Math 5421

An Introduction to Mathematical Climate Models

Spring 2025
1:25 – 3:20 Tuesdays and Thursdays
Blegen Hall 155

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course website
https://www-users.cse.umn.edu/~mcgehee/Course/Math5421/

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Past and Future

What would happen if we stopped burning fossil fuels?

Conventional wisdom seems to be that both the atmospheric CO_2 concentration and the global mean temperature would stop increasing.

Why do we think that the temperature would stop increasing?

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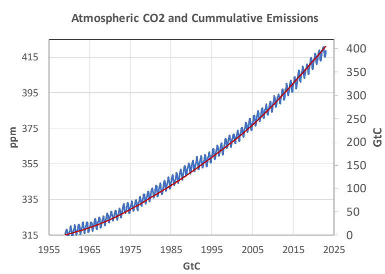
Atmospheric CO2

We analyzed the fossil fuel emissions data and the Mauna Loa CO_2 data and showed that they are correlated.



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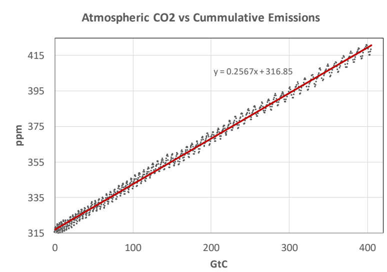

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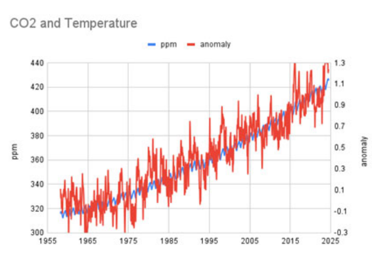
Past and Future

We analyzed the Mauna Loa CO_2 data and the Berkeley Earth temperature data and showed that they are correlated.



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Past and Future

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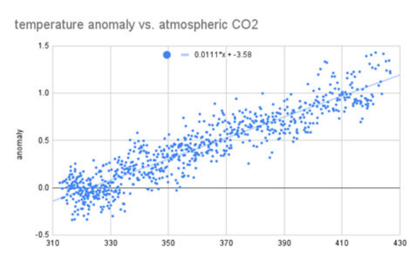

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Past and Future

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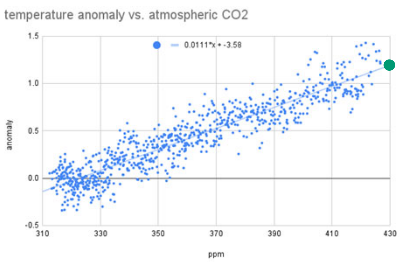

If we hold the CO2 constant, does the temperature stay fixed where it is?

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Past and Future

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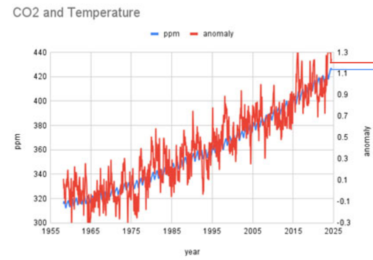

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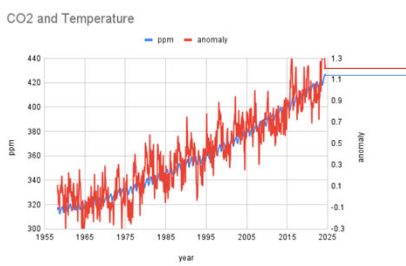

If we hold the CO2 constant, does the temperature stay fixed where it is?

Where could we look for an answer?

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Past and Future

Paleoclimate

Paleoclimatology is the scientific study of climates predating the invention of meteorological instruments, when no direct measurement data were available. As instrumental records only span a tiny part of Earth's history, the reconstruction of ancient climate is important to understand natural variation and the evolution of the current climate.

`https://en.wikipedia.org/wiki/Paleoclimatology`

What can we learn from the paleoclimate?

What have we already learned?

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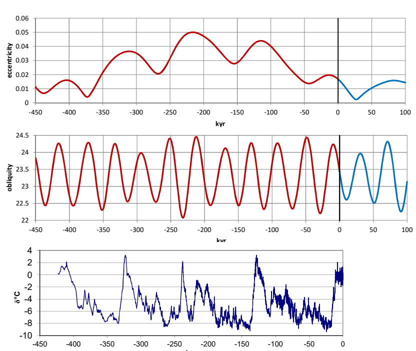
High eccentricity correlates with high GMT.

High obliquity correlates with high GMT.

Glacial cycles show a sharp peak in temperature followed by a quick decrease.



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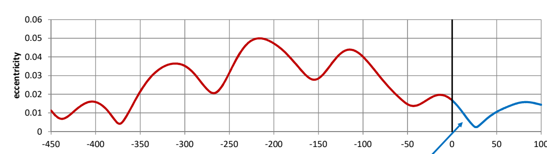

Earth's eccentricity is heading down, indicating a decent into a glaciation with lower temperatures.

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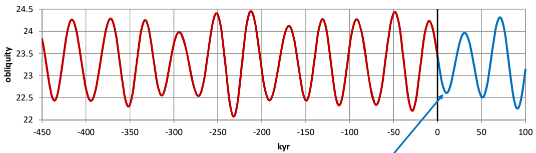

Earth's obliquity is heading down, indicating a decent into a glaciation with lower temperatures.

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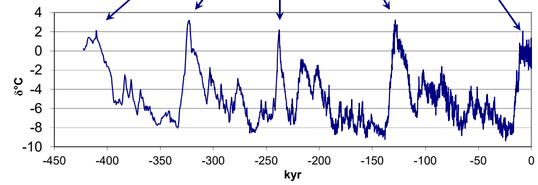
The temperature cycles have a pattern. If the pattern had persisted, we would have been heading down.



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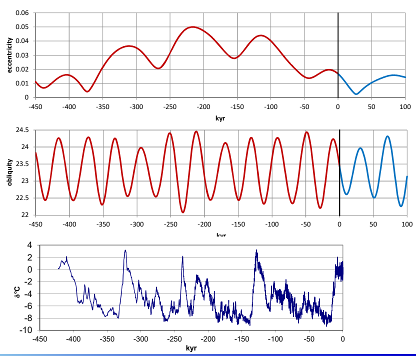
The paleoclimate evidence points to the conclusion that the Earth should be entering a new ice age.

But we're not.

Instead, the Earth is warming and the ice sheets are melting.

The climate is not following the patterns of the last million years.

Something has changed.



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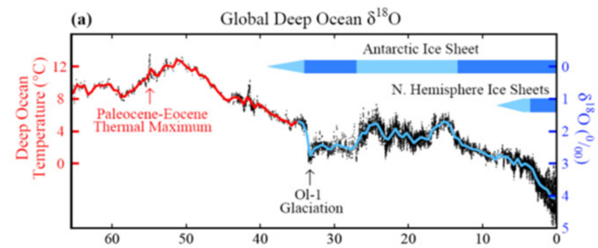
Paleoclimate

It has been a lot hotter in the past.
What do we know about the CO_2?



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

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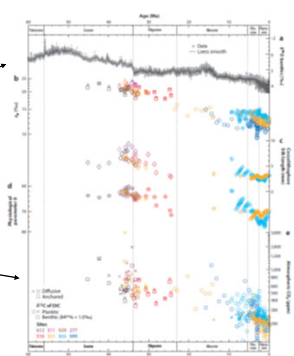
Permafrost Melt

Cenozoic Climate

temperature

atmospheric CO_2



Annu. Rev. Earth Planet. Sci. 2021. **49**:609–41

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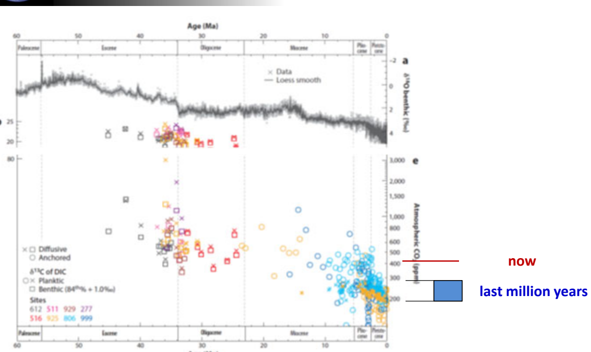
Permafrost Melt



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Permafrost Melt

Those CO_2 data are pretty poor compared to the temperature data.

Do we have anything with more detail?

Yes!

Remember Lake Vostok in Antarctica?

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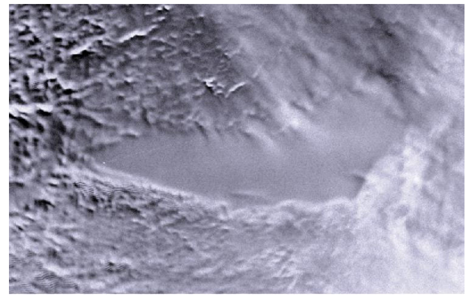
Past and Future

Remember Lake Vostok?



http://svs.gsfc.nasa.gov/vis/a000000/a000900/a000996/index.html

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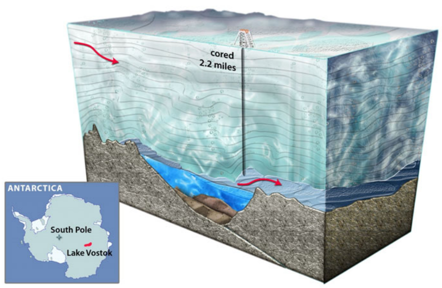
Lake Vostok



http://www.nsf.gov/news/mmg/media/images/lake_vostok_nsf_h.jpg

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Core Samples

Photographs copyright Reto Stöckli, NASA GSFC

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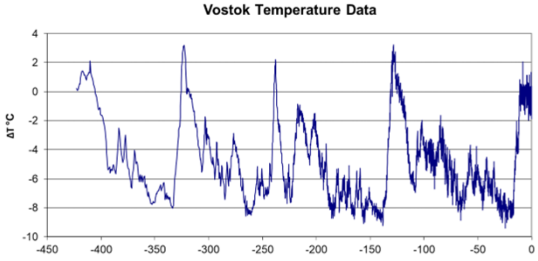
The isotopic content of the ice tells us the temperature of the atmosphere where the snow fell.

Vostok Temperature Data



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The ice trapped bubbles of air are samples of the atmosphere from when the snow compressed into ice.

The contents of the bubbles can be analyzed to determine the atmospheric CO_2 concentration from the time the air was trapped.

https://science.nasa.gov/science-research/earth-science/climate-science/core-questions-an-introduction-to-ice-cores/

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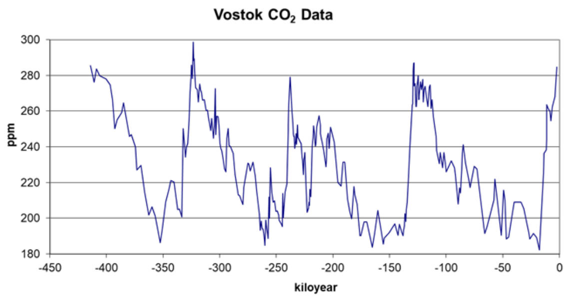

Looks a lot like the temperature data!

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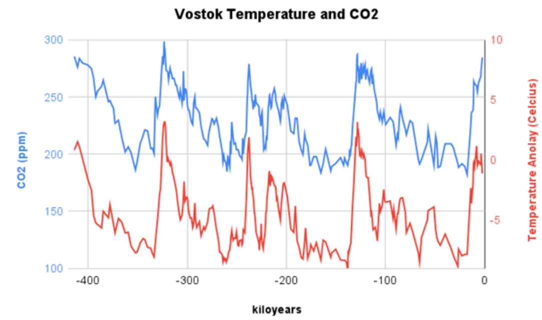
Past and Future



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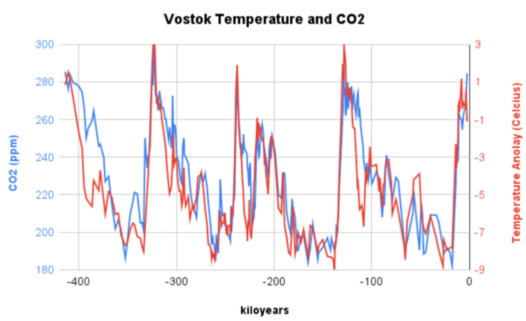

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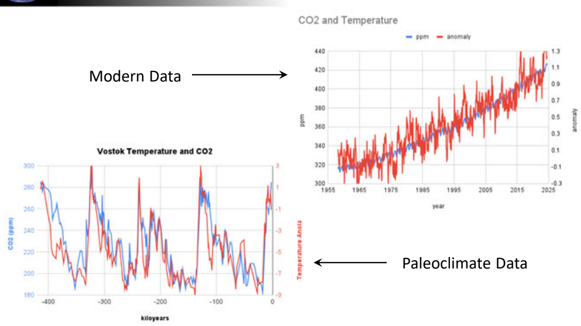

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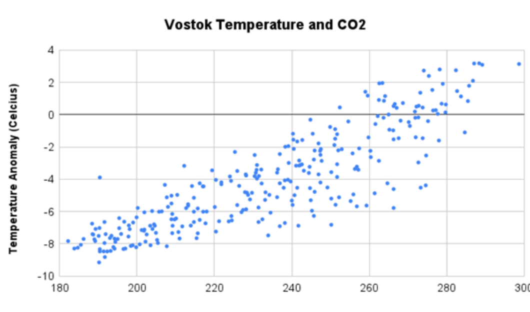

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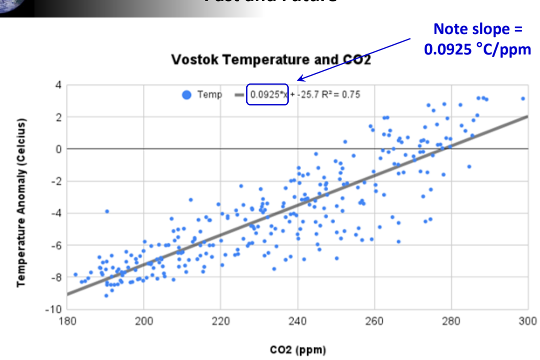

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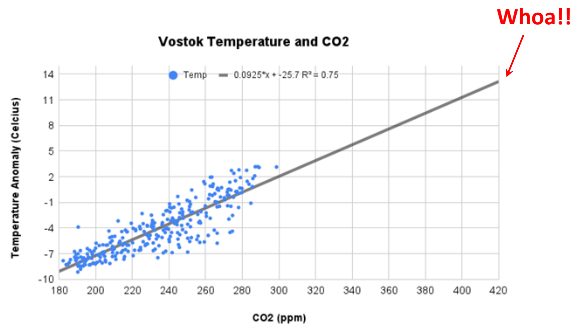

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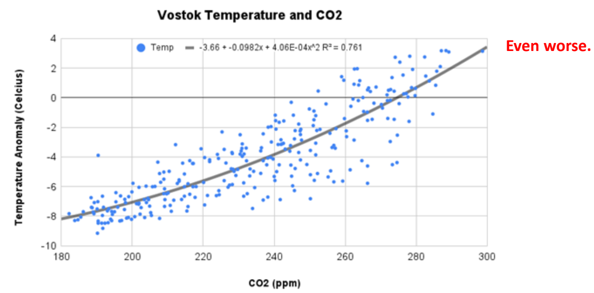
Past and Future



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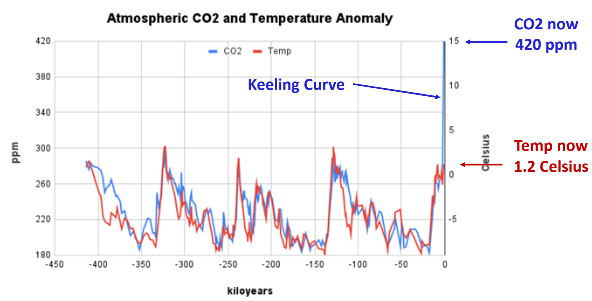
Past and Future



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Past and Future

Discussion

We have not reached the equilibrium corresponding to 420 ppm. When we do, the Antarctic temperature will have increased by 12°C.

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Polar amplification: the polar regions have twice the temperature change than equatorial regions, so the global mean temperature will only increase by 6°C.

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We have data from the last 400,000 years, where the atmospheric CO_2 never got above 300 ppm. Extrapolating to 420 ppm is only speculation.

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Permafrost Melt

Discussion

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We have data from the last 400,000 years, where the atmospheric CO_2 never got above 300 ppm. Extrapolating to 420 ppm is only speculation.

Given the kiloyear timescale for the glacial cycles, we could expect it to take centuries to reach the equilibrium. We still have time to fix the problem.

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Permafrost Melt

What would happen if we stopped burning fossil fuels?

Presumably, the atmospheric CO2 concentration would stop increasing.

What would happen to Earth's temperature?

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Past and Future

What would happen if we stopped burning fossil fuels?

The CO_2 levels in the atmosphere might start creeping down, but feedbacks like melting permafrost might continue to release CO_2.

The patterns for the last 400,000 years indicate that the temperature would continue to rise. The question remains, at what time scale? We may have time to pull carbon out of the atmosphere before the climate changes beyond our abilities to adapt.

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An Introduction to Mathematical Climate Models

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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.

$$\text{temperature change} \sim \overbrace{\text{energy in} - \text{energy out}}^{\text{heat imbalance}}$$

short wave energy from the Sun

long wave energy from the Earth

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Can we measure heat imbalance?

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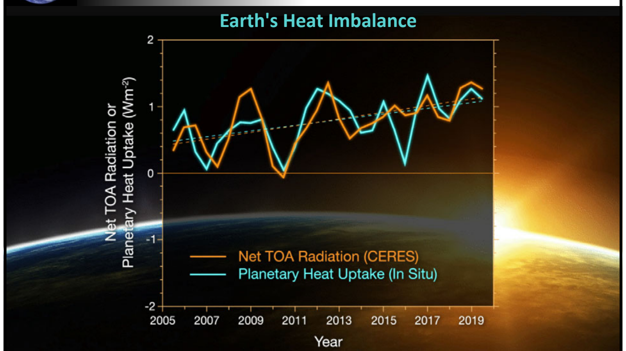
Earth's Heat Imbalance



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

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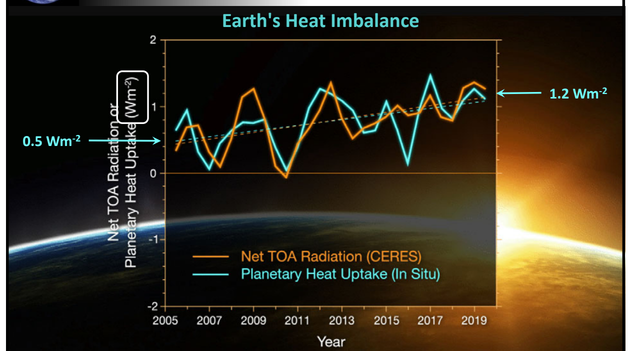
Earth's Heat Imbalance



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Earth's Heat Imbalance

2020 Heat Imbalance

1 Wm^{-2}

Surface area of Earth:
500,000,000 km^2 = 5×10^{14} m^2

Insolation over Earth's surface:
5×10^{14} W = **500,000 GW**

How much is that?

GW = gigawatt
= one billion watts
= 10^9 watts

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Earth's Heat Imbalance

2020 Heat Imbalance

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Insolation over Earth's surface:
5×10^{14} W = **500,000 GW**

How much is that?

Earth's heat imbalance:
500,000 nuclear power plants

Prairie Island Nuclear Power Plant
capacity: **1 GW**

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

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Earth's Heat Imbalance

2020 Yearly Heat Imbalance

Insolation over Earth's surface:
5×10^{14} W = 5×10^{14} Joules/second

seconds in a year:
30 million = 3×10^7

Yearly Heat Imbalance
15×10^{21} Joules = **15 zJ (zettajoules)**

Biologically Stored Energy

total coal reserves: 10^{15} kg
energy content: 3×10^7 J/kg
total energy in coal reserves: 3×10^{22} J

= **30 zJ**

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Earth's Heat Imbalance

Where is the extra heat going?

Mostly into the ocean.

How do we know?

Argo

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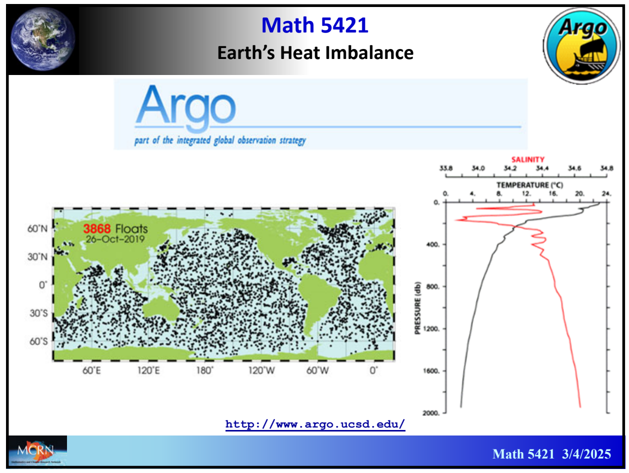

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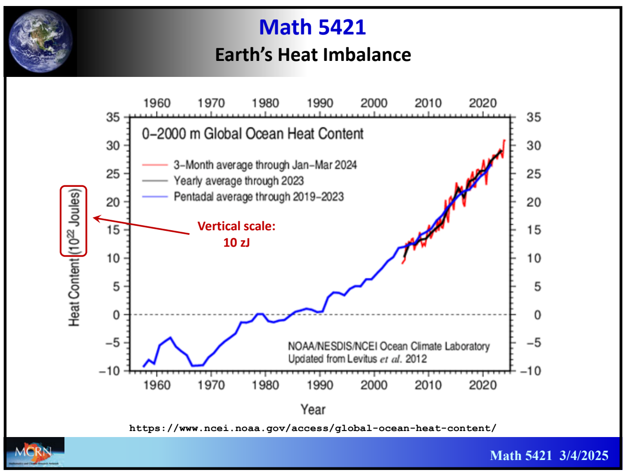

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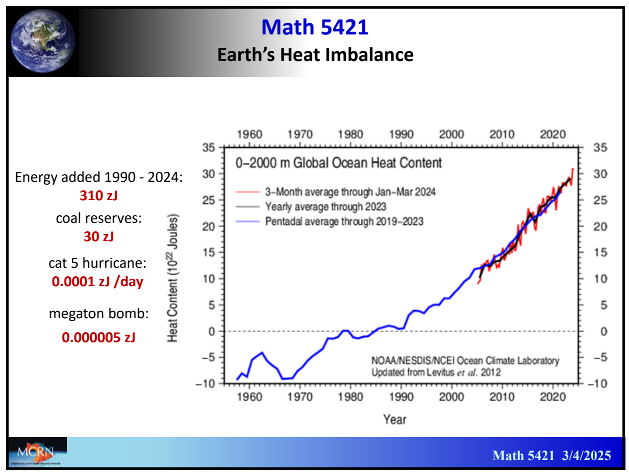

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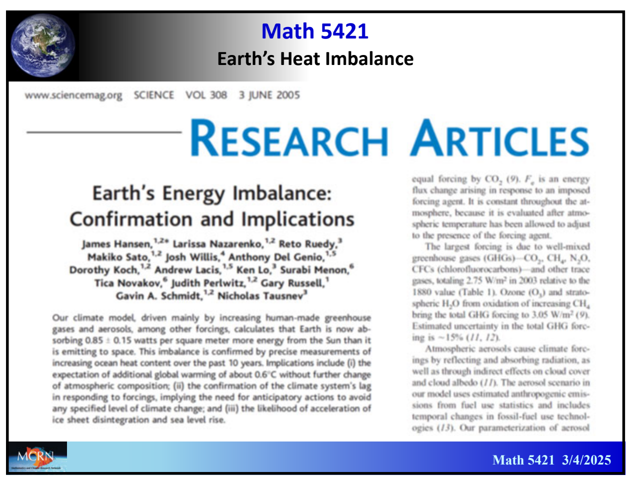

www.sciencemag.org SCIENCE VOL 308 3 JUNE 2005

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,[1,5] 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_e 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

Table S1. Planetary Heat Storage: Ocean, Ice, Air and Land.

Energy required to melt ice and warm the air, land and ocean by specified amounts.[1]

Ocean warming by 1°C through 1 km depth of ocean. Heat storage is 1°C × 10^5 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^{23} 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 10^3 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 ~ π×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

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Earth's Heat Imbalance

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What's this?

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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/cm^2 × 100cal/g × 4.19 joules/cal × area Earth × 0.7 ~1.5 × 10^{23} 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 10^3 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 ~ π×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

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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 = 16.1 zJ (zettajoules)***.

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Earth's Heat Imbalance

Table S1. Planetary Heat Storage: Ocean, Ice, Air and Land.

Energy required to melt ice and warm the air, land and ocean by specified amounts.[1]

What's this?

Ocean warming by 1°C through 1 km depth of ocean. Heat storage is 1°C × 10^5 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^{23} 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 10^3 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 ~ π×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

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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?

Assume a heat imbalance of 1 W/m2.

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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***
= 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/m^2 to turn ice sheets into 1 meter of ocean. If the heat imbalance is 1 W/m^2, the sea level would rise at the rate of 1/9.3 meters per year, or about 0.108 meters per year, or 1.08 meters per decade, or 10.8 meters per century.

How long would it take to melt all the ice?

Assume that, if all the ice melted, it would raise the sea level by 70 meters.

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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/m^2 to turn ice sheets into 1 meter of ocean. If the heat imbalance is 1 W/m^2, the sea level would rise at the rate of 1/9.3 meters per year, or about 0.108 meters per year, or 1.08 meters per decade, or 10.8 meters per century.

How long would it take to melt all the ice?

70 meters/0.1098 meters per year = **650 years**.

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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/m^2 to turn ice sheets into 1 meter of ocean. If the heat imbalance is 1 W/m^2, the sea level would rise at the rate of 1/9.3 meters per year, or about 0.108 meters per year, or 1.08 meters per decade, 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

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 of 1 W/m^2.

What if the imbalance was 2 W/m^2?

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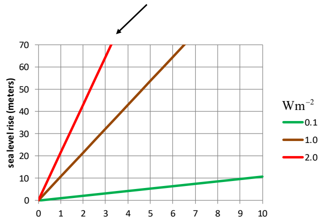
Earth's Heat Imbalance

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 of 1 W/m^2.

What if the imbalance was 2 W/m^2?
325 years



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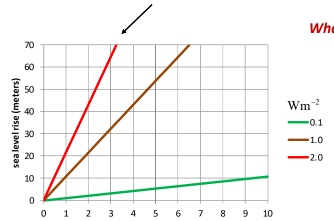
Earth's Heat Imbalance

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 of 1 W/m^2.

What if the imbalance was 2 W/m^2?
325 years

What if the imbalance was 0.1 W/m^2?



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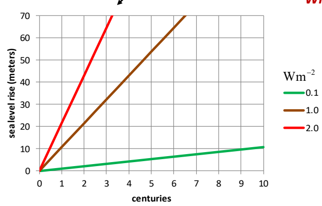
Earth's Heat Imbalance

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 of 1 W/m^2.

What if the imbalance was 2 W/m^2?
325 years

What if the imbalance was 0.1 W/m^2?
6500 years



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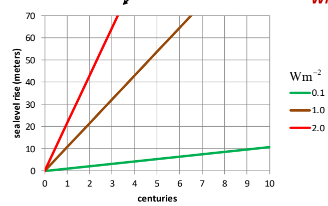
Math 5421
Earth's Heat Imbalance

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 of 1 W/m^2.

What if the imbalance was 2 W/m^2?
325 years

What if the imbalance was 0.1 W/m^2?
6500 years



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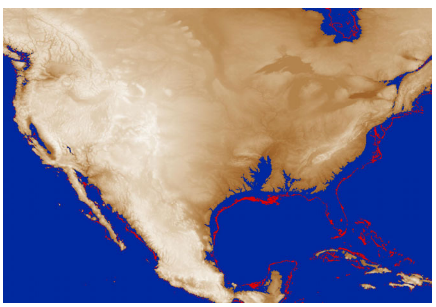
Math 5421
Earth's Heat Imbalance

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



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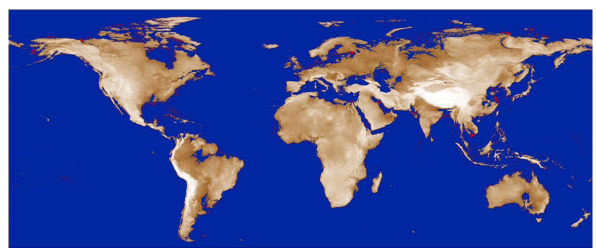
Earth's Heat Imbalance

The Modern Ice-Free Earth
Computer Simulation, Clarence Lehman, Univ. Mn. 2006



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