Celebrating the anniversary of three key events in climate change science

Climate science celebrates three 40th anniversaries in 2019: the release of the Charney report, the publication of a key paper on anthropogenic signal detection, and the start of satellite temperature measurements. This confluence of scientific understanding and data led to the identification of human fingerprints in atmospheric temperature.

Benjamin D. Santer, Céline J. W. Bonfils, Qiang Fu, John C. Fyfe, Gabriele C. Hegerl, Carl Mears, Jeffrey F. Painter, Stephen Po-Chedley, Frank J. Wentz, Mark D. Zelinka and Cheng-Zhi Zou

The 1970s saw growing concern about the potential for anthropogenic climate change. In this Comment, we focus on understanding how the scientific advances arising from the three anniversary events aided efforts to identify human influences on the thermal structure of the atmosphere.

The Charney report

In 1979, the US National Academy of Sciences published the findings of the Ad Hoc Study Group on Carbon Dioxide and Climate. This is frequently referred to as the Charney report[1].

The authors did not have many of the scientific advantages available today: international climate science assessments based on thousands of relevant peer-reviewed scientific papers[2–4], four decades of satellite measurements of global climate change[5], land and ocean surface temperature datasets spanning more than 120 years (ref. [6]), estimates of natural climate variability[7,8] and sophisticated three-dimensional numerical models of Earth's climate system. Nevertheless, the report's principal findings have aged remarkably well. Consider conclusions regarding the equilibrium climate sensitivity (ECS): "We estimate the most probable global warming for a doubling of CO_2 to be near 3 °C with a probable error of ±1.5 °C". These values are in accord with current understanding[9] and are now supported by multiple lines of evidence that were unavailable in 1979. Examples include observed patterns of surface warming, greenhouse gas and temperature changes on Ice Age timescales, and results from multi-model ensembles of externally forced simulations[3,4,9].

There is also better process-level understanding of the feedbacks contributing to ECS uncertainties[10–12]. Charney and co-authors understood that the factor of three spread in ECS was mainly due to uncertainties in the net effect of high and low cloud feedbacks[13]. Reliable assessment of cloud feedbacks required "comprehensive numerical modelling of the general circulations of the atmosphere and the oceans together with validation by comparison of the observed with the model-produced cloud types and amounts". This conclusion foreshadowed rigorous evaluation of model cloud properties with satellite data[14]. Such comparisons ultimately led to the elucidation of robust cloud responses to greenhouse warming[15], and to the 2013 conclusion of the Intergovernmental Panel on Climate Change (IPCC) that "the sign of the net radiative feedback due to all cloud types is likely positive"[10].

The ocean's role in climate change featured prominently in the Charney report. The authors noted that ocean heat uptake would delay the emergence of an anthropogenic warming signal from the background noise of natural variability[16]. This delay, they wrote, meant that humanity "may not be given a warning until the CO_2 loading is such that an appreciable climate

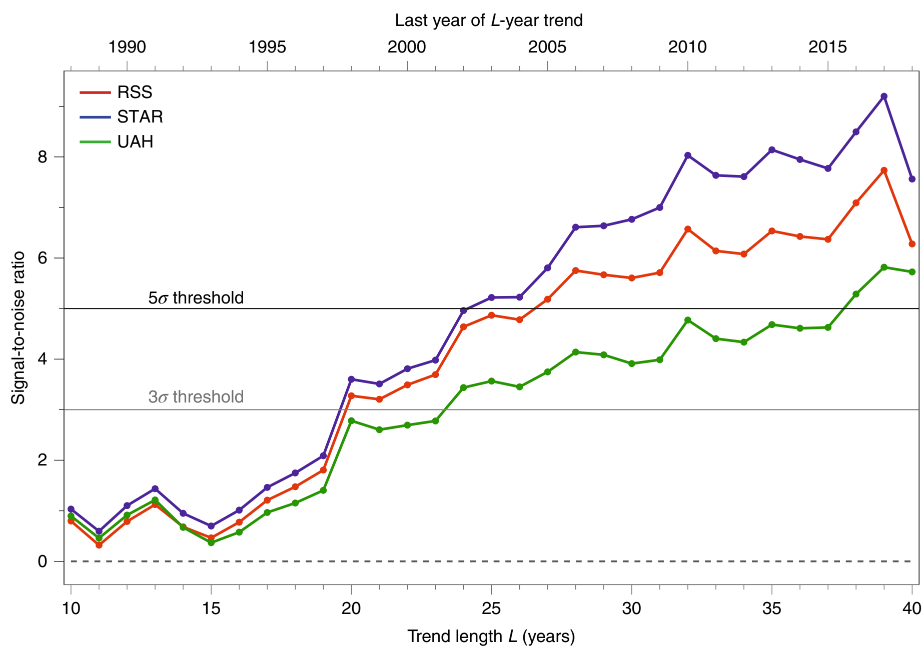

Fig. 1 | Signal-to-noise ratios used for identifying a model-predicted anthropogenic fingerprint in 40 years of satellite measurements of annual-mean tropospheric temperature. The MSU and AMSU measurements are from three different research groups: Remote Sensing Systems (RSS), the Center for Satellite Applications and Research (STAR), and the University of Alabama at Huntsville (UAH). The grey and black horizontal lines are the 3σ and 5σ thresholds that we use for estimating the signal detection time. By 2002, all three satellite datasets yield signal-to-noise ratios exceeding the 3σ threshold. By 2016, an anthropogenic signal is consistently detected at the 5σ threshold. Further details of the model and satellite data and the fingerprint method are provided in the Supplementary Information.

change is inevitable". The finding that "on time scales of decades the coupling between the mixed layer and the upper thermocline must be considered" provided impetus for the development of atmosphere–ocean general circulation models (GCMs).

The authors also knew that scientific uncertainties did not negate the reality and seriousness of human-caused climate change: "We have examined with care all known negative feedback mechanisms, such as increase in low or middle cloud amount, and have concluded that the oversimplifications and inaccuracies in the models are not likely to have vitiated the principal conclusion that there will be appreciable warming". Although the GCMs available in 1979 were not yet sufficiently reliable for predicting regional changes, Charney et al. cautioned that the "associated regional climate changes so important to the assessment of socioeconomic consequences may well be significant".

In retrospect, the Charney report seems like the scientific equivalent of the handwriting on the wall. Forty years ago, its authors issued a clear warning of the potentially significant socioeconomic consequences of human-caused warming. Their warning was accurate and remains more relevant than ever.

Hasselmann's optimal detection paper

The second scientific anniversary marks the publication of a paper by Klaus Hasselmann entitled "On the signal-to-noise problem in atmospheric response studies"[17]. This is now widely regarded as the first serious effort to provide a sound statistical framework for identifying a human-caused warming signal.

In the 1970s, there was recognition that GCM simulations yielded both signal and noise when forced by changes in atmospheric CO_2 or other external factors[18]. The signal was the climate response to the altered external factor. The noise arose from natural internal climate variability. Noise estimates were obtained from observations or by running an atmospheric GCM coupled to a simple model of the upper ocean. In the presence of intrinsic noise, statistical methods were required to identify areas of the world where the first detection of a human-caused warming signal might occur.

One key insight in Hasselmann's 1979 paper was that analysts should look at the statistical significance of global geographical patterns of climate change. Previous work had assessed the significance of the local climate response to a particular external forcing at thousands of individual model grid-points. Climate information at these individual locations was correlated in space and in time, hampering assessment of overall significance. Hasselmann noted that "it is necessary to regard the signal and noise fields as multi-dimensional vector quantities and the significance analysis should accordingly be carried out with respect to this multi-variate statistical field, rather than in terms of individual gridpoint statistics". Instead of looking for a needle in a tiny corner of a large haystack (and then proceeding to search the next tiny corner), Hasselmann advocated for a more efficient strategy — searching the entire haystack simultaneously.

He also pointed out that theory, observations and models provide considerable information about signal and noise properties. For example, changes in solar irradiance, volcanic aerosols and greenhouse gases produce signals with different patterns, amplitudes and frequencies[2–4,8,19]. These unique signal characteristics (or 'fingerprints') can be used to distinguish climate signals from climate noise.

Hasselmann's paper was a statistical roadmap for hundreds of subsequent climate change detection and attribution (D&A) studies. These investigations identified anthropogenic fingerprints in a wide range of independently monitored observational datasets[2–4]. D&A research provided strong scientific support for the conclusion reached by the IPCC in 2013: "It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century"[4].

Forty years of satellite data

In November 1978, Microwave Sounding Units (MSUs) on National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites began monitoring the microwave emissions from oxygen molecules. These emissions are proportional to the temperature of broad atmospheric layers[5]. A successor to MSU, the Advanced Microwave Sounding Unit (AMSU), was deployed in 1998. Estimates of global changes in atmospheric temperature can be obtained from MSU and AMSU measurements.

Over their 40-year history, MSU and AMSU data have been essential ingredients in hundreds of research investigations. These datasets allowed scientists to study the size, significance, and causes of global trends and variability in Earth's atmospheric temperature and circulation, to quantify the tropospheric cooling after major volcanic eruptions, to evaluate climate model performance, and to assess the consistency between observed surface and tropospheric temperature changes[2–4,20].

Satellite atmospheric temperature data were also a useful test-bed for Hasselmann's signal detection strategy. They had continuous, near-global coverage[5]. Data products were available from multiple research groups, providing a measure of structural uncertainty in the temperature retrievals. Signal detection studies with MSU and AMSU revealed that human fingerprints were identifiable in the warming of the troposphere and cooling of the lower stratosphere[8], confirming model projections[21] made in 1967. Tropospheric warming is largely due to increases in atmospheric CO_2 from fossil fuel use[2–4,8,20], and lower stratospheric cooling over the 40-year satellite record[22] is mainly attributable to anthropogenic depletion of stratospheric ozone[23].

While enabling significant scientific advances, MSU and AMSU temperature data have also been at the centre of scientific and political imbroglios. Some controversies were related to differences between surface warming inferred from thermometers and tropospheric warming estimated from satellites. Claims that these warming rate differences cast doubt on the reliability of the surface data have not been substantiated[20,24]. Other disputes focused on how to adjust for non-climatic artefacts arising from orbital decay and drift, instrument calibration drift, and the transition between MSU and AMSU instruments[5,20]. More recently, claims of no significant warming since 1998 have been based on artfully selected subsets of satellite temperature data. Such claims are erroneous and do not call into question the reality of long-term tropospheric warming[25].

A confluence of scientific understanding

The zeitgeist of 1979 was favourable for anthropogenic signal detection. From the Charney report, which relied on basic theory and early climate model simulations, there was clear recognition that fossil fuel burning would yield an appreciable global warming signal[1]. Klaus Hasselmann's paper[17] outlined a rational approach for detecting this signal. Satellite-borne microwave sounders began to monitor atmospheric temperature, providing global patterns of multi-decadal climate change and natural internal variability — information required for successful application of Hasselmann's signal detection method.

Because of this confluence in scientific understanding, we can now answer the following question: when did a human-caused tropospheric warming signal first emerge from the background noise of natural climate variability? We addressed this question by applying a fingerprint method related to Hasselmann's approach (see Supplementary Information 1). An anthropogenic fingerprint of tropospheric warming is identifiable with high statistical confidence in all currently available satellite datasets (Fig. 1). In two out of three datasets, fingerprint detection at a 5σ threshold — the gold standard for discoveries in particle physics — occurs no later than 2005, only 27 years after the 1979 start of the satellite measurements. Humanity cannot afford to ignore such clear signals.

Data availability

All primary satellite and model temperature datasets used here are publicly available. Derived products (synthetic satellite temperatures calculated from model simulations) are provided at: https://pcmdi.llnl.gov/research/DandA/.

Benjamin D. Santer[1]*, Céline J. W. Bonfils[1], Qiang Fu[2], John C. Fyfe[3], Gabriele C. Hegerl[4], Carl Mears[5], Jeffrey F. Painter[1], Stephen Po-Chedley[1], Frank J. Wentz[5], Mark D. Zelinka[1] and Cheng-Zhi Zou[6]

[1]Program for Climate Model Diagnosis and Intercomparison (PCMDI), Lawrence Livermore National Laboratory, Livermore, CA, USA. [2]Dept. of Atmospheric Sciences, University of Washington, Seattle, WA, USA. [3]Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada, Victoria, British Columbia, Canada. [4]School of Geosciences, University of Edinburgh, Edinburgh, UK. [5]Remote Sensing Systems, Santa Rosa, CA, USA. [6]Center for Satellite Applications and Research, NOAA/NESDIS, College Park, MD, USA.

**e-mail: santer1@llnl.gov*

Published online: 25 February 2019
https://doi.org/10.1038/s41558-019-0424-x

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Acknowledgements

We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups for producing and making available their model output. For CMIP, the US Department of Energy's Program for Climate Model Diagnosis and Intercomparison (PCMDI) provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. The authors thank S. Solomon (MIT) and K. Denman, N. McFarlane and K. von Salzen (Canadian Centre for Climate Modelling and Analysis) for helpful comments. Work at LLNL was performed under the auspices of the US Department of Energy under contract DE-AC52-07NA27344 through the Regional and Global Model Analysis Program (B.D.S., J.F.P., and M.Z.), the Laboratory Directed Research and Development Program under Project 18-ERD-054 (S.P.-C.), and the Early Career Research Program Award SCW1295 (C.B.). Support was also provided by NASA Grant NNH12CF05C (F.J.W. and C.M.), NOAA Grant NA18OAR4310423 (Q.F), and by NOAA's Climate Program Office, Climate Monitoring Program, and NOAA's Joint Polar Satellite System Program Office, Proving Ground and Risk Reduction Program (C.-Z.Z.). G.H. was supported by the European Research Council TITAN project (EC-320691) and by the Wolfson Foundation and the Royal Society as a Royal Society Wolfson Research Merit Award holder (WM130060). The views, opinions and findings contained in this report are those of the authors and should not be construed as a position, policy, or decision of the US Government, the US Department of Energy, or the National Oceanic and Atmospheric Administration.

Author contributions

B.D.S. conceived the study and performed statistical analyses. J.F.P. calculated synthetic satellite temperatures from model simulation output. C.M., F.J.W., and C.-Z.Z. provided satellite temperature data. All authors contributed to the writing and revision of the manuscript.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41558-019-0424-x.