Environmental Research Letters

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Environ. Res. Lett. **6** (2011) 044025 (6pp) doi:10.1088/1748-9326/6/4/044025

Patterns of change: whose fingerprint is seen in global warming?

Gabriele Hegerl[1], Francis Zwiers[2] and Claudia Tebaldi[3]

[1] GeoSciences, University of Edinburgh, Edinburgh EH9 3JW, UK
[2] Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC, V8W 3R4, Canada
[3] Climate Central Inc., Princeton, NJ 08542, USA

Received 20 August 2011
Accepted for publication 14 November 2011
Published 7 December 2011
Online at stacks.iop.org/ERL/6/044025

Abstract
Attributing observed climate change to causes is challenging. This letter communicates the physical arguments used in attribution, and the statistical methods applied to explore to what extent different possible causes can be used to explain the recent climate records. The methods use fingerprints of climate change that are identified on the basis of the physics governing our climate system, and through the use of climate model experiments. These fingerprints characterize the geographical and vertical pattern of the expected changes caused by external influences, for example, greenhouse gas increases and changes in solar radiation, taking also into account how these forcings and their effects vary over time. These time–space fingerprints can be used to discriminate between observed climate changes caused by different external factors. Attribution assessments necessarily take the natural variability of the climate system into account as well, evaluating whether an observed change can be explained in terms of this internal variability alone, and estimating the contribution of this source of variability to the observed change. Hence the assessment that a large part of the observed recent warming is anthropogenic is based on a rigorous quantitative analysis of these joint drivers and their effects, and proceeds through a much more comprehensive and layered analysis than a comparison at face value of model simulations with observations.

Keywords: climate change, causes of climate change, climate variability, detection and attribution

Scientific evidence from a wide array of independent observations, including increases in global surface and tropospheric air and ocean temperatures, widespread retreat of snow and ice and rising global average sea levels [1, 2] lead to the conclusion that 'warming of the climate system is unequivocal' [1]. Findings based directly on observations are relatively easy to communicate but explaining why the warming is happening poses a more complex challenge. The assessment [3] that 'most of the observed increase in global average temperatures since the mid-20th century is very likely (>90% probability) due to the observed increase in anthropogenic greenhouse gas concentrations' is often misunderstood. What is the rationale for the >90% number? To what extent have alternative explanations been considered? What uncertainties in modelling the 20th century climate, for example, have been addressed? Here we answer such questions in a manner that we hope will be broadly understandable by non-specialists.

A number of factors can contribute to variations in climate. The climate system generates local and regional variations internally, which we experience as weather and as phenomena such as El Niño that may last months or seasons, or, in the case of other modes of variability, sometimes decades or longer. Examples of slower varying phenomena of climate variability are the Atlantic multidecadal oscillation [4, 5] or the Pacific decadal oscillation [6]. But climate also varies in response to factors external to the climate system that affect the balance between the incoming energy from the sun and the outgoing energy (heat) that the Earth radiates back to space. Over the 20th century, such changes in the energy balance have been substantial, both due to human and natural effects. The amount of solar energy coming into the

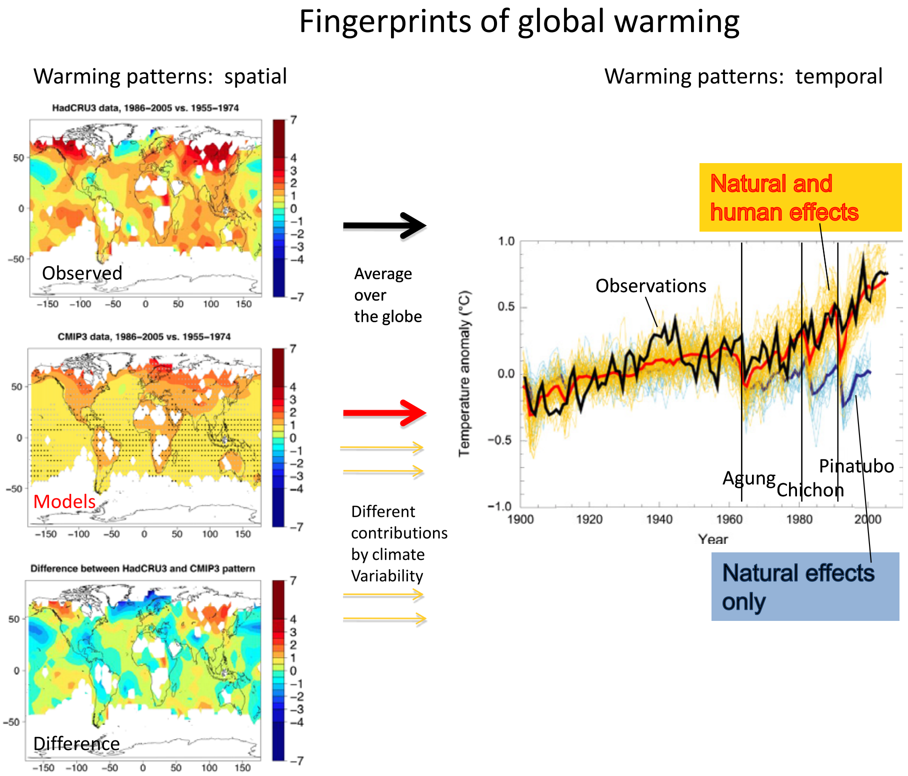

Figure 1. Fingerprints of global warming. (Left) Relative patterns of annually averaged warming (normalized to one for the globe) from the differences in 20 yr average temperatures for 1986–2005 and 1955–74. The top panel shows results from the HadCRUT3 instrumental temperature record [12]. White indicates regions where sufficient observations are not available. The middle panel shows results from the ensemble of 51 simulations from 22 different climate models driven with external forcing including human-induced forcing (greenhouse gas and aerosol changes). Dark stippling is used to indicate grid boxes in which 90% of simulations show a statistically significant increase in surface air temperature at the 5% significance level. Grey stippling is used to indicate grid boxes in which 66–89% of simulations show a statistically significant increase. Note that the climate model average is a mean of many simulations, and thus is expected to be much smoother spatially than the observed change. The bottom panel shows the difference of the two panels above it, as a simplified representation of the portion of the observed pattern driven by natural internally generated variability. (Right) Global average warming since 1900 (°C, relative to the 1901–50 average) from the same observational data, (black; not normalized), and from a suite of climate model simulations that include both human and natural forcing (orange) and natural forcing only (blue). Individual model simulations are shown by thin lines, while their average is indicated by a thick line. Note the effects of strong volcanic eruptions, marked by vertical bars. The effect of natural variability is visible in the behaviour of each individual line relative to the multi-model mean. Patterns like these are used in the attribution of results to characterize response to individual and combined external drivers. Attribution results are based on such space–time patterns, but go far beyond visual comparisons. Adapted from [36] (left) and [3] (right); spatial patterns slightly smoothed, for more details see text.

climate system varies both over the approximately 11 yr long solar cycle and on longer timescales, although the latter is very uncertain. Explosive volcanic eruptions also affected the flow of solar energy into the climate system for short periods, by loading the stratosphere with layers of aerosol particles that reflect incoming sunlight, thus cooling the Earth [1]. Indeed, the temporary cooling observed after major volcanic eruptions is evidence that changes in the energy balance do affect the Earth's surface temperature measurably [7] (see also figure 1, right panel). In addition to these natural influences, human activity has also altered the Earth's energy balance. Greenhouse gases that accumulate in the atmosphere from human activities, such as carbon dioxide and methane, absorb some of the energy that would otherwise radiate to space, thus causing warming at the surface. The burning of fossil fuels has also added other substances in addition to greenhouse gases that influence the energy balance, such as sulfate aerosols, which are similar to those emitted by volcanic eruptions and also cause cooling by reflecting incoming sunlight.

Climate models are a useful tool for investigating how natural and human factors may have affected the mean climate [8]. Because models explicitly calculate the effect of changes in energy balance on the climate, which is the average weather, climate model simulations are meaningful far beyond the time horizon over which weather can be predicted. Climate simulations of the 20th century—in which solar output, explosive volcanic activity, greenhouse gas concentrations and other human factors (principally sulfate aerosols) evolve during the century following their historical paths based on observations and emission data—are able to reproduce the 20th century global average warming well as figure 1, right panel, indicates. This panel also shows that models cannot reproduce the warming of the past several decades when anthropogenic factors are excluded. However, the attribution of observed climate change to human influence goes far

beyond such visual comparisons. Indeed, the comparison of the absolute amount of warming obtained in models and data is not the basis for attributing observed climate change to human influences. Rather, it is temporal and spatial patterns of change (referred to as 'fingerprints') that provide key information on the causes of the observed changes.

Fingerprints used in attribution assessments are grounded in physics. It is clear, and has been observed [9], that greenhouse gas increases have reduced the efficiency with which Earth can radiate heat from the surface to space, which should increase global surface temperature. This warming effect is expected to take time to manifest itself since widespread warming of the ocean surface layers takes years, and warming of the deep ocean takes centuries [10]. Thus, we expect that past changes in global temperature should display a delayed response to changes in the Earth's energy balance. Further, physical reasoning indicates that the slow and steady warming from increasing greenhouse gases should be overlaid by the cooling effects of aerosol changes from human activity and episodic volcanic eruptions, and by the effects of changes in solar output. These time-based fingerprints (see, for example, [11]), based on physical reasoning, are indeed consistent with observed changes that can be documented through the observational record, which now extends back for more than a century (e.g., [12]) over much of the globe. Exceptions are some high latitude areas and tropical land masses, whose coverage has increased in more recent periods, but gaps remain and long-term trends are uncertain in the latter regions (thus left blank in the figure).

The temporal pattern of change in these fingerprints helps us to identify the contributions that each type of forcing has made to observed temperature changes. If nothing but the natural forcing, due to the sum of solar activity and successive large volcanic eruptions (see figure 1, right panel), had been at play over the past several decades the global climate most likely would have cooled over the second half of the 20th century, so natural forcing alone produces a temporal pattern that does not match the long-term evolution of the data. The pattern of change over time also helps to distinguish between greenhouse gas and aerosol influences. The concentration of aerosol particles in the atmosphere, and the magnitude of their effect on climate, is quite uncertain. Nevertheless, data indicate that aerosol changes collectively have had a cooling effect since pre-industrial times, offsetting a part of the warming effect from greenhouse gases. Also, observations suggest that the effect of anthropogenic aerosols has changed little since the mid-1970s, while greenhouse gases and warming have increased since that time [13]. This difference in the time-dependent fingerprints of aerosol and greenhouse gases helps to separate net cooling due to anthropogenic aerosols from greenhouse warming [14, 15], although uncertainty in the aerosol contribution remains.

Our planet's warming also has some distinctive spatial characteristics that, combined with the pattern in time described above, point towards one set of possible causes and away from others. For example, the physics of the atmosphere's radiative balance dictate that the vertical pattern of temperature change in response to greenhouse gas increases (as we move from the surface of the Earth through the different layers of its atmosphere) should consist of warming in the troposphere and cooling above it, in the stratosphere and mesosphere. Observed temperature changes over recent decades show such a vertical structure with cooling in the stratosphere and warming in the troposphere, although the rate of warming in the tropical troposphere is uncertain [16, 17]. However, changes in the brightness of the sun would warm the upper stratosphere and mesosphere as well [3, 18], which is in clear contrast with observations [3, 16].

For surface temperature, attribution focuses on the time evolving and geographical patterns of climate change observed around the globe (see figure 1, left panels). Greenhouse gas increases warm land masses faster than the oceans [19], while aerosol forcing is shorter-lived and hence has a different, and more uncertain, geographical fingerprint (e.g., [20]). Natural variations in the flow of heat into or out of the ocean would cause a different pattern of warming or cooling. Simple physical reasoning is complemented by rigorous statistical methods that are used to identify whether the fingerprints that are anticipated from climate physics are present in the observations, and to quantify their relative importance. Model simulations can be performed in which an individual external factor (greenhouse gases, aerosols, solar or volcanic influences) varies over time while all other external factors are held fixed. These simulations provide fingerprints for the individual external influences [20–22, 15]. A regression technique (called optimal fingerprinting, see [23, 24]) is then used to fit a linear combination of these model-generated fingerprints to the observed pattern of changes. This fit considers that the effect of internal variability (from weather, El Niño, etc) cannot be completely separated from fingerprints, and includes the uncertainty that this causes. The result is an assessment of which fingerprints are simultaneously present in the observations, and quantitative estimates of their contributions to the observed changes.

Figure 1 illustrates the spatial pattern of observed warming, compared to a fingerprint of the climate change expected from human and natural influences combined. The difference between both patterns is a combination of climate variability and errors in the model response to external influence. For the difference pattern shown in the figure, the strongest excursions occur in high latitudes, where highly active climate and atmospheric dynamics lead to variations in climate on all timescales [25], while in the tropics, there is generally less variability, apart from El Niño (e.g., [26] and references therein). So-called optimal fingerprint approaches account for this by putting more emphasis on aspects of the simulated change that is associated with low variability [3, 23, 24], through the use of statistical methods akin to weighted regression. The observed changes in the subtropics and tropics are particularly unusual by this measure, despite the fact that high latitude changes are larger ([26], see figure, middle panel). A range of statistical attribution analyses leads to the conclusion [3, 27] that natural forcing alone is very unlikely to explain the warming of the past fifty years, since the pattern of temperature change in time and space that is expected from solar and volcanic forcing combined does not

match the observed pattern. Moreover, the statistical analyses taken on their own would suggest that greenhouse gas forcing explains at least half the observed warming with a very high level of statistical significance.

A key reason for having high confidence in the results of fingerprinting studies is that they do not depend on the climate models simulating the amplitude of the fingerprints correctly; instead they estimate the exact amplitude from observations. Attribution estimates are thus not predicated on knowing with absolute precision the magnitude of a forcing, or whether climate models respond to a forcing with the correct amplitude. For example, if the true observed response were due to a smaller aerosol signal, balanced by a smaller greenhouse gas signal than that derived from the models, then the results from fingerprint methods would include these possibilities within their uncertainty ranges [3]. Thus, for attribution studies it does not really matter if climate model simulations of the 20th century do not fully explore the uncertainty in the magnitude of both [28]. Similarly, some optimal fingerprinting results using a separate solar signal allow for the possibility that the climate system may have a stronger response to solar forcing than obtained in models [22]. Thus, results from fingerprint methods are more robust and account for uncertainties in forcing and response more completely than the simple comparisons of model simulated and observed changes that are visualized in the right-hand panel of figure 1.

Attribution analyses rely on climate models to provide estimates of natural internal variability. Could the recent observed warming be due to natural internal fluctuations in the climate system that are much larger than those obtained from the climate models? The atmosphere moves heat from place to place (for example, in winter storms), producing a great deal of short-term local variability, and human experience of this large local and daily variability leads naturally to questions about global warming. However, while climate variability on regional scales is large and can create sustained periods of regional warming and cooling (such as those seen in the bottom panel of the figure) by shifting energy around, generating a global, long-term warming requires a net source of energy. In the absence of a source of energy, local variations of atmospheric temperature would be expected to average out globally over time. Is it possible that the added atmospheric energy, experienced as warming, may be coming from the ocean? Ocean temperatures vary in space and time, driving important regional climate fluctuations (such as during alternate phases of ENSO—the cyclical changes in Pacific ocean temperatures that include the well known El Niño events). However, observations of ocean temperatures since the middle of the 20th century show a pattern of warming that would be expected when heat is moving into the oceans from the atmosphere above, not the reverse [29, 30]. Thus, both atmosphere and ocean are warming, and without an external source it is difficult to explain a long-term change in the Earth's energy budget. Also, model simulations of internal and forced fluctuations of temperature that occur from year to year and between decades are consistent with estimates derived from observations given uncertainties [3] over the 20th century, and, if forced with changes in solar radiation and volcanic activity over the past centuries (e.g., [31]). However, the same model simulations indicate that a trend such as observed over the 20th century is exceptionally unlikely to occur by internal variability alone [3]. An assessment of the variability generated by climate models shows that models reproduce the dominant, well sampled and large-scale features of surface temperature variability quite well [32]. Some uncertainty remains in the contribution of variability and forcing to interdecadal variability in the 20th century temperatures e.g., [33]. However, models seem to simulate interdecadal variability of large-scale average temperature reasonably well also on longer timescales [31, 34], and the variability in the observations that is not explained by fingerprints is routinely compared with model variability in detection and attribution work [24]. For all of these reasons, the Intergovernmental Panel on Climate Change (IPCC) *Fourth Assessment Report* (AR4) concluded that it was 'extremely unlikely' ($<5\%$) that the global pattern of warming during the past half-century can be explained by variations generated within the climate system alone [3].

What are the primary uncertainties? Uncertainties in observations of the time and space patterns of change are estimated [12], but are subject to change as new data and improved analyses become available. We interpret these observed changes using fingerprints derived from multiple climate model simulations. The availability of different models developed by different groups increases confidence in detection and attribution results. Nevertheless, we cannot readily estimate possible errors that might be common to all model-generated fingerprints. As discussed above, these errors would be corrected by the fingerprinting method if they were to affect only the amplitude of the response—examples being an over- or underestimated aerosol forcing or transient climate response. In contrast, errors that affect the fingerprint pattern in space and time for all model simulations, on the large spatial scales considered in detection and attribution, would be more problematic. Similarly, the effects of uncertainties in the time–space pattern of some of the external forcings (aerosol sources and distribution over time, for example) cannot always be directly estimated, and we rely on sensitivity tests where the patterns are modified within estimated uncertainty and the effects of these variations are assessed. On the other hand, other proposed mechanisms do not match the suite of strong constraints provided by the observed spatial and temporal patterns of the warming; and a broad range of analyses, studying climate change across ocean, atmosphere and surface, lead to very similar conclusions. To balance this robustness against the remaining uncertainties, the IPCC AR4 author team reduced the nominal high statistical significance levels from the original studies to a likelihood of $>90\%$.

In summary, observations show that the globe has warmed. There must be a reason for that change. The distinctive spatial and temporal patterns of the observed changes have a clear interpretation in light of our knowledge of climate physics, and thus provide the basis to distinguish contributions to this warming from a range of possible

explanations. Rigorous quantitative analyses of the patterns of change in the temperature of the atmosphere and ocean observed over the past half-century, incorporating all known uncertainties in the observations, in our knowledge of climate variability, and feedbacks, underpin the assessment that most of the warming of the past fifty years is 'very likely' (more than 90% likelihood) due to anthropogenic increases in greenhouse gases.

Methods: analysis of multi-model fingerprint in the figure

Details of the temporal fingerprint on the right-hand side of figure 1 are given in [3]. Here, we briefly describe some details concerning the left-hand middle panel of the figure. This figure panel summarizes results from 51 20th century climate simulations from the CMIP3 archive that were produced with 22 Global Climate Models driven with external forcing agents including human-induced forcing (greenhouse gas and aerosol changes). Each of these simulations was extended to 2005 by appending output from the corresponding continuing A1B simulation. All simulations have been regridded to the $5^\circ \times 5^\circ$ grid of [12] prior to analysis and plotting. The GCMs used are BCCR-BCM2.0; CCCMA-CGCM3.1; CCCMA-CGCM3.1.t63; CNRM-CM3; CSIRO-MK3.0; GFDL-CM2.0; GFDL-CM2.1; GISS-AOM; GISS-MODEL-E-H; GISS-MODEL-E-R; IAP-FGOALS1.0.g; INMCM3.0; IPSL-CM4; MIROC3.2-hires; MIROC3.2-medres; MIUB-ECHO-g; MPI-ECHAM5; MRI-CGCM2.3.2a; NCAR-CCSM3.0; NCAR-PCM1; UKMO-HADCM3; UKMO-HADGEM1. Dark stippling is used to indicate grid boxes in which 90% of simulations show a statistically significant increase in surface air temperature between 1955–74 and 1986–2005 according to a one-sided difference of means test (*t*-test; see [35], page 112) conducted at the 5% significance level. Grey stippling is used to indicate grid boxes in which 66–89% of simulations show such an increase. Individual years within 20 yr periods are assumed not to be serially correlated, resulting in a test that may determine significance slightly more frequently than 5% of the time under the null hypothesis of no change if serial correlation was taken into account. Note that the statistical tests applied in fingerprint detection and attribution use samples of internal variability in climate models, and hence, differently from the test used to determine locally significant patterns in the middle panel of the figure, account for autocorrelation of climate data in space and time.

The significance of differences (bottom panel) has not been assessed at the gridbox level, as detection and attribution methods routinely assess the consistency of the entire observed residual pattern (e.g. bottom panel) with estimates of variability generated within the climate system [24].

Acknowledgments

The authors thank Susan Solomon for discussion and many helpful comments and suggestions, and David Gutzler and Mike Lemonick for helpful and constructive suggestions to earlier drafts of this manuscript, as well as two anonymous reviewers for their insightful suggestions. This work was supported by the DOE Office of Science, Office of Biological and Environmental Research (DE-SC004956), NOAA Climate Program Office and NSF (ATM-0296007).

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