INTERGOVERNMENTAL PANEL ON climate change

Working Group I (WG I) – The Physical Science Basis

IPCC Expert Meeting on Detection and Attribution Related to Anthropogenic Climate Change

The World Meteorological Organization
Geneva, Switzerland
14-16 September 2009

Good Practice Guidance Paper on Detection and Attribution Related to Anthropogenic Climate Change

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The Good Practice Guidance Paper is the agreed product of the IPCC Expert Meeting on Detection and Attribution Related to Anthropogenic Climate Change and is part of the Meeting Report.

This meeting was agreed in advance as part of the IPCC workplan, but this does not imply working group or panel endorsement or approval of the proceedings or any recommendations or conclusions contained herein.

Supporting material prepared for consideration by the Intergovernmental Panel on Climate Change. This material has not been subjected to formal IPCC review processes.

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Citation: Hegerl, G.C., O. Hoegh-Guldberg, G. Casassa, M.P. Hoerling, R.S. Kovats, C. Parmesan, D.W. Pierce, P.A. Stott, 2010: Good Practice Guidance Paper on Detection and Attribution Related to Anthropogenic Climate Change. In: *Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Detection and Attribution of Anthropogenic Climate Change* [Stocker, T.F., C.B. Field, D. Qin, V. Barros, G.-K. Plattner, M. Tignor, P.M. Midgley, and K.L. Ebi (eds.)]. IPCC Working Group I Technical Support Unit, University of Bern, Bern, Switzerland.

Executive Summary

The reliable detection and attribution of changes in climate, and their effects, is fundamental to our understanding of the scientific basis of climate change and in enabling decision makers to manage climate-related risk. This paper summarises the discussions and conclusions of the joint Expert Meeting of Working Group I and Working Group II of the Intergovernmental Panel on Climate Change (IPCC WGI/WGII) on *"Detection and Attribution related to Anthropogenic Climate Change"*, which was held in Geneva, Switzerland on 14-16 September 2009. It seeks to clarify methods, definitions and terminology across the two working groups and is intended as a guide for future IPCC Lead Authors. This paper also outlines guidelines for how to assess the relative quality of studies and provides recommendations for good practice in detection and attribution studies. In this respect, it discusses criteria for assessing confidence, outlines data requirements and addresses methods for handling confounding factors.

1. Definitions

This document uses the terms ***external forcing*** and ***external drivers*** in specific ways. *External forcing* refers to a forcing factor outside the climate system that causes a change in the climate system. Volcanic eruptions, solar variations, anthropogenic changes in atmospheric composition and land-use are examples of external forcing that can affect both climate and non-climate systems. In the WGII community, *forcing* often refers to a wider set of influences in impact studies that are external to the system under study and that may or may not include climate. However, to avoid circular definitions within WGI, the term external forcing in this document is limited to the above definition from the glossary of the Synthesis Report of the IPCC's Fourth Assessment Report (AR4). We use the term *external driver* as a broader term 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 (e.g., the reduction of sea ice might act as an external driver on polar bear populations). 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. This definition may be narrower than the terminology used in some impact studies, but is used here to distinguish *confounding factors* from external drivers. Confounding factors could therefore lead to erroneous conclusions about cause-effect relationships. Examples of confounding factors are presented in Section 4.2.

Discussion of the definitions of the fundamental terms ***detection*** and ***attribution*** resulted in minor modifications to definitions used in AR4 to ensure that these terms can be used across the two working groups. *Detection* of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, <10%. *Attribution* is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with an assignment of statistical confidence. The process of attribution requires the detection of a change in the observed variable or closely associated variables, with the latter case being outlined in Section 2, Method II.

2. Methods

To ensure a robust and consistent assessment of attribution results in WGI and WGII of the IPCC's Fifth Assessment Report (AR5), there is a need to clarify the different approaches to attribution of observed changes to specified causes that have been followed in a range of studies. It is also necessary that WGI and WGII be consistent in their use of 'uncertainty terminology' and in their assessment of confidence levels.

Attribution seeks to determine whether a specified set of external forcings and/or drivers are the cause of an observed change in a specific system. For example, increased greenhouse gas concentrations may be a forcing for an observed change in the climate system. In turn, changed climate may be an external driver on crop yields or glacier mass.

The following is a list of attribution approaches that are found in the literature. This list is not meant to be exhaustive but rather to relate the main approaches found in the literature to a specific terminology. The aim is to enable clarity and consistency between the two WGs when assessing attribution results. All methods assume that the definitions of detection and attribution are as outlined above. It is also important to note that the final method (Method IV, Attribution to a Change in Climatic Conditions) is distinct from the other methods in that it addresses the link between impacts and climate as driver, as opposed to the first three methods which address attribution of impacts or climate change to external forcing, including greenhouse gas increases.

Boxes give examples where a method has been applied to a particular problem. The same problem may have been addressed by a different method, and boundaries between methods are not necessarily always clear-cut.

I. Single-Step Attribution to External Forcings

This method comprises assessments that attribute an observed change within a system to an external forcing based on explicitly modelling the response of the variable to external forcings and drivers. Modelling can involve a single comprehensive model or a sequence of models. The attribution step involves detection of a significant change in the variable of interest and comparison of observed changes in the variable of interest with expected changes due to external forcings and drivers (typically derived from modelling approaches). [Box 2.1]

II. Multi-Step Attribution to External Forcings

This method comprises assessments that attribute an observed change in a variable of interest to a change in climate and/or environmental conditions, plus separate assessments that attribute the change in climate and/or environmental conditions to external drivers and external forcings. An example would be the multi-step attribution of declining marine calcification to rising atmospheric carbon dioxide (i.e., changes in marine calcification are attributed to changes in ocean chemistry, which is in a separate step attributed to changes in atmospheric carbon dioxide; see Box 2.2). In the case of climate extremes and rare events, for example, it may not always be possible to reliably estimate from observations whether there has been a change in frequency or intensity of a given type of event. Nevertheless, it may still be possible to make a multi-step attribution assessment of an indirectly estimated change in the likelihood of such an event, if there is a detectable change in climatic conditions that are tightly linked to the probability of that event (for example, a change in the frequency of rare heatwaves may not be detectable, while a detectable change in mean temperatures would lead to an expectation of a change in that frequency). Authors should clearly state when a multi-step attribution has been made.

This method involves a sequence of analyses including synthesis of observational data and model applications. The assessment of the link between climate and the variable of interest may involve a process model or a statistical link, for example, or any other downscaling tool.

It is recommended that the component assessments (or steps) be made explicitly (each with its own level of confidence) and that an overall assessment of the combined result be made. The overall assessment will generally be similar to or weaker than the weakest step. [Box 2.2]

Box 2.1: Example of Single-Step Attribution: Anthropogenic Contribution to Area Burnt by Forest Fires in Canada

Gillett et al. (2004) applied a detection analysis to the area burnt by forest fire in Canada. The authors calculated the regression coefficient of interannual variations in area burnt against regional fire season temperature. They then used this relationship to estimate anthropogenically-forced variations in 5-yr total area burnt over the 20th century by scaling simulated 5-yr mean fire season temperature from an ensemble of climate model simulations with anthropogenic forcing to observed changes. Internal variability in 5-yr total area burnt was estimated from observed interannual variability in area burnt. These estimates of anthropogenically-forced changes in area burnt and internal variability were used together with observed variations in 5-yr total area burnt to apply a detection analysis. The influence of anthropogenic forcing on area burnt by forest fire in Canada was detected. Natural climate forcings were not explicitly accounted for in the analysis, but other work has shown that they have not forced significant temperature trends over North America during the 20th century. The study is a single-step study, because the attribution assessment is directly performed for area burnt rather than by using climate as driver in a separate assessment. Confounding factors and data uncertainties were addressed in the following way: The main upward trend in area burnt in Canada has occurred since the advent of satellite observations, thus reporting bias is unlikely to be responsible for the trend. Lightning is the most important ignition source for forest fires in Canada, accounting for ~85% of the area burnt, and therefore changes in human ignition are unlikely to account for the upward trend. Fire suppression has increased over the period of study and on its own would be expected to have decreased area burnt.

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III. Associative Pattern Attribution to External Forcings

This method comprises a synthesis of large numbers of results (possibly across multiple systems) demonstrating the sensitivity of impacts to a change in climate conditions and other external drivers.

The link between externally forced climate change and this ensemble of results is made using spatial and temporal measures of association. [Box 2.3]

IV. Attribution to a Change in Climatic Conditions (Climate Change)

This method comprises assessments that attribute an observed change in a variable of interest to an observed change in climate conditions. The assessment is based on process knowledge and relative importance of a change in climate conditions in determining the observed effects. This method can be the final step in Multi-Step Attribution, but it can also be used stand-alone to address climate impacts on a variable of interest.

Regardless of the method used, authors should specifically state the causal factor 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 will be increased when attribution of change to a causal factor is robustly quantified and when there is firm understanding of the processes ('process knowledge') that are involved in a proposed causal link (e.g., the link between elevated temperature and declining crop yields is strengthened by understanding of the stress physiology of plants).

Box 2.2: Example of Multi-Step Attribution: Impacts of Rising Atmospheric CO_2 on Reef-Building Corals

The link between rising atmospheric carbon dioxide and the reduced calcifying abilities of reef building of tropical corals illustrates multi-step attribution to external forces. In the first step, declining pH and carbonate ion concentrations are linked to increasing atmospheric concentration of CO_2. This link has a high degree of reliability given that it is based on the laws of physics and chemistry (Kleypas et al. 1999). This relationship has been verified by field measurements that confirm the projections based on these fundamental laws. In the second step, the relationship between the carbonate ion concentration and the calcification of reef-building organisms such as corals has been established by a series of experimental studies (reviewed by Kleypas and Langdon 2006). This step has greater inherent variability than the first step given that it involves a wide range of influences, including genetic makeup and environmental history. The two steps can be verified to a degree by field measurements with a precaution that field settings often involve more than one factor (see discussion on confounding factors). For example, the recent observation by De'ath et al. (2009) of a decline in calcification across over 300 long-lived coral colonies on the Great Barrier Reef is evidence of the impact of ocean acidification, but complicated by the fact that the impact of declining carbonate ion concentrations has been accompanied by increasing sea temperatures. The two steps considered together necessarily involve a greater amount of uncertainty than that associated with each step when considered in isolation. In this specific case, the relative influence of the external drivers (warming and declining carbonate ion concentrations) should be investigated to complete the attribution process. This example is a multi-step example, as the attribution assessment is performed for acidification in a second, separate step.

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Box 2.3: Example of Associative Pattern Attribution: Anthropogenic Influence on Physical and Biological Systems

In associative pattern attribution, the spatial pattern of observed impacts is compared with observed climate trends using statistical pattern-comparison measures. For example, Rosenzweig et al. (2008) based their assessment on more than 29,000 data series (from studies with at least 20 years of data between 1970 and 2004) of significant changes in physical and biological systems outside the range of natural variability. As assessed by the studies' authors, these changes were consistent (or not) with known responses to regional temperature change and a functional understanding of the systems (e.g., thawing permafrost, poleward range shifts of animals and earlier blooming in response to warming) and were also not likely to have been substantially influenced by other driving forces such as land use change (e.g., since they were located in nature reserves). The global and continental patterns of these changes were then compared with observed temperature trends at the same scales. Global temperature trend data due to internal variability of the climate system were obtained from long control simulations with seven different climate models from the WCRP CMIP3 multi-model database at PCMDI, to represent the range of 35-year temperature trends across the globe resulting from natural climate variations. Two different pattern-comparison measures were used to compare the observed and modelled temperature trends with the observed impacts. Because the IPCC WGI concluded that most of the average temperature increases over the past 50 years are due to the observed increase in anthropogenic greenhouse gas concentrations at the global (very likely) and continental (likely) scales (IPCC, 2007), significant attribution was assigned when both spatial statistics methods yielded significantly stronger pattern agreement between observed impacts and observed temperature changes than those occurring with temperature patterns from natural climate variability, as estimated by the control simulations.

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Where models are used in attribution, a model's 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. Confidence in attribution will also be influenced by the extent to which the study considers other possible external forcings and drivers, confounding factors and also observational data limitations. Where two attribution studies are combined in a multi-step analysis, an assessment needs to be made of the extent to which the separate components of the analysis are appropriately related.

For transparency and reproducibility it is essential that all steps taken in attribution approaches are documented. This includes full information on sources of data, steps and methods of data processing, and sources and processing of model results.

3. Data and Other Requirements

When considering attribution studies and determining an assessment of the likelihood used to describe results, data availability and quality are an important consideration. The following conditions should be fulfilled to the extent possible.

- *Data biases and gaps*: Data should be carefully assessed for biases. Particularly problematic are systematic biases, such as data inhomogeneity, which should be corrected to the extent possible. An example of an inhomogeneity is that involving the systematic differences in ship-based sea surface temperature measurements introduced by the use of engine intake compared to earlier bucket measurements. It is also helpful if random biases, such as unevenness in data quality, have been addressed or if the potential influence they may have on results has been estimated. Data gaps should be assessed and appropriately handled. This may include filling data gaps utilizing further observational data, or adapting attribution methods to work with the existing observational data coverage (for example, by restricting analysis of model data to the observational coverage). Ideally, observational datasets should include estimates of remaining uncertainties, such as random sampling errors, systematic biases and uncertainties in correction of biases. Confidence levels estimated for a final attribution result should reflect underlying data quality and potential remaining data biases. In data-poor regions, it may be useful to relax these criteria, although this will lead to reduced confidence in findings.

- To avoid *selection bias* in studies, it is vital that the data are not preselected based on observed responses, but instead chosen to represent regions / phenomena / timelines in which responses are expected, based on process-understanding. Selection criteria should be clearly stated.

- *Spatial scale and temporal resolution* or coverage of data (for example, season) should be matched to the variable of interest. For detection and attribution studies, determining sensitivities of impact models to different spatial scales will help in selecting scales at which the impacts model can be driven and at which the driving climate model performs adequately. Downscaling tools (dynamical and statistical) may help to bridge the difference in scales between climate variables represented in climate models and those required for the variable of interest.

- *Estimates of the variability* internally generated within the climate system or climate-impact system are needed to establish if observed changes are detectable. It is ideal if the observational record is of sufficient length to estimate internal variability of the system that is being considered (note, however, that in most cases observations will contain both response to forcing/drivers and variability). Further estimates of internal variability can be produced from long control simulations with climate models, possibly run through an additional model (e.g., downscaling) to arrive at the variable of interest. Expert judgements or multi-model techniques may be used to incorporate as far as possible the range of variability in climate models and to assign uncertainty levels, confidence in which will need to be assessed. Paleoclimate information may be used to augment understanding of long-term internal variability in both climate and impact studies but should be of high quality and its uncertainty needs to be considered. Note also that paleoclimate data reflect internal variability and response to external forcings combined (the latter are often, but not exclusively, natural forcings).

- *Statistical analysis methods* should be chosen appropriately, taking account of temporal and spatial autocorrelation, sampling changes, observer bias and potential pseudoreplication (e.g., clones derived from one genotype are not true replicates of a species).

- When *downscaling* tools are used, a separate assessment is needed of the performance of these tools at spatial and temporal scales that are consistent with those of the detection or attribution study, using independent observational datasets.

4. Handling External Forcings, Drivers and Confounding Factors

Change in most variables of interest has multiple causes, whether in the climate system itself or downstream in natural or human systems. Therefore, attribution to the external forcing of interest must take into account the other forcings and drivers that affect the variable of interest. The effects of external forcings and drivers may be masked or distorted by the presence of confounding influences or factors. Expert judgement based on as complete an understanding as possible of the data, response processes and potential confounding factors and their possible effects should be used to carefully assess the likelihood that the detection and attribution results are substantially affected by confounding factors.

4.1 External Forcing and Drivers

When external drivers are explicitly included in detection and attribution studies, their influence on an observed change can be estimated. Examples are studies where the relative contribution of greenhouse gases and other anthropogenic as well as natural forcing (solar and volcanic, combined or separate) are considered. External forcings may also impact a system without being mediated by climate, for example, in the case of direct physiological effects of CO_2 on vegetation. Non-climate drivers can have a significant influence on many natural or human systems. For example, the impact of mass coral bleaching events may be affected by the presence or absence of non-climate related drivers such as fishing pressure and pollution. To the extent that the response to greenhouse gas forcing can be separated from the responses to other external forcings and drivers, the change attributable to greenhouse gas forcing can be assessed and further used to produce probabilistic projections of future change.

4.2 Confounding Factors

Confounding factors may lead to false conclusions within attribution studies if not properly considered or controlled for. Examples of possible confounding factors for attribution studies include pervasive biases and errors in instrumental records; model errors and uncertainties; improper or missing representation of forcings in climate and impact models; structural differences in methodological techniques; uncertain or unaccounted for internal variability; and nonlinear interactions between forcings and responses. Specific factors that may directly affect systems include tropospheric ozone affecting health and agriculture; aerosols affecting health and photosynthesis; direct physiological effects of CO_2 on vegetation; and land-use/land cover changes that might complicate the attribution of a change to forcing (unless included as forcing); The following issues and recommendations should be considered by authors with respect to confounding factors:

- Confounding factors (or influences) should be explicitly identified and evaluated where possible. Such influences, when left unexamined, could undermine conclusions of climate and impact studies, particularly for factors that may have a large influence on the outcome.

- Confounding factors should be taken into account as thoroughly as possible, including hypothesis-driven approaches, process-based modeling, statistical means, and expert judgments. With statistical-based assessment, avoidance of over-fitting is essential (e.g., by using independent sections of data to fit and then cross validate a model). Studies should explicitly state how they have handled such influences.

- One study's forcing or external driver can be another study's confounding factor, depending on the study's design and objectives, level of scientific understanding and data availability. For example, increase in CO_2 is treated as a forcing factor in some ecosystem change studies, while in other ecosystem studies focused on response to temperature change, it may be a confounding factor.

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