years. Implications include (i) the expectation of additional global warming of about 0.6°C without further change of atmospheric composition; (ii) the confirmation of the climate system's lag in responding to forcings, implying the need for anticipatory actions to avoid any specified level of climate change; and (iii) the likelihood of acceleration of ice sheet disintegration and sea level rise.

equal forcing by CO_2 (9). F_a is an energy flux change arising in response to an imposed forcing agent. It is constant throughout the atmosphere, because it is evaluated after atmospheric temperature has been allowed to adjust to the presence of the forcing agent.

The largest forcing is due to well-mixed greenhouse gases (GHGs)—CO_2, CH_4, N_2O, CFCs (chlorofluorocarbons)—and other trace gases, totaling 2.75 W/m² in 2003 relative to the 1880 value (Table 1). Ozone (O_3) and stratospheric H_2O from oxidation of increasing CH_4 bring the total GHG forcing to 3.05 W/m² (9). Estimated uncertainty in the total GHG forcing is ~15% (11, 12).

Atmospheric aerosols cause climate forcings by reflecting and absorbing radiation, as well as through indirect effects on cloud cover and cloud albedo (11). The aerosol scenario in our model uses estimated anthropogenic emissions from fuel use statistics and includes temporal changes in fossil-fuel use technologies (13). Our parameterization of aerosol

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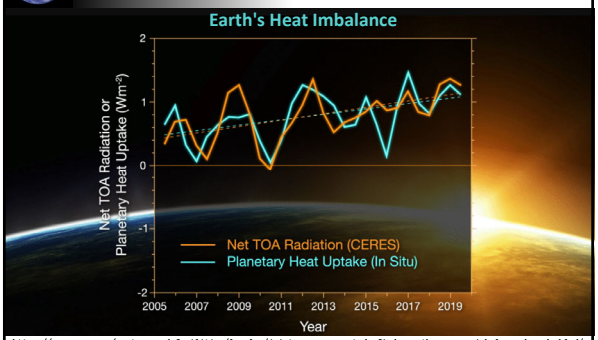
Earth's Heat Imbalance



https://www.nasa.gov/centers-and-facilities/langley/joint-nasa-noaa-study-finds-earths-energy-imbalance-has-doubled/

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Earth's Heat Imbalance

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Ice sheet melting to raise sea level 1 meter. Assume ice starts at –10°C and ends at mean ocean surface temperature (+15°C). Energy required is 100 cal/g (80 cal/g for melting). Energy for 1 meter of sea level: 100g/cm² × 100cal/g × 4.19 joules/cal × area Earth × 0.7 ~1.5×10^{23} joules ~ **9.3 W yr/m²**.

Sea ice melting (all sea ice on planet). Assume ice starts at –10°C and ends at mean ocean surface temperature (+15°C), and that sea ice covers 4% of the planet with mean thickness 2.5 m. Energy required is 250 g cm^2 × 100 cal/g (80 cal/g for melting) × 4.19 joules/cal × 0.04 × area Earth ~ 2.14×10^{22} joules ~ **1.3 W yr/m²**.

Air warming by 1°C. The Earth's atmospheric mass is ~ 10 m of water. Heat capacity of air ~ 0.24 cal/g/°C. Energy to raise air temperature 1°C: 1°C × 1000 g/cm^2 × 0.24 cal/g/°C × 4.19 joules/cal × area Earth ~ 0.26×10^{22} joules ~ **0.32 W yr/m²**.

Land surface warming by 1°C: The depth of penetration of a thermal wave into the Earth's crust in 10 years, weighted by ΔT, is ~10 m. With density ~ 3 g/cm^3, heat capacity ~ 0.2 cal/g/°C, and 0.29 fractional land coverage, land heat storage is 10^3 cm ×3 g/cm^2 × 0.2 cal/g/°C × 1°C ×4.19 joules/cal × area Earth × 0.29 ~ 0.37×10^{22} joules ~ **0.23 W yr**. [In a century the depth of penetration is ~3 times more than in a decade, so heat storage in a century due to 1°C warming is ~ **0.7 W yr/m²**.]

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James Hansen, et al, *Earth's Energy Imbalance: Confirmation and Implications*, SCIENCE 308 (2005), p. 1431

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Earth's Heat Imbalance

What is a watt-year?

A ***watt*** is a unit of power, or energy per unit time, i.e., ***one joule per second***.

A year is about 3.14×10^7 seconds, so a ***watt-year*** is about **3.14×10^7 *joules*.**

What is a watt-year per square meter?

About **3.14×10^7 *joules per square meter*.**

If the heat imbalance at the Earth's surface is one watt per square meter, then the energy imbalance over the course of a year is about **3.14×10^7 *joules per square meter*.**

Earth's surface area: about ***5.1×10^{14} square meters***.

If the heat imbalance at the Earth's surface is one watt per square meter, then the energy absorbed over the whole Earth is about ***1.61×10^{22} joules***.

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Earth's Heat Imbalance

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Earth's Heat Imbalance

How much heat does it take to melt enough of the ice sheets to raise the sea level by one meter?

Assumption: Ice starts at -10°C and ends up as ocean water at +15°C.
Hansen: About 1.5×10^{23} joules ≈ ***9.3 Wyr/m²***

How long does it take to melt enough of the ice sheets to raise the sea level by one meter?

If the heat imbalance at the Earth's surface is one watt per square meter, and if all the heat imbalance goes toward melting the ice sheets, then the time required to raise the sea level one meter is ***9.3 years***.

meters per year: 1/9.3 = ***0.108 m/yr***
= 10.8 cm/yr = 1.08 m/decade = 10.8 m/century

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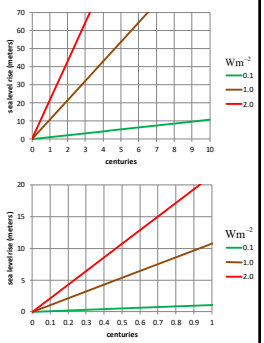
Earth's Heat Imbalance

Suppose that all the heat imbalance goes to melting the ice sheets.

It takes 9.3 Wyr/m² to turn ice sheets into 1 meter of ocean. If the heat imbalance is w W/m², the sea level would rise at the rate of w/9.3 meters per year. At the current imbalance of 1 W/m², the rate is about 0.108 meters per year, or 10.8 meters per century.

Melting all the ice sheets would cause a sea level rise of about 70 meters and would take about 650 years at the current imbalance.



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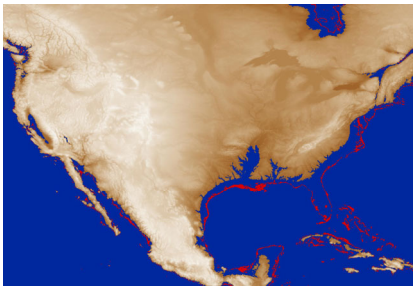
Earth's Heat Imbalance

The USA in the Ice Free Earth
Computer Simulation, Clarence Lehman, Univ. Mn. 2006



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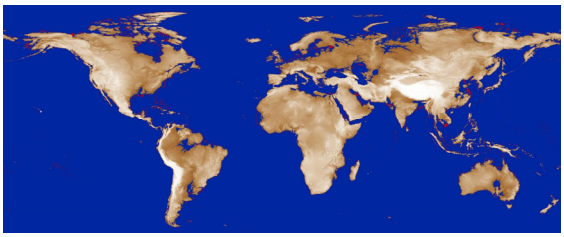

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Earth's Heat Imbalance

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warming the oceans

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James Hansen, et al, *Earth's Energy Imbalance: Confirmation and Implications*, SCIENCE 308 (2005), p. 1431

Math 5490
Earth's Heat Imbalance

How much heat does it take to raise the temperature of the top kilometer of the oceans by 1°C?

Assumption: Warm the top kilometer of the oceans by 1°C
Hansen: About 15×10^{23} joules ≈ ***93 Wyr/m²***

How long does it take to raise the temperature of the top kilometer of the oceans by 1°C?

If the heat imbalance at the Earth's surface is one watt per square meter, and if all the heat imbalance goes toward raising the temperature of the oceans, then the time required to raise the ocean temperature by 1°C is
93 years.

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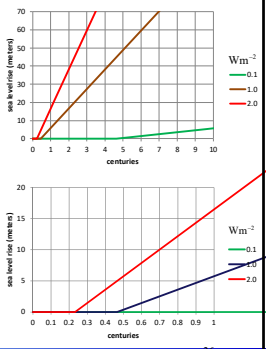
Earth's Heat Imbalance

Suppose now that all the heat imbalance first goes to raising the top kilometer of ocean by 0.5°C, and then goes to melting the ice sheets.

It takes 46.5 Wyr/m^2 to raise the temperature of a kilometer of ocean by 0.5°C. If the heat imbalance is w W/m^2, the increase would be achieved in $46.5/w$ years, after which the sea level would rise at $w/9.3$ meters per year.

At the current imbalance of 1.0 W/m^2, the ocean temperature increase would delay the sea level rise by about 46.5 years.



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melting the sea ice

Ocean warming by 1°C through 1 km depth of ocean. Heat storage is $1°C \times 10^3$ g/cm^2 × 1 cal/g × 4.19 joules/cal × area Earth × 0.7 ~ 15×10^{23} joules ~ **93 W yr/m^2**.

Ice sheet melting to raise sea level 1 meter. Assume ice starts at –10°C and ends at mean ocean surface temperature (+15°C). Energy required is 100 cal/g (80 cal/g for melting). Energy for 1 meter of sea level: 100g/cm^2 × 100cal/g × 4.19 joules/cal × area Earth × 0.7 ~1.5×10^{22} joules ~ **9.3 W yr/m^2**.

Sea ice melting (all sea ice on planet). Assume ice starts at –10°C and ends at mean ocean surface temperature (+15°C), and that sea ice covers 4% of the planet with mean thickness 2.5 m. Energy required is 250 g cm^2 × 100 cal/g (80 cal/g for melting) × 4.19 joules/cal × 0.04 × area Earth ~ 2.14×10^{22} joules ~ **1.3 W yr/m^2**.

Air warming by 1°C. The Earth's atmospheric mass is ~ 10 m of water. Heat capacity of air ~ 0.24 cal/g/°C. Energy to raise air temperature 1°C: 1°C × 1000 g/cm^2 × 0.24 cal/g/°C × 4.19 joules/cal × area Earth ~ 0.26×10^{22} joules ~ **0.32 W yr/m^2**.

Land surface warming by 1°C: The depth of penetration of a thermal wave into the Earth's crust in 10 years, weighted by ΔT, is ~10 m. With density ~ 3 g/cm^3, heat capacity ~ 0.2 cal/g/°C, and 0.29 fractional land coverage, land heat storage is 10^2 cm ×3 g/cm^3 × 0.2 cal/g/°C × 1°C ×4.19 joules/cal × area Earth × 0.29 ~ 0.37×10^{22} joules ~ **0.23 W yr**. [In a century the depth of penetration is ~3 times more than in a decade, so heat storage in a century due to 1°C warming is ~ **0.7 W yr/m^2**.]

[1]Note that 1 W sec = 1 joule, # sec/year ~ $\pi \times 10^7$, area Earth ~ 5.1×10^{18} cm^2, 1 W yr over full Earth ~ 1.61×10^{22} joules, ocean fraction of Earth ~ 0.7, 1 calorie ~ 4.19 joules.

James Hansen, et al, *Earth's Energy Imbalance: Confirmation and Implications*, SCIENCE 308 (2005), p. 1431

Math 5490
Earth's Heat Imbalance

How much heat does it take to melt all the sea ice on the Earth?

Assumptions: Ice starts at -10°C and ends up at +15°C. The ice covers 4% of the planet with a mean thickness of 2.5 meters.
Hansen: About 2.14×10^{22} joules ≈ ***1.3 Wyr/m²***

How long does it take to melt all the sea ice on the Earth?

If the heat imbalance at the Earth's surface is one watt per square meter, and if all the heat imbalance goes toward melting the sea ice, then all the sea ice would be gone in
1.3 years.

Won't happen before 2025!

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Earth's Heat Imbalance

The Good News

- Even if all the current heat imbalance goes into melting the ice sheets, it will take 700 years to melt all the ice.
- The ocean seems to be absorbing most of the heat imbalance, so we have some time before the ice sheets start melting seriously.

The Bad News

- 700 years is a long time, but that is actually a rate of 1 meter of sea level rise per decade. At that rate it may be impossible for coastal cities to adapt.
- As we have seen recently, ocean surface temperature rise is itself a serious problem.
- Once the sea level begins to rise, it could go at a rate of 1 meter per decade, so we should start preparing to adapt to that.

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Question for Discussion

Assuming an energy imbalance of 1.0 W/m2, how long would it take to rase the temperature of the entire ocean by 5 C? (Assume that the average ocean depth is 4300 meters.)

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Questions for Discussion

Assuming an energy imbalance of 1.0 W/m2, how long would it take to rase the temperature of the entire ocean by 5 C? (Assume that the average ocean depth is 4300 meters.)

Same assumptions. How long would it take to melt enough ice to raise the ocean depth by 70 meters, leaving the ocean temperature unchanged?

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Questions for Discussion

Assuming an energy imbalance of 1.0 W/m2, how long would it take to rase the temperature of the entire ocean by 5 C? (Assume that the average ocean depth is 4300 meters.)

Same assumptions. How long would it take to melt enough ice to raise the ocean depth by 70 meters, leaving the ocean temperature unchanged?

Assume that the heat imbalance is such that it takes 20,000 years to raise the temperature of the entire ocean by 5 C. What heat imbalance would account for that rise? (Assume that all other temperatures remain constant and that the ocean depth is 4400 meters.

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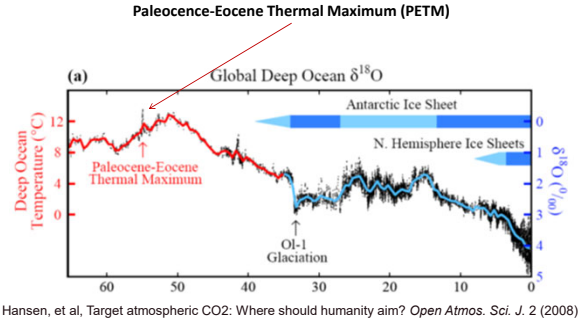
Earth's Heat Imbalance

Paleocence-Eocene Thermal Maximum (PETM)



Hansen, et al, Target atmospheric CO2: Where should humanity aim? *Open Atmos. Sci. J.* 2 (2008)

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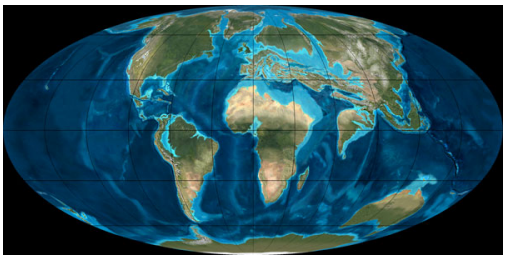
Paleocence-Eocene Thermal Maximum (PETM)



http://static.palaeontologyonline.com/Figure1.jpg

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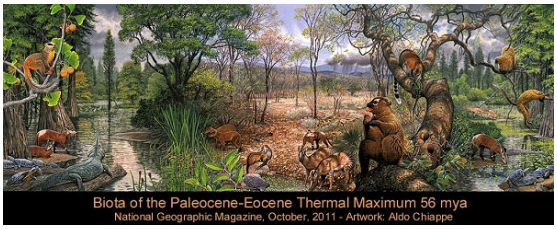
Paleocence-Eocene Thermal Maximum (PETM)



`http://maya-gaia.angelfire.com/mammals_rise_title_thm.jpg`

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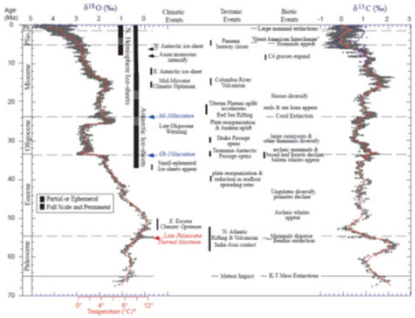

Zachos, *et al*, *Science* 292 (2001), p. 689

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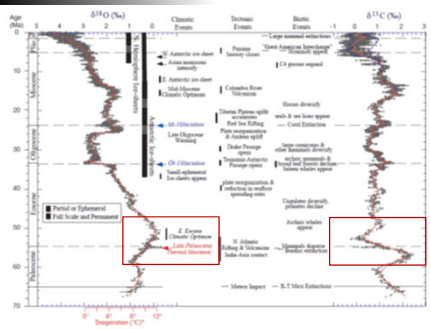

Zachos, *et al*, *Science* **292** (2001), p. 689

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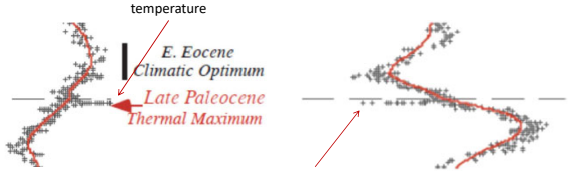
Sharp decrease in $\delta^{18}O$, interpreted as large increase in temperature



Sharp decrease in $\delta^{13}C$, interpreted as massive oxidation of organic carbon

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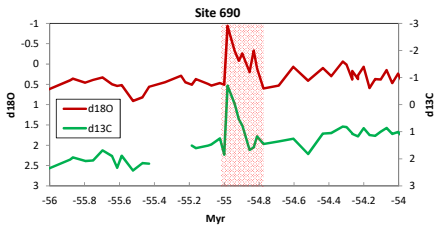
Paleocence-Eocene Thermal Maximum (PETM)

Sharp decrease in $\delta^{18}O$, interpreted as a rapid increase in temperature.

Sharp decrease in $\delta^{13}C$, interpreted as massive oxidation of sequestered organic carbon.



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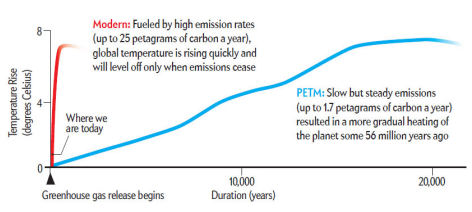
PETM vs Today

Global temperature is rising much more quickly today than it did during the PETM



Lee R. Kump, *The Last Global Warming*, Scientific American, July 2011, p 57