Why Talking About Climate Change Is So Difficult?

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Ten compound questions, with the answers I believe I might give

1. **Tad, the last time you were on this program we covered the thermodynamic foundations of civilization including power flows, material fluxes, overshoot, and the fossil amoeba. You have since published a new paper in Geophysical Research Letters presenting physical evidence that global warming has been accelerating since 2014, driven by a decline in Earth's albedo. Before we get into the mechanics of the albedo, I want to start with a personal question. You've spent four decades studying the hard sciences around petroleum and climate. Was there a point when the data you were analyzing became more than an academic exercise and you began to actually feel the climate and planetary direction we are headed?**

   Answer: The watershed moment for me was 2004, when my first paper about the corn ethanol agrofuel was published, and I was thrusted into the raging debate on the ethanol's efficacy and long-term effects on the ecosphere. In 2007, I participated in the OECD ministerial meetings in Paris on the subject of the devastation wrought by agrofuel plantations in the tropics, and earned wrath of Ms. Paula Dobriansky, the US negotiator on climate change. In 2006, I offered a new class in UC Berkeley: E^4: Earth, Environment, Energy and Economics, and wrote the first version of the course notes, which now is a 550-pages-long, still unpublished book. That course and book provided the systematic thermodynamic framing of human-caused disruptions of the ecosphere. After several years, especially at KAUST in Saudi Arabia, the course evolved towards a fossil-fuel-grounded story of global climate change. A few chapters from that book were adapted into the now published preprint of my book on climate change. Working on the supply of oil and gas, and their ecological and climate impacts gave me a unique understanding of how gravely our global civilization is unsustainable.

2. **One of the most striking findings in your paper is a surprisingly simple relationship: both the hottest and coldest temperatures recorded each year have been rising almost linearly with cumulative CO2 emissions since 1850. This isn't tied to time or annual emissions, but instead with the total cumulative amount of CO2 humanity has added to the atmosphere. Can you explain this relationship, and why cumulative emissions rather than annual emissions is the right variable, and why you find this**

to be one of the most direct and compelling pieces of evidence linking fossil fuel combustion to planetary warming?

Answer:

First of all, Nate, not just the coldest and warmest temperatures on Earth have been increasing linearly with cumulative CO_2 emissions, but also the global mean surface temperature (GMST), the global mean seawater surface temperature (SST), and the global mean land surface temperature (GMLST). The simplest explanation of this linearity of increases of the various global temperatures with cumulative CO_2 emissions goes like this: Because the atmosphere is still operating near the same basic state, same dominant gases, same oceans, same cloud regimes, and same tropospheric structure. Thus a warming of 1°C today produces nearly the same fractional increase in water vapor as a warming of 1°C did fifty or seventy years ago.

$$\Delta T \xrightarrow{\text{Clausius–Clapeyron}} \Delta q \xrightarrow{\text{greenhouse effect}} \Delta F_{\mathrm{WV}} \xrightarrow{\text{warming}} \Delta T$$

Observations show that relative humidity does not change dramatically as the climate warms. Different regions of the Earth maintain different characteristic humidity levels—for example, the Sahara remains much drier (25% RH) than the tropical oceans (85% RH)—but the average relative humidity within each region tends to remain approximately constant. Consequently, as temperature increases, atmospheric water-vapor concentrations rise approximately according to the Clausius–Clapeyron relation, increasing the greenhouse effect and amplifying the initial warming.

A simplified analytic theory behind the translation of cumulative CO_2 emissions into ΔT was developed by Matthews et al in 2009 and MacDougall et al. in 2013-2017, in a series of brilliant papers that introduced the transient climate response to cumulative CO_2 emissions metric (TCRE). MacDougall stated in 2016 that "The [TCRE] metric was developed once researchers noticed that the cumulative CO_2 versus temperature change curve [*inverting the cause and effect*] was nearly linear for almost all Earth system model output."

Formally

$$\begin{aligned} \mathrm{TCRE}(t) &= \frac{\Delta T(t)}{E(t)} = \frac{\Delta T}{\Delta c_a}\,\frac{\Delta c_a}{E} \\ E(t) &= \int_{-\infty}^{t} r(\tau)\mathrm{d}\tau \end{aligned} \tag{1}$$

Here $E(t)$ is the cumulative CO_2 emissions at time t and r is the rate of emissions. Notice the an operational definition of the "$-\infty$" might be the year 1850 or 1976.

In order for TCRE to be constant for the oceans since 1850, and for the Earth piecewise during 1850-1976 and 1976-2024 – both slopes on the right-hand-side of Equation $(1)_1$ must be constant. It turns out that $\Delta c_a/E$ is constant, and so is $\Delta T/\Delta c_a$.

Both these insights are independent of GCMs and tell us that the Earth tries to maintain stasis for as long as she can. But GCMs tell us why exactly this happens. MacDougall et al. showed that the path-independence of TCRE arises from the partitioning ratio of anthropogenic carbon between the ocean and the atmosphere being almost the same as the partitioning ratio of enhanced radiative forcing between the ocean and space.

The approximate constancy of the ratio

$$\frac{\Delta T}{\Delta c_a}$$

over multi-decadal periods is not obvious a priori because neither the greenhouse effect nor the carbon cycle is strictly linear. Several physical mechanisms combine to produce this near-linearity:

(a) **The logarithmic forcing law for CO_2.**
Radiative forcing increases approximately as

$$\Delta F_{\mathrm{CO_2}} = 5.35 \ln\left(\frac{c_a}{c_{a,0}}\right),$$

which becomes nearly linear over limited concentration ranges such as 278–435 ppm.

(b) **Approximately constant climate sensitivity.**
Over the observed temperature range, the Earth's net radiative restoring feedback remains approximately linear:

$$\Delta T \approx \lambda \, \Delta F,$$

where λ varies only weakly with temperature.

(c) **The dominance of water-vapor feedback.**
Water vapor is the dominant greenhouse substance in the atmosphere, but it acts primarily as a feedback rather than a forcing. As the atmosphere warms, the Clausius–Clapeyron relation allows it to retain approximately 7% more water vapor per degree Celsius of warming. Because relative humidity remains nearly constant on global scales, atmospheric water-vapor concentrations increase with temperature. The additional water vapor enhances infrared absorption and amplifies the initial warming. Over the historical range of climate change, however, this amplification changes only gradually, so the effective gain of the water-vapor feedback remains approximately constant. As a result, each increment of warming produces roughly the same additional greenhouse amplification, helping to maintain the observed near-linearity between global temperature and atmospheric CO_2 concentration.

(d) **Slow evolution of cloud feedbacks.**
Cloud feedbacks are highly uncertain but appear to vary much more slowly than the underlying warming signal, allowing them to be approximated by a nearly constant effective feedback over the historical interval.

(e) **Ocean heat uptake acts as a low-pass filter.**
The oceans absorb most of the excess energy, damping short-term variability and smoothing the temperature response to forcing.

(f) **The airborne fraction of emitted CO_2 is approximately constant.**
Historically, roughly 40–50% of anthropogenic CO_2 emissions have remained in the atmosphere, implying

$$\Delta c_a \propto E,$$

where E is cumulative CO_2 emissions.

(g) **Compensating nonlinearities.**

The logarithmic dependence of forcing on CO_2 concentration and the increasing airborne burden of carbon are partly offset by the growth of feedbacks and thermal inertia, producing an approximately linear temperature response over the historical range.

Consequently,

$$\Delta T \propto \Delta c_a \propto E,$$

which explains why both the transient climate response to cumulative carbon emissions (TCRE) and the observed relationship between global temperature and cumulative CO_2 emissions are approximately constant.

Illustration 14. Major components of the Earth's radiative forcing. Shown are the principal radiative forcing components used in our climate model: the warming effect of increasing atmospheric CO_2, the mean net negative forcing from volcanic aerosols, land-use change, and cryosphere changes, the CERES-measured top-of-atmosphere forcing associated with the decline of planetary albedo, and an effective residual forcing term that accounts for clouds and other processes prior to the satellite era.

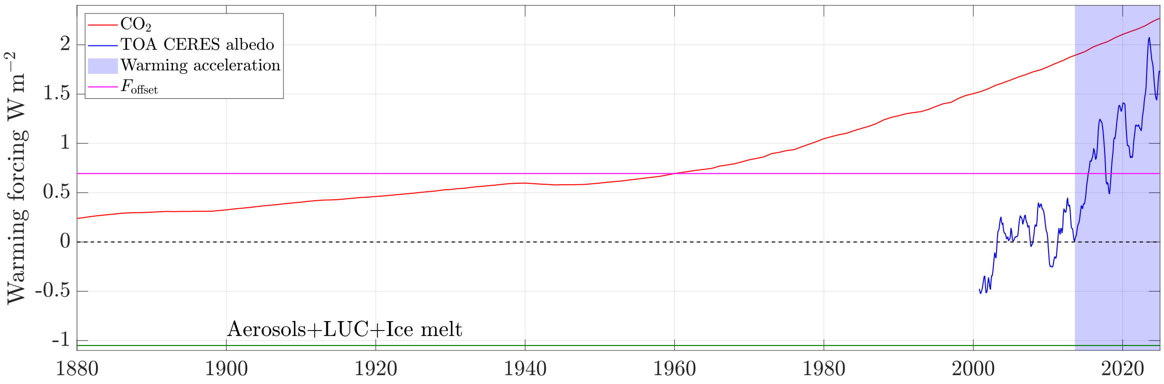


Figure 1: Time evolution of the major forcing components. Of particular interest is the rapid increase in albedo-related forcing after approximately 2014, indicating that the Earth began absorbing substantially more solar energy. This feature is not merely a visual impression. Three independent change-point diagnostics identify a statistically significant transition during 2014–2015. The Pettitt test places the initial shift near 2014.2, while the Bayesian and Bai–Perron analyses identify a subsequent acceleration near 2015.1. Together, these results suggest a transition to a persistently higher absorbed-shortwave-radiation regime.

3. **Your new paper presents a highly consequential finding that demonstrates an acceleration in global warming since 2014 on top of greenhouse gases, due to declining planetary albedo. Can you walk us through what albedo is, how we are actually measuring this, and why a seemingly small change turns out to matter so much?**

   Answer: Climate is controlled by the amount of sunlight absorbed by Earth and the amount of infrared energy emitted to space. These quantities – together with their difference–define Earth's radiation budget (ERB). The Clouds and the Earth's Radiant Energy System (CERES) project provides satellite-based observations of ERB and clouds. NASA provides measurements from CERES instruments flying on several satellites along with data from many other instruments to produce a comprehensive set of ERB data products for climate, weather and applied science research.

   Global warming is driven by an imbalance in the Earth's energy budget, often referred to as *net radiative forcing*. In our simplified framework, this imbalance is represented by four principal terms. The largest positive contribution is the greenhouse-gas forcing caused by the steadily increasing concentration of atmospheric CO_2. Although carbon dioxide is only a trace constituent of the atmosphere, it plays an outsized role in regulating the Earth's average temperature. I will return to this crucial point later.

   The second term is a net negative forcing that combines the cooling effects of volcanic aerosols with the influences of land-use change and cryosphere changes. The remaining two terms can only be estimated directly from modern satellite observations, which began around 2000. The first is the top-of-atmosphere (TOA) forcing associated with changes in the Earth's reflectivity, or planetary albedo, measured by the CERES satellites. The second is an effective residual forcing that represents the combined influence of clouds and other processes not explicitly included in the model and extends the reconstruction back to 1880.

4. **You write that only about 20% of the radiative perturbation from declining albedo shows up as surface warming, while the other 80% is absorbed by the oceans. What does that mean for what's already locked in, even if we stopped everything tomorrow?**

   One of the most intriguing features of recent climate observations is that several seemingly independent indicators begin to change at approximately the same time. Around 2014, global temperatures start to accelerate, Antarctic sea ice enters a period of rapid decline, ocean heat uptake increases, and satellite observations indicate that the Earth is reflecting less sunlight back into space.

   My working hypothesis is that these changes are connected and may reflect a broader reorganization of the climate system. However, the observational record is still relatively short, and science advances by testing hypotheses rather than by declaring conclusions prematurely. At present, the evidence is sufficient to identify a remarkable coincidence in timing, but not yet sufficient to establish a definitive causal mechanism.

   What we can say with confidence is that the climate system observed by satellites since about 2014 appears different from the one observed during the first decade of the twenty-first century. Whether this marks the emergence of a new climate regime or an episode of unusually persistent natural variability remains an open question. The answer will become clearer only as the observational record continues to lengthen. Our simple climate model does a remarkably good job reproducing the evolution of global mean surface temperature (GMST) from 1880 to the present. With the forcing history prescribed, the two most important model parameters are the equilibrium climate sensitivity, λ, which converts radiative forcing into a temperature response, and the attenuation of the observed planetary-albedo forcing by ocean heat uptake.

One of the most interesting results is that only about 20% of the top-of-atmosphere radiative perturbation associated with the decline in planetary albedo appears directly as an increase in GMST. The remaining 80% is absorbed by the oceans, where it is stored as heat. In this sense, the oceans act as a giant low-pass filter, damping short-term fluctuations in the Earth's energy balance and delaying their full expression in surface temperature. Rather than warming the atmosphere immediately, most of the excess energy is mixed downward into the upper ocean.

Our best-fit model suggests that this additional heat is distributed through roughly the upper 200–300 meters of the ocean. Because seawater has an enormous heat capacity, this layer can absorb vast quantities of energy while producing only a modest increase in temperature. The consequence is both reassuring and troubling: reassuring because the oceans temporarily buffer the rate of atmospheric warming, and troubling because the accumulated heat remains in the climate system for decades, committing the Earth to additional warming long after the initial forcing has occurred.

Illustration 14. Major components of the Earth's radiative forcing. Shown are the principal radiative forcing components used in our climate model: the warming effect of increasing atmospheric CO_2, the mean net negative forcing from volcanic aerosols, land-use change, and cryosphere changes, the CERES-measured top-of-atmosphere forcing associated with the decline of planetary albedo, and an effective residual forcing term that accounts for clouds and other processes prior to the satellite era.

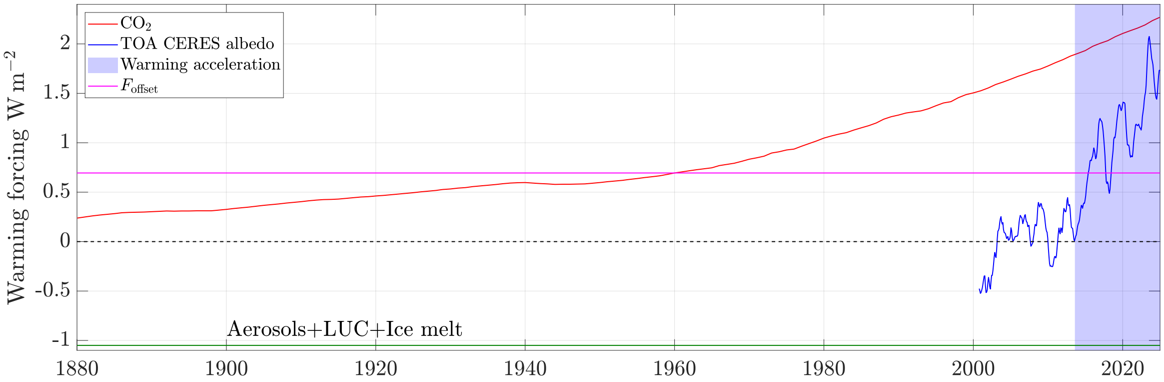


Figure 2: Time evolution of the major forcing components. Of particular interest is the rapid increase in albedo-related forcing after approximately 2014, indicating that the Earth began absorbing substantially more solar energy. This feature is not merely a visual impression. Three independent change-point diagnostics identify a statistically significant transition during 2014–2015. The Pettitt test places the initial shift near 2014.2, while the Bayesian and Bai–Perron analyses identify a subsequent acceleration near 2015.1. Together, these results suggest a transition to a persistently higher absorbed-shortwave-radiation regime.

Illustration 15. A Surprisingly Simple Explanation of Global Warming. Despite its simplicity, the four-component energy-balance model captures the evolution of global mean surface temperature (GMST) remarkably well between 1880 and the present. The agreement improves further when the observed decline in planetary albedo is included explicitly, suggesting that reduced reflection of sunlight may have contributed to the recent acceleration of global warming.

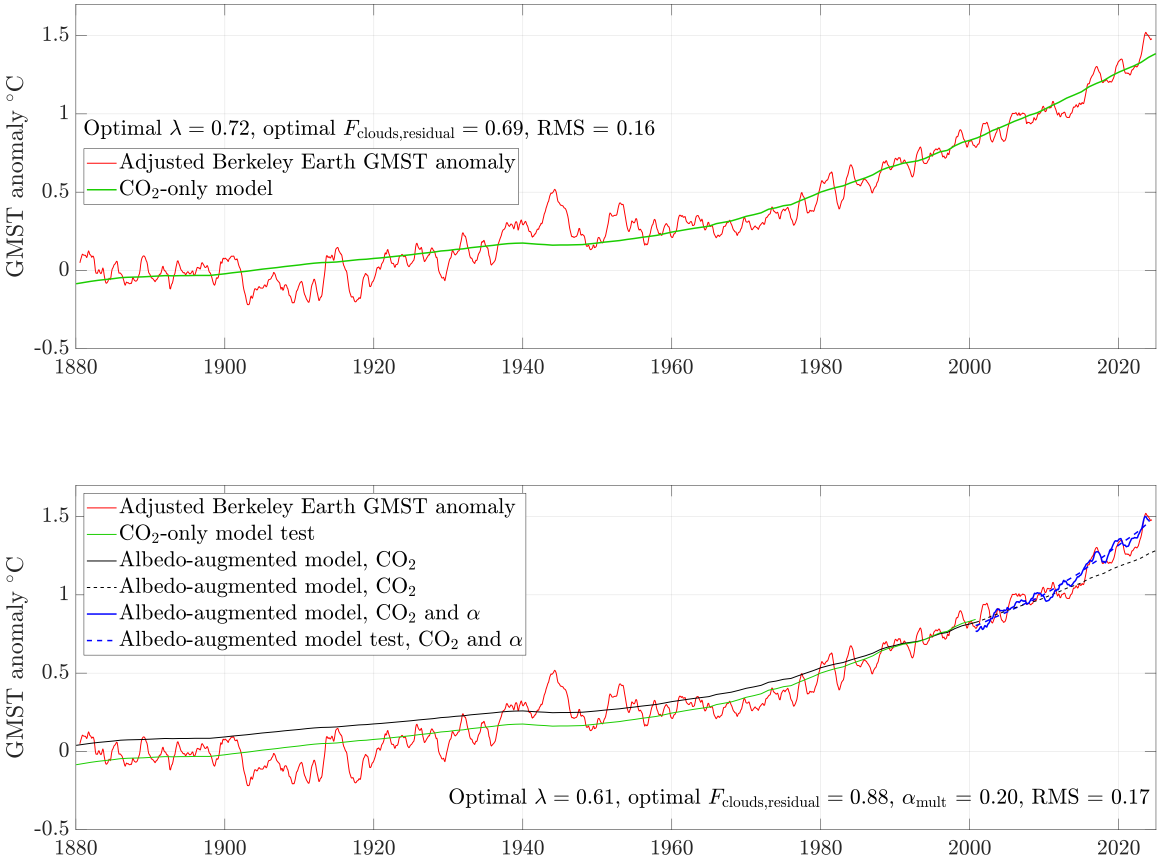


Figure 3: (**Top**) The null hypothesis assumes that changes in GMST are driven solely by the radiative forcing associated with increasing atmospheric CO_2. (**Bottom**) The alternative hypothesis includes both CO_2 forcing and the additional forcing arising from the observed decline in planetary albedo measured by the CERES satellites. The albedo-augmented model provides a statistically superior fit to the observed temperature record, particularly during the recent period of accelerated warming.

Illustration 16. The Earth's atmosphere gets the headlines, but the oceans get most of the heat. This chart summarizes the central result of our *Geophysical Research Letters* paper. The left panel shows the modeled GMST response to the observed CERES planetary-albedo forcing after attenuation by the upper ocean. Several effective mixed-layer depths are considered, ranging from 50 to 1000 m. Also shown are the raw CERES top-of-atmosphere (TOA) albedo anomaly and the same anomaly scaled by a factor of 0.2. The comparison suggests that only about 20% of the radiative perturbation associated with declining planetary albedo is expressed directly as surface warming. The remaining 80% is absorbed by the oceans. The best agreement with observations is obtained when the excess heat is distributed through the upper 200–300 m of the ocean. In effect, the oceans act as a giant low-pass filter on the Earth's energy balance, damping short-term fluctuations and delaying their full expression in surface temperature. The right panel shows the corresponding cumulative heat uptake implied by the filtered CERES shortwave anomaly for different ocean depths, together with the cumulative heat absorbed at the top of the atmosphere. Over the 24-year CERES record, an effective upper-ocean layer approximately 300 m deep absorbs most of the additional energy associated with the observed decline in planetary albedo.

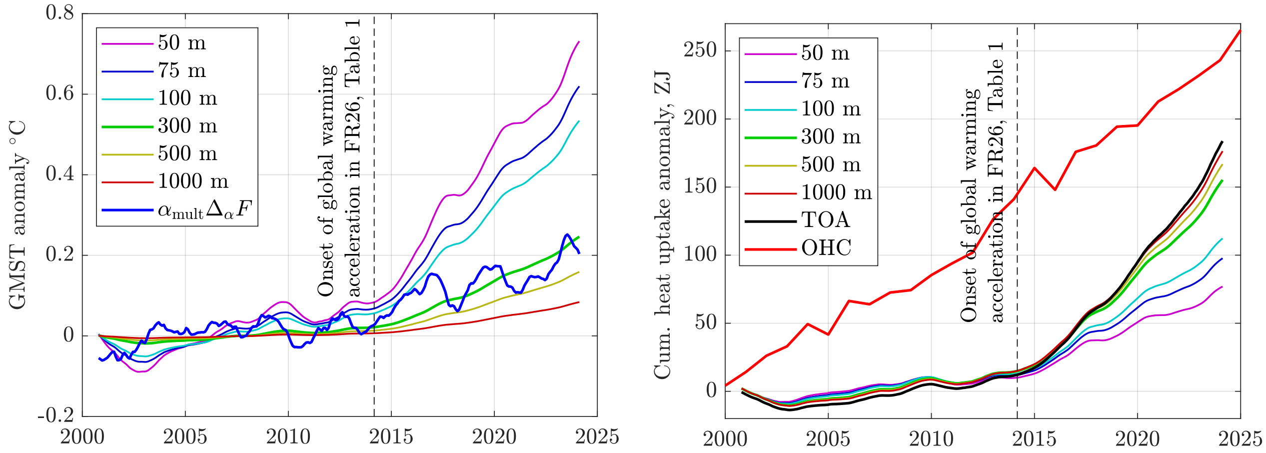


Figure 4: (**Left**) Modeled GMST response to the observed decline in planetary albedo for different effective upper-ocean depths. The attenuation of the temperature response indicates that most of the additional absorbed solar energy is stored in the oceans rather than immediately warming the atmosphere. (**Right**) Corresponding cumulative heat uptake anomalies. The comparison suggests that an effective upper-ocean layer approximately 200–300 m deep absorbs most of the excess energy associated with the observed albedo decline, providing a physically consistent explanation for the muted surface-temperature response. The red Ocean Heat Content (OHC) series is shifted downward by 60 ZJ to set its value to zero in January 2000, enabling direct comparison of the slopes of the two curves. Following the pronounced post–March 2014 increase in slope, the cumulative heat uptake curve exhibits a smaller magnitude but a steeper trend than the OHC curve. This divergence is consistent with the hypothesis that declining planetary albedo contributes to the recent acceleration of Earth-system heat uptake.

5. **What is Planck's blackbody radiation law?**

Answer:

To understand the greenhouse effect, we first need to understand how warm objects emit energy.

Everything around us emits electromagnetic radiation. A candle flame glows visibly because it is hot. A human body also emits radiation, but at much longer wavelengths that are invisible to our eyes and can only be detected with an infrared camera. The hotter an object becomes, the more energy it emits and the shorter the wavelength at which most of that energy is concentrated.

In 1900, the German physicist **Max Planck** discovered the mathematical law that describes this emission. His result, now known as **Planck's blackbody radiation law**, tells us how much energy is emitted at each wavelength by an ideal object called a *blackbody*—an object that absorbs all incoming radiation and emits the maximum possible amount of thermal radiation at a given temperature.

The detailed mathematical expression is

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{\exp\left(\dfrac{hc}{\lambda k_B T}\right) - 1},$$

where T is the temperature, λ is the wavelength, h is Planck's constant, c is the speed of light, and k_B is Boltzmann's constant.

Fortunately, the audience does not need to remember this equation. What matters are its consequences.

(a) **Hotter objects emit more energy.**
The total energy emitted by a blackbody increases very rapidly with temperature. In fact,

$$F = \sigma T^4,$$

where σ is the Stefan–Boltzmann constant. Doubling the temperature increases the emitted energy by a factor of sixteen.

(b) **Hotter objects emit at shorter wavelengths.**
The wavelength at which emission is strongest is given by Wien's law,

$$\lambda_{\max} = \frac{2898}{T},$$

where $\lambda_{\max}$ is measured in micrometers and T in kelvin.

(c) **Every object has its own thermal fingerprint.**
A hot star, a campfire, a human body, and the Earth all emit different spectra because they have different temperatures.

For example, the surface of the Sun has a temperature of approximately 5800 K. Its emission peaks near

$$\lambda_{\max} \approx 0.5\ \mu\text{m},$$

which lies in the visible part of the spectrum.

The Earth's surface, by contrast, has an average temperature of about 288 K. Its emission peaks near

$$\lambda_{\max} \approx 10\ \mu\text{m},$$

in the infrared part of the spectrum.

This difference is fundamental to climate. The Earth receives mostly visible sunlight from the hot Sun, but it loses energy by emitting infrared radiation. Greenhouse gases such as water vapor, carbon dioxide, methane, and ozone absorb part of this outgoing infrared radiation, slowing the escape of heat to space.

Thus, Planck's law provides the foundation for understanding the Earth's energy balance, the greenhouse effect, and ultimately global warming. Without Planck's discovery, modern climate science would not exist.

6. **What is the greenhouse effect ?**

   Answer:

   The term *greenhouse effect* is actually a bit misleading. Earth does not have a glass roof like a greenhouse. A real greenhouse stays warm mainly because the glass suppresses convection. The atmospheric greenhouse effect operates differently: certain gases absorb and re-emit infrared radiation, making it more difficult for heat to escape directly to space.

   Because this topic is often misunderstood, it helps to look at the Earth's infrared emission spectrum. The chart shows the thermal radiation emitted by the Earth's surface and the smaller amount that actually escapes to space. The difference between these two curves is the greenhouse effect in action.

   Notice the relatively transparent regions between approximately 790–974 cm^{-1} and 1100–1240 cm^{-1}. These are known as *atmospheric windows*. In these spectral intervals, infrared radiation can escape directly from the surface to space. The jagged structure of the observed spectrum reflects variations in the emissivity of rocks, soils, vegetation, and oceans.

   Outside these windows, greenhouse gases absorb infrared radiation strongly. The dominant absorbers are water vapor (H_2O), carbon dioxide (CO_2), ozone (O_3), methane (CH_4), and nitrous oxide (N_2O). Each gas absorbs radiation at specific wavelengths corresponding to the rotational and vibrational motions of its molecules.

   Moving from left to right in the chart, the first broad absorption region is produced primarily by rotational transitions of water vapor. Next comes the strongest absorption band of carbon dioxide, centered near 667 cm^{-1} (15 μm). Farther to the right lies the prominent ozone band near 1042 cm^{-1} (9.6 μm), caused by the asymmetric stretching vibration of the ozone molecule. Additional broad absorption features arise from water vapor and carbon dioxide at shorter wavelengths.

   The shaded area between the ideal blackbody emission from the Earth's surface and the radiation observed at the top of the atmosphere represents energy that does not escape directly to space. Instead, it is absorbed and re-emitted within the atmosphere. This trapped energy is what we call the **greenhouse effect**.

Water is the most important greenhouse agent in the present-day atmosphere. Water vapor accounts for roughly 50–60% of the greenhouse effect, while clouds contribute an additional 15–25%. Carbon dioxide is responsible for approximately 15–25%, with ozone, methane, nitrous oxide, and other gases contributing the remaining 5–10%.

Yet carbon dioxide occupies a special role. Water vapor responds rapidly to temperature changes, whereas atmospheric CO_2 can remain elevated for centuries. By influencing the average temperature of the planet, carbon dioxide controls how much water vapor the atmosphere can hold. A cooler atmosphere contains less water vapor; a warmer atmosphere contains more. In this sense, carbon dioxide acts as the Earth's long-term climate control knob, while water vapor serves as a powerful amplifier of the warming.

The greenhouse effect can be summarized in three steps:

(a) Greenhouse gases make the atmosphere partially opaque to infrared radiation, causing the Earth to radiate heat to space from higher, colder layers of the atmosphere rather than directly from the surface.

(b) Adding more greenhouse gases raises the effective altitude from which the Earth radiates to space. Because temperature generally decreases with height in the lower atmosphere, these higher layers are colder and emit less infrared radiation.

(c) To restore the balance between absorbed sunlight and emitted infrared radiation, the surface and lower atmosphere must warm until the Earth again radiates as much energy to space as it receives from the Sun.

The signature of this process is visible directly in the observed spectrum. The deep "ditch" centered near 667 cm^{-1} marks the absorption band of carbon dioxide. A second prominent notch near 1042 cm^{-1} is produced by ozone. These missing portions of the spectrum represent energy that would otherwise escape to space were it not absorbed by greenhouse gases.

The broad depressions on either side of these features reveal the influence of water vapor, which lowers the effective radiating temperature far below the temperature of the Earth's surface. Together, these spectral fingerprints provide direct observational evidence of the greenhouse effect and explain why the Earth's average surface temperature is approximately 15°C instead of the roughly $-18°$C expected for a planet without an infrared-absorbing atmosphere.

Illustration 17. Seeing the Greenhouse Effect from Space. The jagged black curve shows the outgoing infrared radiation measured at the top of the atmosphere by NASA's IRIS instrument aboard the Nimbus 4 satellite. The horizontal axis is the spectroscopic wavenumber, $\tilde{\nu}$, equal to the inverse of wavelength expressed in centimeters. Lower wavenumbers correspond to longer wavelengths and lower photon energies. The observation was made over North Africa, where the surface temperature was approximately 26 °C (299 K). The smooth red curve represents the ideal Planck blackbody spectrum emitted by a surface at that temperature. If the Earth had no atmosphere, the observed spectrum would closely follow this red curve. Instead, large portions of the outgoing radiation are absorbed by atmospheric gases before they can escape to space. As a result, the Earth radiates to space as though it were much colder, with an effective emission temperature of only about 255 K. The difference between the surface temperature and the effective radiating temperature is caused by the greenhouse effect: the absorption and re-emission of infrared radiation by water vapor, clouds, carbon dioxide, ozone, methane, and other greenhouse gases. In this particular observation, the greenhouse effect maintained a surface temperature approximately 44 K warmer than the effective temperature at which the Earth radiated energy to space.

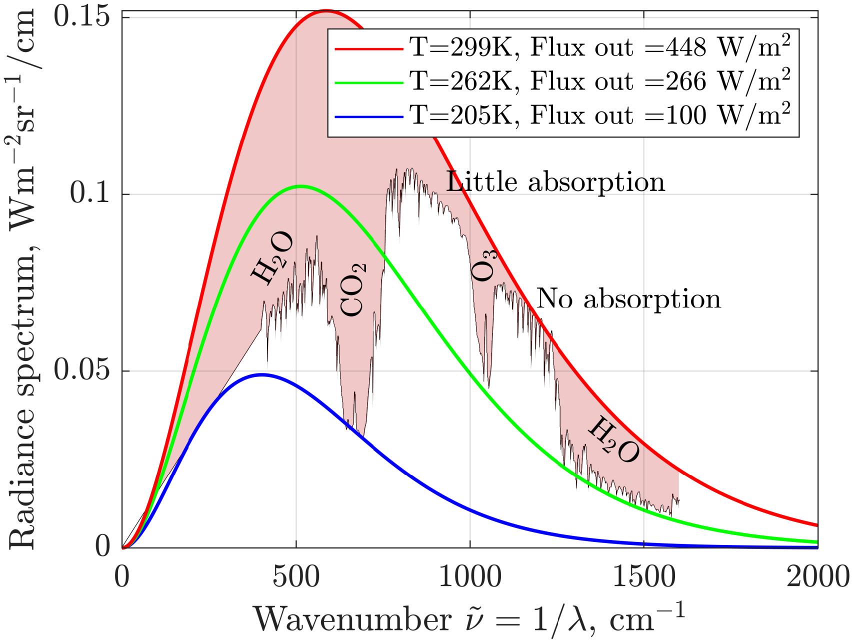


Figure 5: Outgoing longwave radiation spectrum of the Earth (black curve) measured by the IRIS instrument on NASA's Nimbus 4 satellite on May 5, 1970. The corresponding wavelengths range from approximately 6.3 to 25 μm, spanning the mid- and far-infrared regions of the electromagnetic spectrum. The red curve is the Planck blackbody spectrum for a surface temperature of 299 K. The shaded pink area represents thermal radiation absorbed by greenhouse gases before it can escape to space. The deep spectral features reveal the fingerprints of water vapor, carbon dioxide, ozone, and other atmospheric constituents. These pioneering satellite observations provided some of the earliest direct measurements of the Earth's greenhouse effect and laid the foundation for modern monitoring of the planetary energy balance.

7. **Why Is Climate Change So Difficult to Understand — and Even Harder to Discuss?** *Answer:* There are at least three broad reasons.

   The first is evolutionary. Human beings evolved to respond to immediate, visible threats: a predator, a fire, an enemy attack, or a failed harvest. We are much less equipped to recognize slow-moving dangers that unfold over decades and centuries. Climate change is precisely such a threat. Most people associate it with dramatic events such as wildfires, floods, droughts, heat waves, and severe storms. These events can be devastating, but they are only the most visible symptoms of a deeper problem.

   Some of the most consequential impacts develop slowly and therefore attract less attention. The retreat of glaciers in the Himalayas threatens long-term water supplies for hundreds of millions of people. The continued loss of ice from Antarctica and Greenland is raising sea level, placing many of the world's largest cities, ports, and coastal regions at increasing risk. Because these changes occur gradually, societies often postpone action until the consequences become difficult or impossible to reverse on human time scales.

   The second reason is complexity. Understanding climate change requires assembling evidence from many fields, including physics, chemistry, oceanography, meteorology, ecology, and economics. Imagine a jigsaw puzzle with ten thousand pieces. Even for an educated observer, assembling the full picture is challenging. For those who have not had the opportunity to study the relevant science, many pieces of the puzzle are simply missing. It is therefore understandable that the overall picture can appear confusing or incomplete.

   The third reason is ideological and cultural. When people encounter phenomena they do not fully understand, they often turn to familiar beliefs, political identities, or simplified explanations. This tendency creates fertile ground for misinformation and for individuals or organizations that deliberately distort scientific findings. Climate science is especially vulnerable because its conclusions emerge from a vast body of evidence rather than from a single experiment or observation.

   There is also a deeper cultural challenge. Far more people are familiar with religious texts than with atmospheric physics or paleoclimate research. Many therefore expect scientific knowledge to provide simple, definitive answers. Science works differently. It is a gradual and often messy process of testing ideas, collecting evidence, correcting mistakes, and refining understanding. Progress usually comes through many small advances and only occasionally through major breakthroughs. As a result, scientific explanations evolve over time and rarely fit into a single sentence that everyone can immediately understand.

   For all of these reasons, climate change is not merely a scientific problem. It is also a challenge of human psychology, education, communication, and culture.

8. **When we talk about "global warming," what exactly is warming?**

   Answer: The Earth has no single thermometer. There is no giant sensor hanging in space that tells us the temperature of our planet.

   Instead, scientists combine millions of measurements collected from weather stations, ships, ocean buoys, and satellites. From these observations they estimate the average temperature of the Earth's surface. We call this quantity the *global mean surface temperature*, or GMST.

   At first glance this sounds simple. In reality it is one of the largest scientific data-processing efforts ever undertaken. Every month, temperatures measured at thousands of locations around the world must be combined into a single global estimate.

Nota bene, the global ocean observing system is not a single network. It is a federation of observing systems: weather stations, satellites, drifting buoys, Argo floats, tide gauges, moorings, and deep-ocean observatories. The Trump administration is currently targeting one important component—the Ocean Observatories Initiative – but not, as far as public information shows, the global drifting buoy array or the Argo float program.

Rather than reporting the absolute temperature of the Earth, scientists usually report a *temperature anomaly*: how much warmer or colder the planet is compared with a reference period. My preferred reference period is 1850–1900, before large-scale industrial emissions began to alter the climate significantly. Other widely used reference periods include NASA's 1951–1980 baseline and the 1961–1990 baseline used by the British HadCRUT dataset and many IPCC assessments. These choices do not change the warming trend itself; they merely shift the zero point. One baseline can always be translated into another.

The calculation of global temperature anomalies involves several steps:

(a) **Data collection**: Temperature observations are gathered from weather stations, ships, ocean buoys, and satellites.
(b) **Local averaging**: Monthly mean temperatures are calculated for each observing location.
(c) **Reference climate**: A long-term baseline period is selected to represent average climate conditions.
(d) **Anomaly calculation**: The temperature for a given month is compared with the average temperature for the same month during the baseline period.
(e) **Global averaging**: The land and ocean anomalies are combined into a single global value.

The result is a monthly estimate of how much warmer or cooler the Earth's surface is relative to a chosen reference climate. When scientists say that the Earth has warmed by approximately 1.5°C since preindustrial times, they are referring to a change in this global mean surface temperature.

But temperature is only part of the story.

The modern climate observing system extends far beyond thermometers. Weather stations tell us what is happening at specific locations. Satellites show us the entire planet at once. They monitor clouds, atmospheric water vapor, aerosols, sea ice, glaciers, vegetation, ocean temperatures, and many other aspects of the Earth system.

Most importantly, satellites allow us to measure the Earth's energy balance. At the most fundamental level, the climate system obeys a simple accounting rule:

$$\text{Energy In} = \text{Energy Out} + \text{Energy Stored}. \tag{2}$$

Sunlight enters the climate system. Some of it is reflected back to space by clouds, aerosols, ice, snow, deserts, and the oceans. The remainder is absorbed by the Earth and eventually leaves as infrared radiation.

If the incoming and outgoing energy fluxes are exactly balanced, the climate remains stable. If more energy enters than leaves, the excess energy must accumulate within the climate system. Today, roughly 90% of this excess energy is stored in the oceans, with smaller fractions warming the atmosphere, land, and melting ice.

A useful analogy is a bank account. If \$100 enters your account every day but only \$99 leaves, the daily imbalance appears small. Yet over time the surplus accumulates into a substantial amount.

The Earth's climate system behaves in much the same way. A seemingly tiny imbalance in the planetary energy budget, sustained for decades, leads to enormous heat accumulation.

One of the greatest achievements of modern climate science has been measuring this imbalance directly from space. Satellite missions such as CERES (*Clouds and the Earth's Radiant Energy System*) continuously monitor the energy entering and leaving the Earth. Their observations show that our planet is currently absorbing significantly more energy than it emits.

I will return to this topic later when discussing a decline in the Earth's reflectivity, or *albedo*, observed by the CERES satellites. This decline allows more sunlight to be absorbed and contributes additional warming beyond that caused by increasing greenhouse-gas concentrations alone.

Satellite observations have transformed our understanding of the planet. Images collected over the last six decades helped mobilize international action to halt the destruction of the stratospheric ozone layer, documented widespread coral bleaching caused by warming oceans, and revealed the accelerating loss of tropical forests.

Satellites have also provided some of the clearest evidence of climate change. Missions such as GRACE, ICESat, and CryoSat have measured the shrinking ice sheets of Greenland and Antarctica, the retreat of mountain glaciers, and the continuing decline of Arctic sea ice. These measurements allow scientists to quantify changes that would otherwise be impossible to observe on a planetary scale.

Today, more than a thousand Earth-observing satellites continuously monitor the atmosphere, oceans, land surface, and cryosphere. Yet much of the information they provide remains unfamiliar to the general public.

Key illustrations for a general audience. Using several visuals, I will follow this sequence: How do we know? → What are we measuring? → What is changing? → Why it matters?

Illustration 1. One planet. One climate system. One experiment being conducted in real time with bad outcomes. For most of human history, we experienced climate only locally: the weather outside our homes, farms, and cities. Satellites changed that perspective. For the first time, humanity could see the Earth as a single interconnected system of oceans, continents, clouds, ice, and living ecosystems. Climate science seeks to understand how energy, water, carbon, and life interact within this fragile blue sphere.

Figure 6: The Earth as seen from space. This iconic "Blue Marble" view reminds us that our atmosphere, oceans, ice sheets, forests, and cities are all parts of a single planetary system. Portions of California are visible along the eastern edge of the Pacific Ocean. Image credit: NASA.

Illustrations 2–4. The global thermometer network. The foundation of modern climate science is a worldwide network of meteorological stations that continuously measure air temperature, precipitation, wind, pressure, and other atmospheric variables. The colors indicate the length of each station's observational record. Some stations have been collecting data for more than a century, allowing scientists to track climate changes across multiple generations.

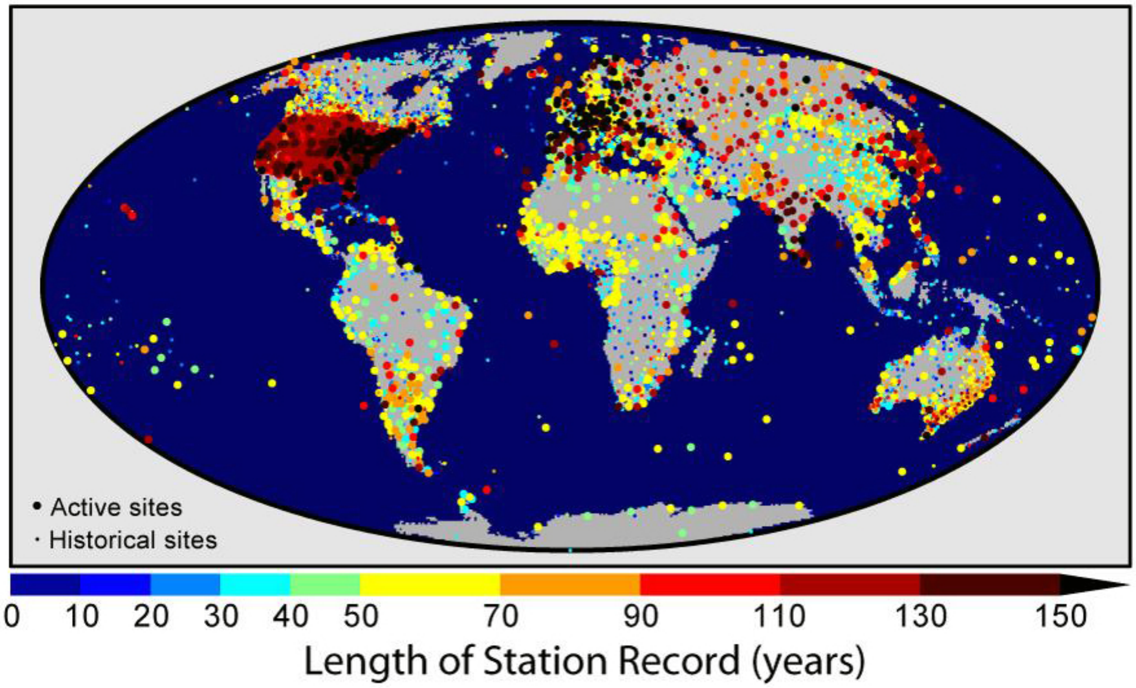


Figure 7: Global distribution of land-based meteorological stations and the duration of their records. Together with ships, ocean buoys, weather balloons, and satellites, these stations form the backbone of the Earth's climate observing system. Tens of thousands of stations operate around the world, ranging from small local sites to major national weather observatories.

Illustration 3. Global ocean observing network. Active Argo floats in Feb 2022. Each float that costs between $20,000 and $150,000, depending on its capabilities, is launched from a ship. There is no central funding for Argo. Each of the 30 countries that operate floats obtains their own national funding to buy floats, prepare and launch them and to process and distribute the data. Argo is part of the Global Ocean and Global Climate Observing Systems. The total annual cost of Argo is estimated at $40million/year.

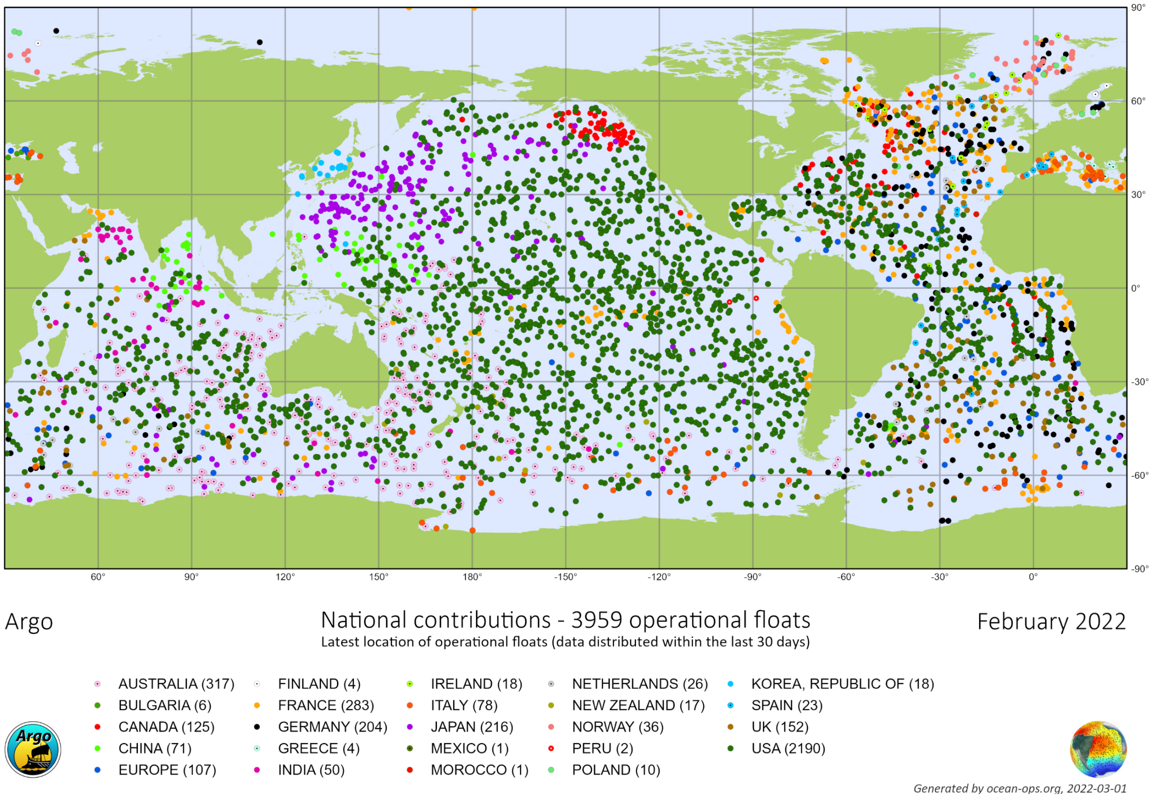


Figure 8: Each time they surface, the roughly 4,000 active Argo floats transmit measurements collected throughout the upper 2,000 m of the ocean. Using satellite communications, including the Jason series of ocean-observing satellites, these data are relayed to scientists around the world within hours.

Illustration 4. Global ocean observing network. Status of the global drifting buoy array. The current target size of the array is about 1,250–1,300 active drifting buoys worldwide arranged on roughly a $5^\circ \times 5^\circ$ grid. NOAA now describes the system as a global array of more than 1,300 satellite-tracked surface drifters.

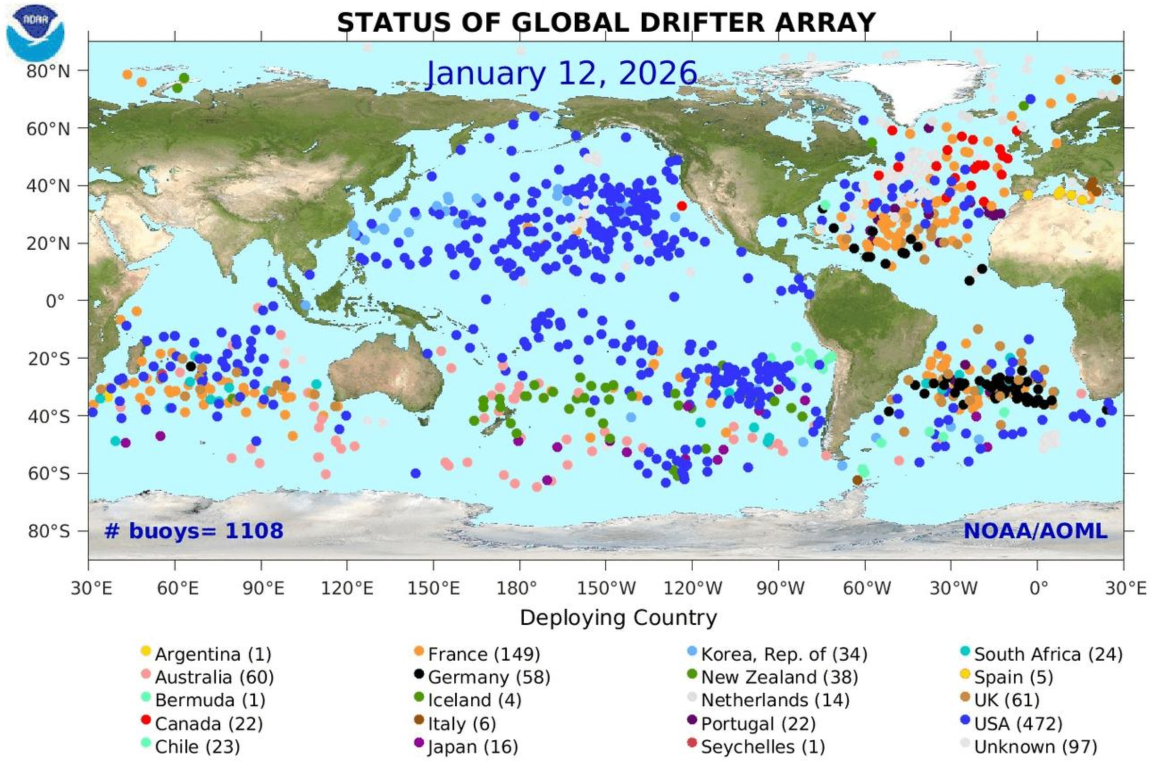


Figure 9: This famous NOAA/AOML "Status of the Global Drifting Buoy Array" map is often shown in climate and oceanography presentations, the exact number depends on the date of the image.

Illustration 5. Taking Earth's Temperature. The three most widely used reconstructions of global mean surface temperature (GMST) are produced by Berkeley Earth, British HadCRUT5, and NASA GISTEMP. After rebasing all three datasets to the common 1880–1900 reference period, Berkeley Earth and HadCRUT5 remain closely aligned throughout most of the record, while NASA GISTEMP exhibits a modest but systematic divergence after the early twentieth century. This difference is not caused by the choice of baseline and most likely reflects differences in the treatment of historical sea-surface temperatures, spatial infilling, and sea-ice regions rather than any disagreement about the overall warming of the Earth. The upper panel shows the raw GMST reconstructions. The lower panel shows the same records after statistical adjustment to remove the short-term influences of El Niño events, major volcanic eruptions, and variations in solar activity.

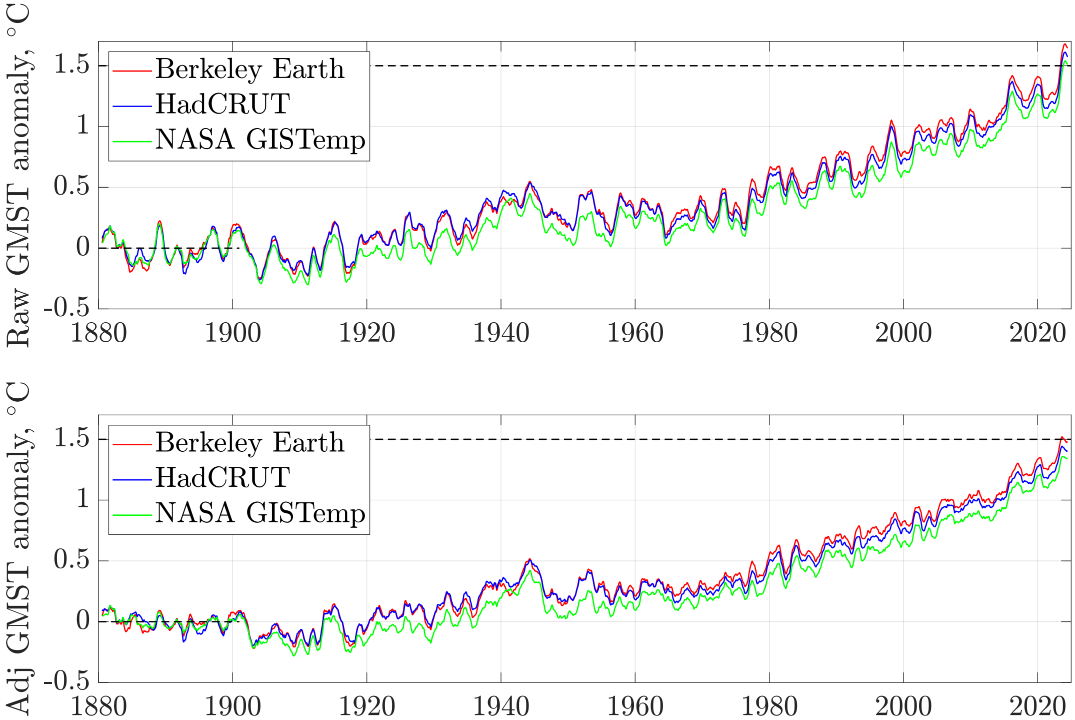


Figure 10: Three independent reconstructions of global mean surface temperature. The upper panel shows the original records, while the lower panel shows the records after removing the effects of El Niño variability, volcanic aerosols, and solar forcing. Despite methodological differences, all three datasets reveal a remarkably consistent long-term warming of the Earth.

Illustration 6. When a Coral Reef Dies. Climate change is not an abstract concept. These photographs show the same coral reef only a few months apart. The transformation is so dramatic that the image has been titled *"Coral Reef or Coral Debrief?"* Warm ocean water caused the corals to expel the microscopic algae that provide most of their food and color. What was once a thriving ecosystem became a pale, dying landscape.

Figure 11: Airport Reef, Tutuila, American Samoa, before and after a major coral-bleaching event (December 2014 → February 2015). The loss of color signals severe biological stress caused by unusually warm ocean temperatures. Photograph: XL Catlin Seaview Survey / The Ocean Agency.

Illustration 7. Weighing Greenland from Space. The GRACE satellites do not photograph ice loss directly; they measure tiny changes in the Earth's gravity field and can therefore "weigh" the Greenland Ice Sheet from orbit. Since 2002, Greenland has been losing ice at an average rate of about 264 billion tons per year. In total, more than 5.5 trillion tons of land ice have melted or flowed into the ocean. Spread over Greenland's coastal zone, this lost ice would be equivalent to a layer of meltwater several meters deep.

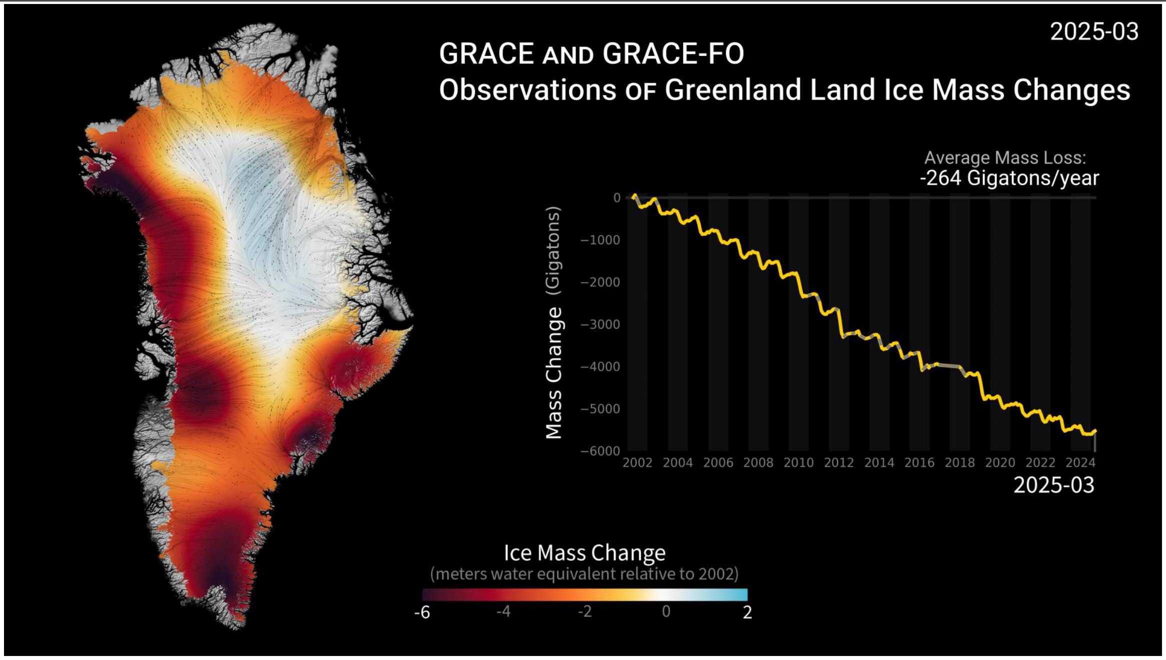


Figure 12: Ice-mass loss from the Greenland Ice Sheet measured by the GRACE satellite missions. The colors show regions of greatest ice loss, concentrated along the coast where glaciers discharge ice into the ocean. Together, Greenland and Antarctica are major contributors to global sea-level rise.

Illustration 8. Watching the Arctic Turn Blue. These satellite images compare the minimum Arctic sea-ice extent in September 1979 and September 2021. Similar losses continued during the following five years. The disappearance of Arctic sea ice is one of the most visible and dramatic indicators of a warming planet. Since 1979, the late-summer ice cover has shrunk by nearly 40%, exposing vast areas of dark ocean that absorb far more sunlight than reflective ice, and decrease the Earth's albedo.

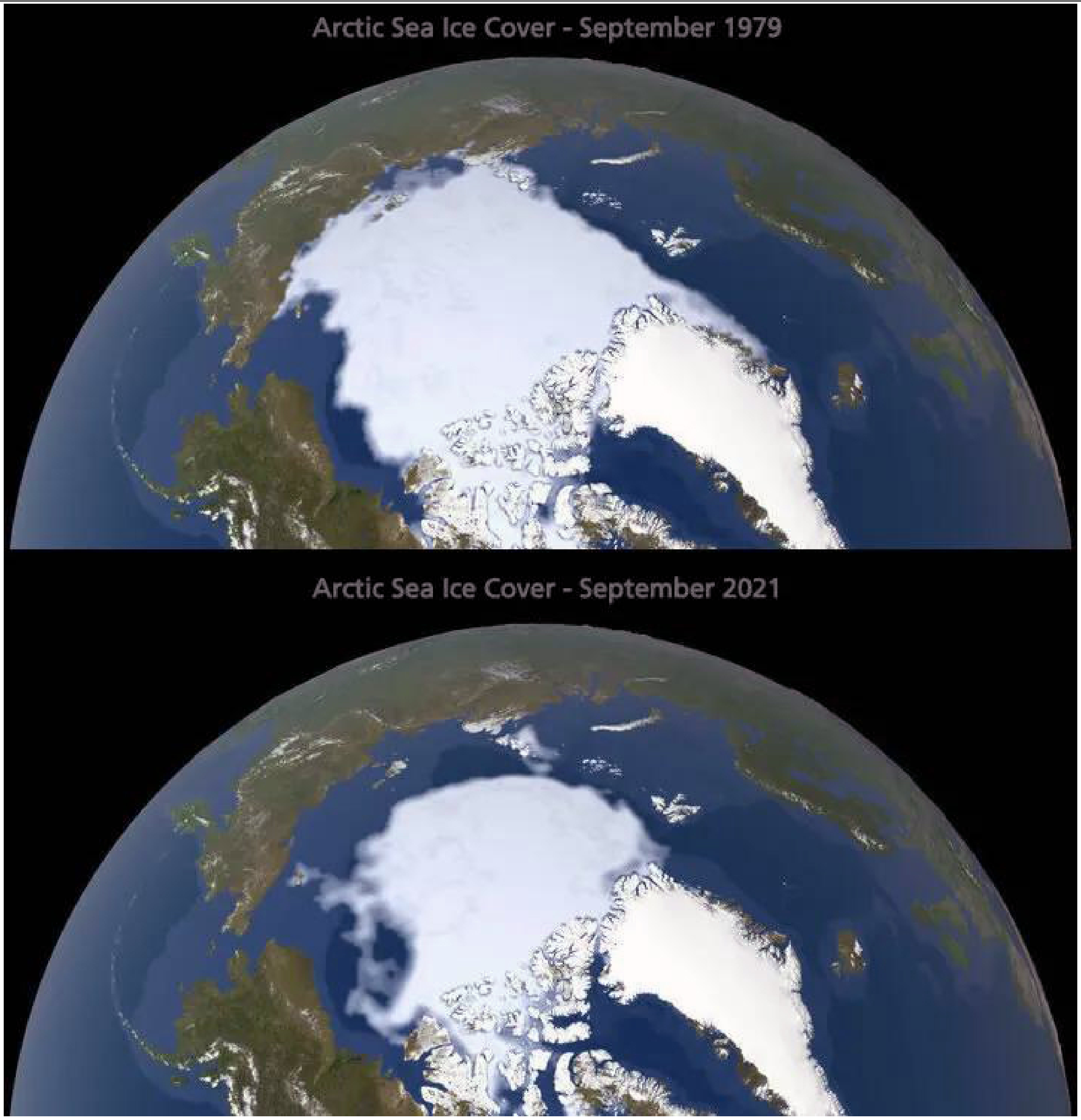


Figure 13: Decline of Arctic sea ice observed by satellites. Unlike the melting of land ice in Greenland and Antarctica, the loss of floating sea ice does not directly raise sea level. However, it amplifies global warming by reducing the Earth's reflectivity, alters atmospheric and oceanic circulation patterns, and disrupts marine ecosystems that depend on the presence of seasonal ice.

Illustration 9. Two Melting Poles, One Warming Planet. The Arctic still is Earth's air conditioner, but it has been losing sea ice for nearly half a century. Antarctica joined the decline since 2014, but its loss has been surprisingly rapid. These satellite observations track the annual minimum and maximum sea-ice areas in the Arctic and Antarctica from 1979 to 2025. The areas are expressed in units of the land area of Texas to provide a familiar scale. The Arctic exhibits a long-term decline in sea ice throughout the record, particularly during summer. In contrast, Antarctic sea ice remained relatively stable until about 2014, after which both summer and winter ice extents declined rapidly. Together, these observations reveal profound changes occurring at both ends of the Earth.

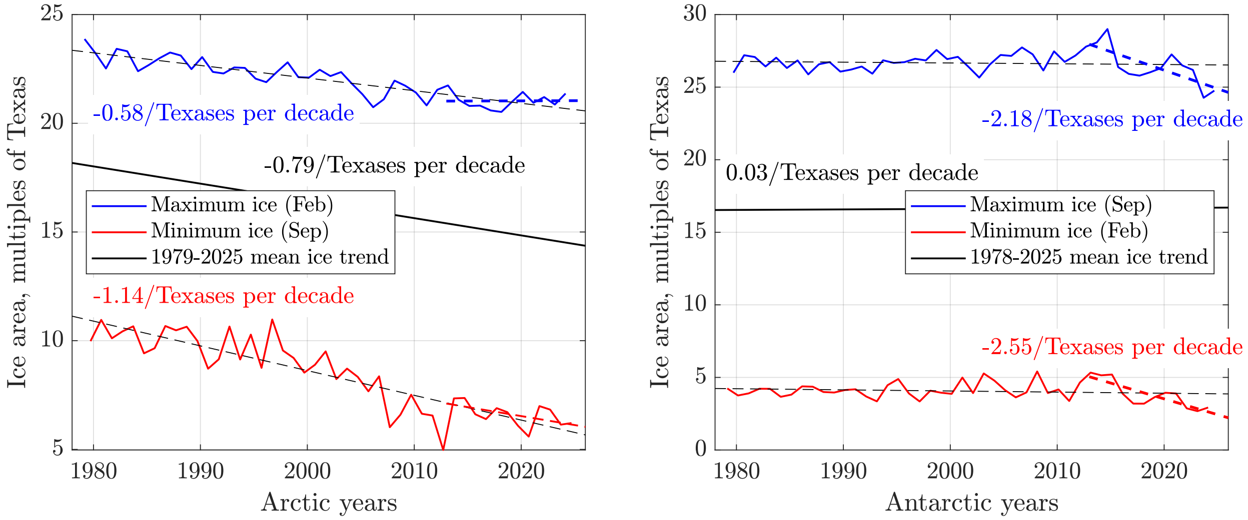


Figure 14: Satellite-derived anomalies of minimum and maximum sea-ice area in the Arctic (top) and Antarctica (bottom), expressed as multiples of the land area of Texas. Arctic sea ice has declined steadily since 1979 at an average rate of approximately 1.14 Texas-equivalents per decade. Antarctic sea ice remained comparatively stable until about 2014, after which its decline accelerated, yielding a long-term trend of approximately 2.55 Texas-equivalents per decade. Although the loss of floating sea ice does not directly raise sea level, it reduces the Earth's reflectivity, amplifies warming, alters atmospheric and oceanic circulation, and threatens polar ecosystems. In Antarctica, the concurrent weakening and collapse of floating ice shelves reduces the resistance to glacier flow, accelerating the discharge of land ice into the ocean and thereby contributing to global sea-level rise.

9. **The mean temperatures hide the sometimes brutal excursions from the mean caused by extreme events. Can you give examples?**

   Answer:

   The European heat wave of 2026. In late May 2026, western and central Europe experienced one of the most extraordinary early-season heat waves ever recorded. A persistent high-pressure system, often referred to as a *heat dome*, transported unusually warm air from North Africa into Europe and trapped it there for several days. Large regions of Portugal, Spain, France, the United Kingdom, Ireland, Belgium, the Netherlands, and Germany experienced temperatures 10–15°C above the long-term average for late May.

   The event shattered numerous national and local temperature records. The United Kingdom recorded its earliest temperature above 35°C, reaching 35.1°C at Kew Gardens. Ireland established a new May temperature record of 30.6°C at Shannon, while Wales reached 32.9°C in Cardiff. More than 350 French municipalities reported their highest May temperatures on record. Particularly remarkable was the timing: temperatures more typical of July occurred several weeks before the beginning of climatological summer.

   Although the 2026 event was not as deadly or prolonged as the famous European heat wave of 2003, it was exceptional for its geographic extent, its intensity, and its occurrence so early in the year. The heat wave provided another example of the increasing frequency of extreme temperature events in a warming climate, with unusually warm nighttime temperatures further increasing stress on human health, agriculture, infrastructure, and ecosystems.

   The Pakistani heat wave of 2026. Right now, Pakistan is suffering from a deadly heat wave with temperatures exceeding 50°C, and little or no air conditioning for the poor population. This heat wave is killing people, especially old and children.

   https://www.nytimes.com/2026/06/08/world/asia/pakistan-heat-wave.html

   “Climate change has become a stress test for survival,” said Mashooque Birhmani, head of the Sujag Sansar Organization, a local nonprofit in Dadu, Pakistan. “It exposes the fragility of everything: governance, agriculture, electricity, water, health and people’s ability to earn a living.”

   Looking ahead, Mr. Khaliq said his biggest concern was for his children.

   “I don’t know whether my children will still be able to make a living from this land in Dadu,” he said, “or whether they will have to leave and find a future somewhere else.”

   Extreme events in 2024/2025. All 67 extreme heat events between May 2024 and May 2025 – identified as significant due to record-breaking temperatures or severe impacts on human populations or infrastructure – were found to have been influenced by climate change . These heatwaves are becoming increasingly frequent, prolonged, and lethal. Beyond the immediate threat to human health – especially for the poor, elderly, and other vulnerable populations – extreme heat also endangers crops, insects, birds, and countless other species vital to ecological stability. In Europe alone, approximately 62,000 people died from heat-related causes in 2022; comparable mortality data are generally unavailable elsewhere.

You may be wondering: why did so many remote Pacific and Caribbean islands experience such prolonged heatwaves in 2024 and 2025? The answer lies in the oceans surrounding them. Since the early 1980s, the world's oceans have experienced increasingly frequent and intense marine heatwaves (MHWs), culminating in the most powerful global MHW ever observed in 2023. These vast regions of exceptionally warm seawater acted as giant heat reservoirs, preconditioning nearby islands for the prolonged atmospheric heatwaves that followed between May 2024 and May 2025. Attribution studies indicate that the long-term increase in MHW frequency and intensity is overwhelmingly driven by anthropogenic climate change.

Iceland and East Greenland provide another striking example of how rapidly climate risks are changing. Following the exceptional heatwave of 13–22 May 2025, both regions moved sharply upward in rankings of locations most affected by global warming. During this event, local temperatures exceeded their preindustrial averages by

$$T_{\text{local,anomaly}} = T_{\text{local}} - T_{\text{local,preindustrial}} \approx 11\text{–}14^\circ\text{C}.$$

Attribution analyses concluded that this Greenland ice-melt event was roughly forty times more likely to occur in today's climate than in the preindustrial world. Although public attention often focuses on tropical beaches and summer vacations, extreme warming in the Arctic may have even greater global consequences because it accelerates ice loss, raises sea level, and amplifies climate change across the Northern Hemisphere.

The largest heatwave ever observed on Earth. In March 2022, Antarctica experienced the most extreme heatwave anomaly ever recorded anywhere on the planet. Across more than three million square kilometers of East Antarctica—an area roughly the size of India—air temperatures rose by as much as 40°C (70°F) above normal. No previously documented heatwave, on any continent, had produced such a large departure from the local climate.

The event resulted from a remarkable chain of atmospheric circumstances. The tropical Pacific was already in a La Niña state, and unusually warm waters in the Indian Ocean helped generate a series of powerful tropical storms. Several evolved into tropical cyclones, whose heat and moisture were subsequently entrained into a highly amplified atmospheric river. A giant meander in the jet stream acted like an atmospheric conveyor belt, allowing warm, moisture-laden air from the Indian Ocean to flow thousands of kilometers into the coldest place on Earth.

$$\begin{aligned}&\text{Warm Indian Ocean} \rightarrow \text{Rossby-wave amplification} \rightarrow \text{Atmospheric river}\\&\rightarrow \text{Latent heat release} \rightarrow \text{Antarctic heatwave}\end{aligned} \tag{3}$$

One casualty of this event was the vulnerable Conger Ice Shelf, located east of Dome C, the site of some of the most famous Antarctic ice-core drilling projects. The deep ice cores extracted from Dome C preserve a frozen archive of the atmosphere, allowing scientists to reconstruct the Earth's climate and greenhouse-gas concentrations over the last 800,000 years. Shortly after the heatwave, the ice shelf collapsed. Yet the consequences could have been far worse. The heatwave occurred in March, when Antarctica is transitioning into its long, dark winter and temperatures remain far below freezing. Even after an extraordinary warming of 40°C, temperatures over much of the affected region remained below freezing.

The deeper concern is what such an event implies for the future. If a comparable heatwave were to occur during the Antarctic summer, when temperatures are already much closer to the melting point, widespread surface melting could result. Such an event would threaten ice shelves that currently act as buttresses holding back the flow of continental ice into the ocean. Whether the March 2022 heatwave was an isolated extreme or an early indication of a changing Antarctic climate remains an open question. What is beyond dispute is that it demonstrated the ability of the atmosphere to deliver extraordinary amounts of heat to the coldest place on Earth.

An interesting aspect is that several recent Antarctic extremes – including the March 2022 heatwave and some sea-ice-collapse episodes—have been associated with unusually strong Rossby-wave activity and atmospheric rivers. Many researchers are investigating whether a warmer climate is making such extreme poleward heat transports more likely, although the evidence is not yet definitive.

Think of the jet stream as a giant river of air flowing around the planet. When it develops large meanders: the northward bulges (ridges) transport warm tropical air toward the poles, the southward bulges (troughs) transport cold polar air toward lower latitudes.

Thus the March 2022 Antarctic heatwave and the deadly February 2021 Texas freeze are, dynamically speaking, opposite sides of the same Rossby-wave phenomenon.

Why was the Indian Ocean so warm during a La Niña? Many people think that La Niña cools the entire planet. It does not. La Niña is primarily a Pacific Ocean phenomenon. During a La Niña event, strong trade winds pile warm surface water into the western Pacific and neighboring eastern Indian Ocean. As a result, large parts of the tropical Indian Ocean remain unusually warm.

An even more important fact is that the Indian Ocean has been warming steadily for more than a century. In fact, it is the fastest-warming tropical ocean basin on Earth. The western Indian Ocean has warmed by roughly 1.2°C since the beginning of the twentieth century, substantially more than many other tropical-ocean regions.

Therefore, when the Antarctic heatwave occurred in March 2022, the atmosphere was drawing moisture and heat from an Indian Ocean that was already much warmer than it would have been during a similar La Niña event fifty or one hundred years earlier. In this sense, natural climate variability supplied the atmospheric pathway, while long-term global warming supplied additional heat and moisture.

Illustration 10. What a Warming Climate Looks Like. This event occurred unusually early in the warm season. Many locations experienced temperatures more typical of July than of May. The heat wave was not merely unusual; it shattered long-standing temperature records by whole degrees Celsius rather than by tenths of a degree. A persistent *heat dome* transported hot air northward from North Africa and trapped it over western and central Europe for several days. The event was also accompanied by exceptionally warm nights, with some locations experiencing *tropical nights* (minimum temperatures above 20°C), increasing health risks because people, animals, and infrastructure had little opportunity to cool down.

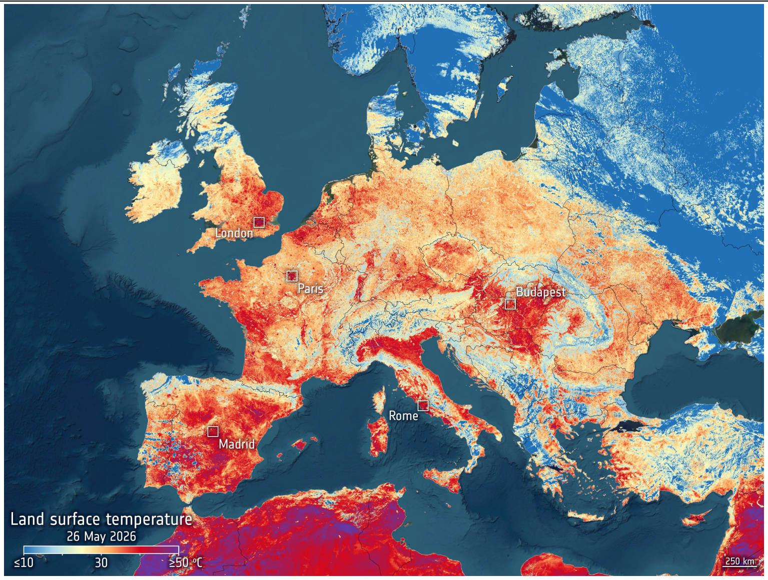


Figure 15: Temperature anomalies during the May 2026 European heat wave. The event affected much of western and central Europe, including Portugal, Spain, France, the United Kingdom, Ireland, Belgium, the Netherlands, and parts of Germany. Temperatures were commonly 10–15°C above the long-term average, making this one of the most intense and geographically extensive late-spring heat waves ever recorded in Europe.

Illustration 11. The Oceans Are Running a Fever. The relative power of all major marine heatwaves (MHWs) recorded between 1981 and 2023 is computed directly from high-resolution satellite observations of sea-surface temperature (SST) between 60°S and 60°N. Marine heatwaves are defined as events lasting at least five consecutive days during which SST exceeds the local 90th percentile of the 1985–2014 climatological distribution. By the end of 2023, the largest global MHW on record had reached a cumulative power of 53.6 billion °C days km^2, more than three standard deviations above the 1982–2023 historical norm. The event lasted 120 days, the longest duration in the satellite record and about three times the average MHW duration, while spanning approximately 320 million km^2, or more than 96% of the global marine area.

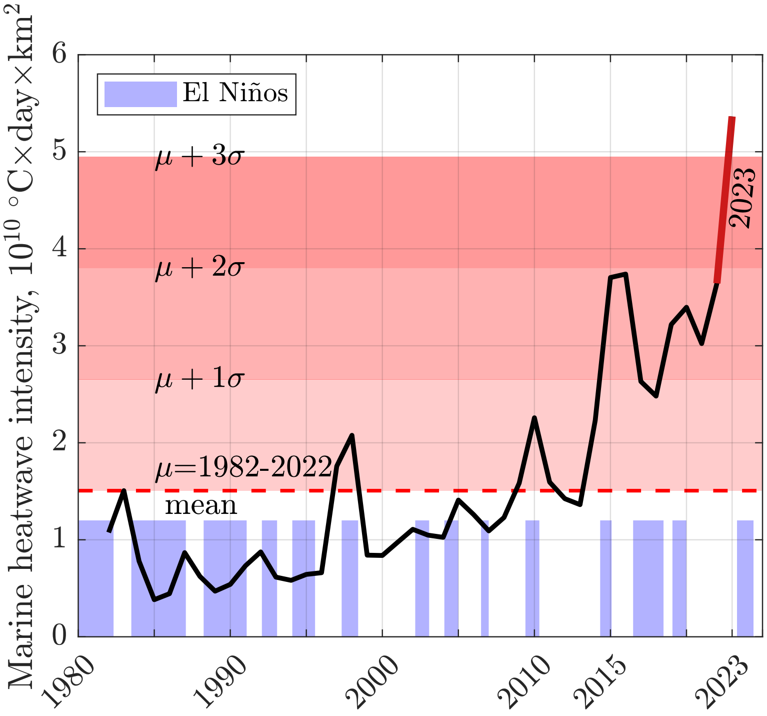


Figure 16: Extreme marine heatwaves since 1981. Event intensity is quantified as the product of the area-weighted SST anomaly above the threshold, event duration in days, and affected ocean area in km^2. A mild positive correlation with El Niño events is apparent.

Illustration 12. Even paradise is getting too hot. If you are planning a vacation in Tuvalu, Kiribati, the Maldives, Aruba, Dominica, Saint Vincent and the Grenadines, Grenada, Guadeloupe, Montserrat, Barbados, Antigua and Barbuda, Micronesia, Saint Kitts and Nevis, Martinique, Puerto Rico, or similar tropical destinations, be aware that these islands experienced some of the longest heatwaves on Earth during 2024–2025. Places long known for their remarkably stable and pleasant climates are now spending increasing portions of the year under unusually hot conditions. Attribution studies indicate that much of this additional heat is a consequence of human-caused climate change. At the opposite end of the spectrum are countries where unusually hot weather during 2024–2025 was still dominated by natural climate variability. These include South Korea, Uruguay, Malta, Pakistan, Iceland, Japan, Canada, Czechia, North Korea, Vatican City, and India. Interestingly, in several of the world's largest emitters—including the United States, China, and Russia—the causes of extreme heat remain roughly split between natural variability and climate change. This ambiguity makes climate change harder for many people to recognize because weather still appears to fluctuate naturally from year to year. As the planet continues to warm, however, the balance will increasingly shift toward climate change as the dominant driver of extreme heat.

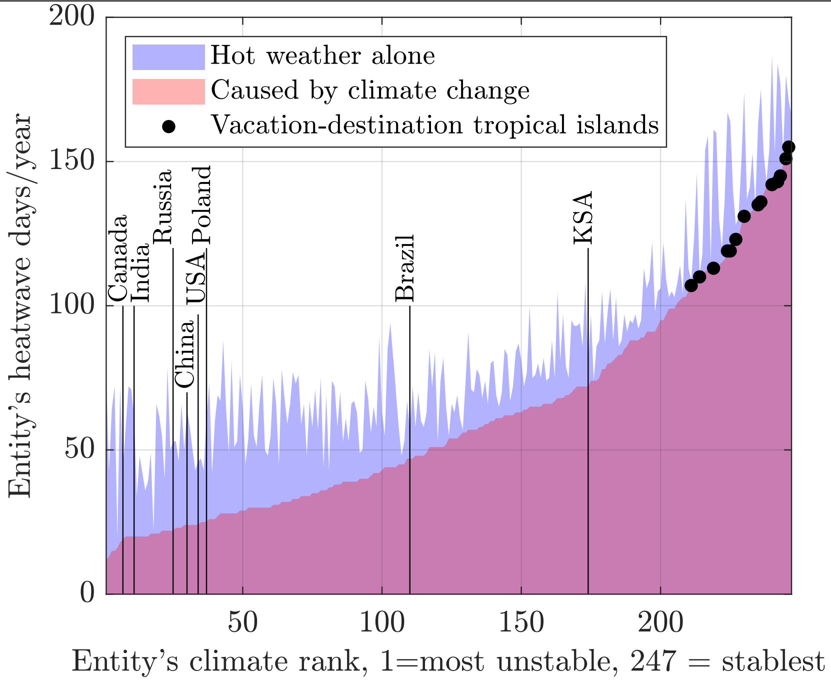


Figure 17: Heatwave days recorded in 247 countries between 1 May 2024 and 1 May 2025. Temperature anomalies were measured relative to the Global Mean Surface Temperature (GMST) anomaly using the 1850–1900 period as the preindustrial baseline. Countries farther to the right experienced a larger fraction of heatwave days attributed to human-caused climate change.

Illustration 13. The most extreme heatwave ever observed. In March 2022, East Antarctica experienced the largest temperature anomaly ever recorded anywhere on Earth. Across more than three million square kilometers—an area roughly the size of India—air temperatures rose by as much as 40°C (70°F) above the seasonal average. No previously documented heatwave, on any continent, had produced such a large departure from normal climatic conditions. The event demonstrated that even the coldest place on Earth is vulnerable to extraordinary incursions of heat and moisture transported from lower latitudes. Although temperatures remained below freezing over much of the affected region, the heatwave revealed the remarkable ability of the atmosphere to transfer vast amounts of energy across the planet in just a few days.

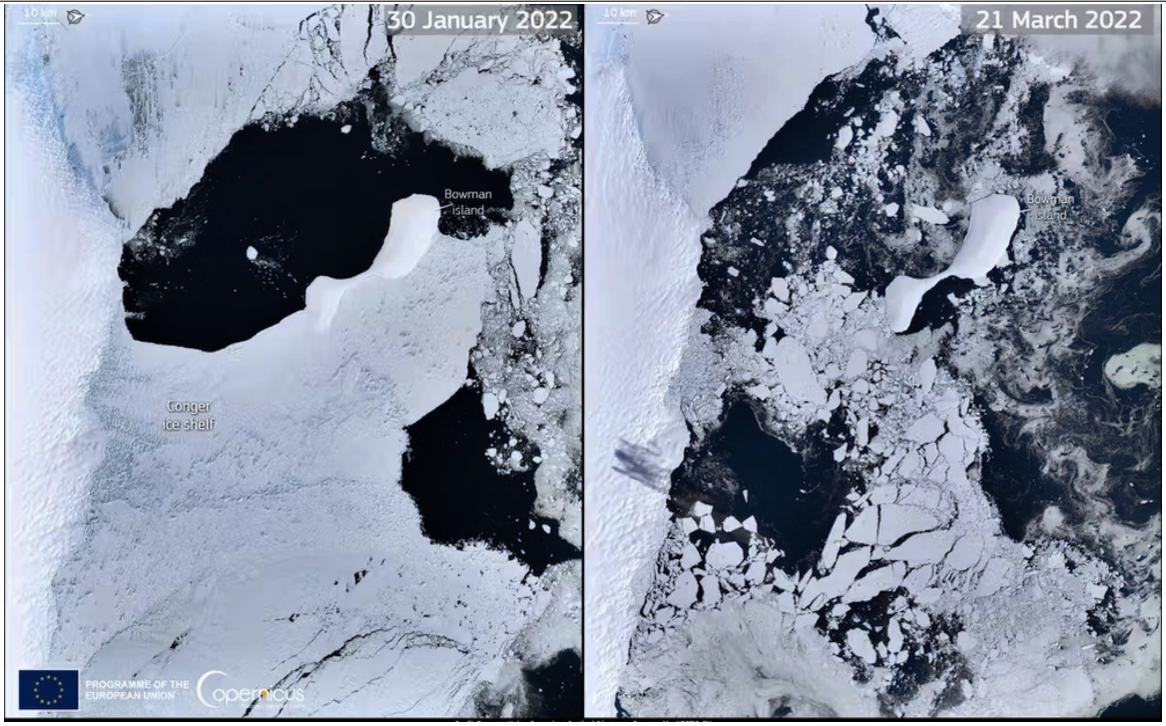


Figure 18: The March 2022 Antarctic heatwave was produced by an atmospheric river guided by an unusually amplified Rossby-wave pattern in the Southern Hemisphere. Warm, moist air originating over the Indian Ocean was transported deep into East Antarctica, producing the largest temperature anomaly ever observed anywhere on Earth.

10. **Why is El Niño the planet's climate heartbeat?**

Answer: El Niño is the warm phase of the El Niño–Southern Oscillation (ENSO), the dominant year-to-year climate fluctuation on Earth. It begins in the tropical Pacific, but its consequences spread through the atmosphere to many parts of the world.

In normal conditions, easterly trade winds push warm surface water toward Indonesia and Australia. This piles up warm water in the western Pacific and allows cold, nutrient-rich water to rise along the coast of South America. The sea surface is therefore warm in the west and cool in the east. Warm water favors rising air, clouds, and rain; cool water favors sinking air and higher surface pressure. Thus the normal tropical Pacific has low pressure and heavy rainfall in the west, and higher pressure and drier conditions in the east.

During El Niño, this pattern weakens or reverses. The trade winds slacken, the warm surface water spreads eastward, and upwelling of cold water near South America is suppressed. The eastern and central Pacific warm, surface pressure falls there, and the usual east–west atmospheric overturning cell, called the Walker circulation, weakens. This coupling between ocean temperature, air pressure, wind, and upwelling is the physical engine of ENSO (*NOAA Climate.gov*, 2026, 2021).

The pressure–temperature feedback. The key feedback is simple:

> Warmer eastern Pacific water lowers surface pressure, weakens the trade winds, reduces cold-water upwelling, and allows the eastern Pacific to warm further.

This is a positive feedback during El Niño growth. In La Niña, the opposite occurs: stronger trade winds intensify upwelling, cool the eastern Pacific, strengthen the east–west pressure gradient, and reinforce the normal Walker circulation.

Southern Oscillation Index (SOI). The Southern Oscillation Index (SOI) measures the atmospheric component of the El Niño–Southern Oscillation (ENSO). It is based on the normalized difference in sea-level pressure between Tahiti in the central-eastern Pacific and Darwin, Australia, in the western Pacific:

$$\mathrm{SOI} \propto P_{\mathrm{Tahiti}} - P_{\mathrm{Darwin}}, \tag{4}$$

where P_{Tahiti} and P_{Darwin} are the local sea-level pressures.

Under normal conditions, pressure is relatively high over the eastern Pacific and lower over the western Pacific, producing easterly trade winds that blow from South America toward Indonesia. This pressure gradient maintains the Walker circulation and promotes upwelling of cold water along the west coast of South America.

During El Niño, pressure falls in the eastern Pacific and rises in the western Pacific. The pressure difference weakens, the SOI becomes negative, and the trade winds weaken. Warm surface water then spreads eastward and suppresses cold-water upwelling.

During La Niña, the opposite occurs. Pressure rises in the eastern Pacific and falls in the western Pacific, strengthening the pressure gradient. The SOI becomes positive, easterly trade winds intensify, and cold-water upwelling increases.

The atmospheric pressure difference, trade winds, sea-surface temperatures, and tropical rainfall are tightly coupled:

$$\text{Pressure} \iff \text{Trade Winds} \iff \text{Ocean Temperature} \iff \text{Convection and Rainfall.} \tag{5}$$

This coupled ocean–atmosphere feedback forms the physical basis of ENSO.

As El Niño develops, warm sea-surface temperature anomalies spread into the central and eastern equatorial Pacific. The associated shift of deep tropical convection and latent heat release alters planetary-scale atmospheric wave patterns, strengthening the subtropical jet stream over the Pacific and displacing the winter storm track southward.

In the Northern Hemisphere, the mature El Niño pattern typically features a stronger Pacific jet stream extending toward the southern United States, bringing wetter conditions to California and the southern tier of North America and drier conditions to the Pacific Northwest. The physical chain of causality may be summarized as

$$\text{Warm SST} \to \text{Deep Convection} \to \text{Latent Heat Release} \to \text{Rossby Waves} \to \text{Jet Stream Shift.} \tag{6}$$

Rossby waves. Rossby waves are large-scale atmospheric and oceanic waves that arise from Earth's rotation and the variation of the Coriolis force with latitude. They appear as broad north–south meanders in the jet stream and can extend across entire ocean basins or continents.

When tropical convection associated with El Niño shifts eastward into the central and eastern Pacific, the accompanying release of latent heat acts as a source of atmospheric disturbance. This disturbance excites Rossby waves, which propagate poleward and eastward, altering the position and strength of the jet streams and changing storm tracks far from the tropical Pacific.

$$\begin{gathered}\text{El Niño} \to \text{Shifted tropical convection} \to \text{Rossby waves} \\ \to \text{Jet-stream changes} \to \text{Heatwaves and cold outbreaks}\end{gathered} \tag{7}$$

These atmospheric teleconnections explain how temperature anomalies in the equatorial Pacific can influence weather patterns across North America, South America, Asia, and other regions of the world. Thus the dramatic heat waves in Antarctica and the deep freezes in Texas and Florida are two sides of the same coin.

Atmospheric rivers usually move from west to east because they are embedded in the planet's prevailing westerlies. Extraordinary poleward events, such as the March 2022 Antarctic heatwave, occur when large Rossby waves bend the jet stream into a giant north–south meander, allowing tropical heat and moisture to reach the poles.

Development of an El Niño event. A typical El Niño develops in stages:

(a) **Neutral state.** Strong easterly trade winds maintain a warm western Pacific and a cool eastern Pacific.

(b) **Disturbance.** Bursts of westerly wind or weakening trade winds allow warm water to move eastward along the equator.

(c) **Ocean adjustment.** The thermocline—the boundary between warm surface water and cold deeper water—deepens in the eastern Pacific. This reduces cold upwelling.

(d) **Atmospheric response.** The central and eastern Pacific warm, deep convection shifts eastward, and the pressure difference between the western and eastern Pacific weakens.

(e) **Mature El Niño.** The warm anomaly peaks, usually near boreal winter, altering rainfall, storms, drought patterns, and global mean temperature.

(f) **Decay and recharge.** Ocean heat is redistributed, the trade winds recover, and the system may return to neutral conditions or overshoot into La Niña.

Climate impacts. El Niño is not merely a local warming of the Pacific. It shifts tropical rainfall and launches atmospheric wave patterns that affect weather far from the equator. Common impacts include drought risk in Indonesia, Australia, parts of South Asia, and southern Africa; enhanced rainfall in parts of the Americas and East Africa; changes in tropical cyclone activity; coral bleaching risk; reduced fisheries productivity off Peru and Ecuador; and a temporary rise in global mean surface temperature (*NOAA Climate.gov*, 2026, *NOAA Climate Prediction Center*, 2026).

Effect of climate change. Climate change does not create ENSO; ENSO is a natural coupled ocean–atmosphere oscillation. But global warming changes the background state on which ENSO develops. A warmer atmosphere holds more water vapor, so El Niño-related rainfall extremes can become more intense. A warmer ocean raises the baseline for marine heatwaves and coral bleaching. A warmer land surface increases the heat stress associated with El Niño droughts.

The IPCC assessment summarized by NOAA states that ENSO will remain the dominant mode of interannual climate variability in a warmer world, and that ENSO-related rainfall variability is very likely to increase, even though changes in ENSO sea-surface-temperature amplitude remain more uncertain (*NOAA Climate.gov*, 2021, *IPCC*, 2021). In practical terms, future El Niño events may not all become stronger in the same way, but their impacts will occur on a hotter, moister, more energetic planet.

Key illustrations for a general audience.

Illustration 18. ENSO: The Planet's Largest Climate Oscillation. The El Niño–Southern Oscillation (ENSO) is the largest natural climate oscillation on Earth. It arises from coupled interactions between the tropical Pacific Ocean and the atmosphere above it. ENSO alternates irregularly between three states: El Niño, La Niña, and neutral conditions. During El Niño, the eastern Pacific becomes unusually warm; during La Niña, it becomes unusually cool. These shifts in ocean temperature are accompanied by changes in atmospheric pressure, trade winds, rainfall, and storm tracks that influence weather patterns across much of the globe.

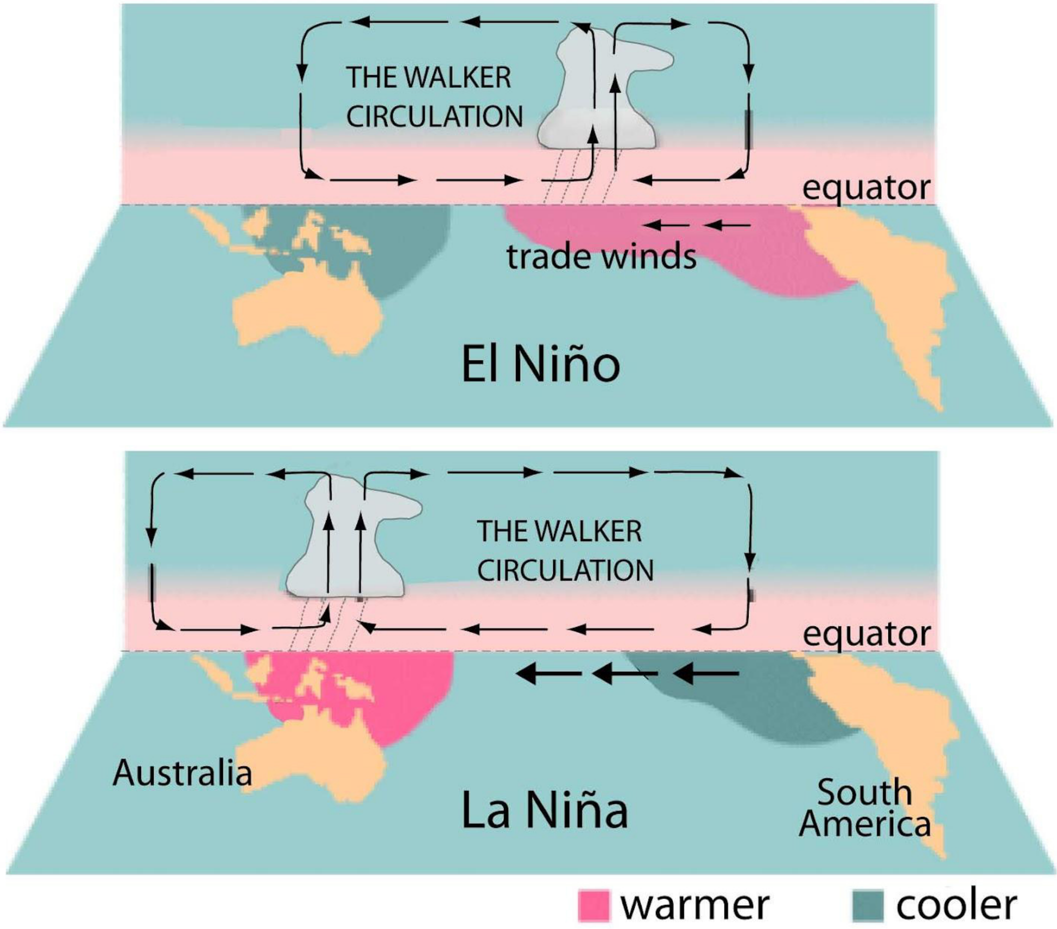
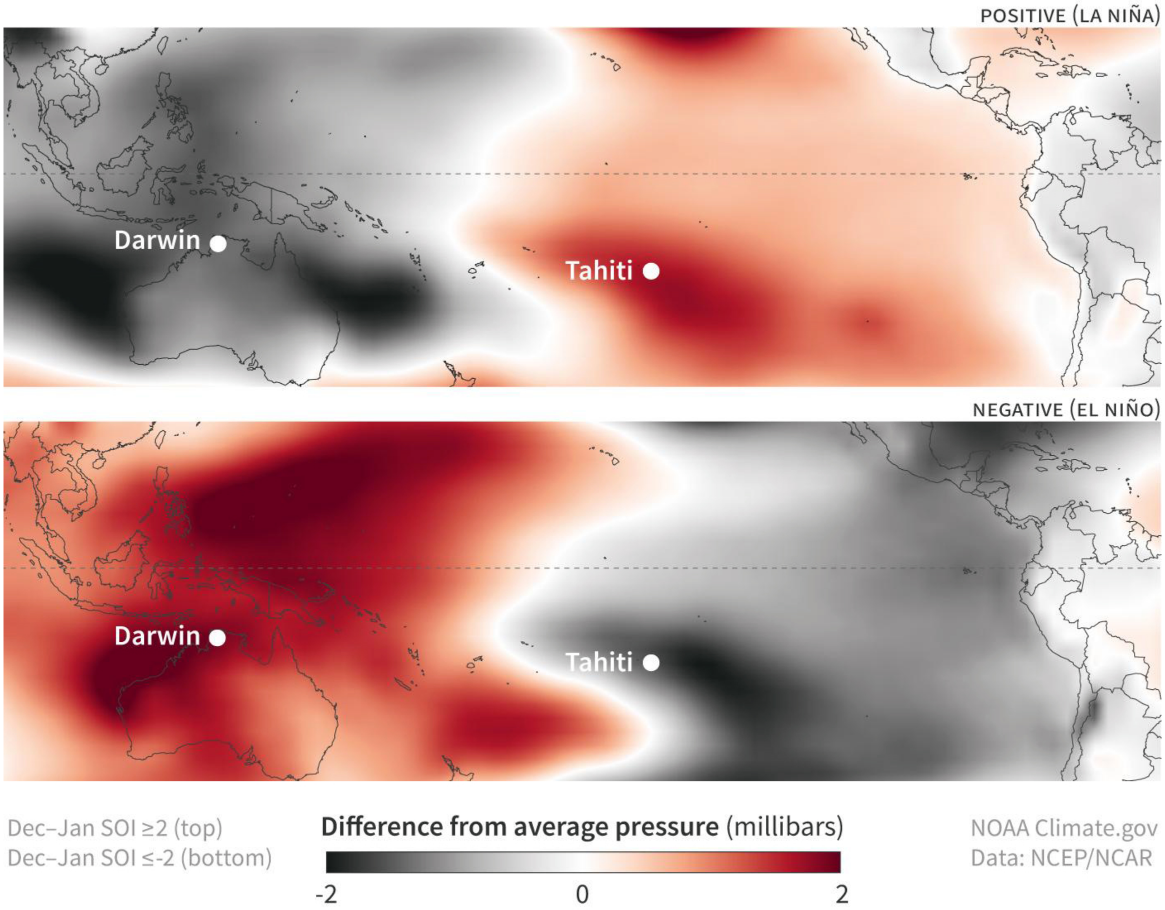


Figure 19: Schematic representation of the El Niño–Southern Oscillation (ENSO). El Niño and La Niña are opposite phases of a coupled ocean–atmosphere oscillation centered in the tropical Pacific. Through changes in sea-surface temperature, atmospheric pressure, trade winds, cloud cover, and rainfall, ENSO redistributes enormous quantities of heat around the planet. As a result, this Pacific phenomenon influences droughts, floods, tropical cyclones, monsoons, and temperature extremes on nearly every continent.

Illustration 19. The Atmospheric See-Saw of the Pacific. The Southern Oscillation Index (SOI) measures the difference in sea-level atmospheric pressure between Tahiti in the central Pacific and Darwin, Australia. It is one of the oldest and most important indicators of the El Niño–Southern Oscillation (ENSO). Negative SOI values correspond to El Niño conditions, when pressure falls in the eastern Pacific and rises in the west. Positive SOI values correspond to La Niña conditions, when the normal pressure pattern strengthens and the trade winds intensify.



NOAA Climate.gov
Data: NCEP/NCAR

Figure 20: The Southern Oscillation Index (SOI), a measure of the atmospheric component of ENSO. During El Niño events, the SOI becomes strongly negative as the usual east–west pressure gradient weakens or reverses. During La Niña events, the SOI becomes strongly positive as the pressure gradient strengthens. These pressure changes drive variations in the Pacific trade winds and help regulate the transfer of heat between the ocean and atmosphere.

Illustration 20. The Pacific Ocean in Its Normal State. Under normal conditions, strong easterly trade winds blow from the Americas toward Indonesia and Australia, pushing warm surface water westward across the tropical Pacific. This creates a pronounced east–west temperature contrast: warm water accumulates in the western Pacific, while cold, nutrient-rich water rises to the surface along the coast of South America through a process known as upwelling. Atmospheric pressure is relatively low over the warm western Pacific, where vigorous thunderstorms and heavy rainfall occur, and relatively high over the cooler eastern Pacific. Together, these oceanic and atmospheric circulations form the Walker circulation, one of the most important components of the Earth's climate system.

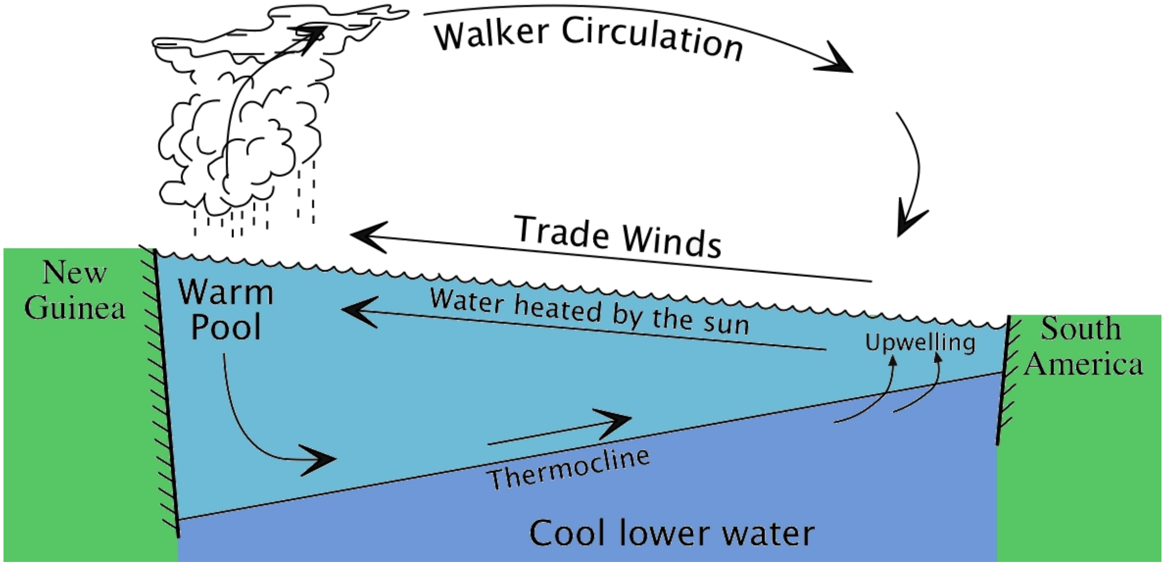


Figure 21: Normal conditions in the tropical Pacific Ocean. Strong easterly trade winds maintain a large east–west temperature gradient, with warm surface waters and intense rainfall concentrated near Indonesia and cooler waters dominating the eastern Pacific. The resulting Walker circulation helps regulate weather patterns throughout the tropics and provides the baseline state from which El Niño and La Niña events develop.

Illustration 21. El Niño: When the Pacific Changes the World's Weather. During an El Niño event, the normally strong easterly trade winds weaken, allowing warm surface waters that are usually concentrated in the western Pacific to spread eastward across the equatorial ocean. The upwelling of cold, nutrient-rich water along the coast of South America is suppressed, sea-surface temperatures rise in the eastern Pacific, and atmospheric pressure falls. As rainfall and tropical thunderstorms migrate eastward, weather patterns are disrupted around the globe.

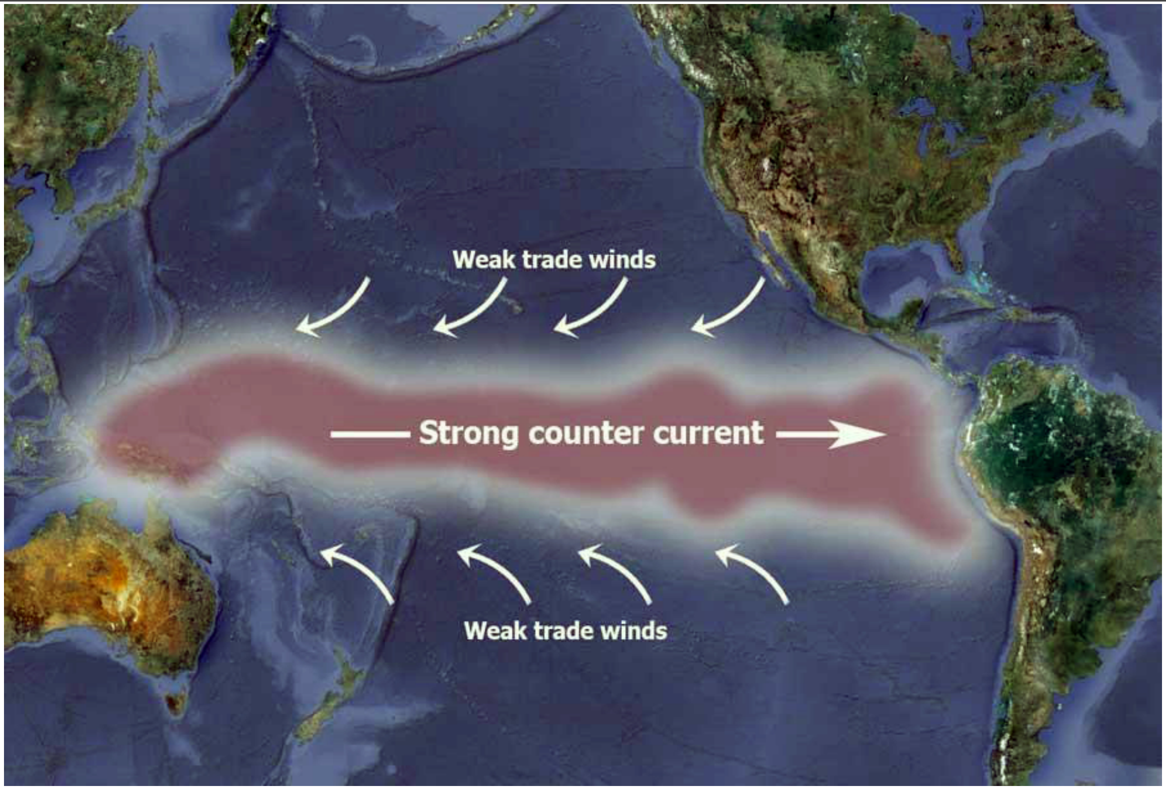


Figure 22: Schematic of El Niño conditions in the tropical Pacific. A weakened Walker circulation allows warm water to flow eastward along the equator, while reduced upwelling permits the eastern Pacific to warm substantially. The resulting redistribution of heat and moisture alters atmospheric circulation patterns worldwide, affecting rainfall, droughts, floods, tropical cyclones, and temperature extremes far beyond the Pacific basin.

Illustration 22. The runaway feedback that powers El Niño. One of the most important feedbacks in the climate system is the Bjerknes positive feedback. A modest warming of the eastern equatorial Pacific lowers atmospheric pressure there and weakens the easterly trade winds. Weaker trade winds reduce the upwelling of cold, deep water along the coast of South America and diminish the westward transport of warm surface water. As a result, the eastern Pacific warms even further, reinforcing the original disturbance. This self-amplifying ocean–atmosphere interaction is responsible for the rapid growth of El Niño events.

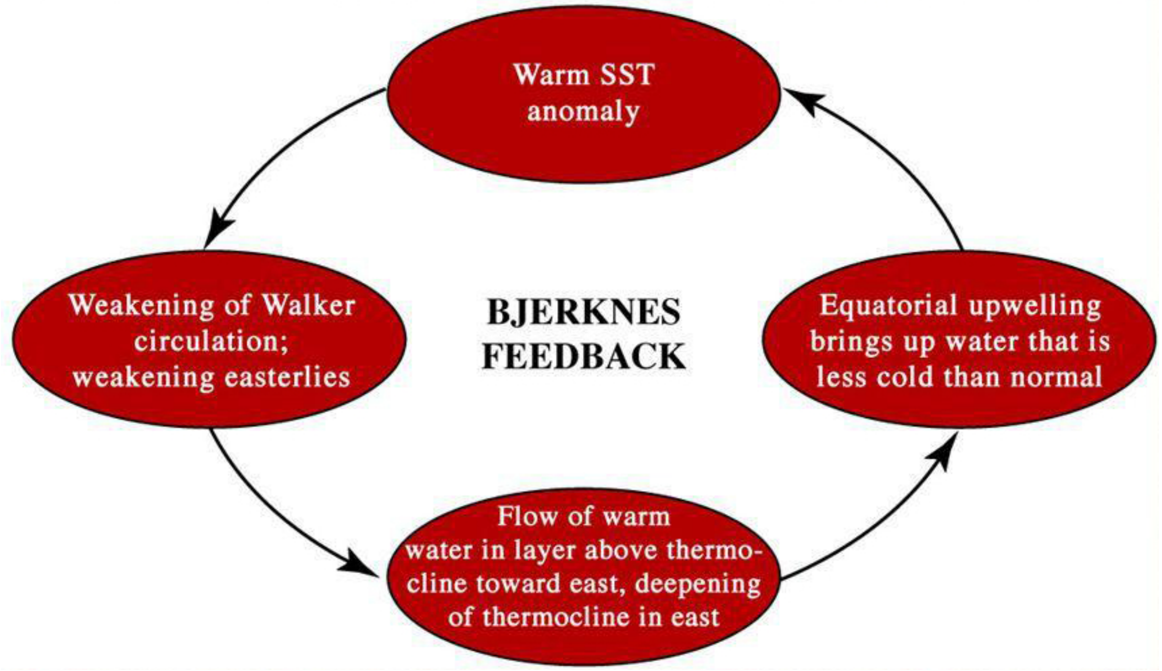


Figure 23: The Bjerknes positive feedback, the fundamental mechanism that amplifies El Niño events. Warm water in the eastern tropical Pacific weakens the normal east–west pressure gradient and the trade winds. Reduced upwelling of cold water allows sea-surface temperatures to rise further, creating a self-reinforcing cycle of ocean warming and atmospheric change. Although the feedback does not continue indefinitely, it is the engine that transforms a modest oceanic perturbation into a major global climate event.

Illustration 23. The Same El Niño, but a Much Warmer World. El Niño is a natural oscillation of the climate system, not a consequence of global warming. However, each El Niño now occurs on a warmer planetary baseline than the previous one. The oscillation continues, but its warm peaks are superimposed on a steadily rising background temperature, allowing new records to be reached more easily.

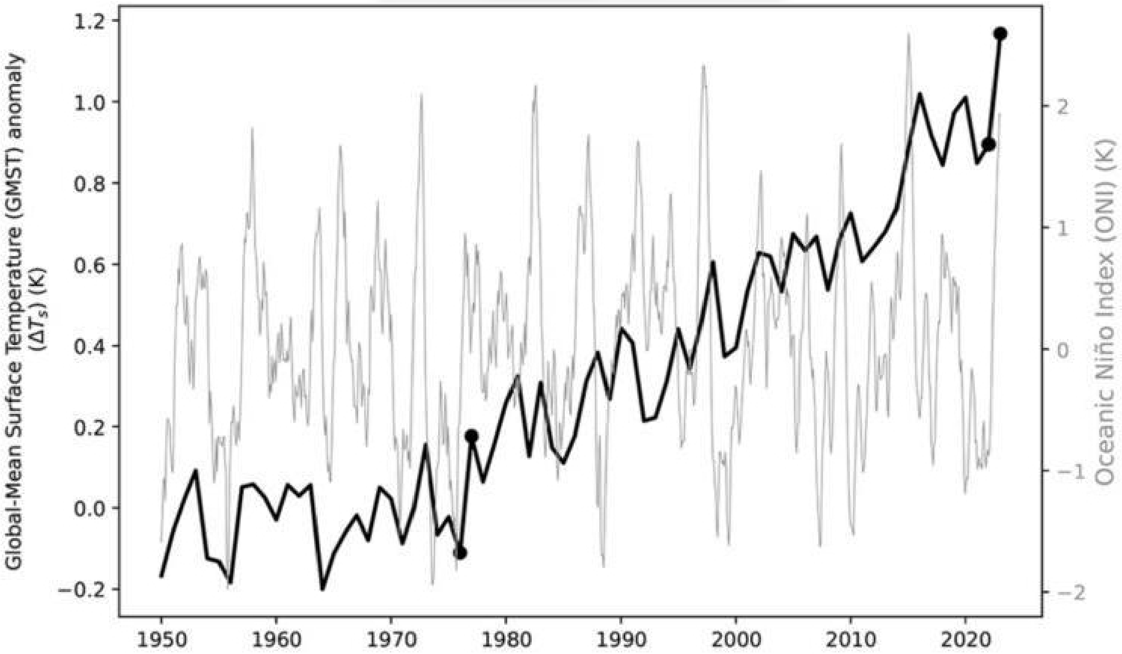


Figure 24: NASA's GISTEMP record illustrates how global warming raises the baseline on which El Niño events occur. The black markers highlight two similarly strong El Niño events, one in 1976–1977 and the other in 2022–2023. Although the oceanic perturbations were comparable, the later event occurred in a world that was already substantially warmer. As a result, similar El Niño forcing now produces much higher global temperatures and a greater likelihood of record-breaking heat.

11. **What is the single biggest misconception smart people have about climate change, and what does that misconception cause them to underestimate?**
    Answer: Many people believe climate change is primarily an environmental or moral issue. In reality, it is a direct consequence of the scale and structure of the global energy system. Without physically replacing tens of terawatts of reliable fossil energy, declarations, treaties, and intentions cannot change outcomes. This misconception leads to systematic underestimation of the inertia and difficulty of transition.

12. **What's the most direct connection between fossil-fuel burning and climate breakdown?**

    Answer:

    That's an excellent question, Nate. For more than a century, climate skeptics have repeated an argument first advanced by the Swedish physicist Ångström in the early twentieth century. The claim was that the warming effect of carbon dioxide must quickly saturate and become insignificant. Others argue that because water vapor is a much more abundant greenhouse gas than CO_2, changes in carbon dioxide cannot matter very much.

    Modern spectroscopy and atmospheric physics have thoroughly disproved these arguments. During the last 180 years, humanity has released more than two trillion tons of carbon dioxide into the atmosphere through the burning of coal, oil, natural gas, and through land-use change. Roughly half of that carbon dioxide remains in the atmosphere today. As a result, atmospheric CO_2 concentrations have risen from about 278 parts per million (ppm) in 1850 to approximately 435 ppm today. Before the Industrial Revolution, atmospheric CO_2 fluctuated within a relatively narrow range of roughly 260–280 ppm for at least six thousand years.

    Once we recognize how rapidly we have altered the composition of the atmosphere, the next question becomes obvious: What are the most direct and observable consequences?

    My answer is surprisingly simple. The strongest evidence is found in the Earth's temperature extremes. The hottest and coldest temperatures recorded each year have increased almost linearly with cumulative CO_2 emissions. In other words, as humanity adds more carbon dioxide to the atmosphere, both the hottest and the coldest parts of the climate system shift upward together. This relationship is one of the clearest observational links between fossil-fuel combustion and planetary warming.

    The acceleration is remarkable. Globally, the rate of increase of annual temperature maxima rose from approximately 0.03°C per decade before 1976 to about 0.18°C per decade afterward, a six-fold increase. A further acceleration may have occurred around 2011, with rates approaching 0.30°C per decade. The coldest temperatures warmed as well, increasing from roughly 0.05°C per decade before 1976 to approximately 0.20°C per decade afterward.

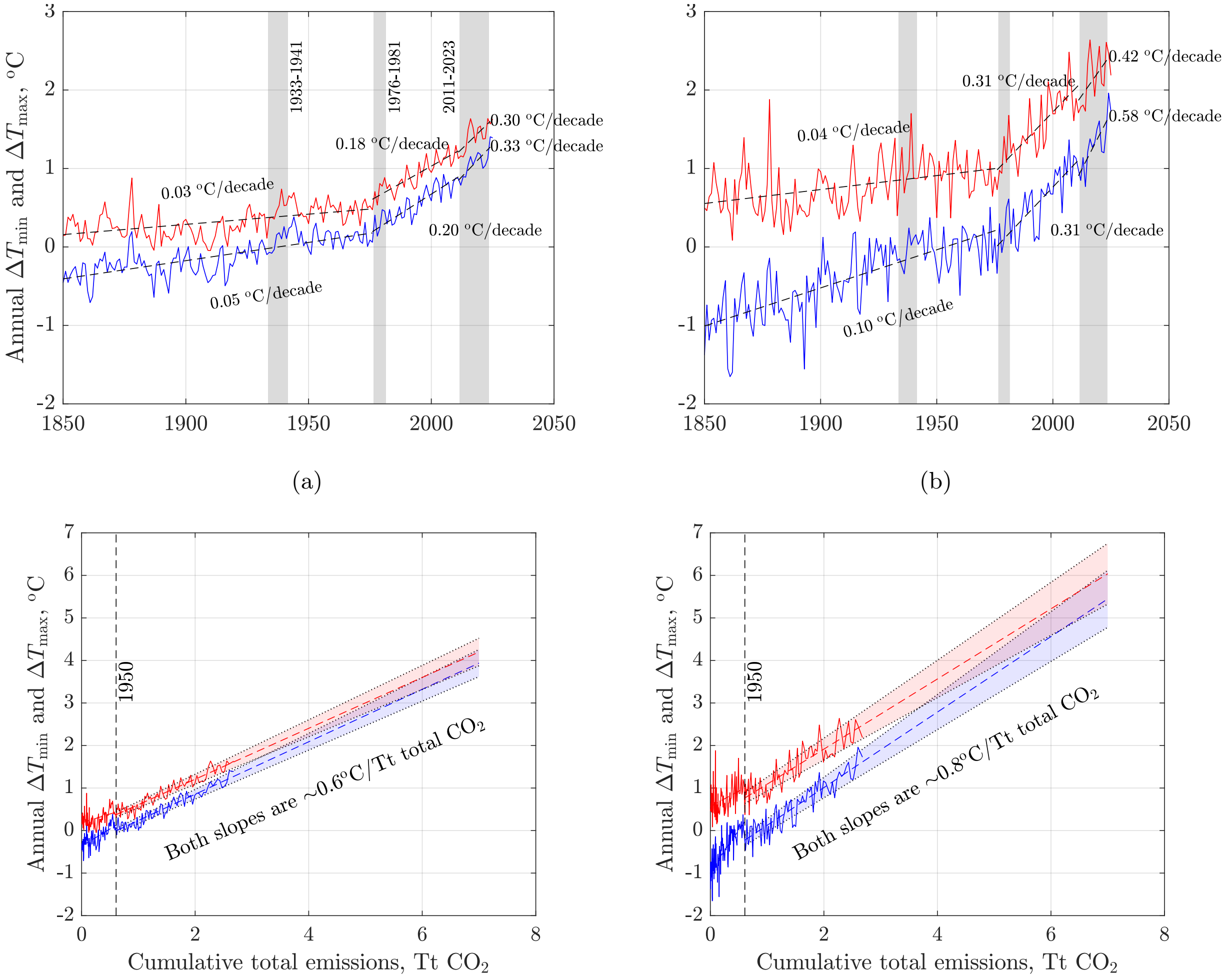
    The signal is even stronger over land, where people live. The annual temperature maxima over land accelerated from approximately 0.04°C per decade before 1976 to 0.31°C per decade afterward, while the annual minima increased from about 0.10°C to 0.31°C per decade. Both may have accelerated again after 2011.

    The faster rise of cold extremes implies that winters are warming more rapidly than summers and nights more rapidly than days. This asymmetry reduces respit for ecosystems, agriculture, infrastructure, and people to recover from daytime and summertime heat stress. In many already hot regions, including parts of the Middle East, South Asia, and sub-Saharan Africa, increasingly warm nights pose a growing threat to human health because the body loses its ability to cool and recover during sleep.

The key insight emerges when we stop plotting temperature extremes against time and instead plot them against cumulative CO_2 emissions. The apparent slope changes largely disappear. What remains is a remarkably simple relationship: each additional increment of cumulative carbon emissions pushes the Earth's temperature extremes upward. The climate system may fluctuate from year to year because of El Niño events, volcanic eruptions, and other natural processes, but the long-term trajectory is overwhelmingly governed by the total amount of carbon dioxide humanity has added to the atmosphere.

Our chart provides a striking visualization of this relationship. The coldest and hottest monthly temperatures recorded each year rise together, approximately linearly, with cumulative CO_2 emissions. This simple observation may be the most direct and compelling evidence that fossil-fuel combustion is driving the ongoing warming of our planet.

Illustration 24. Temperature extremes track cumulative CO_2 emissions. The strongest and most direct observational link between fossil-fuel combustion and climate change may be found in the evolution of temperature extremes. As humanity emits more carbon dioxide, both the hottest and the coldest temperatures experienced each year rise almost linearly. This relationship holds globally and over land, where most people live.



(a)

(b)

(c)

(d)

Figure 25: Annual maximum (red) and minimum (blue) monthly temperatures between 1850 and 2025 for the entire Earth **(a)** and for global land areas only **(b)**. Both temperature extremes exhibit a pronounced acceleration beginning around 1976. For the globe, the warmest temperatures increased at approximately 1.8°C per century after 1976, while the coldest temperatures increased at approximately 2.0°C per century. Over land, where warming is amplified, both rates increased to about 3.1°C per century. A second acceleration may have occurred around 2011. Since then, the warmest temperatures have increased at approximately 3.0°C per century globally and 4.2°C per century over land. The coldest temperatures have increased even faster, at approximately 3.3°C per century globally and 5.8°C per century over land. Panels **(c)** and **(d)** show the same temperature extrema plotted against cumulative anthropogenic CO_2 emissions. The apparent slope changes seen when temperature is plotted against time largely disappear. Instead, both the hottest and coldest temperatures increase approximately linearly with cumulative CO_2 emissions, highlighting the fundamental role of cumulative carbon emissions in driving long-term climate change.

13. **How could climate science be wrong?**

Answer: That is exactly the right question to ask. Science advances not by proving itself correct, but by continuously trying to prove itself wrong. Every scientific theory remains provisional. The real question is not whether climate science *could* be wrong, but *how wrong* it could be and what observations would demonstrate that.

The first thing to understand is that climate science is not a single theory. It is a vast collection of observations and physical laws accumulated over nearly two centuries. Some parts are as secure as any knowledge in science. Others remain uncertain.

For example, climate science would be fundamentally wrong if one of the following observations were true:

- Atmospheric carbon dioxide were not increasing.
- Carbon dioxide did not absorb infrared radiation.
- Multiple satellites showed the Earth losing more energy to space than it receives from the Sun.
- The oceans were not accumulating heat.
- The atmosphere and oceans were not warming.
- Sea level were not rising.
- Glaciers and ice sheets were not losing mass.

None of these statements is true. All have been measured independently by multiple observing systems. We know that atmospheric CO_2 has increased from roughly 278 ppm before the Industrial Revolution to approximately 435 ppm today. We know from laboratory spectroscopy that CO_2 absorbs infrared radiation and you just saw the 667 1/cm IR absorption ditch. We know from satellites that the Earth currently absorbs more energy than it emits to space. We know from millions of temperature measurements, thousands of ocean floats, and multiple satellite missions that the oceans, atmosphere, and cryosphere are changing in the direction predicted by greenhouse-gas theory. Can all of them be wrong?

Where climate science becomes less certain is in the details. How rapidly will warming proceed? How sensitive is the climate system to a doubling of atmospheric CO_2? How will clouds respond? How quickly will ice sheets destabilize? Will climate change occur smoothly or through abrupt transitions? These are active research questions.

Indeed, if climate science has a historical tendency, it is not toward exaggeration but toward underestimating certain risks. Examples include the rapid decline of Arctic sea ice, the recent collapse of Antarctic sea ice, the acceleration of ice loss from Greenland, and the growing frequency of extreme heat events. The climate system has repeatedly shown itself capable of changing faster than many scientists expected.

In my view, the most plausible way climate science could be wrong is not that greenhouse gases do not warm the planet. That conclusion rests on fundamental physics established over more than a century. The more realistic possibility is that important feedbacks remain poorly understood and that the climate system may prove either somewhat less sensitive or considerably more sensitive than our current best estimates suggest.

Thus the honest scientific answer is this: climate science could be wrong in many details, but it is exceedingly unlikely to be wrong about the central conclusion that increasing greenhouse-gas concentrations warm the planet. To reject that conclusion would require overturning a vast body of evidence from spectroscopy, thermodynamics, atmospheric physics, oceanography, glaciology, satellite observations, and direct measurements of the Earth's energy balance.

Science welcomes skepticism. What it cannot accept is skepticism that ignores the observations.

Richard Feynman, one of 2-3 top physicists of all times, and my teacher and hero, argued that uncertainty is not a weakness of science but one of its greatest strengths. Science does not begin with certainty; it begins with doubt. Every scientific conclusion is provisional and remains open to revision if better evidence appears. What distinguishes science from ideology or religion is not that scientists know all the answers, but that they are willing to change their minds when observations demand it.

In his 1955 address *The Value of Science*, he said: "Scientific knowledge is a body of statements of varying degrees of certainty – some most unsure, some nearly sure, but none absolutely certain."

One of the greatest challenges in discussing climate change with an non-science audience is that science and religion answer fundamentally different human needs.

Religion often seeks meaning, moral guidance, community, and comfort in the face of uncertainty, suffering, and death. Science seeks something different: an increasingly accurate description of reality. The two enterprises may occasionally overlap, but their methods are fundamentally different.

Science begins with doubt. Every scientific idea, no matter how successful, remains subject to revision if new observations demand it. Scientific knowledge is therefore never absolute. It consists of propositions held with varying degrees of confidence, from tentative hypotheses to conclusions supported by overwhelming evidence.

Many people find this uncomfortable. Human beings naturally prefer certainty to uncertainty, simple stories to complex explanations, and clear moral narratives to probability distributions. Science offers none of these comforts. It asks us to live with incomplete knowledge while continually testing our beliefs against reality.

Richard Feynman considered this willingness to live with uncertainty one of science's greatest virtues. In his and my view, it is far better to acknowledge what we do not know than to embrace explanations simply because they are emotionally satisfying.

Climate science is therefore not asking people to place their faith in scientists. It is asking them to examine the evidence: the measurements of atmospheric carbon dioxide, the warming oceans, the retreating glaciers, the changing energy balance of the Earth, and the temperatures recorded by millions of thermometers. The conclusions remain open to revision, but any revision must explain the observations better than the current understanding does.

Science is not a destination. It is a path. Its strength lies not in certainty, but in its relentless willingness to confront reality, even when reality is inconvenient, surprising, or frightening.

14. How could I be wrong?

Answer: This is perhaps the most important question any scientist can ask and I ask it every day. If a hypothesis cannot be wrong, it is not science. The challenge is therefore not merely to explain the observations, but also to identify the assumptions that might later prove incomplete or incorrect.

The most obvious possibility is that I am over-attributing a common cause to several phenomena that began changing around the same time. Since approximately 2014, global temperatures appear to have accelerated, Antarctic sea ice has declined rapidly, ocean heat uptake has increased, and CERES observations suggest that the Earth is reflecting less sunlight back to space. These developments may indeed be connected through a common physical mechanism. Equally, they may represent several partially independent processes whose timing happens to overlap. The observational record is not yet long enough to distinguish these possibilities with high confidence.

A second source of uncertainty is the relatively short duration of the CERES satellite record. Twenty-six years is a very short interval in climate science. The most dramatic albedo anomalies occur near the end of the record, particularly during the strong 2023–2024 El Niño event. Future observations may confirm that a genuine transition occurred around 2014–2015, or they may reveal that part of the apparent change resulted from low-frequency natural variability superimposed on a longer-term trend.

BUT, the most interesting discovery was not the large El Niño spike of 2023. The more interesting discovery is that when 19 more months of new satellite observations became available through 2026, the Earth's albedo continued to follow almost exactly the decline predicted from the earlier record.

The representation of the ocean is another simplification. My model suggests that the observed attenuation of top-of-atmosphere albedo forcing can be explained by heat uptake into roughly the upper 200–300 m of the ocean. This estimate is physically plausible and consistent with the timescale of the CERES observations. Nevertheless, the real ocean is not a uniformly mixed slab. Heat uptake varies spatially and temporally and is influenced by currents, mixing processes, and large-scale circulation changes that are only approximately represented in a simple energy-balance model.

Cloud feedbacks remain perhaps the greatest uncertainty in climate science. In my framework, the residual forcing term may include the combined effects of clouds, aerosols, circulation changes, and other processes that are not separately resolved. It is therefore possible that the apparent role of declining albedo reflects several interacting mechanisms rather than a single dominant cause.

Finally, I may place too much emphasis on the remarkably linear relationship between cumulative CO_2 emissions and temperature extremes. The linearity observed for 175 years is striking and physically meaningful, but it may be an emergent property of several interacting processes rather than a fundamental law. Greenhouse gases, aerosols, land-use change, ocean heat uptake, and internal variability all contribute to the climate response.

None of these uncertainties challenges the central conclusion that increasing greenhouse-gas concentrations warm the Earth. Rather, they affect our understanding of the magnitude, timing, and mechanisms of the observed changes.

Therefore, my most defensible conclusion is not that a specific causal mechanism has been proven, but that multiple independent observations suggest that the climate system observed since approximately 2014 differs from the one observed during the first decade of the twenty-first century. Whether this represents a true climate-regime shift, the emergence of a new feedback, or the superposition of several coupled processes remains an open scientific question. Continued observations will determine which interpretation proves correct.

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