NEWS FEATURE:

Climate research is gaining ground

The past five years have been an interesting time for the climate and for climate policy. But how has climate science evolved since *Nature Climate Change* first launched?

Olive Heffernan

Since *Nature Climate Change* launched its first issue in 2011, the world has experienced the warmest five-year period on record. 2015 has been the hottest year since measurements began, and the global average temperature is now 1 °C above the pre-industrial average, which is halfway to the 2 °C threshold. Temperature increases of more than 2 °C above pre-industrial levels could have catastrophic consequences, including changes to the polar ice sheets, sea levels, food production, water supplies and biodiversity, to name but a few. Furthermore, daily average CO_2 levels now often exceed 400 ppm. Year after year, the world reaches new milestones indicative of increasingly extreme climate change. This includes the unprecedented low California snowpack in the winter of 2015, as well as events in 2012 — the all-time low of Arctic summer sea ice and the record melting of the Greenland ice sheet.

There are, however, reasons for cautious optimism. Politically, the journal launched in an era of post-Copenhagen despair. Yet now, we are in a post-Paris glow, with, at least, an agreement in place that binds nations to emissions reductions targets of their own offering, and that sets a process in place for reviewing those targets. Perhaps even more promising is the falling cost of renewable energy technologies such as solar and wind, which are already proving to be cost-effective alternatives to fossil fuels — renewable energy accounted for more than half of the added capacity in the global power sector since 2011.

The tide is turning, if slowly. Much work still has to be done in transitioning to a renewable energy economy and in understanding the changes that lie ahead. But just how far have we come in the past five years, a timeframe during which the IPCC launched its Fifth Assessment Report on climate science? Here, scientists give their views on some of the greatest gains that have been made in climate science — both physical and social — since the very first issue of *Nature Climate Change*.

Attributing extreme events

In the last few years, the ability to attribute extreme climate events such as storms, floods and wildfires to climate change has developed rapidly. The first paper to attribute an extreme weather event to climate change was published more than a decade ago[1], but in recent years, the number has hugely increased.

Broadly, there is stronger evidence linking human-driven climate change to an increased likelihood and intensity of extreme heat events, but the evidence linking anthropogenic climate change to storms and precipitation-related events is more mixed[2]. Furthermore, attribution science is moving from linking global-scale changes in heat extremes, for example, to attributing specific events at regional scales — such as the Argentinian heatwave of 2014 — to human activity.

That means that the impact of greenhouse gas emissions can increasingly be detected at a local scale. Since 2011, an annual report has been released documenting extreme events of the past year and the extent that they can be attributed to climate change[3].

"We've made great strides in moving from the global to the local perspective with detection and attribution," says Thomas Stocker, co-chair of Working Group I in the IPCC's Fifth Assessment Report. "We're still far away from being able to say that the well in my garden is drying up because of climate change but the science is moving in that direction," he adds.

Scientists are also looking at more effective approaches for attribution. Recently, work led by Peter Stott of the UK Met Office called for climate attribution to become more operational, involving timely and robust assessments rather than reactive responses to extreme events[4].

A study led by Kevin Trenberth of the National Centre for Atmospheric Research

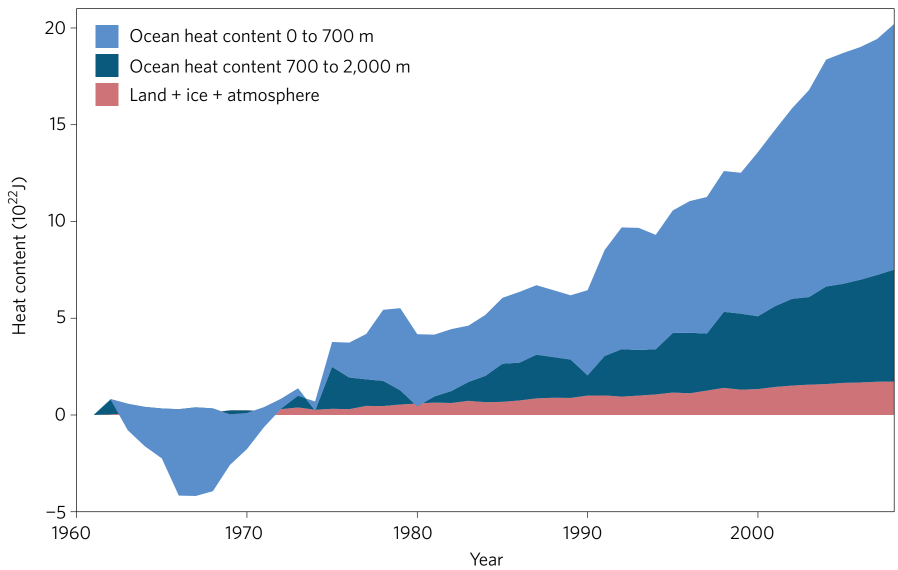


Figure 1 | Global heat content. The ocean has the capacity to hold large amounts of heat, relative to the rest of the climate system, and its heat content has been increasing rapidly in recent years. Figure 1 reproduced with permission from ref. 31, Elsevier.

(NCAR) in Boulder, Colorado, also recently argued for a new approach to attribution. The authors say[5] that there may be a better way of linking extreme events to warming. They say that, rather than focusing on the atmospheric circulation changes that result in a storm, scientists should be looking at the effects of thermodynamic change in the system, such as how the impact of the storm was boosted by temperature changes in the ocean.

Tracking the missing heat

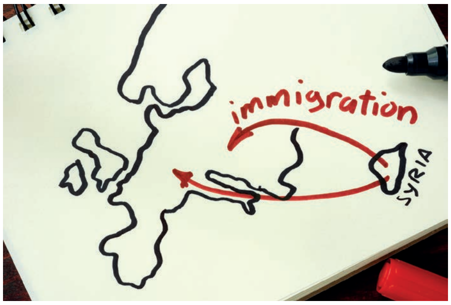
In 2013 and 2014, an alleged slowdown in the average rate of surface warming — by about 0.05 °C per decade since 1998 — captured much of the media's attention on climate change. It also left unanswered questions for scientists who struggled to explain how the Earth's surface could be cooling when a net energy flux of about 1 W m^{-2} should be warming the system.

An early paper in *Nature Climate Change*, led by NCAR's Jerry Meehl[6], suggested that during so-called hiatus periods, the deep ocean — especially below 300 m — might well be taking up more heat. Since then, several studies have confirmed this using observational data — in particular from the near-global network of Argo floats.

Using a reanalysis method that samples data from various sources such as Argo, in 2013 Magdalena Balmaseda and colleagues reported[7] in *Geophysical Research Letters,* that 30% of ocean warming had occurred below 700 m in the previous decade. "Most of what's happened with understanding ocean heat content is simply down the availability of Argo data to 2,000 metres," says Kevin Trenberth, a co-author on the paper. Also using Argo data, Dean Roemmich of Scripps Institution of Oceanography at the University of San Diego, California and colleagues reported[8] in February 2015 that the heat entering the ocean at depths of 0–2,000 m had increased by 0.4 to 0.6 W m^{-2} over the period 2006–2013, and that half of the warming occurred below 700 m.

In January of this year, another study[9] reported that nearly half of industrial era increases in ocean heat content have occurred in recent decades and that more than one-third of the heat entering the ocean accumulates below 700 m (Fig. 1). Led by Peter Gleckler of Lawrence Livermore National Laboratory in California, the study used a variety of data sources going back to 1865, including the Argo data for more recent years.

Overall, since Meehl's 2011 study[6] in *Nature Climate Change*, scientists have developed a much better understanding



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of how heat is stored in the ocean, and at what depths. "In particular, the amount of heat going much deeper than 700 metres is much larger than most people thought," says Trenberth.

Measuring migration

A few years ago, the predictions were dire: by 2050, the world would see 150 million refugees, claimed the Environmental Justice Foundation, a UK non-profit organization. Fifty million environmental migrants by 2010, said the UN in 2005. But where are all these climate refugees? Since 2011, whether climate change is forcing people to relocate has become a hotly contested issue.

On one hand, there is much research suggesting that the environment does play a role in people's location decisions. For example, research published in 2014 in *Nature Climate Change* suggests[10] that heat stress drives long term and long distance migration of farmers in Pakistan. More recently, a paper in *Proceedings of the National Academy of Sciences* reported[11] that anthropogenic climate change made the recent drought in Syria two to three times more likely to occur. The migrant farmers themselves — of which there have been at least one million — point to the drought as a motivator for their relocation to overcrowded cities.

But it is not as simple as that. In November 2011, not long after *Nature Climate Change* launched, a UK government-funded Foresight report revealed that the relationship between climate change and migration is complex, and often countertintuitive[12]. "What we now understand is that one of the major hazards is people moving towards environmental risks rather than away from them," says Neil Adger, one of the report's authors and a human geographer at the University of Exeter.

For example, there may be 114 to 192 million additional people living in the floodplains of urban areas in Asia and Africa by 2060 relative to 2000.

"Another insight that we've gained is that there is an inverse correlation between people's vulnerability and their ability to move," says Adger. Specifically, the scientists found that in the coming decades millions of poor people may become trapped by climate change, unable to move. "That understanding turned the whole field on its head," he says.

Assessing aerosols

Just six months after the launch of *Nature Climate Change*, a seminal report from the United Nations Environment Programme and the World Meteorological Organization highlighted approaches that could effectively mitigate warming agents with a short lifespan such as ozone and black carbon[13]. Since then, scientists have taken big strides in understanding these short-lived climate forcers (SLCFs) and their contribution to planetary warming.

"Over the past five years we've gone from highlighting the large potential for climate mitigation from SLCFs to understanding the various timescales at which their mitigation would play an important role," says Joeri Rogelj, a researcher at the Energy Program of the International Institute for Applied Systems Analysis in Vienna, Austria.

Some of the early work showed that mitigation of SLCFs could go a long way to reducing warming over the next decade, in addition to having the co-benefits of improving air quality and food security[14,15]. Furthermore, scientists reported that mitigating SLCFs including methane, tropospheric ozone, hydrofluorocarbons and black carbon could slow sea-level rise, by as much as 24–50% by the end of the century[16].

More recent work in 2014, led by Rogelj, shows that mitigating SLCFs is more complex than originally thought, however. That is in part because some of the prominent SLCF sources are from combustion processes that also emit CO_2. And so efforts to phase out those SLCFs will be dealt with through efforts to phase out CO_2, meaning that additional efforts would bring limited benefits[17]. Furthermore, scientists have in the past five years developed a more detailed understanding of the complex interplay between warming SLCFs and climate cooling agents. "If you ban dirty biomass burning to reduce black carbon, you would mitigate for organic carbon too, which is a cooling agent," says Rogelj.

As such, it's becoming clear that methane, which is emitted from sources such as land-use change and tends to be emitted alone, could be a potentially more effective target for SLCF mitigation than black carbon. Nevertheless, it's still recognized that mitigating black carbon could have important regional benefits in places such as the Arctic[18].

Data-rich social science

Environmental social science has, over the past few years, seen some major advances. For one, sociologists, who traditionally have tended towards descriptive research, are now embracing techniques that have more predictive capacity. "It's changing over generations," says Dana Fisher, a professor of Sociology at the University of Maryland.

One example comes from Fisher's own work, published last May[19]. Writing with Lorien Jasny at the University of Exeter and Jospeh Waggle, also of the University of Maryland, Fisher examined the role of echo chambers in transmitting climate-related information among political elites in the US. Echo chambers are structures that allow information to be repeated and reinforced among networks of people who share the same ideology, thus blocking the flow of information that runs counter to their beliefs.

Although this notion has been around the social science literature for some time, the study by Jasny, Waggle and Fisher formalizes and tests the hypothesis empirically. Their study — which confirms the prevalence of echo chambers in US climate policy circles — also sets out a method that other social scientists can adapt to test hypotheses relating to the perception and understanding of climate change more generally.

Another advance in social science research is the recent explosion of interest in data mining. "We're scrambling to have people who can do social science research using data scraping from the internet," says Fisher. She recalls the UN negotiations in Copenhagen in 2009, when climate activists were using the internet to organize, but no one was analysing the data. The large volumes of data now available — for free — on the internet are opening up huge potential for novel analyses in the social sciences generally.

Some recent examples come from sociologist Justin Farrell of Yale University in New Haven, Conneticut. In two recent studies, Farrell combined social network analysis with computational text analysis to assess, first, the structure and political influence of the climate change counter-culture in the US[20], and secondly, the link between corporate funding and polarization of opinion on climate change in the US[21].Both studies covered the same twenty-year period 1993–2013, and involved the analysis of huge volumes of data. For example, in the second study, Farrell gleaned data from the internet on all 164 organizations involved in the climate change countermovement between 1993 and 2013, as well as the more than 40,000 texts produced by this network.

"Now the methods for data scraping have evolved but we still need to get a handle on how to interpret the data," says Fisher. Farrell agrees. "While there is a great deal of optimism (and sometimes hubris), with the explosion of available data, it will be important to develop and utilize the right methods for the right research questions," he warns. But, he says, the future of computational social science is very bright.

Re-engineering the Earth

One of most controversial areas of climate research — geoengineering — is increasingly capturing the attention of both physical and social scientists. Climate scientists regularly caution that geoengineering schemes are no substitute for mitigating climate change. But there's also been a growing sense in the research community that it's better to have all the information to hand on the potential risks and benefits of intentionally altering the Earth's climate. Geoengineering schemes are broadly divided into two categories: solar radiation management (SRM), which aims to reduce warming by reflecting sunlight, and carbon dioxide removal (CDR) and sequestration, which aims to reduce warming by sequestering CO_2 from the atmosphere. These areas are scientifically independent and have progressed at different speeds in the past five years.

In the area of CDR, there has been a move towards learning by doing. For example, there has been more field experimentation on ocean fertilization, showing its ability to sequester CO_2 in the deep ocean on the timescale of centuries[22]. There are also now a number of pilot projects worldwide for direct air capture of carbon, such as one launched last June by a Vancouver-based start-up called Carbon Engineering.

In the field of SRM, since 2011, much effort has gone into using modelling studies to understand how such schemes could affect both temperature and precipitation patterns. Research by scientists such as Piers Forster at the University of Leeds and Jim Haywood at the UK's Met Office Hadley Centre suggests that SRM schemes could have hugely detrimental impacts on global precipitation patterns[23] and that injection of sulfate aerosols in the Northern Hemisphere, for example, could disrupt rainfall in the Southern Hemisphere[24]. Other research, by David Keith of Harvard, however, suggests that moderate solar reduction would be effective in reducing warming for all world regions; the capacity to restore precipitation to its pre-industrial levels is less clear-cut, but generally positive.

SRM has not yet reached the stage of field experimentation. "We're at a bit of an impasse," says Matthew Watson, a geoengineering researcher at the University of Bristol. "A lot of modelling and social science work has been done and the next rubicon to cross is field trials." That is in no small part due to public and political opposition. In 2013 two separate studies, one led by Rob Bellamy at the University of Oxford and another led by Nick Pidgeon of Cardiff University suggested that proposals to inject aerosols into the stratosphere may be the least likely scheme to gain public support[25,26]. "Field trials are really difficult here in the UK, and I don't see them going

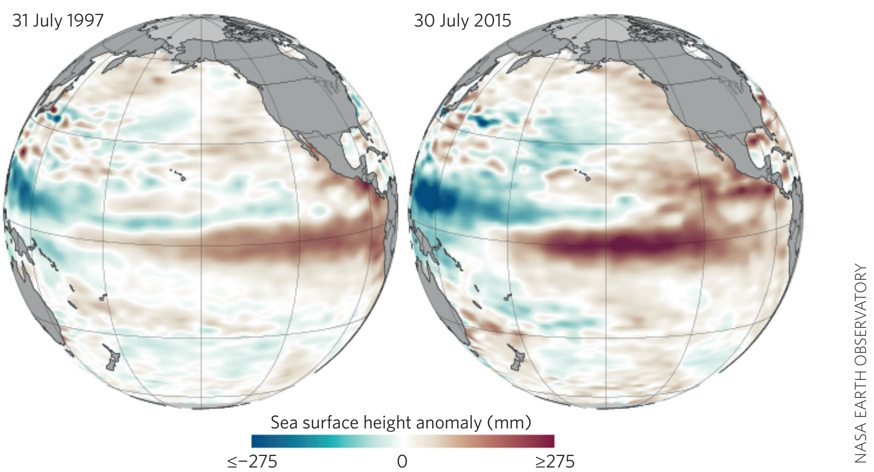

Figure 2 | Sea surface height anomalies in the lead up to the 1997/98 and 2015/16 El Niño events. El Niño events are characterized by a build up of warm water in the eastern Pacific Ocean.

anywhere soon," says Mike Hulme of King's College, London.

Climate communication

Climate communication research has blossomed from its infancy into a much more sophisticated field. "The multidisciplinary climate communication field has matured significantly over the past five years: we have a growing cadre of climate change communication researchers, several centres dedicated to studying the topic, and an exponentially growing number of publications," explains Susanne Moser of Stanford University, California.

The research itself has expanded into exploring public awareness and perception of climate change in remote regions such as the Nigerian savanna and French Polynesia. Conversely, there have also been more studies on public perception globally, with more comparisons of opinions and attitudes between and within nations[27].

Scientists are also digging deeper into the factors, such as emotions and attachments — for example, place identity — that govern how people receive and respond to messages on climate change[28]. However, Moser says the challenges ahead are far more difficult and daunting, such as understanding how to move people from awareness and concern to action, and how to effectively confront hopelessness, despair and disengagement.

Human influence on natural variability

One important question in attribution research is whether human-driven climate change can alter the likelihood of positive phases of natural modes of variability, such as the El Niño Southern Oscillation (Fig. 2), the Pacific Decadal Oscillation, and the Arctic Oscillation.

In its Fifth Assessment Report, the IPCC focused far more attention on this issue than in previous reports. Meanwhile, modelling studies have come a long way in unravelling the relationship between sea surface temperatures, greenhouse warming and the likelihood and severity of El Niño events. Research by Seon Tae Kim of the Commonwealth Scientific and Industrial Research Organization, Australia, for example has suggested there will be an increase in the magnitude of ENSO up until 2040, after which it will taper off[29]. A separate modelling study by Wenju Cai, also of CSIRO Australia[30] predicts a doubling of the likelihood of extreme El Niño events as the climate changes.

"The issues of how these things are interacting with one another is a substantial one," says Kevin Trenberth. "If you look at 2015, I don't think you can look at any event and say it was El Niño or global warming because it's really a combination of both," he says.

The past five years have been an interesting and productive time for climate research, with steady progress being made on a number of fronts in the physical and social sciences. The examples given here by no means represent an exhaustive list of recent advances in the field. Rather, they serve as an illustration of the diversity and scope of the frontiers of modern climate research. Many other areas of study have made great headway, and deserve equal consideration. Examples include the progress by physical scientists in understanding the factors governing ice sheet instability and advances by economists in comprehending consumer behaviour around energy consumption. In such a far-reaching field as climate research, it may be daunting to consider the challenges ahead. But looking back on the past five years, and the progress that has been made, it is both exciting and hopeful. ❐

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Correction

In the Feature "Climate research is gaining ground" (*Nature Clim. Change* **6,** 335–338; 2016), the surname of Dana Fisher was spelt incorrectly in the main text. Corrected in the online versions after print: 15 April 2016.

Correction

In the Feature "Climate research is gaining ground" (*Nature Clim. Change* **6,** 335–338; 2016), the affiliation for Mike Hulme should have been 'King's College London'. Corrected in the online versions after print: 22 April 2016.