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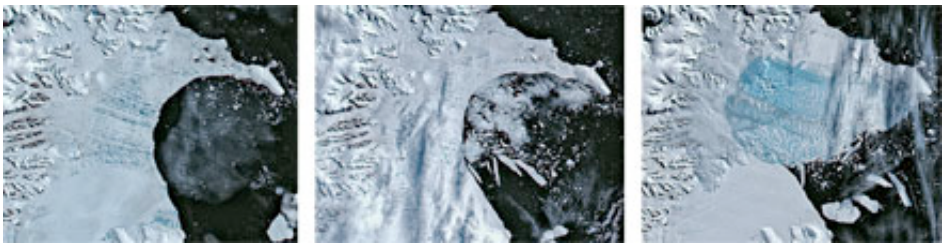
Global Warming And Climate Change

Believers, deniers, and doubters view the scientific forecast from different angles

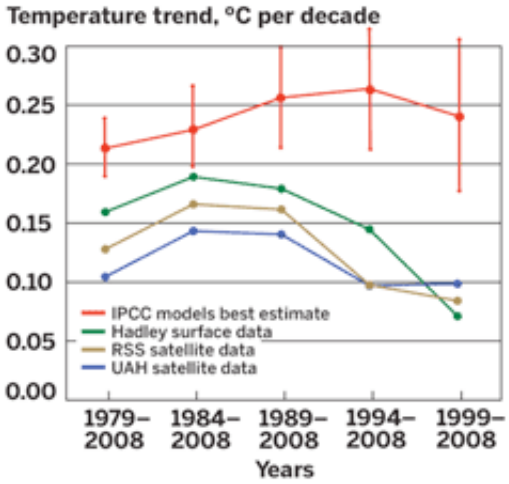
Stephen K. Ritter



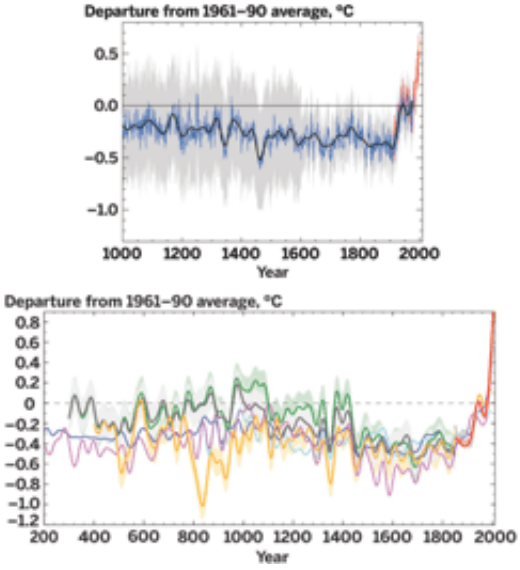
NASA

Breakdown Satellite images show the sudden collapse of the Larsen B Ice Shelf, in Antarctica, from Jan. 31 to March 7, 2002 (from left). A total of 3,250 km2 of the shelf collapsed.

OVERSHOOTING Warming trends calculated by 22 climate models (range shown by vertical bars) used by IPCC overshoot actual measurements from selected surface and satellite data sets. Global-warming skeptics say this observation indicates that IPCC models aren't yet perfected and suggests IPCC's long-term predictions on global warming are too high.



Courtesy of John Christy



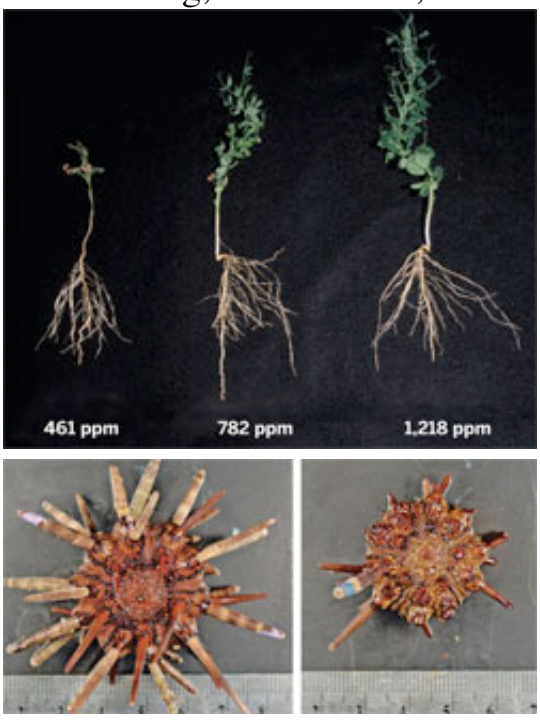
Courtesy of Michael Mann

View Enlarged Image

HOCKEY STICK A plot of average temperature across the Northern Hemisphere (top) used by IPCC in its 2001 assessment, dubbed the "hockey stick" because of its shape, was decried by global-warming skeptics as hiding the Medieval Warm Period (950–1250) and Little Ice Age (1400–1700) and overemphasizing warming in the late 1900s. Data from tree rings, corals, ice cores, and historical records are shown in blue, and thermometer readings are in red; uncertainties in the data are in gray. The hockey stick data have since been substantiated with similar temperature reconstructions by other groups (bottom).

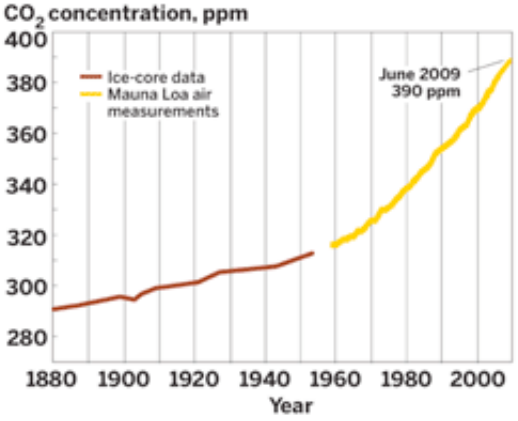
Courtesy of Michael Mann

THE GOOD AND THE BAD Weather station placement can lead to a bias in temperature readings that, if not properly accounted for, can skew current trends and thus climate model projections. A classic Stevenson screen station (white box) with a mercury thermometer in Orland, Calif., is properly sited (top), but a newer electronic temperature sensor in Marysville, Calif., is too close to a building, exhaust fans, and an asphalt parking lot (bottom).



Courtesy of Craig Idso

THE MERITS AND DEMERITS OF CO_2 Pea plants grow bigger and faster (top) under higher CO_2 conditions current global concentration is 390 ppm as do lobsters and some other sea dwellers. But other creatures, like the pencil urchin (bottom), suffer devastating effects in acidified water stemming from high CO_2 conditions.



ON THE RISE Global atmospheric CO_2 concentration has risen since the Industrial Revolution began in the late 1700s—more rapidly since 1950—and currently is about 390 ppm, the highest level in at least 800,000 years, based on Antarctica ice-core data (no data available for the period 1954–58).

Michael Ernst/Woods Hole Research Center

Whether or not global warming stemming from human activities is occurring is developing into the great scientific debate of our time. If it's true, the larger questions are what the climate consequences will be and whether or not there is anything anyone can do about it.

Policymakers meeting in Copenhagen just wrapped up two weeks of discussions driven by those questions. At C&EN press time, they had failed to agree on an international treaty to control greenhouse gas emissions in an effort to stave off global warming while preserving current standards of living. An underlying cause that seems to be holding everything up is a renewed upwelling of uncertainty in the science behind the debate.

Mainstream climate scientists maintain that man-made global warming is happening. But a few global-warming skeptics argue that there is still a lot of guesswork in how those scientists came to that conclusion.

At the root of the for-and-against arguments is a lot of good science—science that is still unfolding. There is no question that Earth's atmospheric carbon dioxide concentration has increased since the Industrial Revolution began in the late 1700s, with most of the rise coming since 1950. And there is agreement that the CO_2 increase is largely the result of emissions from burning fossil fuels. Another piece of data that everyone agrees with is that the global average temperature has risen since 1850, when reliable instrument temperature measurements began, with most of the warming occurring since 1970.

But here the cordial agreements stop. At the heart of the global-warming debate is whether that warming is the direct result of increasing anthropogenic CO_2 levels or whether it is simply part of Earth's natural climate variability.

On the one hand is the majority opinion disseminated in peer-reviewed reports over the past 20 years by the Intergovernmental Panel on Climate Change (IPCC), an entity established by the United Nations Environmental Program and the World Meteorological Organization. IPCC's fourth assessment, "Climate Change 2007," concludes that "warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level."

The assessment stipulates that "most of the observed increase in global average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations." For IPCC, "very likely" means more than 90% statistical certainty.

On the other hand, if IPCC's 90% statement were viewed from a different angle, it would read that there is a 10% likelihood that the current warming trend might arise from natural climate variability. And there is a vocal minority of climate scientists, along with a collection of other scientists and nonscientists and the organizations that support them, who are rallying together to stand behind that 10%.

Some of these antagonists have been labeled "climate-change deniers" because they believe the current warming period is one of Earth's natural temperature swings and that the climate system is insensitive to humanity's greenhouse gas emissions and atmospheric pollutants. Another group, growing in number, doesn't necessarily disagree with IPCC's findings on global warming but doubts that it can all be attributed to anthropogenic effects.

One common thread pulling this contingent of deniers and doubters together is that they take exception to the notion that there is a "consensus" agreement on the science—that the science is settled and human-caused global warming is a foregone conclusion.

Leading the charge of these global-warming antagonists is the Nongovernmental International Panel on Climate Change (NIPCC), which issued the non-peer-reviewed report "Climate Change Reconsidered" in June. NIPCC is an international coalition of scientists—with 35 participants relative to the 2,500 participants in IPCC's 2007 assessment—convened to provide a "second opinion" on the scientific evidence available on the causes and consequences of climate change, says atmospheric physicist S. Fred Singer, who organized and led the NIPCC effort. Singer is president of the Science & Environmental Policy Project, a public policy institute based in Arlington, Va. The NIPCC report was published by the Heartland Institute, a Chicago-based public policy organization.

Global-warming theory is valid in principle, Singer says, and no one doubts CO_2's role as a greenhouse gas. "The only contentious aspect of the IPCC assessment is attribution—what is the cause of global warming and climate change," Singer explains. "We have looked at every bit of data that IPCC has brought forth, and we see no credible evidence for human-caused global warming.

None."

The skeptics suggest that some key studies excluded from the IPCC assessment after peer review, and research published since the 2007 assessment's cutoff date, would compromise IPCC's conclusions. The NIPCC report states that because IPCC's climate models, which are used to study past climate change and to provide estimates of future climate trends, are imperfect, they must be wrong and therefore should be discarded in favor of the idea that natural climate variability rules.

In addition, NIPCC and its supporters suggest that trying to control CO_2 emissions will be too expensive and will raise energy costs, causing disproportionate hardship for people living on the world's social and economic fringes. The ultimate point of that argument is that if Earth's climate system is driven mostly by nature and is not influenced by humankind, there isn't a lot that anyone can do to control it, despite best intentions. NIPCC further points out that extra CO_2 and a little extra warmth might not be so bad after all because it will help increase plant growth—which IPCC also projects. Such increases, NIPCC says, will in turn boost forestry and agriculture, leading to an improvement in gross domestic products and standards of living throughout the world.

Singer says IPCC is an organization established and run by national governments, not scientists, and as such, its assessments should be viewed as political findings, not scientific findings. Indeed, IPCC has been taken to task by all sides for allowing government representatives to fine-tune the scientific conclusions of its assessment reports after the peer review process.

Global-warming antagonists charge that the point of this gerrymandering is to artificially demonstrate and build support for anthropogenic global-warming theory and the UN's ulterior motive of rationing fossil-fuel-based energy. In the same vein, climate-change protagonists charge that NIPCC takes its contrarian view solely because it is indirectly financed by the oil and gas industry and other business and conservative political interests.

The climate debate is becoming ever more contentious as both sides ratchet up efforts to discredit each other in order to influence public opinion. The most recent episode came in late November, when e-mail messages exchanged between prominent climate scientists were purloined and posted on the Internet. Some of the selected messages suggest that the scientists have been taking measures in recent years to exert tighter control over the peer review process of some climate journals (see page 7).

The scientists who wrote the e-mails say they have little choice but to take such steps because a few researchers persist in submitting papers with flawed arguments or that lack sufficient data to support the conclusions. Despite the peer review system, they say, a few of these papers have been published in what some climate scientists have labeled "activist journals."

The skeptics counter that the "climategate" e-mails prove IPCC and leading climate scientists have evolved from being brokers of scientific information on climate science to being gatekeepers of information, preventing some valid but contradictory data from coming to light.

"It's a closed cooperative," Singer says. "If you have a different view, you can't get into that closed circle. NIPCC was established to break up that monopoly."

Climate theory is built on the assumption that Earth maintains a balance between incoming solar energy in the form of ultraviolet and visible light that it absorbs and the amount of heat in the form of infrared radiation that it redirects back toward space. Variables that cause this energy balance to change and affect the global average temperature are called forcings because they force the temperature up or down. Forcings include changes in the sun's brightness and other influences that operate on roughly 11-year and longer length cycles; aerosols and particulate matter originating from the oceans, volcanic eruptions, and man-made air pollution (C&EN, Aug. 24, page 26); and changes in the amount of heat-trapping greenhouse gases such as CO_2 in the atmosphere.

Of all the forcings, CO_2 is key for anthropogenic global warming because it's the only variable that is changing by a significant amount. Atmospheric CO_2 has increased from about 280 ppm in 1750 to nearly 390 ppm today. IPCC says this amount far exceeds the natural range of 180–300 ppm as measured in the air bubbles of ice cores covering the past 800,000 years, a period spanning the past six ice ages. Also of note is that the rate of CO_2 growth accounts for about 55% of the estimated amount of man-made CO_2 emissions, which means that nature is currently sequestering about half of the CO_2 that people generate. But based on a recent ocean study, Earth's capacity to naturally sequester CO_2 appears to be decreasing (C&EN, Nov. 23, page 9).

Greenhouse gases are mostly transparent to incoming UV and visible light, but they hold back the outgoing IR—like the roof of a greenhouse. Adding anthropogenic CO_2 to natural amounts of CO_2 already in the atmosphere is making Earth's greenhouse blanket slightly thicker. Theoretically, with all other variables remaining steady, this increase in CO_2 traps more heat and increases the global average temperature.

The amount of warming directly caused by the extra CO_2 is relatively weak, though. By definition, CO_2 has a global-warming potential of 1 per molecule over 100 years and serves as a standard by which to compare other gases; for example, the global warming potential is 25 for CH_4, 298 for N_2O, and 22,800 for SF_6, according to IPCC. Diatomic gases such as nitrogen and oxygen, which make up most of the atmosphere, weakly absorb IR radiation, so they are not counted as greenhouse gases. But these gases do contribute to physical and chemical interactions in the atmosphere, which can impact climate.

Water vapor is by far the most abundant and influential greenhouse gas. Its concentration depends on the vagaries of air temperature—warm air holds more moisture and cooler air is drier—and it soaks up most of the IR heat emanating from Earth's surface. But water vapor is not considered a forcing. Nor is it assigned a global-warming potential, because it has a relatively short residence time of about 10 days in the atmosphere, compared with a century or longer for CO_2.

Some global-warming antagonists assert that climate models can't be accurate if they don't include water vapor. But they do. Water vapor is a key component of the models, but it's factored in as a

feedback, rather than a forcing. Feedbacks are physical processes that change in response to a temperature change and subsequently amplify or diminish the effects of forcings. For water vapor, when the temperature goes up or down, its concentration quickly adjusts to increase or decrease the trapping of heat.

Ozone is another important component of the atmosphere, but because it is not evenly dispersed and is short-lived, being constantly created and destroyed in the atmosphere, it doesn't have an assigned global-warming potential either. Ozone filters UV light and contributes to cooling in the stratosphere, which is located more than 20 km above Earth's surface. It also functions as a greenhouse gas and contributes to warming in the troposphere 6–20 km above the surface.

Aerosols, the forcings with the most uncertainty in their effects, are a suspension of fine particulate matter or droplets arising from volcanic emissions, smoke, oceanic haze, and air pollution. Some aerosols form directly, but others form during oxidation processes in the atmosphere. For example, sulfur dioxide and other sulfur compounds originating from burning fossil fuels and from volcanoes and phytoplankton are converted into sulfate aerosols in the atmosphere by hydroxyl radicals and other oxidants. Ozone also generates hydroxyl radicals that contribute to aerosol formation.

Climate scientists know that aerosols exert an overall cooling influence on climate—a negative forcing—by scattering incoming light and playing a role in forming and dissipating clouds. But they have had difficulties in adequately accounting for aerosol effects on greenhouse gases in climate models.

Water in the form of clouds is also difficult to parameterize in models because cloud formation is dynamic and clouds have a fleeting existence. Clouds are the most uncertain feedback to plug into models because they give rise to both positive and negative influences: Low clouds primarily prevent surface heat from escaping into space, and high clouds reflect incoming sunlight.

Overall, water vapor and clouds are responsible for about 60% of the greenhouse effect, followed by CO_2 at about 26%, and then smaller contributions from CH_4, O_3, and other gases. In the absence of natural greenhouse warming, Earth's average temperature would be about –18 °C (0 ° F), essentially a frozen planet. The natural greenhouse effect warms Earth by some 33 °C, to about 15 °C (59 °F).

The combined forcings and feedbacks stemming from Earth's current oceanic, continental, and atmospheric makeup are the cause and effect that moderate Earth's energy balance. As described in the 2007 IPCC report, the global energy balance is about 240 watts per m^2. The combination of forcings arising from anthropogenic effects, including increases in greenhouse gas emissions minus decreases from aerosols, totals 1.6 W/m^2.

IPCC has concluded that that extra bit of energy, coupled with ensuing net positive feedbacks, has nudged up the global average temperature. As laid out in the 2007 assessment, warming during the 100-year period from 1906 to 2005 caused a global average temperature increase of 0.74 °C, to about 16 °C (61 °F).

Climate scientists rely on the measured temperature data to set up a framework for using models to predict future trends. One of the key inputs to the framework is a measure known as "climate sensitivity," which is the change in global average temperature in response to the combination of forcings and consequent feedbacks. Climate sensitivity is gauged by the global temperature change after a doubling of atmospheric CO_2 concentration. Assuming all other forcings and feedbacks remain constant, a doubling of CO_2 will lead to a 1 °C rise in temperature.

Deciding on what climate sensitivity value to plug into models is crucial to predicting future trends. Overall negative feedbacks, or low climate sensitivity, mean that man-made global warming would likely be indistinguishable from natural climate variability. But if the feedbacks are sufficiently positive—a high climate sensitivity—then human-caused global warming would not only be visible but also potentially catastrophic.

Weighing all the evidence, IPCC projects a sensitivity in the range of 2.0 to 4.5 °C, with a most likely value of about 3 °C. That range is given because of the uncertainties in the strength of the feedbacks, but the sensitivity is unlikely to be less than 1.5 °C, according to IPCC. These values also roughly correspond to the temperature increase IPCC projects will occur between now and 2100.

The NIPCC report claims that IPCC has completely misinterpreted climate sensitivity. NIPCC scientists assert it might be possible that positive feedbacks to CO_2 forcing are extremely small, nonexistent, or offset by negative feedbacks so that natural forcings unrelated to anthropogenic CO_2 are actually causing the observed warming. They suggest that a climate sensitivity of 0.6 °C or less is more realistic.

It's fitting that the simplest measurement of the climate debate—temperature—is fraught with controversy. There isn't one giant thermometer that is consulted to obtain global average temperature. Rather, thousands of measurements are taken each day around the globe from monitoring stations on land, buoys and ships at sea, weather balloons, and satellites. The data are melded together by different climate research groups to create running sets of global average temperatures.

Global-warming antagonists say that the surface temperatures in the most popular data sets are skewed by what is called the urban heat island effect, whereby buildings, pavement, and other heat-retaining or heat-reflecting artifacts located near monitoring stations inflate temperature values. They assert that using the biased data confuses the analysis of the current warming trend and leads climate models to overestimate future warming.

To prove that case, retired television meteorologist Anthony Watts has led a grassroots effort to visually inspect U.S. weather-monitoring stations. Watts, who curates the blog "Watts Up With That?" which provides information and commentary on climate change and other topics, targeted the 1,220 stations in the U.S. Historical Climate Network, a part of the U.S.'s system of about 9,000 weather stations.

Watts notes that of the roughly 1,070 stations checked so far, 91% of them fail the National

Weather Service's requirement of being located 30 meters or more away from an artificial heat source such as a building or parking lot. Watts says his goal is to complete the survey and provide a detailed analysis of the temperature trend data from the stations. His preliminary assessment indicates that many of the stations show artificially high temperatures. An initial report was published in March by the Heartland Institute, and a final report is expected in 2010, he notes.

Once a firm believer in CO_2-induced global warming, Watts says he is now less certain. "No doubt global warming has occurred," Watts says. "But what is the true cause of the observed temperature increases?"

The bias in temperature readings is a well-known problem to climate scientists, especially for older monitoring stations located where urban centers have sprung up around them, notes geophysicist Michael E. Mann, director of Pennsylvania State University's Earth System Science Center. Mann, one of the scientists whose e-mails were flagged in the climategate dustup, is part of a group of climate scientists who run the website "RealClimate," which provides news and commentary on global warming and climate change.

When a bias is noted in the long-term temperature record for a site, Mann says, the data are not used or corrected to account for the problem. Much of the work to estimate global surface temperature changes has been devoted to teasing out these urban heat island effects, Mann adds. There are different ways to do it, he says, but basically scientists compare weather stations in the same region to estimate what the temperature bias is for an individual station.

IPCC examined the urban heat island effect in the 2007 assessment and concluded that it might indeed have impacts on local temperature readings. But IPCC determined that the errant heating has a negligible influence on long-term global average temperature measurements of less than 0.006 °C per decade over land and has no effect over the oceans.

"You can eliminate urban stations from a data set or ignore land and look only at ocean data, and you still get a similar warming trend as you do with the corrected data," Mann says. "So the argument that the urban heat island effect somehow contaminates our ability to estimate global surface temperatures just doesn't hold water."

That explanation still hasn't satisfied global-warming antagonists, some of whom are suggesting that surface temperature measurements be abandoned in favor of atmospheric measurements. Their rationale is made possible by satellite data compiled by several groups, including atmospheric scientist John R. Christy and meteorologist Roy W. Spencer of the Earth System Science Center at the University of Alabama, Huntsville (UAH), who were the first to use satellite data to track global average temperatures.

Christy, the UAH center's director, explains that satellite measurements are based on detecting microwaves emitted by oxygen molecules in the troposphere. The intensity of those microwaves relates directly to the temperature of the O_2 molecules and, when mathematically converted with an algorithm, serves as a thermometer for the atmosphere. Although it's proxy data, rather than a direct temperature reading, the UAH team has verified the accuracy of the measurements by

comparison with weather balloon data.

Satellite data are collected nearly uniformly around the globe, unlike surface data for which there are gaps in monitoring remote land and ocean regions, Christy notes. And atmospheric data remove any bias from heat island effects. So Christy and a few scientists believe the satellite data could provide a better measure of temperature change than surface data.

But other climate scientists aren't convinced because the algorithm used to convert microwave readings requires making assumptions that increase the uncertainties in the temperature measurements. Like surface measurements, the satellite data need correcting, and the Christy-Spencer data have needed to be adjusted several times. The satellite instrument readings are affected by heat from sunlight in day/night cycles, satellite orbital drift and orbital decay over time, and coordination of multiple satellites to ensure instruments are calibrated and the measurements are made consistently.

In the end, absolute values of temperature are not what scientists are after anyway, but rather trends in warming or cooling over time. There's an approximately 0.13 °C warming per decade reflected in the UAH atmospheric data set for 1979–2008, Christy notes, compared with 0.17 °C warming per decade for the most popular surface measurements over the same period.

Although global-warming skeptics would disagree, Mann says, statistically there really isn't a discrepancy between the surface data and the satellite data, and there is no reason to throw out the surface record. "For the past 30 years, the satellite data actually validate the surface temperature trend for warming," Mann points out. "What's more important about the surface record, though, is we can reliably go much further back in time."

Besides taking atmospheric data, Christy's research involves developing data sets to explore trends in surface temperatures. Specifically, he is looking beyond urban heat island effects at how land-use changes stemming from agriculture and urbanization affect temperature. One of his key findings is that data from Alabama, California, and Africa show that the recent increases in global average surface temperatures are related to higher nighttime readings.

For example, in California's San Joaquin Valley, one of the U.S.'s most productive farming regions, the daytime temperature has increased little over the past 100 years, Christy says. But the nighttime temperatures of the valley are now about 4 °C higher than a century ago. Meanwhile, in the Sierra Nevada Mountain foothills to the east, the daytime and nighttime temperatures have essentially been static over the past century.

Christy says the shift in natural dry, brown scrub to irrigated green fields in the San Joaquin Valley and other large farming regions means less heat is absorbed, and it provides a cooling effect on daytime temperatures. In contrast, the additional moisture in the ground holds in heat that is released at night, leading to the warmer nighttime readings. This is not a heat island effect, Christy proposes, nor is it fully related to heat radiating back into space and being trapped by CO_2. "In some areas, the observed warming is more consistent with land-use change than our understanding of greenhouse gas effects," he believes.

Christy thinks a better approach in compiling surface data for modeling could be to use only the daytime high temperatures, rather than the daily low and high temperatures, to eliminate the possible bias in nighttime readings. Christy acknowledges that most climate scientists don't agree with his methods or conclusions; although he was an IPCC lead author for its 2001 assessment, not all of the data he submitted to IPCC for the 2007 assessment were included, he says.

When looking at longer term temperature trends, climate scientists must rely on historical records and proxy data from a variety of sources, an area where Mann has focused his research efforts. Combinations of data from ice cores, tree rings, sea sediment cores, and instrument readings are cobbled together to give a reasonable estimate of past temperatures, he explains. Even then, these temperature "reconstructions" reliably go back only about 2,000 years, Mann says.

Several unique features in this temperature record are hot spots for the climate-change debate. Global-warming antagonists such as Singer point to these features as proof that past temperatures and CO_2 levels have been higher and lower than today, indicating that natural variability is the norm in climate change and that the impact of human activities is not discernable—that there is weak or no anthropogenic warming.

For example, the Medieval Warm Period, which peaked from about 950 to 1250, was a time marked by higher solar activity, fewer major volcanic eruptions to create cooling aerosols, and warming impacts from oscillating ocean-atmosphere circulation patterns such as the El Niño-Southern Oscillation in the tropical South Pacific that occurs every few years, Mann says. Patterns such as El Niño redistribute heat already in the oceans and are not directly related to global warming or cooling.

The Medieval Warm Period climate anomaly affected mostly the North Atlantic region, and at its height, the average temperature in the Northern Hemisphere, depending on the climate data set viewed, rose about 0.3 °C above average. In some areas, the temperature rise was about the same as or exceeded the comparable 0.8 °C value today. But as Mann's and other temperature reconstructions show, the global average temperature remained below the current global average (*Science* **2009,** *326,* 1256).

In an attempt to shoot down this evidence, the NIPCC report presents data that suggest temperatures during the Medieval Warm Period were actually higher than those reported in the IPCC report and higher than today. NIPCC also notes that fossil and other paleoclimate data at some 250 sites spread across all seven continents now substantiate that the Medieval Warm Period was global in its reach and supports the climate variability thesis.

"It wasn't just a regional effect—that's absolutely not true," notes geographer Craig D. Idso, founder and chairman of the Center for the Study of Carbon Dioxide & Global Change, in Tempe, Ariz., and coauthor of the NIPCC report, along with Singer.

"This is a key part of the battle in the climate debate," Idso says. "If we can show that the temperature varies naturally with little influence from greenhouse gases, then the current warm period is nothing more than the recurrence of the natural climate-change cycle."

After the Medieval Warm Period came a cooling-off period known as the Little Ice Age, which hit its nadir between 1400 and 1700. The temperature dip—as low as –0.7 °C below average—stemmed from low solar activity and increased volcanic activity, with cooling effects from ocean-atmosphere oscillations. Like the Medieval Warm Period, it was of limited scope in the Northern Hemisphere and not global in nature, according to IPCC.

A climate conundrum related to these historical temperature swings is the infamous "hockey stick" graph used in IPCC's 2001 assessment. The graph, which depicts one of Mann's temperature reconstructions, shows muted warming and cooling over the Medieval Warm Period and Little Ice Age because the temperatures are averaged over the entire Northern Hemisphere and not localized to Europe, where most people lived during those periods. Global-warming skeptics say the graph makes it look as though the anomalies didn't exist. The graph also shows a sudden upturn in temperature in the late 1900s attributed to rising CO_2 concentrations so that the overall graph looks like the profile of a hockey stick lying on its side.

IPCC chose to feature Mann's reconstruction over other similar data sets in its 2001 summary report for policymakers to show that it's warmer now than it has been over the past 1,000 years. Some skeptical scientists pointed out errors in Mann's and coworkers' descriptions of the data sets used, which Mann confirmed and announced in a published correction. Meanwhile, other skeptics took it a step further and claimed there were actual flaws in the statistical methods used to combine the data to make the reconstruction. Global-warming antagonists seized the opportunity to assert that the graph was an effort to hoodwink the public by showing a warming trend that was not real, which led to a congressional inquiry.

Mann's data held up to scrutiny by a National Academy of Sciences review panel, which "acquitted" the data but made specific suggestions on how scientists should improve temperature reconstructions. Now, 10 years later, Mann reports that his original finding has been confirmed by other data sets his group has generated and by more than a dozen independent estimates using different arrays of data and different statistical methods (*Proc. Natl. Acad. Sci. USA* **2008,** *105,* 13252). Yet the hockey stick graph is labeled as disingenuous in the NIPCC report.

"It was unfortunate that some contrarian circles made it seem as if the entire edifice of climate change rested on our one reconstruction data set," Mann says. "We still have the same conclusion from a decade ago and have even extended it to the past 2,000 years."

Global-warming antagonists, carrying the banner of natural climate variability, still say that the temperature fluctuation from the Medieval Warm Period to the Little Ice Age is clear evidence that nature rules when it comes to climate change. They add that the current warming isn't being caused by anthropogenic CO_2 but is instead simply a continuation of Earth's recovery from the Little Ice Age.

That is a bit misleading, Mann says. "Suggesting that Earth recovers from climate changes implies that the climate system works in a completely different way than we know it does based on physics," he observes. "The climate doesn't rebound. It isn't like a spring that someone pulls and

lets go. The primary changes are due to the response to forcings.

“If natural variability was primarily ruling what we see today, we would still be in the Little Ice Age,” Mann continues. “We should have seen cooling in the past few decades because solar output has dropped off and there have been relatively more volcanic eruptions. To those who say today’s warming is natural variation, the natural forcings are actually pushing us in the wrong direction.”

Looking at climate features during the past century provides additional hot spots for the climate debate. For example, the higher solar output in the early-20th century contributed to a warm stretch in the 1930s. But as the solar output waned, temperatures cooled in the late 1940s and then remained steady for several decades, even though the post-World War II era was a time marked by industrial development, more cars, and a rapid rise in CO_2 levels.

NIPCC and global-warming critics point to a lack of CO_2-temperature correlation to discount IPCC’s pro-anthropogenic assessments. “With IPCC, sometimes you get a CO_2-temperature correlation, and sometimes you don’t,” Singer says. “IPCC and others try to skip over or explain that problem away. But you can’t do that. For global-warming theory to be completely valid, that correlation has to be present at all times.”

IPCC points out that during the 1945–75 period, CO_2-forced warming was countered by lower solar activity, emissions from volcanoes, and an increase in particulates and atmospheric aerosols generated from increased fossil-fuel emissions. Some climate scientists have suggested that when pollution regulations and improved technology reined in man-made emissions and the air began to clear in the late 1970s, CO_2 forcing again emerged on top, leading to the current warming trend that has accelerated as CO_2 levels continue to rise. The “global dimming” caused by aerosols and particulates is the basis of one of the proposed geoengineering technologies to offset global warming (C&EN, Nov. 23, page 28).

During the past 20 years, several events point to natural climate variability’s influence on temperature, but overall the warming trend due to rising CO_2 levels is now unmistakable, IPCC says. For example, warming stopped in 1991–93, when the eruption of Mount Pinatubo, in the Philippines, spewed out massive amounts of sulfur compounds. These compounds formed aerosols and drove down the average global temperature about 0.2 °C. The volcano erupted at the beginning of an El Niño warming event, which offset some of the volcano’s cooling effects. The ensuing El Niño in 1998, dubbed the “El Niño of the Century,” made that the hottest year ever recorded (although in some data sets, 2005 was warmer), with a global average temperature that was 0.5 °C above the modern average.

Since 1998, temperatures have leveled off, even as CO_2 concentrations have continued to rise at a faster rate, leading to a “climate canard,” often referenced in climate-change discussions, that global warming has stopped. Global-warming antagonists say it’s yet another example of the CO_2-temperature correlation falling apart.

But Mann points out that by cherry-picking data, recent temperatures could appear to be warming

or cooling. Scanning the 10-year trend from 1998 to 2007, it looks like temperatures are cooling because 1998 was an uncharacteristically warm year. But taking the 10 years from 1999 to 2008, there is a warming trend, even though 2008 was the coolest year since 2000 because it included El Niño's cooling phase, known as La Niña. In addition, every year from 2001 to 2008 is among the top 10 warmest years in the historical record.

Temperatures never increase or decrease in a smooth, linear fashion, Mann says, but yield a jagged pattern. Mann and other climate scientists caution that it's difficult to make much sense of climate change by looking at time frames as short as 10 years because the shorter the trend, the more it is dominated by natural variability noise. Looking further back, the linear 25-year trend from a data set generated by NASA's Goddard Institute for Space Studies (GISS) at Columbia University shows global temperatures rising 0.19 °C per decade, Mann says. That trend matches IPCC's model estimate of anthropogenic warming, he adds. And measurements taken in recent weeks by climate research centers worldwide indicate that 2009 will be one of the warmest years on record, at about 0.4 °C above average.

"We can always go back far enough into the geological record and see time intervals where it was warmer or cooler than it is today," Mann says. "No one is disputing that." For example, the early Cretaceous period 100 million years ago, when dinosaurs roamed Earth, was certainly substantially warmer than today, and CO_2 levels were substantially higher, he notes. "But that doesn't contradict the fact that we are increasing greenhouse gas concentrations today at a faster rate than Earth has ever seen to our knowledge and that the temperature and other changes that are taking place are happening at a far greater rate," Mann adds.

Beyond current temperature observations, global-warming antagonists are seizing on the temperature discrepancies proposed by Christy and others as proof that IPCC's projections of Earth's future climate—based on models using the possibly biased data—are faulty. For example, Christy has shown that the IPCC model average temperature—IPCC's best guess—has been increasing about 0.25 °C per decade over the past 30 years, which is significantly higher than several measured data sets, including UAH's satellite value of about 0.13 °C per decade. The measured data fall outside the range of the model projections.

"That means the IPCC models are overestimating what is actually happening, which indicates that the models are retaining too much heat and the climate sensitivity is set too high," Christy says. It also suggests that IPCC's long-range temperature predictions could be too hot, he adds.

While Christy spends his time mulling over temperature data, Spencer, his UAH colleague, is trying to better understand the intricacies of climate sensitivity. IPCC concludes that the effect of anthropogenic CO_2 on temperature, even though it is a small forcing, gets magnified by positive feedback, Spencer says. "That's where a minority of us disagree. We think that climate change is the result of fairly strong natural forcings operating on a fairly insensitive climate system," he adds.

To explain, Spencer says that he thinks climate modelers have been misinterpreting cause and effect when it comes to how clouds and temperatures vary together in the climate system. He says

modelers tend to associate decreasing cloud cover after warming with positive cloud feedback—warming causing a cloud decrease to let in more sunlight. In reality, he thinks it is the decrease in clouds caused by natural, chaotic fluctuations in global ocean-atmospheric circulation patterns that mostly causes the warming—a natural forcing.

"If you make that misinterpretation, it skews the rest of the analysis into man-made global warming—it gives the illusion that the climate system is much more sensitive than it really is," Spencer says. "If the climate system is less sensitive, this means that the extra CO_2 pumped into the atmosphere is not enough to cause all the observed warming over the past 100 years—some natural mechanism must also be involved."

Spencer's candidate is the Pacific Decadal Oscillation (PDO), an ocean-atmospheric circulation pattern similar to and influenced by El Niño but occurring in the North Pacific Ocean and running on a 60-year cycle. During PDO's positive phase, the western Pacific cools, the eastern Pacific warms, and land in North America warms; during the negative phase, the opposite occurs.

"Unfortunately, the data now show us that we have underestimated the climate crisis."

For instance, PDO was positive from about 1915 to 1945, when there was a global-warming trend, Spencer says. PDO went negative from 1945 to 1977, when global temperatures were cooler, and went positive again in 1978, which was the onset of the current warming period.

Melting of Arctic ice provides evidence for this on-off cycle, Spencer claims. In late 2007, the Northwest Passage in the Arctic Ocean opened, a rare event that allows ships to travel the relatively short distance between the Atlantic and Pacific Oceans. Spencer points out that the Northwest Passage also opened in 1939 and 1940, just as the previous PDO positive phase was coming to an end.

Because CO_2 concentrations in the 1940s were lower, Spencer suggests anthropogenic warming could not have caused the melting back then, when Arctic temperatures were nearly as warm as they are now. He also suggests the current warming could be caused by the same effect. Spencer estimates that the PDO effect can explain about 70%, or 0.5 °C, of the 0.74 °C global warming observed during the past century and that anthropogenic CO_2 is responsible for the other 30%, or about 0.2 °C.

A new negative PDO phase might be getting started, Spencer says. If cooler temperatures prevail in the coming 30 years, the trend might verify his hypothesis, which has not been published but is in the process of being vetted by the climate science community.

Based on his work and studies by a few other groups, it looks like net negative feedbacks can operate on year-to-year time scales, Spencer says. But on the long term, it might be that net positive feedbacks prevail.

There is only one Earth to observe and test with climate models, and attempts to do so are severely limited by humanity's relatively short existence and the inherent complexity of the global climate system. That is why IPCC's 2007 assessment was based on 18 different models that made

different assumptions—and provided a range of results.

Climate modelers tend to spend much of their time checking the models, which are based on differential equations with few to many variables, to confirm if large-scale features work properly. For example, they must make sure that ocean currents go the right way and that it rains and snows where it should. There are problematic areas in which models still don't work well, such as predicting Indian monsoons correctly, the NIPCC report notes. But it does not discount the models from being "good enough to be useful," Mann says.

One success is modeling the climate change stemming from the 1991 eruption of Mount Pinatubo. The eruption spewed sulfates into the atmosphere, and the resulting aerosols led to cooling for about three years, which was enough time for water vapor to equilibrate to cooler sea-surface temperatures. IPCC's modelers have been able to accurately simulate the decrease in water vapor in line with satellite observations and match the global temperature decrease that occurred, a good sign that the feedback parameters are accurate and that climate sensitivity is set about right, Mann says.

On the other hand, NIPCC points to one climate "fingerprint" that suggests a discrepancy between IPCC model projections and reality. IPCC climate models predict that the lower part of the troposphere in the tropics should be warming at a rate that is 1.3 times faster than at ground level, UAH's Christy notes. Warming from solar variability or other known natural factors will not yield this characteristic pattern, only sustained anthropogenic greenhouse gas effects, Christy says.

But in the measured satellite and balloon temperature data, collected from two altitude ranges—the lower troposphere from sea level to about 10 km, and the lower stratosphere above 15 km—"we find that the warming is the same or a little less in the atmosphere than at the surface," Christy says. "This discrepancy has caused a lot of consternation because it's another example showing that the models are retaining too much heat." Singer is more emphatic, stating that the mismatch "clearly falsifies the hypothesis of anthropogenic global warming."

The real test, however, is running models over a modern 100-year period with and without anthropogenic effects included and then comparing the results with the observed data. IPCC modelers carried out this test for the 2007 assessment. When they left out anthropogenic effects, the models failed to match the observed temperature trend. When the simulations included the anthropogenic forcings and feedbacks, the observations matched quite well, making it reasonable to assume the model projections for future temperature trends are valid.

"That really shows that the only way we can explain the current warming trend is through human impacts," Mann points out. "With the low sensitivity proposed by NIPCC and others, there is no other way to explain the swings in climate that we know have happened."

Singer retorts that although IPCC claims to be able to reproduce the 20th-century temperature history using the models, "the only way they can do it is by arbitrarily choosing parameters to make it work—it's a curve-fitting exercise," Singer says. "If you have enough arbitrary parameters, you can make any model work. The problem with that is people who claim models agree with observations at some point have to go back and change the parameters when new scientific details

emerge in order to keep the models in agreement."

For example, Singer points to a recent study by atmospheric chemist Drew T. Shindell and colleagues of NASA's GISS that sheds new light on aerosol effects. They found that methane interactions with hydroxyl radicals and other oxidants during aerosol formation increase methane's global-warming potential by 20–40% (C&EN, Nov. 2, page 13).

The implications of the study are that CH_4 in combination with other minor forcings such as CO and volatile organic compounds add up to nearly equal CO_2 as a forcing, Shindell says. He adds that the study suggests that by controlling sulfate emissions to prevent aerosol formation and clean up the air, we are inadvertently increasing global warming by reducing the cooling effects of the aerosols and increasing the impact of CH_4.

The Shindell study seemingly would lead to alterations in climate models, Singer points out, and in order to keep the models in agreement with past temperature observations, some other parameters would have to be arbitrarily adjusted. "That just doesn't wash," he says.

As climate change has taken the scientific spotlight, new papers on climate change are coming out every week in top-tier journals such as *Science* and *Nature*. They almost exclusively support IPCC's assessment of anthropogenic global warming.

A team of 26 climate scientists issued an independent, non-peer-reviewed report, "The Copenhagen Diagnosis," late last month to summarize recent findings that have been reported since the cutoff date for IPCC's 2007 report. This unofficial IPCC update is designed to tide over policymakers until the next assessment wraps up in 2013. It was timed to come out just ahead of the Copenhagen climate conference.

Mann, one of the new report's authors, says it confirms IPCC's 2007 assessment that anthropogenic global warming is unequivocal and notes that warming by 2100 could exceed earlier projections. It further concludes that global ice sheets are melting faster than predicted and that sea-level rise, due to expansion of the warming oceans and the melting ice, is expected to be higher than previously forecast. One reason for the discrepancy could be that climate models used in the 2007 assessment included fast feedbacks such as water vapor but omitted slow feedbacks such as melting ice and changing vegetation patterns, the report notes.

As climate physicist and report coauthor Stefan Rahmstorf of Germany's Potsdam Institute for Climate Impact Research put it, "Unfortunately, the data now show us that we have underestimated the climate crisis."

The report concludes that "global CO_2 emissions must peak and then decline rapidly within the next five to 10 years for the world to have a reasonable chance of avoiding the very worst impacts of climate change."

Some scientists had already projected that IPCC was too conservative in its warnings. For example, leading climate modeler James E. Hansen, a climate physicist at GISS, has projected that

if atmospheric CO_2 levels reach about 450 ppm, which is on pace to happen in the next 25 years, Earth could reach a "tipping point" at which warming exacerbated by strong positive feedbacks will disrupt climate for centuries, with the harshest result being a possible sea-level rise of tens of meters.

Despite the scientific evidence laid out by IPCC and mainstream climate scientists, it's difficult for them to rebut NIPCC's analysis and the claims of global-warming skeptics. Most climate scientists don't even try, and in fact many climate scientists on both sides of the debate admit that they haven't bothered to read NIPCC's report, as it just repeats what they already know.

According to IPCC's information and communications officer, Carola Traverso Saibante, IPCC has not officially evaluated NIPCC's report and doesn't plan to. IPCC appears to be keeping its head down and working on it next assessment. As Traverso Saibante says, "IPCC's role is only to assess the science and disseminate its findings."

For Penn State's Mann, one of the few scientists C&EN talked to who acknowledged scrutinizing the NIPCC report: "It was disappointing to see that it is nothing other than a regurgitation of a number of contrarian myths about climate change. Beyond the editorialized comments, it terribly misrepresents the science."

For UAH's Christy, who says he did not participate in or read the NIPCC report, he recognizes that human activities are contributing to climate change. But he urges caution in evaluating what to do about model projections, and he has provided expert testimony to congressional committees to that effect, telling them that legislation to control CO_2 emissions will be expensive and not have any significant effect on global warming.

"It really doesn't matter what the climate sensitivity is, proposals for controlling CO_2 or geoengineering to increase aerosols to cool the planet will not put much of a dent at all into whatever is going to happen," Christy says. He adds that it would only disadvantage people living in developing countries and impoverished regions of the U.S. and other Western countries. Yet, Christy says, aborting the control of CO_2 emissions should be no excuse for reducing environmental protection. "We shouldn't undo the good things that have been done to clean the air and water. More should be done, especially in developing countries," he says.

Climatologist Michael Hulme of the University of East Anglia, in England, comments that the scientific evidence backing the basic idea of human activity changing the global climate system is now overwhelming, even if there are still gaps in knowledge and scientific predictions for future consequences are uncertain.

"It is vital that we understand the many valid reasons for disagreeing about global warming and climate change," Hulme says. "We must recognize that they are rooted in different political, national, organizational, religious, and intellectual cultures—our different ways of seeing the world.

"But we must not hide behind the dangerously false premise that consensus science leads to

consensus politics. In the end, politics will always trump science. Making constructive use of the idea of climate change means that we need better politics, not merely better science."

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