23 Detection and Attribution of Climate Change and Its Impacts

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23.1 INTRODUCTION

The concept of change builds upon the assumption that some kind of constancy or repeatability naturally exists in the system of interest, and that change is a negation of such constancy. For example, one may compare some characteristic of temperature (e.g. its average, at a location of interest, regionally, or globally), for two different longer time periods, e.g. 30-year climatological standard normals. When detecting a significant difference in the distribution of temperature between the two periods, one might conclude that this temperature has differed between the two periods. This, in turn, would lead to the conclusion that something in the system has changed.

Usually, the nature of the change is of interest. For example, one might observe a trend as a continued change that occurs over time. This trend might be viewed either as a manifestation of a time-dependent deterministic component (possibly with a known underlying mechanism), or simply as a tendency in the statistical properties of the process.

Detection is the act of extraction of particular information from a larger stream of information (e.g. determination of presence or absence of a useful signal in telecommunication). It is the process of becoming aware that a change has occurred. The process of detection is germane to the work of any detective attempting to reconstruct a sequence of past events, based on whatever information is available and considered relevant.

Detection of change in a time series of observations (e.g. related to climate and its impacts) means demonstrating that a system has changed in some statistical sense, i.e. that an observed change is unusual, significantly different from what can be explained by natural internal variability. Detection itself does not identify a cause for the change.

Detectability, i.e. the possibility of detecting a change depends on signal-to-noise ratio, and the relative size of the trend *versus* any natural variability (amplitude and duration of change). It may not be possible to detect a weak signal amidst a strong natural variability.

Usually trends of simple shape (linear, low-order polynomial, piecewise linear, i.e. broken line, exponential, etc.) are considered. Different trend shapes are possible, including steeper trends similar to abrupt step-like changes. There is a continuum of cases and, in practice, the terms “trend” and “change” can be almost interchangeable. One can also speak of trends in a non-parametric, comparative sense; e.g. an increasing

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trend means that the values that occur later are usually higher than those that occur earlier. Even if the specific shape of the trend is unknown, it may still be called strong or weak, e.g. if the probability that a later value is higher than the earlier one is close to 1, or to 0.5, respectively. The methodology of statistical testing of change detection in flood records is reviewed in Chapter 22 of this book (Sheng Yue *et al.*, 2012).

Once a change is detected, the process of attribution of change can be carried out and can be regarded as establishing a cause–effect relationship, by assigning a cause or a source. In their review of detection and attribution of climate change and climate change impacts, Hegerl *et al.* (2010) distinguish the terms *external forcings* and *external drivers* for both climate change and climate change impact studies. The former refers to a forcing factor outside the climate system that causes a change in the climate system. Among external forcings are: volcanic eruptions, solar irradiance variations, and anthropogenic changes in atmospheric composition and land use. They can affect both climate and non-climate systems. However, since the term *forcing* is often interpreted in a broader sense, to describe influences in impact studies that are external to the system under study and that may or may not include climate, Hegerl *et al.* (2010) proposed the term *external driver* to indicate any external forcing factor outside the system of interest that causes a change in the system. Changes in climate can thus act as external drivers on other systems. A *confounding factor* is one that affects the variable or system of interest but is not explicitly accounted for in the design of a study. It indeed confounds the analysis and may lead to erroneous conclusions about cause–effect relationships.

Attribution involves comparison of observed changes in the variable of interest with expected changes due to external forcings and drivers (derived, for example, from modelling approaches). Following Hegerl *et al.* (2010), climate change attribution can be understood as demonstration that the detected change of the variable of interest (e.g. temperature) is consistent with a combination of external forcings (e.g. volcanic eruptions, solar irradiance variations, and anthropogenic changes in atmospheric composition and land use). Attribution is further supported if the observed change is not consistent with alternative, physically-plausible explanations that exclude important elements of the given combination of forcings.

Santer *et al.* (2006) states that detection of climate change is analogous to detecting a person's fever by measuring her or his body temperature, while the attribution is analogous to diagnosing the cause of the fever through a set of medical tests.

Here we review different facets of detection and attribution of climate change, e.g. change in temperature (described by various indices: e.g. annual mean, maximum, minimum, seasonal mean, seasonal amplitude, diurnal amplitude, temperature records), precipitation, wind speed, etc.; and climate change impacts. Particular reference will be given to temperature change, where attribution is most straightforward.

23.2 ATTRIBUTION OF GLOBAL WARMING IN A MULTI-FACTOR CONTEXT

Atmospheric warming currently occurs at different spatial scales, including globally. It is unabated and unequivocal (IPCC, 2007). This trend is evident, for example, from observations of air temperature, which show clear increase at a range of scales, from local, *via* regional, to continental, hemispheric, and global. The updated 100-year linear trend (1906–2005), based on CRU UEA data, reflects a 0.74°C (0.56 to 0.92°C) global mean near-surface atmospheric temperature increase, while global warming rates over the periods 1956–2005 and 1981–2005 were much stronger (0.128°C/decade and 0.177°C/decade, respectively). That is, the global warming rate over the 25-year period was more than 2.4 times faster than it was over the 100 years (IPCC, 2007).

Figure 1 illustrates the global temperature anomaly, based on NASA GISS data and analyses. According to these, the year 2010 tied (even slightly surpassed) 2005 (http://www.giss.nasa.gov/research/news/20110112/) as globally the warmest year in the instrumental, thermometer-based, record extending since 1880, despite the cold La Niña phase continuing from early summer of 2010 (until the end of 2010 and into 2011), and low sunspot numbers.

The very warm year 1998 (with strong El Niño) was a positive outlier (warmer than the value corresponding to the long-term trend). Like many others, Zorita *et al.* (2008) assessed that the observed clustering of globally warm years would be very unlikely to occur by chance in a stationary climate. Figure 1 also shows that expecting a smooth (monotonic) increase of temperatures would be futile, in view of the strong natural variability.

One can illustrate the warming at thousands of individual stations, worldwide. Figure 2 presents the mean annual temperature observed at one of the long-running stations, Potsdam in Germany, that provides a continuous series since 1893 of high-quality daily data. The diagram shows a clear increasing temperature trend (Fig. 2), and the rate of increase grows with time. The slope of the regression line for the recent 25 years (1984–2008) was 0.55°C/decade, that is nearly twice as strong as during the 50 years (1959–2008) (0.3°C/decade), and five times stronger than for the 100 years (1909–2008) (0.11°C/decade) (Kundzewicz & Huang, 2010). However, it should be noted that shifting the time horizons of concern in Fig. 2 changes the results. The recent acceleration of warming in Potsdam is much stronger than the global average, but it also shows that the quasi-periodical oscillations have been very marked, as individual years may fall distinctly below or rise much above the trend line. For instance, 1934 was a very warm year and 1940 was a very cold year in Potsdam. For either of these years, the deviations from the trend were high. Comparison of Figs 1 and 2 shows that the behaviour of annual temperature in Potsdam differs greatly from

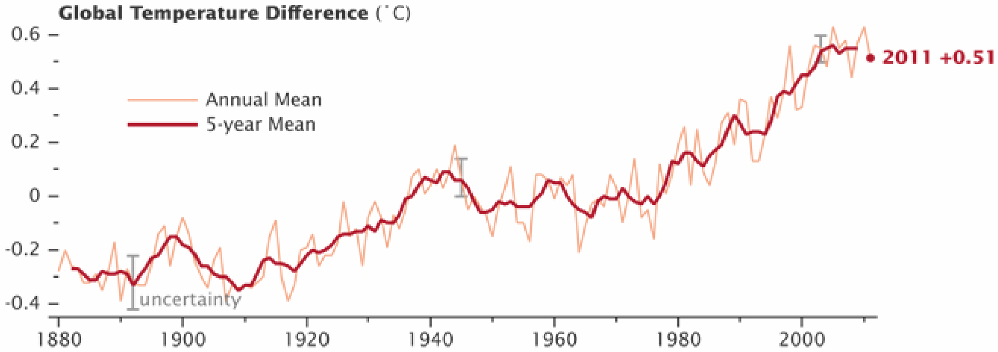

Fig. 1 *Global temperature anomaly 1880–2011. Source: GISS (NASA), http://www.giss.nasa.gov/research/news/20120119/616910main_gisstemp_2011_graph_lrg%5B1%5D.jpg.*

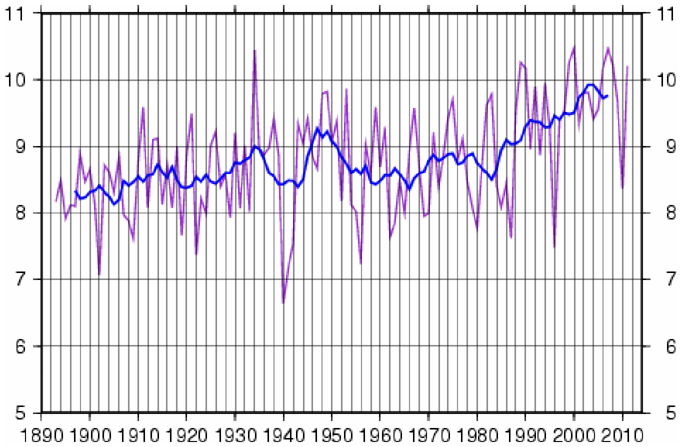

***Fig. 2** Mean annual temperature in Potsdam (Germany) 1893–2011. Source: Säkularstation Potsdam Telegrafenberg, www.klima-potsdam.de.*

the global diagram. For instance, 2010, globally the warmest year, was not a record warm year in Potsdam. Nevertheless, summer 2010 was the warmest on record at the European continental scale (Barriopedro *et al.*, 2011)

Once a warming is detected, it is natural to state the problem of attribution. The mean global temperature of our planet has changed many times in the Earth's history – there have been many warmer and many colder intervals. Possible causes of climate change (cf. Fig. 3) can be divided into five groups:

(a) changes in the solar irradiance (illustrated by sunspot numbers);

(b) changes in orbital parameters (time scale of tens of millennia so irrelevant to the present climate change occurring on a time scale of decades);

(c) changes in the composition of the Earth's atmosphere – greenhouse gases (water vapour, carbon dioxide, methane and nitrous oxide), aerosols and dust;

(d) changes in the properties of the Earth's surface (albedo, vegetation, permeability, water storage); and

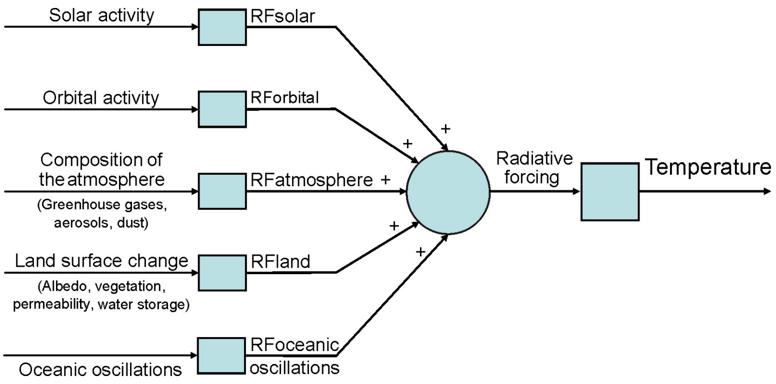

***Fig. 3** Temperature is driven by a sum of radiative forcings (RFs).*

(e) oceanic oscillations, i.e. quasi-periodic change of processes of ocean heat intake and heat release.

The mechanisms (a), (b) and (e) above are purely natural and humankind probably has no influence on them. Variability of temperature indices, at various spatial scales, can be also partly explained by the natural oscillations (cf. (e)) in the ocean and atmosphere systems (such as ENSO – El Niño Southern Oscillation, NAO – North Atlantic Oscillation, AMO – Atlantic Multi-decadal Oscillation). Mechanisms (c) and (d) illustrated in Fig. 3 can be influenced by both natural and anthropogenic factors.

Climate change attribution statements play a very important role in the assessments of the Intergovernmental Panel on Climate Change (IPCC). The essential statements in each of the four assessment reports of IPCC have evolved. In 1990, the First Assessment Report of IPCC (FAR) reported "*little evidence of detectable anthropogenic influence on climate*". In 1995, the Second Assessment Report (SAR) noted a "*discernible human influence on climate*". In the light of accumulated evidence gathered in the periods from the second to the third report and from the third to the fourth, the attribution statements were stronger in the last two reports. In 2001, the Third Assessment Report (TAR) stated that "*most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations*", while in 2007, the Fourth Assessment Report (AR4) conveyed the message that "*most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations*". The qualifiers "likely" and "very likely" in the last two statements were defined to correspond to the probability in excess of 66% and 90%, respectively.

Human activities have changed the chemical composition of the atmosphere, and have had an identifiable effect on global climate. Many different "fingerprint" studies show that observed climate changes over the past 50 years cannot be explained by natural factors alone. Certainly, unequivocal attribution would require active (controlled) experiments with multiple copies of the climate system, which is not possible. Therefore, recourse to mathematical modelling is needed and attribution can only be done within some margin of error.

Attribution of recent climate change is an effort to scientifically explain the cause of changes observed recently in the Earth's climate. Attribution has particularly focused on changes observed during the period of instrumental temperature record, when records cover the whole globe and are most reliable. Over the last several decades, human activity has grown fastest and observations of the upper atmosphere have also become available. The dominant mechanisms to which recent climate change has been attributed all result from human activity. They are:

(a) increasing atmospheric concentrations of greenhouse gases (GHG) enhancing warming potential;
(b) global changes to land surface, such as deforestation (enhancing warming potential);
(c) changing atmospheric concentrations of aerosols (exerting a cooling effect).

Over the past century, human activities have released increasing quantities of greenhouse gases into the atmosphere. The natural range of the atmospheric concentration of carbon dioxide over the last 650 000 years, as determined from ice cores, was from 180 to 300 ppm. Hence, recent atmospheric carbon dioxide concentrations, for Mauna Loa (where since 1958 the longest direct observation record of atmospheric CO_2 concentrations exists in proxy baseline conditions) with annual minimum near to 389 ppm and maximum exceeding 394 ppm (Fig. 4), are far beyond the upper limit of the historical range. Isotopic analysis of atmospheric CO_2 confirms that indeed fossil fuel burning is the source of most of the CO_2 increase, unlike during prior interglacial periods. Fossil fuels accumulated over the geological time scale are being burnt now, within decades. The recent annual CO_2 concentration growth rate is high, although there has been a considerable year-to-year variability in growth rates (Fig. 4).

Carbon dioxide has been identified as the dominant greenhouse gas forcing, even if its abundance in the atmosphere is lower in comparison to water vapour, the dominant greenhouse gas overall. However, water vapour has a very short atmospheric lifetime (approx. 8 days) and is nearly in a dynamic equilibrium. Methane and nitrous oxide and some anthropogenic gases, such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6), also contribute to radiative forcing and to the intensification of the natural greenhouse effect.

A part of climate change is also attributed to land use. While most of the anthropogenic increase in CO_2 concentrations over the last 250 years has likely resulted from burning fossil fuels, a part stems from changes in land use, primarily deforestation, that reduced carbon dioxide sequestration and released carbon dioxide directly through biomass burning. Also, certain changes in terrestrial albedo, influencing radiative forcing, in addition to being driven by the extent of snow and ice, are driven by land use (e.g. deforestation, urbanization, constructing large artificial water reservoirs) and, locally, these effects can be very strong.

Aerosols, small particles or droplets suspended in the atmosphere, are also responsible for temperature change. They counteract the GHG-driven warming by exerting some cooling effect, e.g. in such regions as South Asia (albeit the net result of anthropogenic temperature change remains warming).

It is unlikely that a rapid warming of the 20th century can be explained by natural variability (Hegerl *et al.*, 2007). The summary of scientific understanding of changes in radiative forcing of climate in the last two and half centuries, introduced by IPCC, is presented in Fig. 5.

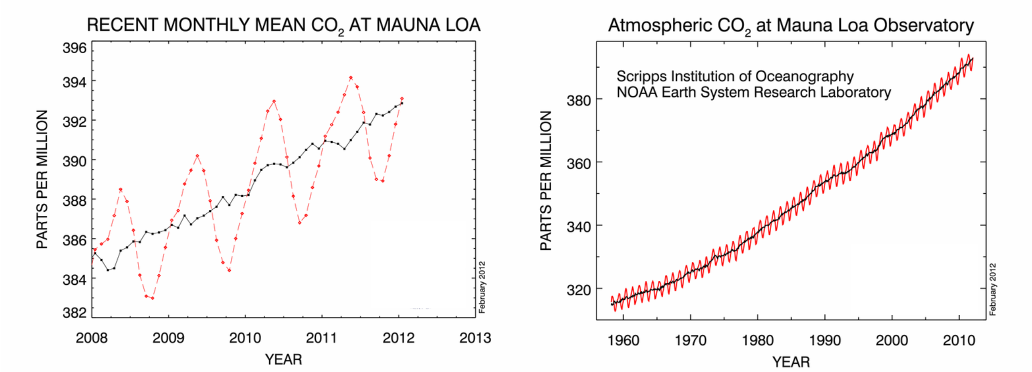

Fig. 4 *Carbon dioxide concentration at Mauna Loa (1959–2012). Source ESRL (NOAA), http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html.*

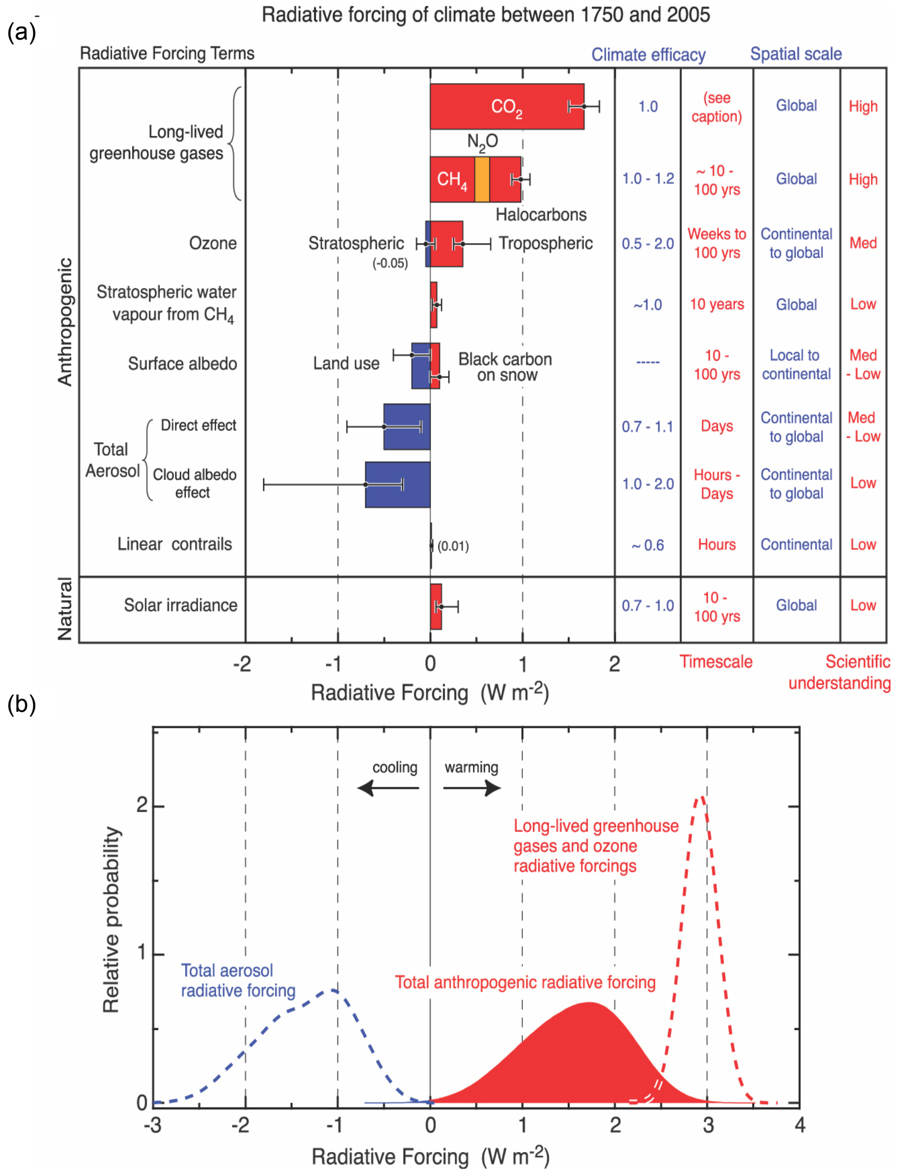

Fig. 5 *(a) Global mean radiative forcings (RF) of climate between 1750 and 2005, from various agents and mechanisms, grouped by agent type. Columns indicate climate efficacies and time scales represent the length of time that a given RF term would persist in the atmosphere after the associated emissions and changes ceased. No CO_2 time scale is given, as its removal from the atmosphere involves a range of processes that can span long time scales, and thus cannot be expressed accurately with a narrow range of lifetime values. (b) Probability distribution functions (PDFs) from combining anthropogenic radiative forcings in (a). Three cases are shown: the total of all anthropogenic RF terms (red filled curve); LLGHGs and ozone RFs only (dashed red curve); and aerosol direct and cloud albedo RFs only (dashed line). For details, see Forster et al., 2007, Fig. 2.20 and accompanying material.*

23.3 CONTROVERSY ABOUT DETECTION AND ATTRIBUTION OF CLIMATE CHANGE

Attribution studies to date have focused overwhelmingly on large-scale (global) temperature changes, with continental and regional scale being of increasing interest. Meehl *et al.* (2004) and IPCC (2007) showed that global climate models are able to reconstruct the historical temperature record (Fig. 6). This allows us to decompose the associated temperature changes into various forcing factors, such as greenhouse gases, man-made sulfate emissions, solar variability, ozone changes – both stratospheric and tropospheric, and volcanic emissions, including natural sulfates. The lack of warming from the 1940s to the 1960s, clearly visible in Figs 1 and 6, can be attributed largely to sulfate aerosol cooling.

However, some controversy remains about detection and attribution of climate change to anthropogenic forcing, and of climate change impacts to anthropogenic climate change. The principal problem is the complexity and multiplicity of contributing factors. Some effects could be achieved in a number of different ways, so that identification of the combination of factors responsible for change may not be unique.

Furthermore, despite progress with the development of climate models, there are still limitations to them. The climate models (AOGCMs, i.e. Atmosphere–Ocean General Circulation Models) available today cannot reconstruct all details of the temperature series of the 20th century. Reproducing broad-scale features of observed temperature (Fig. 7) has nevertheless been interpreted as a considerable success, since earlier models could not achieve such accuracy.

A message conveyed by Fig. 7, for example, is that natural climate forcings alone (sun and volcanoes) do not explain the warming observed in the last decades. A key interest in the successful simulation of historical climate changes is that confidence in projections for the future from the same models is enhanced.

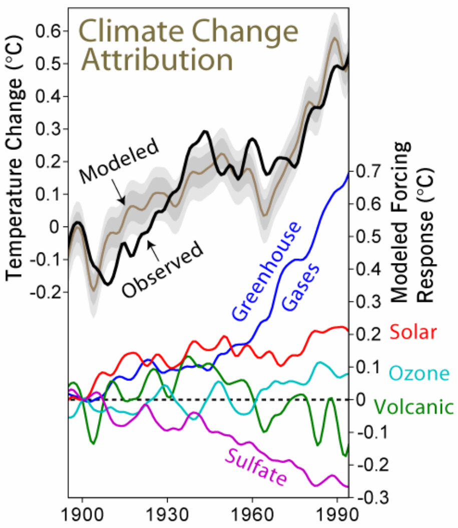

Fig. 6 *Climate change attribution to the main different drivers (reproduced from http://en.wikipedia.org/wiki/File:Climate_Change_Attribution.png).*

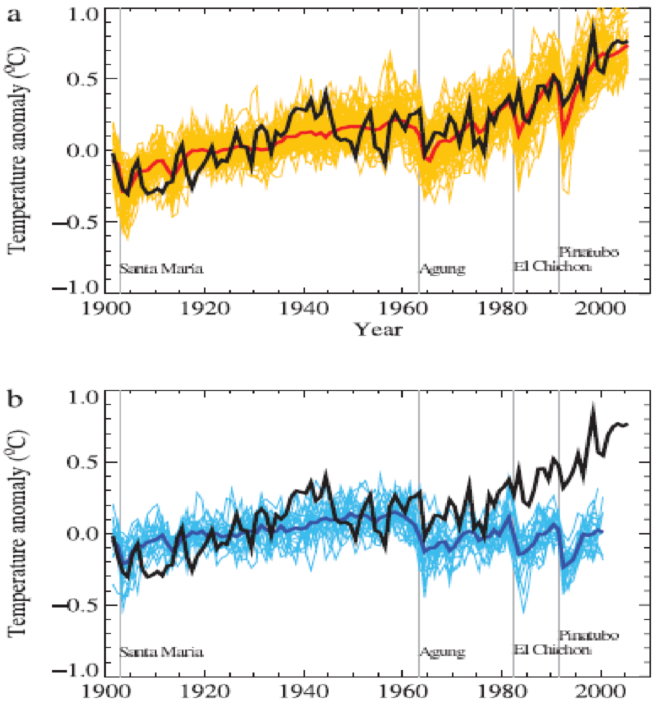

Fig. 7 *Comparison between global mean surface temperature anomalies (°C) from observations (black) and AOGCM simulations forced with (a) both anthropogenic and natural forcings and (b) natural forcings only. All data are shown as global mean temperature anomalies relative to the period 1901 to 1950, as observed (black, Hadley Centre/Climatic Research Unit gridded surface temperature data set (HadCRUT3)) and, in (a) as obtained from 58 simulations produced by 14 models with both anthropogenic and natural forcings. The multi-model ensemble mean is shown as a thick red curve and individual simulations are shown as thin yellow curves. Vertical grey lines indicate the timing of major volcanic events. The multi-model ensemble mean is shown as a thick blue curve and individual simulations are shown as thin blue curves. For details, see Hegerl et al. (2007), Fig. 9.5.*

A particular limitation to global detection studies is the reliability of the underlying climate data. One might have thought that there should be no disagreement about the interpretation of thousands of long time series of temperature records from thermometers worldwide. The uneven distribution of temperature records necessitates careful analysis during the spatial averaging for the global mean. Due to minor differences in the methods applied, even the rankings of globally warmest years, estimated by competing institutions differ.

23.4 DETECTION AND ATTRIBUTION OF CLIMATE CHANGE IMPACTS

The growing emissions of greenhouse gases and the on-going change of the land surface affect, through the changing climate, many natural systems and almost every aspect of human life on Earth. Yet, the direct attribution of observed changes ("impacts") to these global changes is difficult, due to the indirect linkage between force and effect.

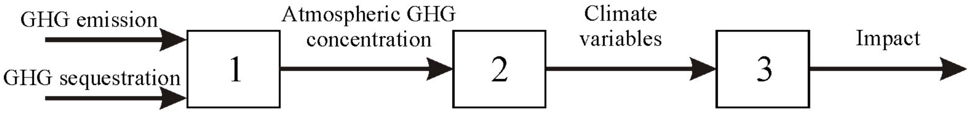

***Fig. 8** Structure of the process of attribution of climate change impacts.*

The different steps to systematic attribution of climate change and its impacts are illustrated in Fig. 8. The three blocks there represent the following transfer functions:

1. from emission and sequestration of greenhouse gases to atmospheric greenhouse gas concentration;
2. from GHG concentrations to climate variables (temperature, precipitation, etc.); and finally
3. from climate variables to climate change impacts.

Hegerl *et al.* (2010) distinguish two basic approaches to the attribution of climate change and its impacts: single-step attribution (direct attribution) and multi-step attribution (joint attribution). Direct attribution comprises assessments that attribute an observed change within a system to an external forcing (external driver) based on explicit modelling of the response of the variable to external forcings and drivers (Hegerl *et al*., 2010). In direct attribution, the affected system and its interaction with climate are relatively well understood and can therefore be modelled mathematically.

Joint (multi-stage) attribution is usually required for climate change impact assessments, comprising the attribution of an observed change in a variable of interest to a change in climate conditions (climate variables), the change in climate conditions being then separately attributed to external forcings and drivers (Hegerl *et al*., 2010). The assessment of the link between climate and the variable of interest, represented as block (3) in Fig. 8, may involve a statistical approach or a process model, for example. The quality of the overall assessment will generally echo the weakest link in the chain.

For some types of impacts, such as those involving biological systems, there are fairly direct links between temperature and processes and variables. For instance, chemical reaction rate (assumming no restrictions on availability of reagents and catalyst) is an increasing function of temperature. Hence, if human activities are responsible for increase in temperature then they must be assumed to also be responsible for increase in reaction rate. The assessment is then based on process knowledge and can be the final step in joint attribution or a standalone tool to address climate impacts on a variable of interest.

Using multi-step attribution, climate change impacts have been linked to regional warming for numerous physical and biological systems, such as the cryosphere (retreating Arctic Sea ice, the melting Greenland ice sheet, loss of permafrost, changing mass balance of many mountain glaciers, reduced snow cover, calving ice shelves, reduced lake and river ice); the hydrosphere (soil moisture, river flow); coastal erosion; sea level rise; and the biosphere (enhanced growing season, changing phenology, behaviour of migratory birds, etc.). The recent five consecutive years: 2007–2011 are the years with lowest summer (September) Arctic Sea ice extent ever observed. These impacts of regional warming (and many others) are therefore attributed, to a large extent, to increasing anthropogenic greenhouse gas concentrations. For example, Gillett *et al.* (2004) attributed change in forest fires (examining fire season temperature *versus* area burnt). De'ath *et al.* (2009) made a two-stage attribution for declining coral calcification (CO_2 to pH of oceanic water, and pH to calcification). Rosenzweig *et al.* (2008) examined associated patterns attributing changes in physical and biological systems.

Some impacts of increasing greenhouse gases are not due to temperature change. For instance, changes in marine calcification are attributed to changes in ocean chemistry, which is – in a separate step – attributed to changes in atmospheric carbon dioxide. A direct fertilization effect on plants, which in turn affects the hydrological cycle, including river flow, results from greater atmospheric concentrations of carbon dioxide.

In the case of weather and climate extremes and other rare events, attribution to anthropogenic forcing is complicated by the fact that any such event might have occurred by chance in an unmodified climate. Therefore, there cannot be direct evidence that occurrence of a particular extreme event such as a flood has been caused by climate change, but it can be stated that the frequency of occurrence of such an event has changed with climate change. Such a change in the frequency of extreme weather events may not be detectable (as the sample of truly large extremes is small), but one can look at the risk of the event occurring, rather than the occurrence of the event itself. For example, human-induced changes in mean temperature have been shown to increase the likelihood of extreme heat waves, such as the record-breaking 2003 event in Europe (Schär *et al.*, 2004), the 2010 heat wave in Russia (Rahmstorf & Coumou, 2011), or the 2000 flood in the UK (Pall *et al.*, 2011).

As summarized by Hegerl *et al.* (2007), scientists reporting on attribution studies should clearly state the causal factor(s) to which a particular change is being attributed, and should identify whether the attribution in question concerns a response to a change in climate and/or environmental conditions and/or other external drivers and forcings. Confidence in assessments grows when attribution of change to a causal factor is robustly quantified and when there is extensive process knowledge, so that the link between changes in climatic variables and in impacts is well understood.

Mathematical models can be used and are being used in attribution, but the models' ability to properly represent the relevant causal link should be assessed. This should include an assessment of model biases and the model's ability to capture the relevant processes and scales of interest. Models should be thoroughly validated (e.g. via a split-sample technique). Confidence in attribution is influenced by the extent to which the study considers other possible external forcings and drivers, confounding factors and also observational data limitations. It is important to reveal full information on sources of data, steps and methods of data processing, and sources and processing of model results for transparency and reproducibility.

23.5 CONCLUDING REMARKS

There is considerable and understandable interest in detection and attribution of changes. Policy makers and the wider public want to know the detail of observed climate change and to understand why it happens. The answer to the latter question undoubtedly would influence decisions on climate change mitigation. Credible attribution will likely demonstrate the need to massively enhance efforts to reduce greenhouse gas emissions. However, the existence of multiple factors and strong natural internal variability (including multi-decadal climate fluctuations) make it difficult to attribute changes in a unique way.

Detection is answering the question of whether change in a variable is larger than could have been produced randomly by internal variability alone. The warming is ubiquitous and evident from observations of the Earth's surface (at global, continental and sub-continental scales), in oceans and in the atmosphere, while non-anthropogenic forcing would likely have produced cooling. Some of the anthropogenic warming is offset by anthropogenic aerosols. Anthropogenic impact is now apparent in other variables, not only temperature.

An individual extreme event cannot be attributed to climate change, but it may be fair to state that the odds of its occurrence may change (in many cases – increase) in the changing (warming) climate, while most of the climate change results from anthropogenic activities.

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