Lessons from Earth's Past
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fixed in carbonate shells, can help researchers estimate where and how fast the conveyor has moved. Today, it appears that a deepwater parcel that forms in the North Atlantic will reach the southernmost Atlantic after about 1400 "^{14}C years," and reach the northeastern Pacific after more than 2200 ^{14}C years; this is equivalent to a deepwater ^{14}C loss of ~250 per mil (‰).

Such old ages and long cycling times are important because they suggest the ocean absorbed, stored, and released vast quantities of carbon in the past. Below 2000-m depth, the gradual aging of modern ocean waters is closely linked to a gradual rise in dissolved CO_2. Today, a 50‰ decrease in global deepwater ^{14}C corresponds approximately to a 7-μmol/kg rise in (natural) dissolved CO_2 in deep water (*14*). Researchers can use this relationship to deduce, from about a dozen existing reconstructions of paleoventilation ages, MOC and CO_2 storage patterns during the LGM and HS1 (see the figure). These "time slices" suggest that deep waters at those times were, on average, ~1000 to ~2000 years older than they are today. Such ages suggest that the ocean absorbed and stored a massive amount of atmospheric CO_2 during the LGM and early HS-1, when atmospheric CO_2 concentrations dropped (*15*). It now appears that deepwater CO_2 concentrations in about half of the ocean's volume then increased to levels that were 14 to 28 μmol/kg higher than today's concentrations. An urgent challenge for paleoceanographers is to improve these estimates by developing a global network of additional paleoventilation ages.

In this context, Thornalley *et al.*'s findings represent real progress. For instance, their extremely old ventilation ages for intermediate and deep waters—together with other high ages—may help explain what happened during the "mystery interval" (*16*), a period of rapid decrease in atmospheric ^{14}C that occurred 17,500 to 14,500 years ago. Overall, the increasing number of apparent ventilation ages of deep and intermediate waters form a highly promising first step to achieving a crucial paleoceanographic objective: linking changes in basin-wide MOC to global climate and the ocean's capacity for storing atmospheric CO_2.

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CLIMATE CHANGE

Lessons from Earth's Past

What can be learned from Earth's past to guide our understanding of life in a warming world?

Jeffrey Kiehl

Climate models are invaluable tools for understanding Earth's climate system. But examination of the real world also provides insights into the role of greenhouse gases (carbon dioxide) in determining Earth's climate. Not only can much be learned by looking at the observational evidence from Earth's past, but such knowledge can provide context for future climate change.

The atmospheric CO_2 concentration currently is 390 parts per million by volume (ppmv), and continuing on a business-as-usual path of energy use based on fossil fuels will raise it to ~900 to 1100 ppmv by the end of this century (see the first figure) (*1*). When was the last time the atmosphere contained ~1000 ppmv of CO_2? Recent reconstructions (*2*–*4*) of atmospheric CO_2 concentrations through history indicate that it has been ~30 to 100 million years since this concentration existed in the atmosphere (the range in time is due to uncertainty in proxy values of CO_2). The data also reveal that the reduction of CO_2 from this high level to the lower levels of the recent past took tens of millions of years. Through the burning of fossil fuels, the atmosphere will return to this concentration in a matter of a century. Thus, the rate of increase in atmospheric CO_2 is unprecedented in Earth's history.

What was Earth's climate like at the time of past elevated CO_2? Consider one example when CO_2 was ~1000 ppmv at ~35 million years ago (Ma) (*2*). Temperature data (*5*, *6*) for this time period indicate that tropical to subtropical sea surface temperatures were in the range of 35° to 40°C (versus present-day temperatures of ~30°C) and that sea surface temperatures at polar latitudes in the South Pacific were 20° to 25°C (versus modern temperatures of ~5°C). The paleogeography of this time was not radically different from present-day geography, so it is difficult to argue that this difference could explain these large differences in temperature. Also, solar physics findings show that the Sun was less luminous by ~0.4% at that time (*7*). Thus, an increase of CO_2 from ~300 ppmv to 1000 ppmv warmed the tropics by 5° to 10°C and the polar regions by even more (i.e., 15° to 20°C).

What can we learn from Earth's past concerning the climate's sensitivity to greenhouse gas increases? Accounting for the increase in CO_2 and the reduction in solar irradiance, the net radiative forcing—the change in the difference between the incoming and outgoing radiation energy–of the climate system at 30 to 40 Ma was 6.5 to 10 W m^{-2} with an average of ~8 W m^{-2} (see the second figure). A similar magnitude of forcing existed for other past warm climate periods, such as the warm mid-Cretaceous of 100 Ma (*8*). Using the proxy temperature data and assuming, to first order,

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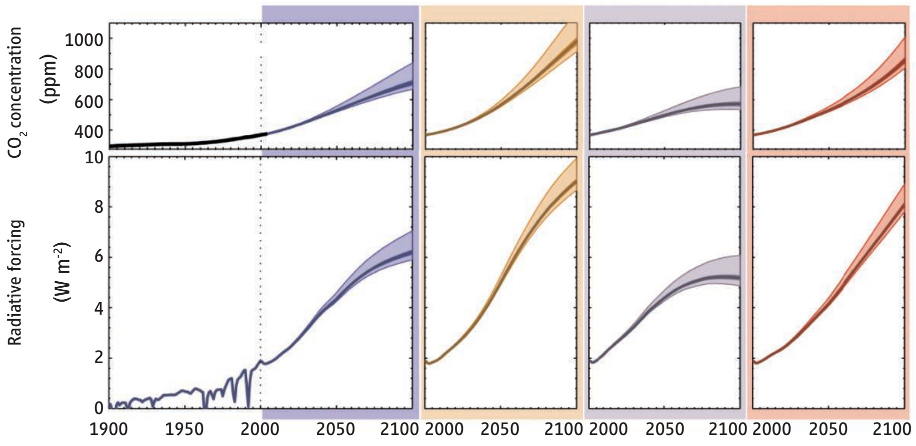
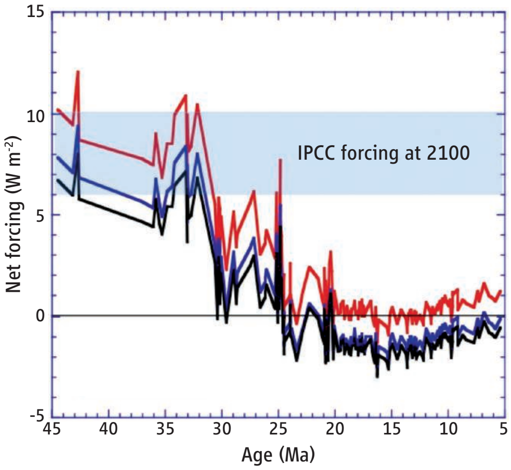


Current and future emissions. Time series for CO_2 concentration and radiative forcing are shown for four scenarios of CO_2 emission into the atmosphere based on energy-economic models described by the IPCC in (*1*). These scenarios are described in the Special Report on Emissions Scenarios by the IPCC. [The graphs are reprinted from (*1*) with permission from Cambridge University Press]

that latitudinal temperature can be fit with a cosine function in latitude (*9*), the global annual mean temperature at this time can be estimated to be ~31°C, versus 15°C during pre-industrial times (around 1750) (*10*). Thus, Earth was ~16°C warmer at 30 to 40 Ma. The ratio of change in surface temperature to radiative forcing is called the climate feedback factor (*11*). The data for 30 to 40 Ma indicate that Earth's climate feedback factor was ~2°C W^{-1} m^{-2}. Estimates (*1*, *11*) of the climate feedback factor from climate model simulations for a doubling of CO_2 from the present-day climate state are ~0.5 to 1°C W^{-1} m^{-2}. The conclusion from this analysis—resting on data for CO_2 levels, paleotemperatures, and radiative transfer knowledge—is that Earth's sensitivity to CO_2 radiative forcing may be much greater than that obtained from climate models (*12*–*14*).



Changes in a warming world. The net radiative forcing due to changes in atmospheric CO_2 concentration and total solar irradiance over the past 45 million years. The three curves represent the range in CO_2 concentration that was reported in (*2*). The shaded region denotes the range in radiative forcing projected to occur by 2100 according to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (*1*).

What is the explanation for this discrepancy in estimating climate feedback strength? On long time scales (centuries to millennia), changes in continental ice formation play a role in Earth's climate system (*12*, *14*). Processes related to vegetation and carbon cycle changes may also be important feedbacks in Earth's climate system (*15*). In the modeling approach, the climate feedback factor in simulations that double CO_2 do not include these slower feedback processes. Although these processes operate on slower time scales than may be of immediate interest to societies, these processes are still important to longer-term adaptation issues. Recent modeling studies on the lifetime of atmospheric CO_2 indicate that if the CO_2 concentration reaches ~1000 ppmv, then the time for natural processes to return it to around 300 ppmv is many tens of thousands of years (*16*, *17*). Thus, if atmospheric CO_2 reaches 1000 ppmv, then human civilization will face another world, one that the human species has never experienced in its history (~2 million years). Also, given this long lifetime for elevated CO_2, slower feedback processes will have time to enter into Earth's future climate change. This magnitude and rate of climate change will be even more challenging for the biosphere to adapt to, including the human species (*18*).

The above arguments weave together a number of threads in the discussion of climate that have appeared over the past few years. They rest on observations and geochemical modeling studies. Of course, uncertainties still exist in deduced CO_2 and surface temperatures, but some basic conclusions can be drawn. Earth's CO_2 concentration is rapidly rising to a level not seen in ~30 to 100 million years, and Earth's climate was extremely warm at these levels of CO_2. If the world reaches such concentrations of atmospheric CO_2, positive feedback processes can amplify global warming beyond current modeling estimates. The human species and global ecosystems will be placed in a climate state never before experienced in their evolutionary history and at an unprecedented rate. Note that these conclusions arise from observations from Earth's past and not specifically from climate models. Will we, as a species, listen to these messages from the past in order to avoid repeating history?

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