Carbon dioxide caused global warming at Ice Age's end, pioneering simulation shows

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Global temperature mirrored and generally lagged behind rising carbon dioxide during Ice Age's deglaciation, pointing to carbon dioxide as the major driver of global warming.

(PhysOrg.com) -- Climate science has an equivalent to the "what came first—the chicken or the egg?" question: What came first, greenhouse gases or global warming? A multi-institutional team led by researchers at Harvard, Oregon State University, and the University of Wisconsin used a global dataset of paleoclimate records and the Jaguar supercomputer at Oak Ridge National Laboratory (ORNL) to find the answer (spoiler alert: carbon dioxide drives warming). The results, published in the April 5 issue of Nature, analyze 15,000 years of climate history. Scientists hope amassing knowledge of the causes of natural global climate change will aid understanding of human-caused climate change.

"We constructed the first-ever record of global temperature spanning the end of the last ice age based on 80 proxy temperature records from around the world," said Jeremy Shakun, a National Oceanic and Atmospheric Administration (NOAA) Climate and Global Change postdoctoral fellow at Harvard and Columbia Universities and first author of the paper. "It's no small task to get at global mean temperature. Even for studies of the present day you need lots of locations, quality-controlled data, careful statistics. For the past 21,000 years, it's even harder. But because the data set is large enough, these proxy data provide a reasonable estimate of global mean temperature."

Proxy records from around the world—derived from ice cores and ocean and lake sediments -- provide estimates of local surface temperature throughout history, and carbon-14 dating indicates when those temperatures occurred. For example, water molecules harboring the oxygen-18 isotope rain out faster than those containing oxygen-16 as an air mass cools, so the ratio of these isotopes in glacial ice layers tells scientists how cold it was when the snow fell. Likewise, the amount of magnesium incorporated into the shells of marine plankton depends on the temperature of the water they live in, and these shells get preserved on the seafloor when they die. The authors combined these local temperature records to produce a reconstruction of global mean temperature. Additionally, samples of ancient atmosphere are trapped as air bubbles in glaciers, providing a direct measure of carbon dioxide levels through time that could be compared to the global temperature record.

Being the first to reconstruct global mean temperatures throughout this time interval allowed the researchers to show what many suspected but none could yet prove: "This is the first paper to definitively show the role carbon dioxide played in helping to end the last ice age," said Shakun, who co-wrote the paper with Peter Clark of Oregon State University. "We found that global temperature mirrored and generally lagged behind rising carbon dioxide during the last deglaciation, which points to carbon dioxide as the major driver of global warming." Prior results based on Antarctic ice cores had indicated that local temperatures in Antarctica started warming before carbon dioxide began rising, which implied that carbon dioxide was a feedback to some other leading driver of warming. The delay of global temperature behind carbon dioxide found in this study, however, shows that the ice-core perspective does not apply to the globe as a whole and instead suggests that carbon dioxide was the primary driver of worldwide warming.

While the geologic record showed a remarkable correlation between carbon dioxide and global temperature, the researchers also turned to state-of-the-art model simulations to further pin down the direction of causation suggested by the temperature lag. Jaguar recently ran approximately 14 million processor hours to simulate the most recent 21,000 years of Earth's climate. Feng He of the University of Wisconsin, Madison, a postdoctoral researcher, plugged the main forcings driving global climate over this time interval into an Intergovernmental Panel on Climate Change (IPCC)-class model called the Community Climate System Model version 3, a global climate model that couples interactions between atmosphere, oceans, lands, and sea ice. The climate science community developed the model with support from the National Science Foundation (NSF), Department of Energy (DOE), and National Aeronautics and Space Administration and used many codes developed by university researchers.

"Our model results are the first IPCC-class Coupled General Circulation Model (CGCM) simulation of such a long duration (15,000 years)," said He, who conducted the modeling with Zhengyu Liu of the University of Wisconsin-Madison and Bette Otto-Bliesner of the National Center for Atmospheric Research (NCAR). "This is of particular significance to the climate community because it shows, for the first time, that at least one of the CGCMs used to predict future climate is capable of reproducing both the timing and amplitude of climate evolution seen in the past under realistic climate forcing."

The group ran simulations that used 4.7 million processor hours in 2009, 6.6. million in 2010, and 2.5 million in 2011. The Innovative and Novel Computational Impact on Theory and Experiment program, jointly managed by leadership computing facilities at Argonne and Oak Ridge National Laboratories, awarded the allocations.

Shaun Marcott and Alan Mix of Oregon State University analyzed data, and Andreas Schmittner, also of Oregon State, interpreted links between ocean currents and carbon dioxide. Edouard Bard of Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement provided data and expertise about radiocarbon calibration.

NSF supported this research through its Paleoclimate Program for the Paleovar Project and NCAR. The researchers used resources of the Oak Ridge Leadership Computing Facility, located in the National Center for Computational Sciences at ORNL, which is supported by DOE's Office of Science. The paleoclimate community generated the proxy data sets and provided unpublished results of the DATED Project on retreat history of the Eurasian ice sheets. The NOAA NGDC and PANGAEA databases were also essential to this work.

Plot twist: the 'bipolar seesaw'

As the dominant theory goes, the variation of Earth's orbit around the sun is responsible for the growth and deterioration of glaciers because it changes insolation, or solar radiation reaching and warming an area. About 21,000 years ago the orbit of the Earth was slightly predisposed to warmer summers in the Northern Hemisphere, and the planet experienced a general warming.

Next comes a plot twist. Geologic data show that about 19,000 years ago, Northern Hemisphere glaciers began to melt, and sea levels rose. Melting glaciers dumped so much freshwater into the ocean that it slowed a system of currents that transports heat throughout the world. Called the Atlantic meridional overturning circulation (AMOC), this ocean conveyor belt is particularly important in the Atlantic where it flows northward across the equator, stealing Southern Hemisphere heat and exporting it to the Northern Hemisphere. The AMOC then sinks in the North Atlantic and returns southward in the deep ocean. A large pulse of glacial meltwater, however, can place a freshwater lid over the North Atlantic and halt this sinking, backing up the entire conveyor belt.

The simulation showed weakening of the AMOC due to the increase in glacial melt beginning about 19,000 years ago, which decreased ocean heat transport, keeping heat in the Southern Hemisphere and cooling the Northern Hemisphere. Other studies suggest this southern warming caused sea ice to retreat and shifted winds around the Southern Ocean, uncorking carbon dioxide that had previously been stored in the deep ocean and venting it to the atmosphere around 17,500 years ago. This rise in carbon dioxide then initiated worldwide warming.

The seesawing of heat between the hemispheres due to the AMOC shutdown explains why Southern Hemisphere warming led the rise in carbon dioxide while Northern Hemisphere temperatures lagged behind and reconciles these patterns with the key role played by carbon dioxide in driving global mean warming. "Differences in the deglacial temperature evolution of the Northern and Southern Hemispheres can largely be explained by variations in the strength of the Atlantic Meridional Overturning Circulation," said He.

Before the team's groundbreaking efforts, researchers could only simulate single time slices of Earth's climate. Just as multiple images are stitched together to make an animation, speedy petascale supercomputers, capable of executing a quadrillion calculations each second, enable stitching together of multiple time slices to produce a continuous simulation. Liu, Otto-Bliesner, and He's group was the first to continuously capture climate from 21,000 years ago to the present day so that scientists could compare the relationship of carbon dioxide and global mean temperature over time. The Nature article covers events up to about 6,000 years ago. The group has since extended the simulation through the present day.

"Climate model output housed at Oak Ridge is currently in the hundreds of terabytes [trillion bytes] and will soon exceed a petabyte, so you need a large facility just to accommodate the large data output," said He. "Right now the climate model output is a top consumer of data storage in Oak Ridge. Also, [continuous simulations] definitely cannot be performed at other sites because the system needs to be quite consistent. This simulation has been run continuously for more than 3 years. Each simulation [step] depends on what happened earlier."

To understand the relevance of the study's finding to today, it is worth considering that carbon dioxide concentrations rose from 185 parts per million (ppm) to 260 ppm over the approximately 10,000 years during which the last ice age ended. In just the past two centuries, human activity has increased concentrations by about the same amount, reaching a carbon dioxide concentration of 392 ppm in 2011—higher than at any time in at least the last 800,000 years.

The work builds on a continuous simulation by Liu and colleagues of Earth's climate between 21,000 and 14,000 years ago, reported in a 2009 Science article detailing the first continuous simulation of climate change during Earth's most recent period of natural global warming. Using ORNL's Cray X1E supercomputer named Phoenix and the even faster Cray XT system called Jaguar, the scientists used nearly a million processor hours in 2008 to run one-third of their simulation, from

21,000 years ago (the most recent glacial maximum) to 14,000 years ago (the most recent major period of natural global warming). The effort validated the ability to simulate large climate changes in the past and is critical for assessing future projections of changes, such as the fate of ocean circulation in the face of continued glacial melting in Greenland and Antarctica.

More information: *Nature* article: www.nature.com/nature/journal/ … ull/nature10915.html

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