Four things to think about when you're thinking about climate change

Warming

Global temperatures have risen about .8 degrees Celsius since the mid-1800s. Studying the heat content in the oceans can tell us why.

BRUCE ANDERSON

WHY THE EARTH IS WARMING

Study disproves two of three hypotheses, aims blame at man-made pollutants

BY CYNTHIA K. BUCCINI

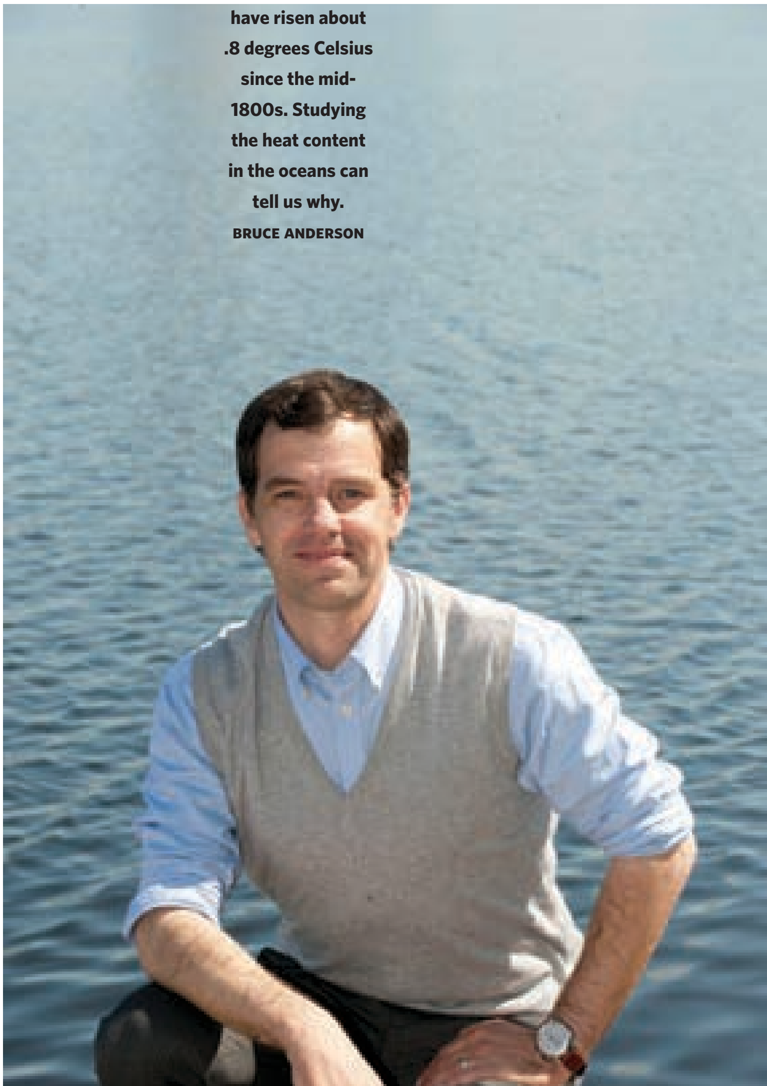
Bruce Anderson didn't set out to prove that the rise in global temperatures since the start of the Industrial Revolution is caused by human activity. And the five-year study that he and four colleagues published in the October 2012 *Journal of Climate* doesn't quite draw that conclusion. But the research does suggest that man-made pollutants are to blame.

The study, which tested three hypotheses about causes of the warming trend, debunks alternative theories that have been floated in recent years. At the same time, says Anderson, a College of Arts & Sciences associate professor of earth and environment, the research strengthens the theory that humans are responsible for the phenomenon, in which carbon dioxide, methane, nitrous oxide, and the other gases we emit accumulate in the atmosphere, trapping heat that radiates outward from the Earth.

The consensus among scientists is that global temperatures have risen about .8 degrees Celsius since the mid-1800s. Anderson believes that focusing on the heat content in the oceans can tell us why. He notes that the oceans store and release nearly 100 times more heat than land surfaces and that nearly 95 percent of the heat added to the environment over the last 50 years has gone into the oceans.

For their study, Anderson and his colleagues—from Washington state, the United Kingdom, and Italy—looked at the heat content

CYDNEY SCOTT



of the oceans from 1950 to 2000 and used complex computer models to test the three hypotheses.

First, Anderson calculated the expected increase in ocean heat resulting from the changes in levels of carbon dioxide and other chemicals. Then he compared those numbers with the observed, or measured, increases in ocean heat over the same period—data that are typically collected from the top 700 meters (about 2,300 feet) of oceans. The two sets of numbers matched.

"What we find," says Anderson, who led the study, "is that the heating of the interior oceans is fully consistent with what we'd expect. That wasn't entirely new. What was new was that we were able, using the same set of data, to also test alternative hypotheses that other people hadn't looked at."

One hypothesis suggests that global warming is the result of what's called internal climate variability, or changes in the interactions between the oceans and the atmosphere. It argues that temperatures are rising because they are drawing heat from deep within the oceans.

That can certainly happen, Anderson says, pointing to El Niño, a warming of the waters in the equatorial Pacific that affects climate around the world.

He estimated how much energy would be needed to drive the increases in global temperatures, and as a result, how much that process would reduce the heat of the interior oceans. He compared those calculations to the measured heat content of the oceans over the five decades. The two sets of numbers did not match.

For the hypothesis to hold water, he says, there would have to be a significant drop in ocean heat in order to feed the increasing global temperatures. But scientists have actually seen a steadily increasing amount of heat over a 50-year period.

The third theory, says Anderson, was the trickiest one to test. "Every so often, particularly in nonscientific literature, there will be a slew of hypotheses that are put out there: increases in the energy output of the sun, changes in gamma radiation, galactic cosmic rays."

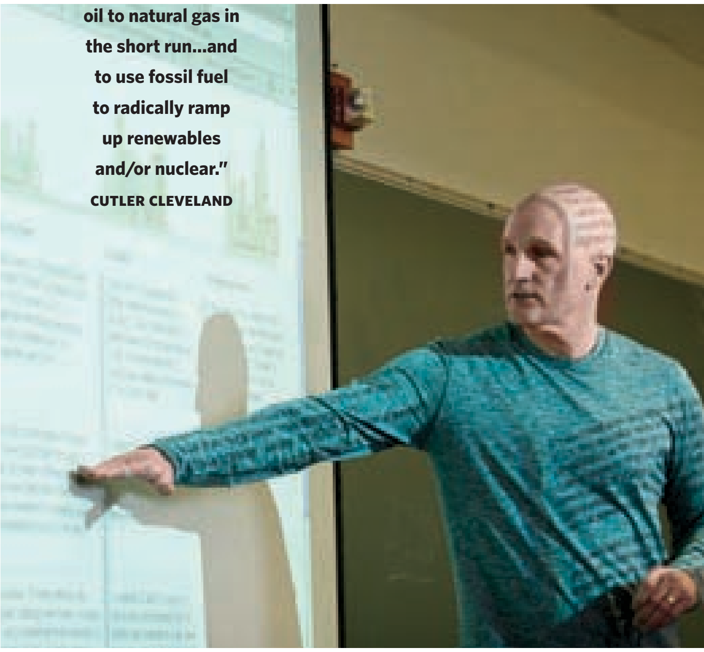
Anderson assumed that there is some unknown source of heat, and proposed that the source added as much heat to the climate system as all of the greenhouse gases combined. How would the heat content of the oceans respond?

He calculated that response and compared it to the observed heat content of the oceans. As with the second hypothesis, the two sets of numbers failed to match.

"We came to the conclusion that, at most, 15 percent of the warming over the last half-century could have been the result of some unknown mechanism for heating the planet," he says.

Anderson believes that the study rejects "in one fell swoop" the idea that there are mechanisms other than human activity that cause climate change.

"You need to shift away from coal and oil to natural gas in the short run…and to use fossil fuel to radically ramp up renewables and/or nuclear."
CUTLER CLEVELAND



KALMAN ZABARSKY

BREAKING THE FOSSIL FUEL HABIT

The promise, and the challenge, of shifting to alternative energy

BY LESLIE FRIDAY

Think of it as a worldwide addiction. At least 80 percent of the energy people use to drive, heat their homes, and power their gadgets comes from fossil fuels such as coal, oil, and natural gas, and the consumption of all of the above contributes to global warming.

Kicking that addiction will be hard. Cutler Cleveland, a College of Arts & Sciences professor of earth and environment and director of the Center for Energy & Environmental Studies, says the transition from fossil fuels to low-carbon alternatives like wind, solar, and nuclear power will require speedy technological advancement, huge capital investments, and the political—and personal—will of ordinary people. Cleveland, who has written or edited six books on ecological economics and energy transitions and is the founding editor in chief of the online reference source *Encyclopedia of Earth*, is convinced that to "avert the more dire scenarios, there needs to be radical surgery now."

Cleveland's convictions come not only from his own research, but also from a series of eight seminars that brought environmental experts from universities in the United States and Europe to BU during the 2010–2011 academic year. The John E. Sawyer Seminars on Energy and Society were sponsored by the University's Frederick S. Pardee Center for the Study of the Longer-Range Future

WEB EXTRA Bruce Anderson explains why global temperatures are rising, and why some theories don't hold water, in a video at bu.edu/bostonia.

and supported by a grant from the Andrew W. Mellon Foundation. "We will have to engineer the transition," he says. "And we've never really done that in the history of humanity."

Still, he sees encouraging growth in some sectors. Government subsidies and technological improvements in the manufacture of turbines have lowered the cost of wind energy, so that it now competes with energy produced by natural gas and coal. But solar, which has also benefited from subsidies and technological advancements, and wind account for only a couple of percentage points of total power generation in the world.

Nuclear power, another low-carbon energy source, currently provides 3 percent of the world's energy, Cleveland says, but its hazardous waste disposal and safety risks make it less desirable than wind and solar.

And biomass—such as switchgrass, corn, or sugarcane converted to biofuel—is another alternative source of energy, but Cleveland is discouraged by the carbon exchange of the biomass process.

"When you compare the energy in the ethanol and all the energy it took" to plant, cultivate, transport, and process it, "it's only a very modest win," he says. "It's certainly way less than the energy gain you get from just producing oil directly from crude."

WEB EXTRA
Through July, Cutler Cleveland will answer your questions about climate change and what you can do at bu.edu/bostonia.

What does his research tell him about the best way to break the fossil fuel habit? The first step should be using fossil fuels to build a sustainable energy infrastructure. "You need to shift away from coal and oil to natural gas in the short run, and probably leave a lot of coal in the Earth's crust," he says. "And you need to use fossil fuel to radically ramp up renewables and/or nuclear."

That means "sticks and carrots, a lot of them," he says. "If you want the transition to happen faster than it otherwise would, you're going to have to alter incentives. And you're going to have to change the price of carbon."

Gas tax hikes, like the one Massachusetts Governor Deval Patrick recently proposed, or divestment from fossil fuels are moves in the right direction. Cleveland thinks federal legislation taxing carbon or an international cap-and-trade system would put a bigger dent in emissions.

Finally, he says, politicians have to address the "third rail of US energy policy"—demand. People need to know that their choices can have a negative impact on the environment. "Working 30 miles from home and driving a Hummer to work alone in the morning is probably one of the most absurd, extravagant behaviors," he says. "We'll look back and say, 'Oh my God!' The excesses of the Romans will look like *Romper Room*."

MEASURING BOSTON'S METABOLISM

Researchers track the city's carbon digestion

BY LESLIE FRIDAY

Imagine looking at Boston as a living, breathing organism. The city consumes energy in the form of resources and services, processes them into gross domestic product, and produces waste. Some of that waste, the carbon dioxide from industrial smokestacks, vehicle exhaust systems, buildings, and even people, contributes to global warming.

Now imagine tracing that carbon. That's what Lucy Hutyra, Nathan Phillips, and a team of researchers plan to do, in an effort to understand where Boston's carbon emissions come from, how carbon is stored, and what the net balance of these activities means for the future of the city—and the planet.

Carbon is "like the life blood that's flowing through the system," says Phillips, a College of Arts & Sciences professor of earth and environment. "Understanding cities and their overall carbon emissions is absolutely crucial to understanding the global carbon cycle and global climate change."

Hutyra, a CAS assistant professor of earth and environment, says nearly 70 percent of global carbon dioxide emissions comes from cities, which cover only 3 percent of the Earth's surface but are home to more than half of the world's population.

In 2009, the National Science Foundation (NSF) and the US Forest Service announced a two-year grant for research in what they call an Urban Long-Term Research Area (ULTRA). Hutyra and Phillips landed a $300,000 exploratory grant for Boston. Their project, called the ULTRA-Ex: Metabolism of Boston, has since expanded to include more than 50 scientists from BU, Harvard, MIT, Northeastern, and the University of Massachusetts. Funders now include NSF,

Understanding carbon emissions in cities is crucial to understanding global climate changes.
NATHAN PHILLIPS

VERNON DOUCETTE

Nearly 70 percent of global carbon dioxide emissions comes from cities, which cover only 3 percent of the Earth's surface but are home to more than half of the world's population.

LUCY HUTYRA

KALMAN ZABARSKY

NASA, the Environmental Defense Fund, and IBM Smarter Cities. The study, while nowhere near complete, has been illuminating in many ways.

One way involves atmospheric carbon. Phillips and other researchers established six observation towers in Massachusetts: one in Nahant, one in Worcester, one in Harvard Forest, in Petersham, and three in Boston. They rigged each with an instrument that records carbon dioxide levels throughout the day.

They found that the levels reflect human activity and the seasons, registering higher during rush hour traffic and peak winter heating months and lower during weekends and summer vacation times. Not surprisingly, readings in rural sites are consistently lower than those at urban sites.

Hutyra's contribution to ULTRA overlaps with her study, funded by an NSF CAREER Award, of how differently plants behave in urban and rural environments. Boston is a relatively green city, with about 28 percent canopy cover, she says. That's important because trees remove carbon dioxide from the air through photosynthesis and they provide shade, which reduces the urban heat island effect and air conditioning's energy demand.

WEB EXTRA **Watch Lucy Hutyra and Nathan Phillips describe their urban metabolism project in a video, and read about the impact of climate change on the economy, at bu.edu/bostonia.**

Since 2010, Hutyra, postdoctoral associate Steve Raciti, and graduate assistants have gone into the urban forest (which could mean two elms along the side of a building) to measure tree circumferences and take soil samples. Their findings, published last year in the journal *Ecological Applications*, showed that carbon concentrations in urban vegetation and soil were higher in a city's forested regions than in residential and other developed land areas. Hutyra thinks urban trees are adapting—and possibly growing faster—in this carbon dioxide–rich environment.

Soil covered by pavement or concrete doesn't fare as well. Raciti, Hutyra, and Adrien Finzi, a CAS professor of biology, wrote last year in *Environmental Pollution* that soil under impervious surfaces in New York City contained 66 percent less carbon and 95 percent less nitrogen than that found in exposed soil. "The soil was also for many purposes dead," says Hutyra. "There was no microbial activity remaining."

Knowing how much carbon is stored in trees and the soil will help determine the amount released into the atmosphere through land development or deforestation.

That's where remote sensing comes in handy. ULTRA collaborators Mark Friedl, a CAS professor of earth and environment, and Curtis Woodcock, a CAS professor and chair of earth and environment, are using satellite imagery to reconstruct the way land cover has changed around Boston since the 1980s. Deforestation results in "a net release of carbon to the atmosphere," Friedl says. "Depending on the age and size of trees in a forest, it could be substantial." The reverse is true as forests flourish in previously developed spaces.

Friedl also uses remote sensing to track seasonal change. As spring arrives earlier and fall later, plants have a longer growing season and absorb more carbon dioxide. This change is visible through satellite imagery, which Friedl double-checks through a system of cameras that take daily pictures of places like Storrow Drive and Boston Common. In 2010, he was stunned to see how greatly the urban heat island effect, and resulting longer growing season, affected city trees. Those in Boston Common leafed out nearly three weeks before those in Harvard Forest, just 70 miles to the west.

"This would be an ivory tower exercise," Phillips says, "if it didn't have an applied goal. And that applied goal is to increase sustainability in Boston and in other cities as well."

TRACKING CHANGE, PREDICTING TROUBLE

By century's end, Arctic will feel like US South

BY LESLIE FRIDAY

Winter is getting warmer, spring is coming earlier, and plants are enjoying an extended growing season in northern areas. But that is not good news.

"It's the initial gold rush," says Ranga Myneni, a College of Arts & Sciences professor of earth and environment, but what will follow will not be pleasant. As vegetation flourishes, it could draw down the water supply, bringing on drought, insect infestations, and forest fires. What was once green, lush land could become brown and barren.

In an article published in March in *Nature Climate Change*, Myneni and 21 collaborators describe how seasonal temperatures and vegetation north of the US-Canada border have shifted over the past 30 years, to what is typically experienced 4 to 7 degrees latitude to the south. Should global warming continue at its current pace, Bruce Anderson, a CAS associate professor of earth and environment, who worked with Myneni on the paper, predicts a further latitudinal shift of as much as 20 degrees south by the end of the century. That means arctic and boreal regions of Canada would look and feel much more like the southern United States.

Myneni has been sounding the alarm on rising temperatures and increased vegetation in these regions for decades, but with this article he hopes to push the envelope by framing change in terms of seasonal shifts.

Seasons are determined by two factors: the Earth's tilt, and the planet's orbit of the sun. Both change only in small, barely perceptible increments over tens of thousands of years. But, Myneni says, "if you change the solar radiation distribution on our planet, you can change the climatic character of the seasons—most importantly, the temperature difference between winter and summer." So, he asks, are seasons changing because of a shift

in solar radiation, or could it be something else?

The work of American scientist Charles David Keeling helps answer that question. Every year from 1958 until his death in 2005, Keeling measured the level of carbon dioxide in the atmosphere from points in Hawaii and Alaska. His data showed that levels of the gas have been increasing and that they fluctuate in an annual cycle as plants absorb carbon dioxide and release oxygen (or photosynthesize) during the northern hemisphere's growing season, and reverse modes (or respire) during the dormant season. Keeling noticed that swings in this cycle, now called the Keeling Curve, were getting larger and were most pronounced during photosynthetic periods. More photosynthesis meant more green, leafy vegetation around

Seasonal temperatures and vegetation north of the US-Canada border have shifted in the last 30 years.

RANGA MYNENI

KALMAN ZABARSKY

the globe. Myneni compared a decade of satellite data about greenness with carbon dioxide levels that Keeling had been plotting over time. The two data sets overlaid nicely.

In 1997, Myneni published his findings in *Nature,* concluding that plant growth in the northern hemisphere had increased by as much as 10 percent over the previous decade, that the increase was driven by a warmer growing season, and that spring was arriving earlier.

Myneni thought the rising levels of carbon dioxide and other greenhouse gases like methane were absorbing thermal radiation reflected from the Earth, preventing it from escaping the atmosphere. The sum effect is a positive feedback loop that continues to warm the Earth, shifting seasonal temperatures.

He noticed that winter temperatures were increasing faster than summer temperatures, leading to earlier springs and a longer growing season. Compton Tucker, a senior scientist at the Goddard Space Flight Center and another contributor to the *Nature Climate Change* paper, says one-third of the northern landscape—a patch roughly the size of the United States—shows vigorously productive vegetation similar to what's typical farther south. In May, scientists at the National Oceanic and Atmospheric Administration reported that the level of carbon dioxide in the atmosphere had reached an average daily level above 400 parts per million, higher than it has been for at least three million years, long before humans evolved.

All of this hardly means "the tropics are approaching," Myneni says. "There's no way mangoes will grow in the Arctic." It does mean that global migration patterns, water supplies, and relations among plant and animal species will alter radically—threatening the existence of cold-tolerant plants and animals that depend upon them.

Anderson points out that as permafrost thaws in the Canadian tundra, greater amounts of organic matter will decompose, releasing additional methane into the atmosphere and adding to the greenhouse effect. "Where we go from here is entirely within our control," he says. That's because the biggest uncertainty is not how our atmosphere will respond to more greenhouse gas concentrations, he says, but how much humans can—or will—control carbon dioxide emissions. ■