This is the print version of the Skeptical Science article 'CO2 lags temperature', which can be found at http://sks.to/lag.

# CO2 lags temperature - what does it mean?

**What The Science Says:**
Increasing concentration of $CO_2$ in the atmosphere increases global temperature.

Increasing global temperature ***also*** increases the concentration of $CO_2$ in the atmosphere.

Yes, you can have both. Antarctic ice core records of past climate change help us understand earth's climate system and show that human-caused climate change is fundamentally different from natural glacial-interglacial climate cycles.

**Climate Myth: CO2 lags temperature**
"An article in Science magazine illustrated that a rise in carbon dioxide did not precede a rise in temperatures, but actually lagged behind temperature rises by 200 to 1000 years. A rise in carbon dioxide levels could not have caused a rise in temperature if it followed the temperature." (Joe Barton, US House of Representatives (Texas) 1985-2019)
- Full Statement

## Background of the myth:

Earth's climate has varied widely over its multi-billion year history - from ice ages characterized by large ice sheets covering many land areas, to warm periods with no ice at the poles. Several factors have affected past climate change, including solar variability, the tilt and wobble of the Earth's orbit relative to the sun, volcanic activity, and changes in the composition of the atmosphere. Using data from Antarctic ice cores, we can explore what climate cycles have looked like over the past 800,000 years (Figure 1). Over this time period, $CO_2$ and temperature are closely correlated, which means they rise and fall together. However, based on some Antarctic ice core data, changes in $CO_2$ appear to *follow* changes in temperatures by about 600 to 1000 years. That is to say that changes in $CO_2$ lag, or come after, changes in temperature. This has led some to incorrectly conclude that $CO_2$ cannot be responsible for the current rise in Earth's temperature.

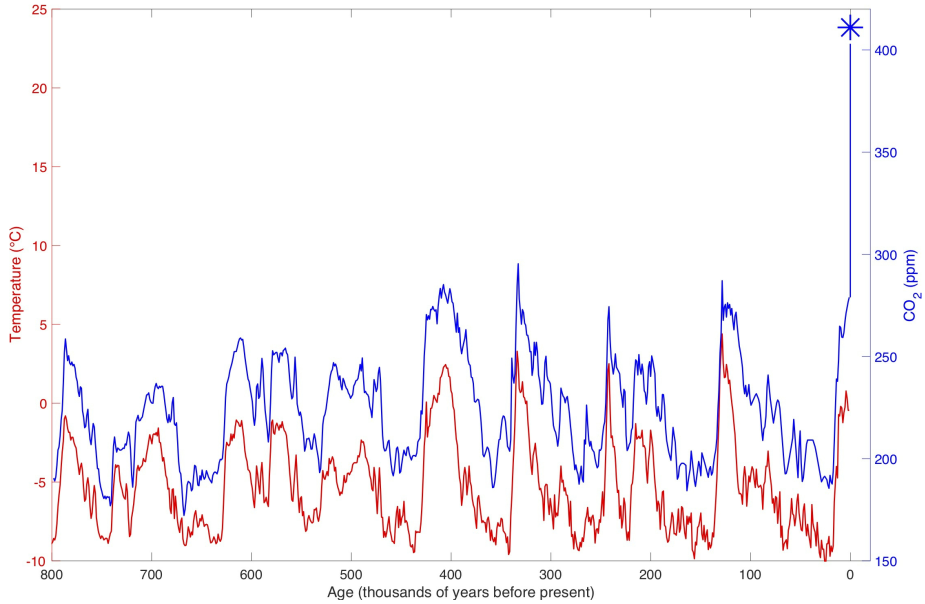


Figure 1. The EPICA Dome C ice core from East Antarctica provides the current longest ice core record, going back 800,000 years. From the core, scientists can measure past levels of $CO_2$ in the atmosphere and estimate temperature changes over the period of the record. The modern level of $CO_2$ in the atmosphere is plotted with the * to provide a reference.

## This myth misses the mark for a number of reasons:

(see Intermediate Rebuttal for a full breakdown)

1. It presents a false dichotomy by claiming that if atmospheric $CO_2$ increased before temperature, then an increase in temperature cannot cause an increase in $CO_2$. In fact, both of these causal relationships are true.
2. It doesn't distinguish between Antarctic and global temperature. Antarctic ice cores give a measure of Antarctic temperature, which increased before global $CO_2$ levels. However, global temperature, as estimated from records all over the planet, increased after rises in $CO_2$.
3. It conflates past climate changes with present climate change. Though it's true that we can learn a lot about Earth's climate from studying the past, we cannot assume that changes that occurred in the past are the same as changes occurring today. In fact, ice core data shows us that present climate change is fundamentally different from past climate changes. Past changes were driven by small changes in Earth's orbit, while current climate change is driven by human emissions of $CO_2$.
4. It is based on old data. While the old data aren't wrong, newer ice cores with higher-resolution data show that the changes in $CO_2$ and Antarctic temperature occurred so close together, that we cannot fully distinguish which happened first.

Each of these four issues with the myth relates to past and present changes in temperature and atmospheric $CO_2$. To fully understand these changes, we need to breakdown the processes within Earth's climate system as a whole.

## Climate System Components

Within the Earth's climate system, there are many complex relationships between the processes that occur in different components of the system. Some of the main components of the system are the atmosphere, ocean, and ice sheets. Each component and the timescale over which it changes play important roles in impacting the state of Earth's climate at any given time.

Earth's atmosphere covers the entire planet and can quickly circulate between the northern and southern hemispheres (over 10s of years). Gases like $CO_2$ persist in the atmosphere for long enough that their concentration is uniform across the planet. Temperature and pressure of the atmosphere impact the circulation patterns of the atmosphere across the planet.

Over much of the Earth, the atmosphere is in direct contact with the surface of the ocean. The temperature and $CO_2$ level of the atmosphere is directly related to those of the ocean surface. However, the ocean is very deep (12,000 feet on average), and the depths of the ocean are isolated from the surface. This large body of water circulates much more slowly than the thin, fast-moving atmosphere and thus is slow to move water between the hemispheres (over 100s of years).

Ice sheets build up over thousands of years on land areas that are cold enough that snow doesn't melt in the summer. The presence of an ice sheet can affect the ocean circulation by providing a source of cold, fresh water melting off the ice and into the adjacent ocean. This input water has a different density than warmer, saltier water in the ocean and can thus affect how water sinks and mixes, in some cases driving ocean circulation on a global scale. A tall ice sheet can also affect atmospheric circulation simply because it pushes air higher in the atmosphere and can effectively sit in the way of moving air masses. In turn, the atmosphere and ocean can affect ice sheets by causing them to grow (with cold temperatures and lots of snow fall) or to retreat (with warm temperatures). Of these three components, ice sheets change over the slowest timescales, taking 1000s of years in some instances to respond to changes in climate conditions.

## External Forcing on Earth's Climate

Earth's climate cycles in and out of ice ages about every 100,000 years, which we can clearly see in the ice core record (Figure 1). This timing is driven by small changes in the orbit around the sun, known as Milankovitch cycles (Hays 1976). We call this an external forcing because it depends on the timing and distribution of energy received from the sun, a component outside of the Earth system.

There are three main changes to the earth's orbit. The shape of the Earth's orbit around the sun (eccentricity) varies between an ellipse and a more circular shape. The earth's axis is tilted relative to the sun at around 23°. This tilt oscillates between 22.5° and 24.5° (obliquity). As the earth spins around its axis, the axis wobbles from pointing towards the North Star to pointing at the star Vega (precession).

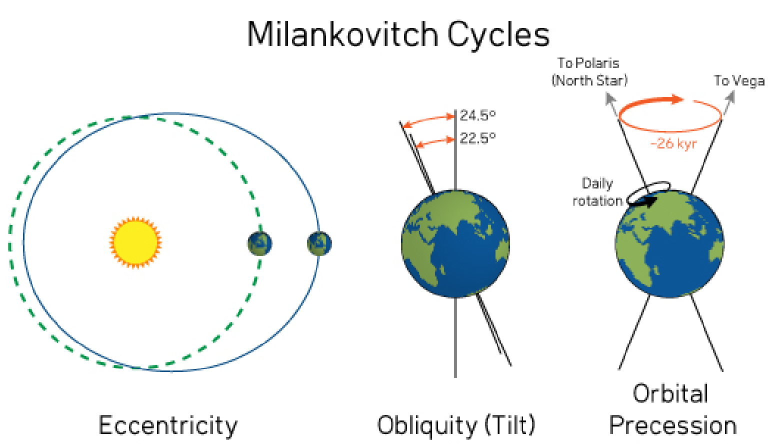


*Figure 2: The three main orbital variations. Eccentricity: changes in the shape of the Earth's orbit. Obliquity: changes in the tilt of the Earth's rotational axis. Precession: wobbles in the Earth's rotational axis.*

The combined effect of these orbital cycles causes long term changes in the amount of sunlight, or insolation, hitting the earth at different seasons, particularly at high latitudes. However, on their own, these small changes in Earth's orbit would not cause very large fluctuations in Earth's climate. Instead, these small changes are amplified into full-blown ice ages due to reinforcing processes that occur between the components of the atmosphere, ocean, and ice sheets (Cuffey 2016).

## Internal Feedbacks on Earth's Climate

The global ice age cycles follow changes in the northern hemisphere insolation because the components of the Earth system amplify the impact in the north over the entire planet. The well-mixed greenhouse gases in the atmosphere play an important role in synchronizing temperature changes in the north and the south due to the direct impact of atmospheric $CO_2$ on temperature. Additionally, interactions between the components of Earth's climate system cause further changes in the global temperature and atmospheric $CO_2$ level (Brook and Buizert 2018). We call these interactions internal feedbacks because they describe changes that depend entirely on processes within the Earth's climate system.

Among the three components of the climate system described above, there are many internal feedbacks that affect both global temperature and atmospheric $CO_2$ level. Because there is more land surface in the northern hemisphere, large ice sheets form over much of North America and Eurasia during ice ages. These large piles of ice in the north begin to melt when northern insolation increases. This cold and fresh melt water disrupts the ocean circulation, slowing the mixing of the global ocean and the transport of heat between northern and southern hemispheres in the water, which is important for determining global temperature (Stocker and Johnsen 2003). These changes in ocean circulation also impact how biological processes in the ocean affect atmospheric $CO_2$ level, for example changes in ocean circulation affect how efficiently plankton move $CO_2$ from the atmosphere into the ocean via photosynthesis (Sigman 2010). At the same time as these ocean changes affect the transport of heat between hemispheres over 100s of years, changes to atmospheric circulation caused by these feedbacks impact this transport much more quickly, over 10s of years (Markle 2017). These examples give just a taste of the many internal feedbacks that occur between the components of the climate system and affect global temperature and atmospheric $CO_2$ level on both slow and fast timescales.

## Putting It All Together

Given the many internal feedbacks that occur between the components of the climate system in response to external forcings on Earth's climate, it's no surprise that the transitions into and out of ice ages are complex. Data from ice cores show us the total effect of these simultaneous processes, all of which we must consider in order to understand what caused the Earth to warm out of the last ice age. The ice core data that show near-simultaneous increase of Antarctic temperature and atmospheric $CO_2$ level provide important information for scientists studying the interplay of these processes. These data reflect the fact that both increased global temperature leads to increased atmospheric $CO_2$ level AND increased atmospheric $CO_2$ level leads to increased global temperature. Scientists use these data alongside computer models of Earth's climate system to better understand how these interactions have caused climate changes in the past and how they may impact future change. Although the primary drivers of past changes differ from current and future changes (variations in Earth's orbit around the sun vs. human emissions of greenhouse gases), the internal feedbacks of the climate system remain the same. Understanding these processes is essential for projecting the impacts of current and future climate change.

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