Celebrating the Anniversary of Three Key Events in Climate Change Science

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In 2019, climate science will celebrate a trifecta of important 40th anniversaries. The first two anniversaries commemorate influential 1979 publications: a National Academy climate science report and a paper outlining a statistical framework for identifying a human-caused warming signal. The third anniversary will mark the availability of 40 years of satellite temperature data. Each event represents a significant scientific advance. The National Academy report, informed by theory and models, found that human-caused increases in heat-trapping greenhouse gases were likely to yield significant global and regional climate signals. The statistical paper introduced a rigorous framework to detect these signals and highlighted the advantages of focusing on global patterns of climate change. Satellite microwave radiometry provided the required global data for pattern studies. This confluence of theory, models, statistical methods, and data eventually led to the identification of a human fingerprint in the changing thermal structure of the atmosphere.

Anniversary 1: The Charney report

In 1979, the report of an "Ad Hoc Study Group on Carbon Dioxide and Climate" was published by the U.S. National Academy of Sciences[1]. This is frequently referred to as the "Charney report" after the Chairman of the Ad Hoc Study Group, acclaimed M.I.T. meteorologist Jule Charney. The Ad Hoc Study Group did not have many of the scientific advantages available today. They could not draw upon multiple international climate science assessments[2–4] and many thousands of relevant peer-reviewed scientific papers. They did not have the benefit of four decades of satellite measurements of global changes in climate[5], land and ocean surface temperature datasets spanning more than 120 years[6], and retrospective "reanalyses" produced by weather forecast models. There were no large multi-model ensembles of climate simulations with human-caused changes in well-mixed greenhouse gases (GHGs), ozone-depleting substances, and particulate pollution[2–4]. They did not have access to sophisticated three-dimensional numerical models of the coupled atmosphere and ocean circulation, with detailed representation of sea-ice, atmospheric chemistry, the land biosphere, and the global carbon cycle. Model and observational estimates of natural climate variability on multi-decadal timescales[7] – a critical element in efforts to identify an anthropogenic global warming signal – were not widely available.

Despite these limitations, the principal findings of the Charney report have aged remarkably well. Consider, for example, the report's conclusions regarding the equilibrium global-mean temperature change for a doubling of pre-industrial atmospheric CO_2 levels: "*We estimate the most probable global warming for a doubling of CO_2 to be near $3°C$ with a probable error of $\pm 1.5°C$*". These estimates of equilibrium climate sensitivity (ECS) are still in accord with current understanding[8], 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[3,4,8]. There is also better process-level understanding of the feedbacks contributing to uncertainties in ECS[9–11].

Charney *et al.* understood that their factor of three spread in ECS was primarily related to uncertainties in feedbacks associated with clouds. They recognized that reliable assessment of the net effect of high and low cloud feedbacks would be challenging[12], and that "*trustworthy answers can only be obtained through comprehensive numerical modeling 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 foreshadowed rigorous comparisons of model cloud properties with satellite data[13]. Such comparisons ultimately led to the elucidation of robust cloud responses to greenhouse warming[14], and to the finding (in the IPCC Fifth Assessment Report in 2013) that "*the sign of the net radiative feedback due to all cloud types is... likely positive*"[9].

The Charney report devoted considerable attention to the critical role of the ocean in climate change. Charney *et al.* understood that heat uptake by the intermediate and deeper ocean would delay the eventual emergence of a human-caused warming signal from the background noise of natural variability. This delay, they wrote, meant that humanity "*...may not be given a warning until the CO_2 loading is such that an appreciable climate change is inevitable*". The report's recognition 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 of the Charney report 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.*" Further, they found that the "*associated regional climate changes so important to the assessment of socioeconomic consequences may well be significant*", but that the GCMs available in 1979 were not yet sufficiently reliable for predicting these regional changes.

In retrospect, the Charney report seems like the scientific equivalent of the handwriting on the wall. Forty years ago, some of the best minds in climate science concluded that humans were actively influencing the climate system. The members of the Ad Hoc Study Group issued a clear warning of the potentially significant socioeconomic consequences of human-caused warming. Their warning was accurate, and remains more relevant than ever.

Anniversary 2: Hasselmann's optimal detection paper

The second scientific anniversary involves a paper written by Klaus Hasselmann. In the late 1970s, Hasselmann was a Director of the Max-Planck Institute for Meteorology in Hamburg, working on such diverse topics as measuring wave spectra from space, the behavior of cosmic rays in random magnetic fields, and the ocean's role in natural climate variability.

In 1978, Hasselmann participated in a conference on "Meteorology over the Tropical Oceans". The conference proceedings were published in 1979. Hasselmann's contribution to the proceedings had no specific connection to tropical meteorology, and was entitled

"*On the signal-to-noise problem in atmospheric response studies*"[15]. This is now widely regarded as the first serious effort to provide a sound statistical framework for identifying a human-caused warming signal.

Prior to Hasselmann's 1979 paper, it was already recognized that GCM simulations yielded both "signal" and "noise" when forced by changes in atmospheric CO_2 or other external factors[16]. The signal was the climate response to the altered external factor. In the 1970s, estimates of the noise of natural internal climate variability were obtained by running an atmospheric GCM, or by performing simulations with a model of the atmosphere coupled to a simple numerical representation of the upper ocean. In the presence of this intrinsic noise, statistical methods were required to identify areas of the world where 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 the needle in a tiny corner of a large haystack (and then proceeding to search the next tiny corner), Hasselmann advocated for a more efficient search strategy, which involved examining the entire haystack simultaneously.

A second key insight from the paper was that scientists have considerable information about signals and noise. Information is available from theory, observations, and models of varying complexity. For example, changes in solar irradiance, volcanic aerosols, and greenhouse gases produce signals with different patterns, amplitudes, and frequencies[2–4,17,18]. These unique signal characteristics ("fingerprints") can be used to discriminate between different climatic influences, and to distinguish climate signals from climate noise.

Hasselmann's paper provided a statistical roadmap for many subsequent studies. These investigations identified anthropogenic fingerprints in a wide range of independently monitored observational datasets[2–4]. Ultimately, this work provided 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].

Anniversary 3: Forty years of satellite temperature data

In November 1978, Microwave Sounding Units (MSUs) on 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. By measuring at different microwave frequencies, MSU and AMSU allowed scientists to estimate global changes in tropospheric and stratospheric temperature. Forty complete years of MSU and AMSU temperature data will be available in early 2019.

This 40-year history has been characterized by scientific successes and by public and political controversies. Consider the successes first. MSU and AMSU data were essential ingredients in many 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[2–4,19].

Satellite atmospheric temperature data were also a useful test-bed for Hasselmann's signal detection strategy. They had continuous, near-global coverage[5], and results were available from multiple research groups. Because each group made different choices in processing the raw microwave emissions measured by the MSU and AMSU instruments, uncertainties in the satellite temperature retrievals could be quantified. This allowed analysts to explore the effect of data uncertainties on anthropogenic signal detection.

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[2–4,18,19]. Tropospheric warming arises primarily from fossil fuel burning and the resulting increases in atmospheric CO_2. Lower stratospheric cooling over the 40-year satellite record is mainly attributable to anthropogenic depletion of stratospheric ozone[20]. In the early 21st century, ozone levels in parts of the lower stratosphere began to recover, largely due to the phasing out of ozone-depleting substances under the Montreal Protocol. This "healing" of the ozone layer contributed to a recovery of lower stratospheric temperature in the early 21st century[20]. In the middle and upper stratosphere, however, where the direct radiative signature of increased CO_2 is clearest, stratospheric cooling continues[21].

Model projections made over 50 years ago by Manabe and Wetherald[22] are broadly consistent with this observational pattern of tropospheric warming and stratospheric cooling. The observed vertical structure of atmospheric temperature change is inconsistent with purely natural changes in the Sun's energy output, volcanic activity, or internal variability, acting either individually or in concert[18].

MSU and AMSU temperature data have also been at the center 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[19,23]. Other disputes focused on how to adjust for non-climatic artifacts arising from orbital decay and drift, instrument calibration drift, and the transition between MSU and AMSU instruments[5,19]. 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[24].

In light of the third anniversary, it is interesting to ask when a human-caused tropospheric warming signal first emerged from the background noise of natural climate variability. To answer the question, we apply a fingerprint method closely related to the approach described in Hasselmann's 1979 paper[15]. We find that an anthropogenic fingerprint of tropospheric warming is identifiable with high statistical confidence in all currently available satellite datasets (Figure 1). In two out of three datasets, fingerprint detection at a 5-sigma threshold occurs no later than 2005, only 27 years after the 1979 start date of the satellite measurements (see Supplementary Information).

Summary

The three anniversaries discussed here are not unrelated. The "zeitgeist" of 1979 was favorable for anthropogenic signal detection[25]. From the Charney report, which relied on basic theory and early climate model simulations, there was clear recognition that fossil fuel burning would yield a global warming signal. Klaus Hasselmann's 1979 paper outlined a rational approach for detecting this signal. With the inception of satellite temperature measurements, scientists began compiling some of the key data required for anthropogenic signal identification. Forty years ago, theory, early modeling results, statistical methods, and climate data started to align. This confluence of scientific understanding and hard data eventually led to the detection of a human-caused tropospheric warming signal.

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25. Popularization of the term “zeitgeist” is frequently attributed to the psychologist E. G. Boring (1886-1968), who noted that: “...ideas do not occur in a vacuum. A new idea, to be accepted or even considered, must be compatible with existing ideas. In other words, a new idea will be tolerated only if it arises within an environment that can assimilate it”. See B. R. Hergenhahn and T. Henley. *An Introduction to the History of Psychology*. Cengage Learning, Boston, 2017. 720 pages.

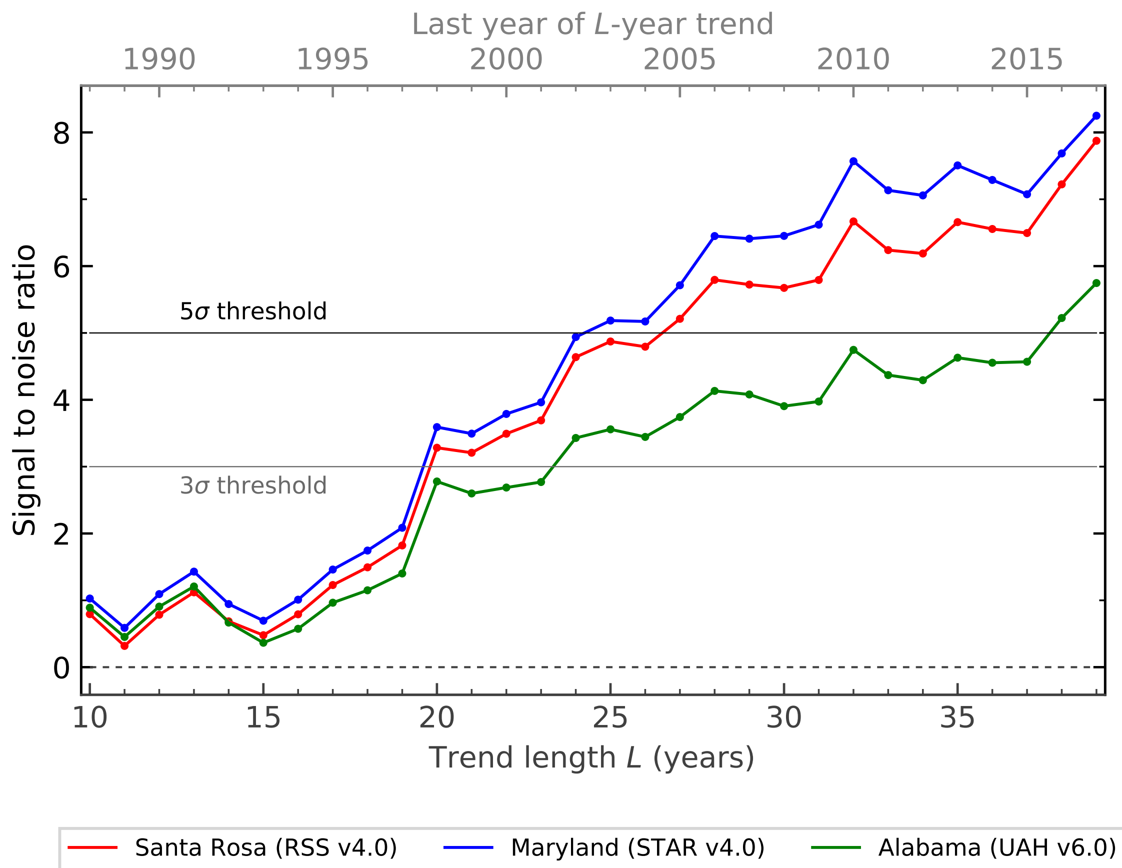

Figure 1: Signal-to-noise ratios (S/N) used for identifying a model-predicted "fingerprint" in satellite measurements of annual-mean tropospheric temperature. The fingerprint is the response to combined anthropogenic and natural external forcing, calculated using simulations of historical climate change performed with 37 different climate models. A pattern similarity metric is applied to estimate the magnitude of the fingerprint in three different time-varying satellite datasets and in long model simulations of natural internal variability. This yields "signal" and "noise" time series, respectively. For each satellite dataset, we fit L-year trends to the signal time series to obtain the numerator of the S/N ratio. The first signal trend is over the 10-year period from 1979 to 1988, the second is over the 11-year period from 1979 to 1989, and the final 39-year signal trend is over the full satellite record (1979 to 2017). The denominator of the S/N ratio is the standard deviation of the multi-model sampling distribution of non-overlapping L-year noise trends, calculated using 7200 years of temperature data from simulations of natural internal variability performed with 36 climate models. The time scale of the noise trends matches the time scale of the signal: *i.e.*, signal trends over 1979 to 1988 are compared with the standard deviation of the sampling distribution of 10-year noise trends, *etc.* The grey and black horizontal lines are the 3σ and 5σ thresholds that we use for estimating the detection time T_d. Further details of the model and observational data and the fingerprint method are provided in the Supplementary Information.

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thors and should not be construed as a position, policy, or decision of the U.S. Government, the U.S. Department of Energy, or the National Oceanic and Atmospheric Administration.