# HOW WE KNOW HUMAN $CO_2$ EMISSIONS ARE CAUSING CLIMATE CHANGE

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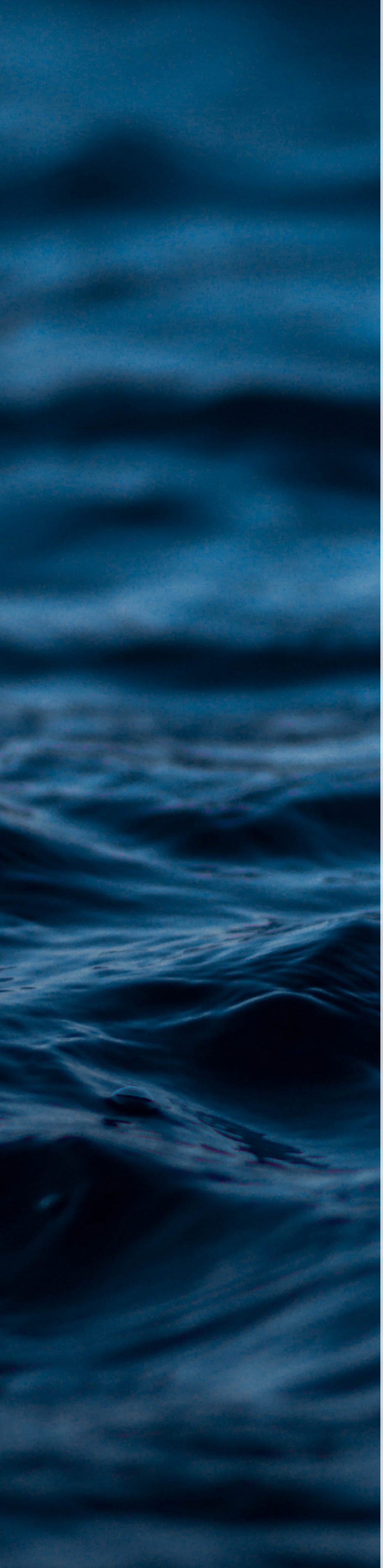


Humans have emitted such vast amounts of carbon dioxide ($CO_2$) since we began burning fossil fuels 250 years ago that we have changed the composition of our atmosphere, increasing its $CO_2$ concentration by 46%. $CO_2$ packs a powerful punch because it acts like a blanket in the atmosphere, trapping heat and warming our planet. The potential for human $CO_2$ emissions to warm the planet was described and calculated more than a century ago. Since that time, many different lines of evidence indicate that human $CO_2$ emissions are driving climate warming. The fact that $CO_2$ remains in the atmosphere a very long time is a critical aspect of our emissions problem. Roughly half of the $CO_2$ produced since humans began burning fossil fuels centuries ago is still in the air because the magnitude and rapid rate of our emissions have overwhelmed the natural processes that cycle $CO_2$ between the atmosphere, land, and ocean. By extension, the $CO_2$ we put in the air now will be around for hundreds to thousands of years into the future. Cutting our emissions as quickly as possible is critical to reducing the devastating impacts of climate change.

## INTRODUCTION

Humans produce an enormous amount of carbon dioxide ($CO_2$)—37 billion metric tons in 2019 alone—by burning coal, oil, and natural gas to produce electricity and power our vehicles (globalcarbonproject.org). This $CO_2$ initially goes into the air. The ocean and the landscape will absorb some of it, but much will linger in the atmosphere. Humans have emitted so much $CO_2$ since we began burning fossil fuels 250 years ago that we have changed the composition of our atmosphere, increasing its $CO_2$ concentration by almost 50%.

The potential for human activity to impact climate has been known for quite some time. In the late 1800s, Swedish scientist Svante Arrhenius warned that burning fossil fuels could cause $CO_2$ to build up in the atmosphere and warm Earth's climate. He knew from work done in the 1820s by mathematician and physicist Joseph Fourier that global temperature was set by a balance between incoming solar radiation heating the planet and that heat (infrared radiation) subsequently escaping into space. Arrhenius put this together with physicist John Tyndall's finding in the 1850s that $CO_2$ absorbs heat, while the major gases in the atmosphere—oxygen and nitrogen—let it pass through. From these two pieces of information, he reasoned that a significant amount of warming could result from burning fossil fuels.

In the 1950s at Scripps Institution of Oceanography, David Keeling developed a precise way to measure the concentration of $CO_2$ in the atmosphere. His initial work showed that $CO_2$ levels in the air from remote locations, away from forests and cities, had a nearly constant $CO_2$ level of around 315 ppm. He set up an instrument to make non-stop measurements of $CO_2$ at a location in Hawaii on the Mauna Loa Observatory. Within just a few years, it became clear that $CO_2$ was accumulating in the atmosphere. In the 60 years since measurements began, $CO_2$ levels have increased 30%, from 315 to 415 ppm (Fig. 1).

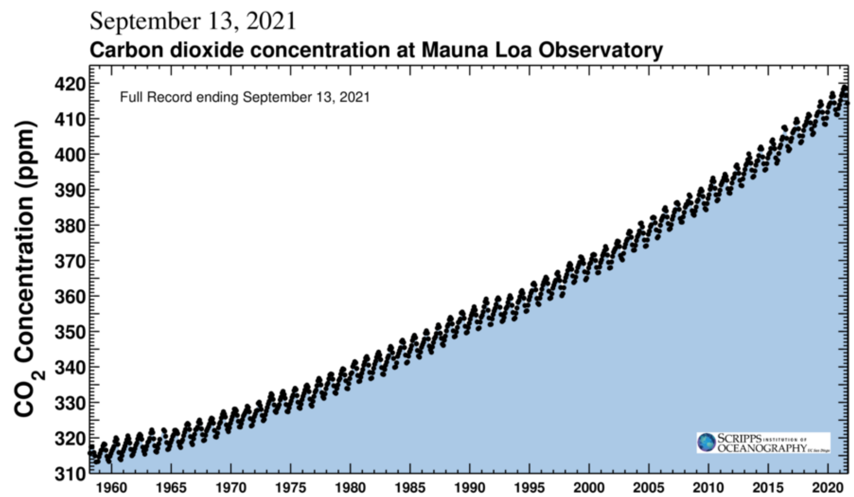



Fig.1. Direct measurements begun in 1958 document the steady increase of $CO_2$ in Earth's atmosphere. The drop and rise of $CO_2$ within each year follows the beginning of the growing season in spring in the northern hemisphere as plants become photosynthetically active, to autumn and winter when plants become largely dormant. | (keelingcurve.ucsd.edu - images changes daily)

The $CO_2$ rise documented by Keeling's measurements covers only the last 60 years or so. When combined with 320 years of $CO_2$ concentrations estimated from natural archives such as ice cores, ocean sediments, and tree rings (known as proxy climate data), the trend revealed is an accelerating increase in $CO_2$ (Fig. 2). The rise is even more startling when viewed over a 10,000-year time frame (Fig. 3).

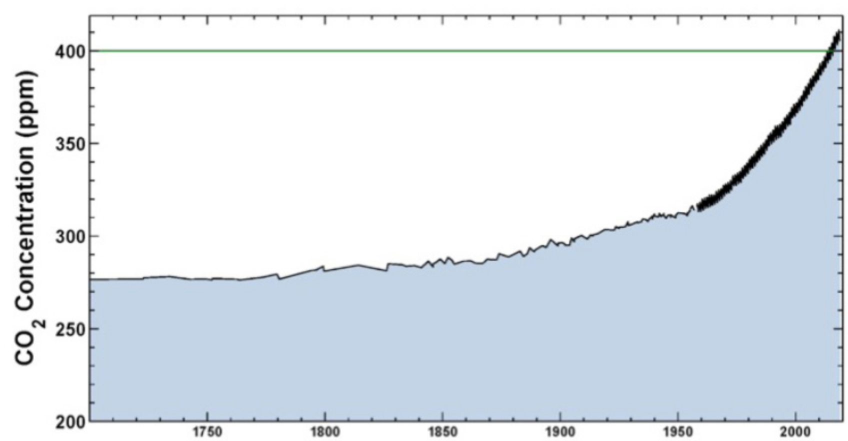



Fig 2. $CO_2$ levels in Earth's atmosphere over the past 320 years. Direct measurements are added to $CO_2$ concentrations estimated from natural archives such as ice cores, ocean sediments, and tree rings (known as proxy climate data). (keelingcurve.ucsd.edu)

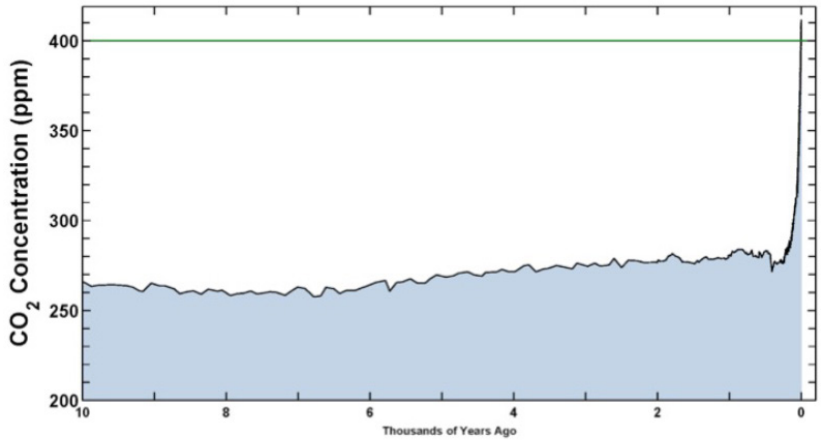



Fig. 3. $CO_2$ levels in Earth's atmosphere over the last 10,000 years. Direct measurements are added to CO2 concentrations estimated from air bubbles in cores of ancient ice. Ice core records provide a high-resolution proxy record of past atmospheres and climates. | (keelingcurve.ucsd.edu)

This rapid increase documented in the Keeling curve corresponds to skyrocketing $CO_2$ emissions in the last 100 years. Emissions reached 35 billion tons per year at the end of the 20th century and have continued their meteoric rise (Fig. 4).

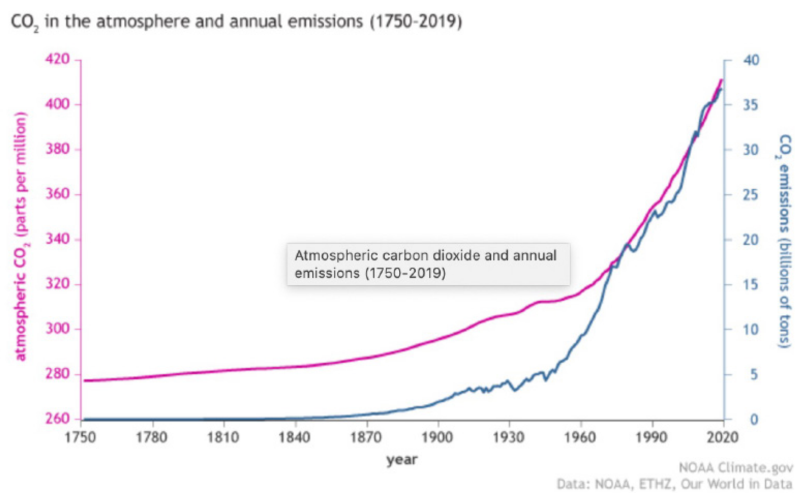



Fig. 4. $CO_2$ levels (pink line; left Y-axis) in the atmosphere have increased along with human emissions (blue line; right Y-axis) since the start of the Industrial Revolution. Emissions skyrocketed to 35 billion tons per year at the end of the 20th century and have continued to rise. (NOAA Climate.gov graph, adapted from original by Dr. Howard Diamond (NOAA ARL). Atmospheric $CO_2$ data from NOAA and ETHZ. $CO_2$ emissions data from Our World in Data and the Global Carbon Project)

The modern rise is unusual both because of its rapidity and because $CO_2$ is moving into a range that the earth has not seen for millions of years. $CO_2$ hasn't been above 400 ppm for at least 2.5 million years, and probably even longer (e.g., Da et al., 2019; Cui et a., 2020). During the past million years, as earth has moved into and out of ice ages, $CO_2$ has fluctuated between ~200 and 300 ppm (Fig. 5). The increase from 200 to 300 ppm during these glacial-interglacial cycles was much slower than the modern rise, taking on the order of 10,000 years or longer. At no point in this period were levels as high or increasing as fast as what we are observing today. The annual rate of increase in atmospheric $CO_2$ over the past 60 years is about 100 times faster than these natural cycles.

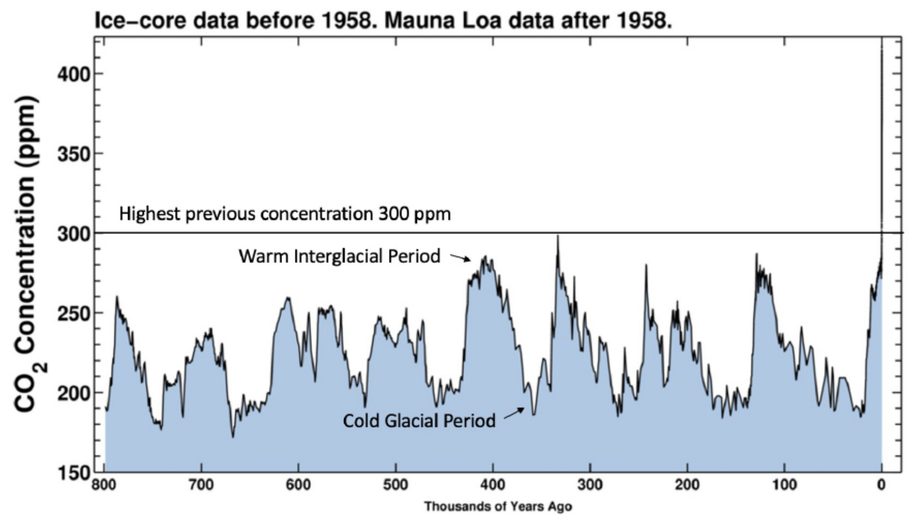
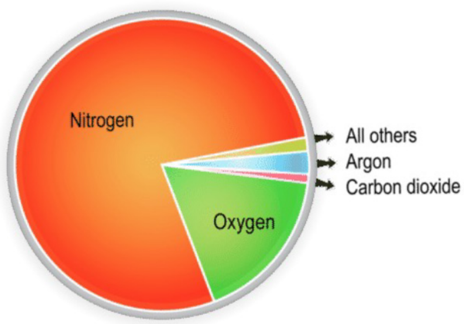



Fig. 5. Data on past atmospheric $CO_2$ concentrations from air bubbles preserved in ice cores from Antarctica. The amount of $CO_2$ in the atmosphere is now much higher and has risen much faster than at any time during these natural glacial-interglacial climate cycles. | (keelingcurve.ucsd.edu).

## A LITTLE $CO_2$ GOES A LONG WAY TO GENERATE WARMTH

Solar energy absorbed by the Earth's surface results in heating. Our planet maintains its temperature by radiating this energy back to space as heat (infrared radiation). Anything that increases or decreases the amount of incoming or outgoing energy disturbs this balance, and global temperature rises or falls in response. $CO_2$ is a major player in the story because as a greenhouse gas it acts like a blanket, holding in some of the heat radiating off Earth's surface, before it is radiated back into space. Adding $CO_2$ and other greenhouse gases to the atmosphere enhances this greenhouse effect, making Earth's surface and lower atmosphere even warmer.

The composition of the atmosphere is 21% oxygen and 78% nitrogen. The last 1% is about half argon and other trace gases, with a tiny fraction being $CO_2$ (Fig. 6). While $CO_2$ constitutes just 0.04% of air, it packs a powerful punch due to its heat trapping ability. To illustrate the power of $CO_2$, consider this: Without this tiny amount of $CO_2$ in the atmosphere, our planet's average annual temperature would be below freezing instead of the 15.6°C/60°F that makes it habitable for life as we know it! Since $CO_2$ traps some of the heat trying to escape into space and sends it back to Earth's surface, the amount of $CO_2$ in our atmosphere is a critical factor in global temperature.




Dry air composition

| Molecule | Symbol | mole fraction in air | |
|---|---|---|---|
| Nitrogen | $N_2$ | 78.08% | |
| Oxygen | $O_2$ | 20.945% | |
| Argon | Ar | 0.934% | |
| Carbon Dioxide | $CO_2$ | 0.04% | 400 ppm |
| Neon | Ne | | 18.2 ppm |
| Helium | He | | 5.24 ppm |
| Methane | $CH_4$ | | 1.8 ppm |
| Krypton | Kr | | 1.14 ppm |
| Hydrogen | $H_2$ | | 0.52 ppm |
| Nitrous Oxide | $N_2O$ | | 0.32 ppm |

Fig. 6. Nitrogen and oxygen make up 99% of air. Most of the remaining 1% is argon, with $CO_2$ constituting just 0.04%. 1 (Hana Zavadska, CK-12 Foundation)

Burning carbon-based fuels like coal, oil, or natural gas to generate electricity and power most vehicles release $CO_2$ into the air. For example, did you know that every gallon of gasoline we burn driving our cars emits about 20 pounds of $CO_2$? The volume of our collective emissions has been—and continues to be—so immense that we are rapidly increasing the amount of carbon dioxide in the atmosphere, which increases the amount of heat trapped and raises global temperature.

## THE OCEAN HAS MASKED THE PROBLEM BY TAKING UP BOTH $CO_2$ AND HEAT

The ocean covers 71% of our planet. It takes up a lot of $CO_2$, so at first it was hard for scientists to imagine that adding $CO_2$ to the air could make much difference. It seemed obvious that much of it would go into the ocean and therefore not affect climate. The ocean takes up $CO_2$ at the surface by dissolving $CO_2$ gas from the atmosphere.

$$CO_2 + CO_3^{2-} + H_2O \leftrightarrow 2HCO_3^{-}.$$

$CO_2$ dissolves in the ocean by binding with a water molecule ($H_2O$) and a carbonate ion ($CO_3^{2-}$) in seawater to form bicarbonate (2HCO3-):

The dissolution of $CO_2$ in seawater also increases the acidity of the water and consumes carbonate ions that are essential for organisms forming calcium carbonate shells and skeletons – the phenomena of ocean acidification (Fig. 7). In fact, the availability of carbonate ions is one of the limiting factors in how much $CO_2$ can dissolve in seawater.

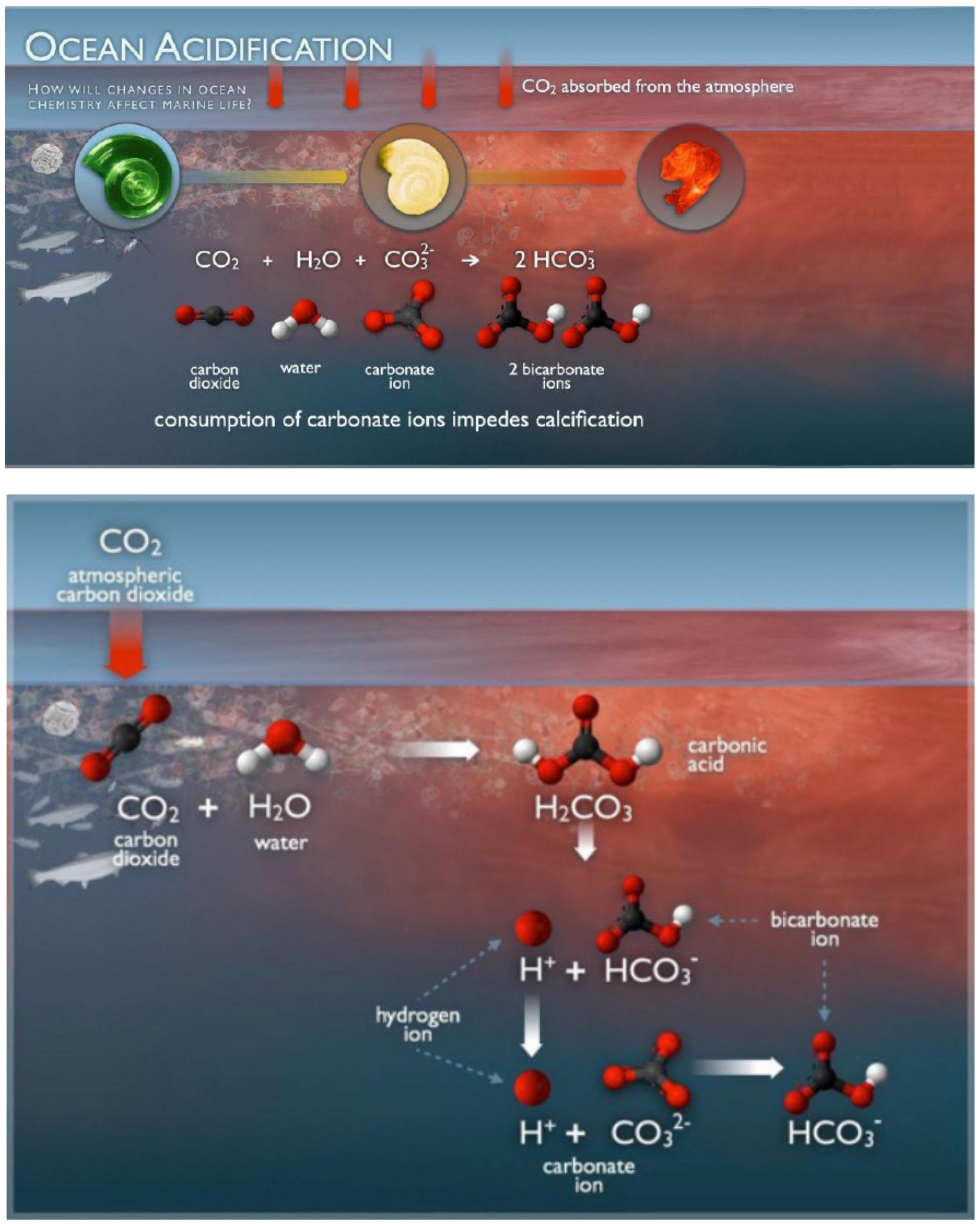



Fig. 7. A scientific illustration depicting the chemistry of ocean acidification. Created for Pacific Marine Environmental Laboratory's Carbon Program.

So, in effect, the ocean is helping to reduce climate warming by taking up some of the $CO_2$ we generate, although with unfortunate consequences for marine life. So far, the ocean has taken up increasingly more $CO_2$ as atmospheric levels have risen. The amount of $CO_2$ being absorbed by the ocean—and its effects—are active areas of research. Recent studies have found that the ocean is currently taking up about 30% of our emissions (Gruber et al., 2019), but at some point, its ability to absorb $CO_2$ will start to decline as carbonate ions are used up and increasing ocean temperatures further reduce its ability to dissolve $CO_2$. This will in turn lead to an increasingly larger percentage of $CO_2$ emissions remaining in the atmosphere.

If we stop emitting $CO_2$, most of what we have added to the atmosphere (up to 80%) will eventually be absorbed by the ocean, but it will take a long time. So far only about the upper 20% of ocean water has absorbed much $CO_2$. That's because only near surface ocean water interacts with the atmosphere, and the vertical circulation that transports surface water to the deep ocean and deep ocean water to the surface takes on the order of 1000 years.

The ocean plays another key role in regulating climate. It absorbs much of the extra heat $CO_2$ traps and sends back to Earth. Over the past several decades, the ocean has absorbed over 90% of the heat due to our $CO_2$ emissions (Purkey and Johnson, 2010). Since water heats up much more slowly than land, this has reduced the full impact of our $CO_2$ emissions on global surface temperatures. While ocean heat storage has masked the magnitude of the warming problem, it comes with serious consequences, including sea level rise, mass losses from ice sheets, fueling of hurricanes, and impacts on marine organisms and ecosystems.

## CO2 HAS GREATER IMPACT THAN OTHER GREENHOUSE GASES

Along with $CO_2$, there are a few other gases that can trap heat in the atmosphere; these are collectively known as "greenhouse gases." The primary greenhouse gases are carbon dioxide, methane, nitrous oxide, and fluorinated gases. While some of these gases are more potent greenhouse gases than $CO_2$, their impact is less because they are emitted in lower amounts and in some cases (e.g., CH4) they don't stick around as long because they react quickly. Thus, $CO_2$ has the largest warming effect.

Many people wonder about the effect of water vapor because it is a stronger greenhouse gas than $CO_2$. It is also much more abundant in the air (as much as 4% vs. just 0.04% for $CO_2$). The greenhouse effect of water vapor is illustrated by how much warmer nights can be in a humid jungle than in a dry desert with the same daytime temperature. So why do we focus on $CO_2$ rather than water when we talk about climate warming? There are several reasons.

First, it matters where gases occur. Water vapor is largely confined to the lower atmosphere and has an effect there. $CO_2$ spreads far and wide, occurring well into the upper atmosphere where it continues to trap heat and reradiate it back to Earth's surface.

In addition, these two gases cycle very differently through Earth's systems. The amount of water vapor in the air is controlled by climate. It readily evaporates and condenses in response to temperature changes, so it quickly and constantly moves in and out of the atmosphere. In contrast, $CO_2$ is a very long-lived gas. Prior to the industrial era, natural cycles that move $CO_2$ through the air, land, and ocean kept atmospheric $CO_2$ concentrations below 300 ppm. Now the magnitude and rate of our fossil fuel combustion far outstrips the ability of these processes to cycle $CO_2$. As a result, $CO_2$ added to the atmosphere hangs around for a long time–300 to 1,000 years–thus affecting many generations of life into the future.

$CO_2$ and water vapor are also related in ways that exacerbate the warming problem. As we add more $CO_2$ to the atmosphere, our planet warms. This warming causes increased evaporation, which increases the amount of water vapor. More water vapor in the air causes even more warming. This type of cycle is called a positive feedback loop and results in water vapor amplifying the warming effects of $CO_2$ and increasing the severity of the climate change problem.

## WHY DOES $CO_2$ HANG AROUND SO LONG?

Carbon naturally cycles rapidly between the atmosphere, the surface ocean and land. This natural cycling is effectively a loop with no net impact on the amount of $CO_2$ in the atmosphere because in a balanced system, just as much carbon is added back as is removed. For the land component, this cycling is largely part of the cycle of life, including the formation and decay of organic matter. For the surface ocean, this cycling is the result of the atmosphere and surface ocean coming into chemical equilibrium. On top of this natural cycling, humans are now flooding the system with extra carbon – $CO_2$ – from the burning of fossil fuels. This extra carbon is spreading along the pathways of this natural cycling, building up in the atmosphere, in the oceans and on land. Unfortunately for us, the longer-term processes in the earth system that operate to moderate $CO_2$ at natural levels operate very slowly, from the 1000-year time frame in the case of processes involving $CO_2$ absorption by the ocean, to 100's of thousands to millions of years in the case of rock weathering, which absorbs $CO_2$, and carbon storage in sedimentary rocks.

In short, burning fossil fuels moves carbon out of the ground, where it has been stored for millennia with no effect on Earth's temperature, and puts it into the atmosphere as $CO_2$, where it greatly affects Earth's temperature. The consequence of accelerating the release of $CO_2$ from fossil fuel storage for two and half centuries, given that the natural drawdown is slow, is that $CO_2$ is rapidly accumulating in the atmosphere. This excess $CO_2$ will be in the air–and continue to warm the planet–thousands of years into the future.

## MORE EVIDENCE OF THE BIG BURN

Burning requires oxygen. Knowing that we are burning massive amounts of fossil fuel, what would you expect to happen to oxygen levels in the atmosphere?

At Scripps Institution of Oceanography, we have developed a way to precisely measure atmospheric oxygen levels. To detect if and how they are changing, we began analyzing air samples from stations around the world in 1991. The data show that oxygen levels across the globe are decreasing and that the rate of decline closely tracks the amount of fossil fuels we are burning. The decrease in oxygen, a tiny fraction of a percent, is too small to have an impact on human health, but it does provide another piece of evidence that fossil fuel combustion is behind the rise in atmospheric $CO_2$ (Fig. 8).

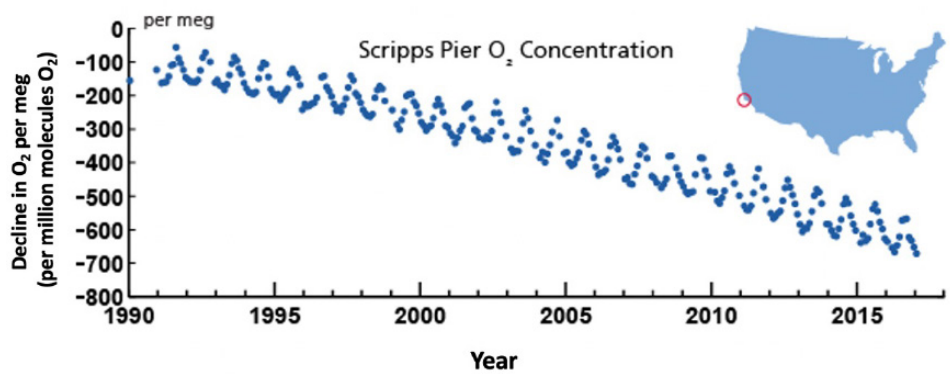



Fig. 8. Atmospheric oxygen levels are decreasing globally due to combustion of fossil fuels. The graph shows oxygen concentration relative to the level around 1985. (http://scrippso2.ucsd.edu)

## FOSSIL FUEL CO2 CAN BE IDENTIFIED BY ITS ISOTOPIC FINGERPRINT

$CO_2$ enters the atmosphere as emissions from fossil fuel combustion but also from other sources such as the ocean and the terrestrial biosphere (land plants and soils). We know the concentration in the atmosphere both from direct measurement of air samples starting in 1958, and from natural climate archives (e.g., bubbles in ice cores) for earlier times. How do we know that the increase in atmospheric $CO_2$ is from burning fossil fuels?

The key lies in the carbon atoms themselves. There are three forms of carbon atoms: 12C, 13C, and $^{14}C$ (Fig. 9). Alternative forms of the same atom, called isotopes, behave the same way chemically but have slightly different masses. About 99% of carbon on Earth is 12C and about 1% is 13C. $^{14}C$, created naturally in the upper atmosphere when cosmic rays displace a proton from the nucleus of a nitrogen atom, occurs in trace amounts. While 12C and 13C are stable, $^{14}C$ is radioactive and slowly decays over time.

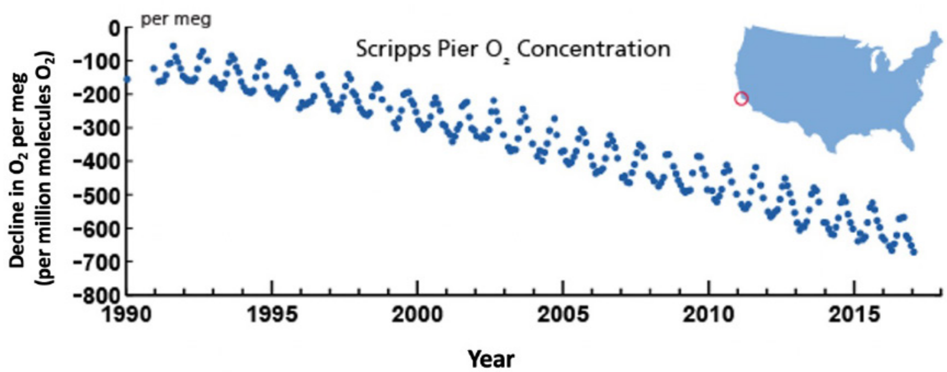



Fig. 9. The three isotopes of carbon atoms differ in their number of neutrons. (https://www.qsstudy.com/physics/isotopes)

This property makes the amount of $^{14}C$ useful for dating carbon-containing materials up to about 50,000 years old, after which time it has decayed away. It also means that different sources of $CO_2$ each have a distinct isotopic "fingerprint" that scientists can measure. Fossil fuel reserves are unique among carbon sources in being so old (10s to 100s of millions of years) that they no longer possess any $^{14}C$. Before humans began burning fossil fuels, the air had a background level of $^{14}C$ due to inputs from natural sources. If the increase in $CO_2$ in the air is from fossil fuels, which lack $^{14}C$, the percentage of the carbon atoms that contain $^{14}C$ would be diluted and decrease over time. Careful measurements of air samples from a global network confirm that the $^{14}C$ percentage of atmospheric $CO_2$ is, in fact, decreasing as $CO_2$ levels rise. A decrease in the $^{14}C$ content of atmospheric $CO_2$ is known as the Seuss Effect, named after Hans Seuss who, in 1955, showed that fossil fuel burning was changing the $^{14}C$ content of the atmosphere by analyzing tree rings. Studies of $^{14}C$ provide yet another piece of evidence proving that the increase in $CO_2$ in the atmosphere is mainly due to fossil fuel combustion.

## WHAT WILL IT TAKE TO SLOW CLIMATE WARMING?

The amount of $CO_2$ humans produce globally by burning fossil fuels can be calculated. Although atmospheric $CO_2$ concentration is rapidly rising, the amount is actually less than expected based on the amount of fuel burned. Research shows that the rise of $CO_2$ in the atmosphere represents only about 57% of the $CO_2$ we emit (Fig. 10). Where does the rest of it gone? The other 43% is taken up by the ocean and terrestrial biosphere.

What does this mean for efforts to slow climate warming? We would have to cut emissions by 57% to flatline $CO_2$ at this point in time. Eventually the ocean, land plants, and soil will slow and then stop taking up excess $CO_2$, meaning we would have to cut emissions even more to compensate. A stabilization scenario typically involves cutting our $CO_2$ emissions by more than half quite quickly, and then cutting additionally over time. Meeting this challenge will require a multi-pronged, cooperative, global effort that begins immediately, led by massive emissions reductions through a transition to cleaner energy. Implementation of strategies for reducing the $CO_2$ backlog in the atmosphere (for example, carbon sequestration) will also be necessary. Understanding the causes of climate change in general—and specifically the impact of human $CO_2$ emissions on the climate system—is essential for the development and deployment of effective solutions, swept along by public demand. Education is

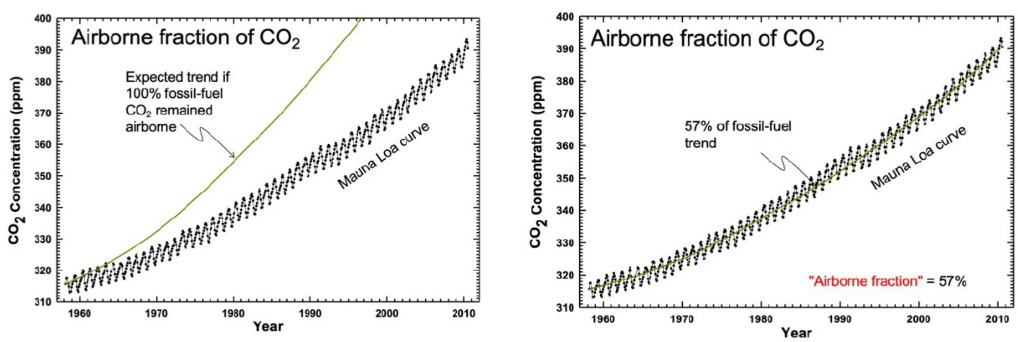



Fig. 10. The amount of $CO_2$ measured at Mauna Loa compared to the predicted curve if 100% of the $CO_2$ produced by burning fossil fuels remained in the atmosphere (left). The trend in the atmospheric measurements of $CO_2$ reflects that only 57% of the CO2 produced by fossil fuel burning remains in the atmosphere, the other 43% being removed from the atmosphere by other carbon sinks such as the ocean and terrestrial biosphere (right).

BIOGRAPHY
Ralph Keeling is professor of geochemistry in the Geosciences Research Division of Scripps Institution of Oceanography, University of California, San Diego. His research focuses on atmospheric composition, the carbon cycle, and climate change. He is considered a leading investigator of the global oxygen cycle for his precise measurements and analysis techniques.

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Measuring $CO_2$ in the atmosphere - keelingcurve.ucsd.edu

Measuring $O_2$ in the atmosphere - http://scrippso2.ucsd.edu

The ocean's role in climate - https://tos.org/oceanography/article/the-oceans-role-in-climate

Ocean absorbing $CO_2$ - https://www.ncei.noaa.gov/news/global-ocean-absorbing-more-carbon

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