

# THE REAL HOLES IN CLIMATE SCIENCE

Like any other field, research on climate change has some fundamental gaps, although not the ones typically claimed by sceptics. **Quirin Schiermeier** takes a hard look at some of the biggest problem areas.

The e-mails leaked from the University of East Anglia's Climatic Research Unit (CRU) in November presented an early Christmas present to climate-change denialists. Amid the more than 1,000 messages were several controversial comments that — taken out of context — seemingly indicate that climate scientists have been hiding a mound of dirty laundry from the public.

A fuller reading of the e-mails from CRU in Norwich, UK, does show a sobering amount of rude behaviour and verbal faux pas, but nothing that challenges the scientific consensus of climate change. Still, the incident provides a good opportunity to point out that — as in any active field of inquiry — there are some major gaps in the understanding of climate science. In its most recent report in 2007, the Intergovernmental Panel on Climate Change (IPCC) highlighted 54 'key uncertainties' that complicate climate science.

Such a declaration of unresolved problems could hardly be called 'hidden'. And some of these — such as uncertainties in measurements of past temperatures — have received considerable discussion in the media. But other gaps in the science are less well known beyond the field's circle of specialists. Such holes do not undermine the fundamental conclusion that humans are warming the climate, which is based on the extreme rate of the twentieth-

century temperature changes and the inability of climate models to simulate such warming without including the role of greenhouse-gas pollution. The uncertainties do, however, hamper efforts to plan for the future. And unlike the myths regularly trotted out by climate-change denialists (see 'Enduring climate myths', page 286), some of the outstanding problems may mean that future changes could be worse than currently projected.

Researchers say it is difficult to talk openly about holes in understanding. "Of course there are gaps in our knowledge about Earth's climate system and its components, and yes, nothing has been made clear enough to the public," says Gavin Schmidt, a climate modeller at NASA's Goddard Institute for Space Studies in New York and one of the moderators and contributors to the influential RealClimate blog. "But this climate of suspicion we're working in is insane. It's really drowning our ability to soberly communicate gaps in our science when some people cry 'fraud' and 'misconduct' for the slightest reasons."

*Nature* has singled out four areas — regional climate forecasts, precipitation forecasts,

aerosols and palaeoclimate data — that some say deserve greater open discussion, both within scientific circles and in the public sphere.

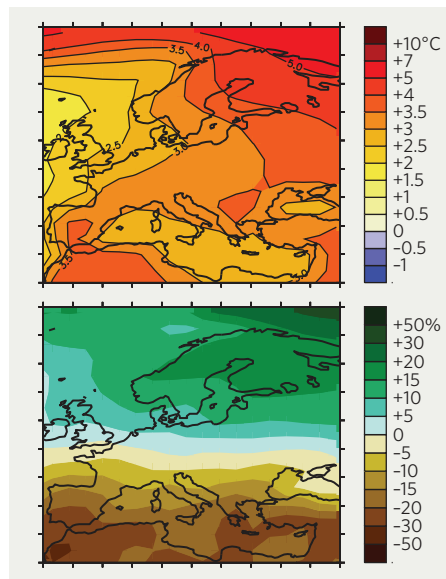
## Regional climate prediction

The sad truth of climate science is that the most crucial information is the least reliable. To plan for the future, people need to know how their local conditions will change, not how the average global temperature will climb. Yet researchers are still struggling to develop tools to accurately forecast climate changes for the twenty-first century at the local and regional level.

The basic tools used to simulate Earth's climate are general circulation models (GCMs), which represent physical processes in the global atmosphere, oceans, ice sheets and on the land's surface. Such models generally have a resolution of about 1–3° in latitude and longitude — too coarse to offer much guidance to people. So climate scientists simulate regional changes by zooming in on global models — using the same equations, but solving them for a much larger number of grid points in particular locations.

However, increasing the resolution in this

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Climate simulations for Europe for the end of the current century suggests warming (top) of more than 3°C relative to the end of the twentieth century. Precipitation projections (bottom) indicate drying of southern Europe and wetter conditions in northern Europe.

way can lead to problems. Zooming in from GCMs bears the risk of blowing up any inherent weakness of the ‘mother’ model. If the model does a poor job of simulating certain atmospheric patterns, those errors will be compounded at the regional level. Most experts are therefore cautious when asked to make regional predictions.

“Our current climate models are just not up to informed decision-making at the resolution of most countries,” says Leonard Smith, a statistician and climate analyst at the London School of Economics and Political Science.

“You need to be very circumspect about the added value of downscaling to regional impacts,” agrees Hans von Storch, a climate modeller at the GKSS Institute for Coastal Research in Geesthacht, Germany, who has recently contributed to a regional climate assessment of the Hamburg metropolitan region. If the simulations project future changes in line with the trends already observed, von Storch has more confidence in them. But if researchers run the same model, or an ensemble of models, multiple times and the results diverge from each other or from the observed trends, he cautions, “planners should handle them with kid gloves. Whenever possible, they’d rather wait with spending big money on adaptation projects until there is more certainty about the things to come.”

Downscaled climate models face particular uncertainty problems dealing in regions with

complex topography, such as where mountains form a wall between two climatically different plains. Another potential source of error comes from projections concerning future greenhouse-gas emissions, which vary depending on assumptions about economic developments.

All the problems, however, do not make regional simulations worthless, as long as their limitations are understood. They are already being used by planners at the local and national levels (see graphs, left). Simulations remain an important tool for understanding processes, such as changes in river flow, that global models just cannot resolve, says Jonathan Overpeck, a climate researcher at the University of Arizona in Tucson. Overpeck is part of a research team that is using statistical techniques to narrow down divergent model projections of how much average water flow in the Colorado River will decrease by 2050. Researchers hope that by improving how they simulate climate variables such as cloud coverage and sea surface temperatures, they will further reduce the uncertainties in regional forecasts, making them even more useful for policy-makers.

### Precipitation

Rising global temperatures over the next few decades are likely to increase evaporation and accelerate the global hydrological cycle — a change that will dry subtropical areas and increase precipitation at higher latitudes. These trends are already being observed and almost all climate models used to simulate global warming show a continuation of this general pattern<sup>1</sup>.

Unfortunately, when it comes to precipitation, that is about all the models agree on. The different simulations used by the IPCC in its 2007 assessment offer wildly diverging pictures of snow and rainfall in the future (see graphic, right). The situation is particularly bad for winter precipitation, generally the most important in replenishing water supplies. The IPCC simulations failed to provide any robust projection of how winter precipitation will change at the end of the current century for large parts of all continents<sup>2</sup>.

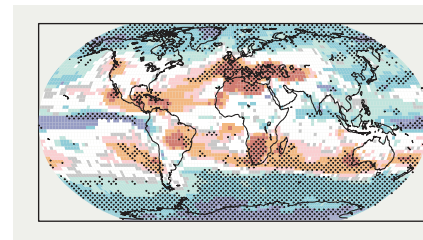
Even worse, climate models seemingly underestimate how much precipitation has changed already — further reducing confidence in their ability to project future changes. A 2007 study<sup>3</sup>, published too late to be included into the last IPCC report, found that precipitation changes in the twentieth century bore the clear imprint of human influence, including drying in the Northern Hemisphere tropics and subtropics. But the actual changes were larger than estimated from models — a finding that concerns researchers.

“If the models do systematically underestimate precipitation changes that would be bad news”, because the existing forecasts would already cause substantial problems, says Gabriele Hegerl, a climate-system scientist at the University of Edinburgh, UK, and a co-author on the paper. “This is, alas, a very significant uncertainty,” she says.

Climate scientists think that a main weakness of their models is their limited ability to simulate vertical air movement, such as convection in the tropics that lifts humid air into the atmosphere. The same problem can trip up the models for areas near steep mountain ranges. The simulations may also lose accuracy because scientists do not completely understand how natural and anthropogenic aerosol particles in the atmosphere influence clouds. Data on past precipitation patterns around the globe could help modellers to solve some of these issues, but such measurements are scant in many areas. “We really don’t know natural variability that well, particularly in the tropics,” says Hegerl.

The uncertainties about future precipitation make it difficult for decision-makers to plan, particularly in arid regions such as the Sahel in Africa and southwestern North America. ‘Mega-droughts’ lasting several decades have struck these areas in the past and are expected to happen again. But the models in use today do a poor job of simulating such long-lasting droughts. “That’s pretty worrying,” says Overpeck.

Increasing the resolution of models will not be enough to resolve the convective processes that lead to precipitation. To forecast precipitation more accurately, researchers are trying, among other things, to improve the simulation of key climate variables such as the formation and dynamics of clouds. Furthermore, high-resolution satellite observations are increasingly being used to validate and improve model realism.



Projections of precipitation change for 2090–99. Blue indicates increases in precipitation and brown denotes drying. White represents areas of uncertainty, where less than two-thirds of models agreed on whether precipitation would increase or decrease. Stippled areas indicate where 90% of the models agreed on the sign of the change.

## Enduring climate myths

Climate scientists grapple with real uncertainties, but those who doubt the reality of human-driven global warming usually ignore those issues and, instead, perpetuate a series of claims that do not hold up to scrutiny. What follows is a selection of myths about climate:

### Climate models can't provide useful information about the real world.

Models can reproduce much of the climate variation over the past millennium, but projections for the future are subject to well-described uncertainties, both in the understanding of climate and in estimates of future economic development. They cannot therefore provide decision-makers with exact information of the rate of future changes, but they can offer useful general information and they unconditionally predict a warmer world.

### Global warming stopped ten years ago.

Climate is not weather. The climate is the multi-decade average of the constantly changing state of the atmosphere. Natural variations can cause temperatures to rise and fall from year to year or decade to decade. Although global temperatures did not rise as quickly in the past decade as in previous ones, the most recent decade was the warmest on record.

### Temperatures were higher in pre-industrial times.

The consensus of proxy-based reconstructions of pre-industrial climate is that the second half of the twentieth century was probably warmer than any other half-century in more than a millennium. Warmer periods did occur in the more distant past, albeit under different orbital and geological conditions. In any

case, warm spells in the past do not disprove human influence on climate today. The cause of any particular climate change needs to be investigated separately.

### Temperature records taken in the lower atmosphere indicate that the globe is not warming.

A decade ago, there seemed to be a discrepancy between surface and tropospheric temperatures. But this issue was resolved when long-standing calibration problems with satellite sensors were discovered. Satellite measurements show that the lower atmosphere is warming at a rate consistent with the predictions of climate models.

### A few degrees of warming are not a big deal.

In the most recent ice age, the world was only a few degrees cooler on average than it is today. The current rate of warming is in all likelihood

unique in the history of humankind. There may be no such thing as an 'optimum' temperature for the planet, but modern human societies are adapted to the weather patterns and sea levels of the past millennia. The rapidity of global warming substantially adds to the problem.

### Measured increases in temperature reflect the growth of cities around weather stations rather than global warming.

Climate researchers have taken great care to correct for the impact of urbanization in temperature records by matching data from more-urban stations with data from rural ones. Moreover, some of the largest temperature anomalies on Earth occur in the least populated areas, including around the Arctic and the Antarctic Peninsula. Measurements also show warming of the surface ocean and deeper marine layers.

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## Aerosols

Atmospheric aerosols — airborne liquid or solid particles — are a source of great uncertainty in climate science. Despite decades of intense research, scientists must still resort to using huge error bars when assessing how particles such as sulphates, black carbon, sea salt and dust affect temperature and rainfall.

Overall, it is thought that aerosols cool climate by blocking sunlight, but the estimates of this effect vary by an order of magnitude, with the top end exceeding the warming power of all the carbon dioxide added to the atmosphere by humans.

One of the biggest problems is lack of data. "We don't know what's in the air," says Schmidt. "This means a major uncertainty over key processes driving past and future climate."

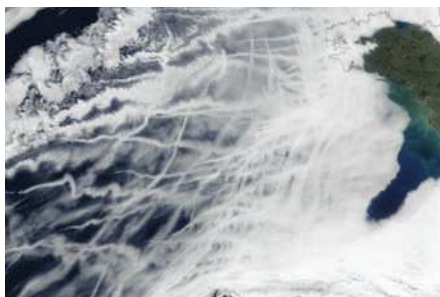
To measure aerosols in the sky, satellite and ground-based sensors detect the scattering and absorption of solar radiation. But researchers lack enough of this kind of data to complete a picture of aerosols across the globe. And a complex set of coordinated experiments is required to determine how aerosols alter climate processes.

Some aerosols, such as black carbon, absorb sunlight and produce a warming effect that might also inhibit rainfall. Other particles such as sulphates exert a cooling influence by reflecting sunlight. The net effect of aerosol pollution on global temperature is not well established.

And various studies have produced conflicting conclusions over whether global aerosol pollution is increasing or decreasing.

The relationship between aerosols and clouds adds another layer of complication. Before a cloud can produce rain or snow, rain drops or ice particles must form and aerosols often serve as the nuclei for condensation. But although some aerosols enhance cloudiness, others seem to reduce it. Aerosols could also have a tremendous impact on temperatures by altering the formation and lifetime of low-level clouds, which reflect sunlight and cool the planet's surface.

Scientists have yet to untangle the interplay between pollution, clouds, precipitation and temperature. However, NASA's Glory satellite, an aerosol and solar-irradiance monitoring mission scheduled for launch in October, will



The thin white lines show how aerosols from ship exhausts brighten clouds over the Atlantic Ocean.

provide some greatly anticipated data. Still, atmospheric researchers say that ground-based sensors capable of determining the abundance and composition of aerosols in the atmosphere are needed just as much.

## The tree-ring controversy

Many of the e-mails leaked from the CRU computers came from a particular group of climate researchers who work on reconstructing temperature variations over time. The e-mails revealed them discussing some of the uncertainties in centuries worth of climate information gleaned from tree rings and other sources.

Records of thermometer measurements over the past 150 years show a sharp temperature rise during recent decades that cannot be explained by any natural pattern. It is most likely to have been caused by anthropogenic greenhouse-gas emissions. But reliable thermometer records from before 1850 are scarce and researchers must find other ways to reveal earlier temperature trends.

Palaeoclimatology relies on records culled from sources such as tree rings, coral reefs, lake sediments, stalagmites, glacial movements and historical accounts. As trees grow, for example, they develop annual rings whose thickness reflects temperature and rainfall. Proxies such as these provide most knowledge of past climate fluctuations, such as the Medieval Warm Period from about 800 to 1300 and the Little

J. DESCLOITRES/MODIS/NASA/GSFC

Ice Age, centred on the year 1700.

When proxy records for the Northern Hemisphere are stitched together, they show a pattern resembling a hockey stick, with temperatures rising substantially during the late twentieth century above the long-term mean conditions. This type of work was pioneered in 1998 by Michael Mann, a climate researcher then at the University of Virginia in Charlottesville, and his co-authors<sup>4</sup>. In a subsequent publication<sup>5</sup>, they concluded that the decade of the 1990s was probably the warmest decade, and 1998 the warmest year, in at least a millennium. That work figured prominently in the 2001 assessment by the IPCC.

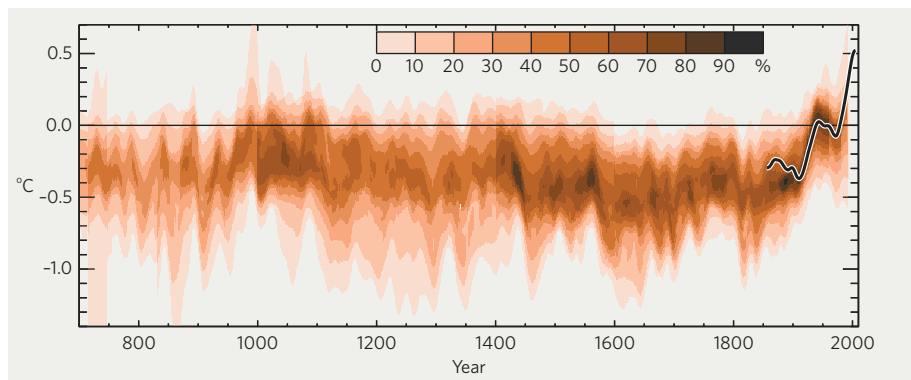
But the use and interpretation of such proxy records has generated considerable controversy. One notable critic, Stephen McIntyre, a retired Canadian mining consultant and editor of the Climate Audit blog, has spent much of the past decade challenging the work of Mann and other scientists whose e-mails were leaked. McIntyre has doggedly attacked the proxy records<sup>6</sup>, particularly the statistics used to analyse tree-ring data.

Many scientists are tired of the criticisms, and the IPCC concluded that it is “likely” that the second half of the twentieth century was the warmest 50-year period in the Northern Hemisphere during the past 1,300 years. But legitimate questions remain about paleoclimate proxies, according to the IPCC<sup>7</sup>.

Climate scientists are worried in particular about tree-ring data from a few northern sites. By examining temperature measurements from nearby, researchers know that tree growth at these locations tracked atmospheric temperatures for much of the twentieth century and then diverged from the actual temperatures during recent decades. It may be that when temperatures exceed a certain threshold, tree growth responds differently.

The ‘divergence’ issue also made an appearance in the CRU affair. In the most frequently quoted of the CRU e-mails, the former director of the centre, Phil Jones, mentioned a ‘trick’ — namely using actual observations of late-twentieth-century temperatures instead of tree ring data — to ‘hide the decline’ in the response of trees to the warming temperatures.

On the surface, Jones’s phrasing seems damning. Indeed, a graph of Northern Hemisphere temperature produced for the World Meteorological Organization in 2000 with Jones’s help fails to make clear that instrumental records from the nineteenth and twentieth centuries were spliced onto proxy data for the past mil-



**Northern Hemisphere temperature estimates made using data from tree rings and other sources — graphed relative to the average of 1961–90. The curve includes data from 10 studies, with darker colours representing greater consensus. There is considerable disagreement about conditions around 1000AD; most studies indicate temperatures were substantially cooler then, but a few suggest warming comparable to that of the twentieth century. There is much stronger agreement for the warm conditions since 1900. The heavy black line is temperature recorded by thermometers.**

lennium because of the divergence issue. The figure did, however, contain clear references to papers that discussed the divergence issue.

“They show what was, at the time, the best estimate of how temperatures evolved over time,” says Hegerl. “However, with hindsight, they could have been a bit clearer how this was done, given the high profile that figures like this can have.”

Aside from the issue of clarity, the decision to exclude the tree-ring records that diverge from the instrumental data makes sense, says Thomas Stocker, co-chair of the IPCC’s working group on the physical basis of climate change.

The tree ring divergence problem is restricted to a few high-latitude regions in the Northern Hemisphere and is not ubiquitous even there, he says.

Still, the divergence issue remains a source of debate within the scientific community. “I’m worried about what causes the divergence,” says Hegerl. “As long as we don’t understand why they diverge, we can’t be sure that they accurately represent the past.” So improving the usefulness of proxies will require a better understanding of how different species of trees grow and respond to climate change.

Another outstanding problem in proxy research is the large range of uncertainty for temperatures from before about 1500. Studies published in 2004 (ref. 8) and 2005 (ref. 9), based on a combination of proxies of different resolution, suggest that fluctuations in global temperature during the past millennium may have been larger than initially thought. However, these studies still show late twentieth century warming to be unprecedented, says von Storch. And

the most recent decade was warmer still.

Even with ongoing questions about the proxy data, the IPCC’s key statement — that most of the warming since the mid-twentieth century is “very likely” to be due to human-caused increases in greenhouse-gas concentration — remains solid because it rests on multiple lines of evidence from different teams examining many aspects of the climate system, says Susan Solomon, the former co-chair of the IPCC team that produced the 2007 physical science report and a climate researcher with the US National Oceanic and Atmospheric Administration in Boulder, Colorado.

“The IPCC’s team of scientists,” she says, “would not have said that warming is unequivocal based on a single line of evidence — even if it came from Moses himself.”

**Quirin Schiermeier is a senior reporter with Nature based in Munich.**

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