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

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

Meeting Report

Edited by:
Thomas Stocker, Christopher Field, Qin Dahe, Vicente Barros,
Gian-Kasper Plattner, Melinda Tignor, Pauline Midgley, Kristie Ebi

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

14-16 September 2009
Geneva, Switzerland

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Preface

The reliable detection and attribution (D&A) of changes in climate and their effects is fundamental to understanding the scientific basis of climate change and in enabling decision makers to manage climate-related risk. Working Group I and Working Group II of the Intergovernmental Panel on Climate Change (IPCC WGI & WGII) therefore held a joint Expert Meeting on *Detection and Attribution Related to Anthropogenic Climate Change* in Geneva, Switzerland, from 14 to 16 September 2009. The Expert Meeting provided a valuable opportunity for the D&A communities within WGI and WGII to work together to develop consistency and coherence of terminology, explore the methods used, and develop a better understanding across the two IPCC Working Groups.

The scientific core of this meeting report summarises the discussions and conclusions of the Expert Meeting on D&A. It seeks to clarify methods, definitions and terminology across the two Working Groups, and is intended as a stand-alone *Good Practice Guidance Paper* for IPCC Lead Authors. The Guidance Paper will thus serve as a reference document for D&A science and reporting that can also help stakeholders in the interpretation and application of statements in WGI and WGII reports. The meeting report further includes the extended abstracts of the presentations from the Expert Meeting as well as a general, non-comprehensive bibliography on literature relevant to D&A.

We extend our sincere thanks to the IPCC Secretariat and the World Meteorological Organization for hosting the meeting and for the excellent arrangements. We also thank the members of the Scientific Steering Committee who provided invaluable advice on the planning of the meeting as well as help in carrying out the programme. We would like to thank all participants who contributed to a very constructive and fruitful meeting where exchanging views and knowledge resulted in more clarity on the issues involved and the current status of scientific understanding. In particular, the members of the core writing team put in many hours of effort following the meeting in order to produce the Good Practice Guidance Paper in a timely fashion, for which we are very grateful.

We are sure that the good experience of the Expert Meeting can serve as a foundation for further fruitful collaboration and exchange between the two IPCC WGs on the topic of detection and attribution of anthropogenic climate change, in particular among the authors of the relevant chapters of the IPCC's Fifth Assessment Report.

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

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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.

Reference

Gillett, N.P., A.J. Weaver, F.W. Zwiers, and M.D. Flannigan, 2004: Detecting the effect of climate change on Canadian forest fires. *Geophys. Res. Lett.,* **31**(18), L18211, doi:10.1029/2004GL020876.

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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Kleypas J.A., R.W. Buddemeier, D. Archer, J.-P. Gattuso, C. Langdon, B.N. Opdyke, 1999: Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. *Science*, **284**, 118-120.

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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This non-exhaustive list of references is provided by the Core Writing Team as a resource for the reader.

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Annex 1: Proposal

WMO

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

UNEP

INTERGOVERNMENTAL PANEL
ON CLIMATE CHANGE

THIRTIETH SESSION
Antalya, 21-23 April 2009

IPCC-XXX/Doc.12
(26.III.2009)

Agenda item: 4
ENGLISH ONLY

SCOPING OF THE IPCC 5TH ASSESSMENT REPORT

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

(Submitted by the Co-Chairs of IPCC Working Group I and Working Group II)

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Proposal for a Joint IPCC WGI/WGII Expert Meeting on Detection and Attribution Related to Anthropogenic Climate Change

Submitted by the Co-Chairs of IPCC Working Group I and Working Group II

Background

In the IPCC Fourth Assessment Report in 2007, the WGI report concluded that "it is likely that there has been significant anthropogenic warming over the past 50 years averaged over each continent except Antarctica," but that "difficulties remain in reliably simulating and attributing observed temperature changes at smaller scales." Combining this with several sets of evidence including that "Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases," WGII was able to conclude that "Anthropogenic warming over the last three decades has likely had a discernible influence at the global scale on observed changes in many physical and biological systems." Improving technical aspects of detection and attribution, especially harmonizing terms and definitions, is an important goal to advance this topic, with emphasis on impact-relevant changes in the climate system and impacts in natural and human systems. The expert meeting will cover the full set of fundamental detection and attribution issues, including techniques, interpretation and specific examples that are relevant to changes in climate and impacts for the Fifth Assessment Report (AR5).

Aims of Expert Meeting

1. Develop consistency and coherence of terminology used for detection and attribution in WGI and WGII, and better understanding of the methods used by the two working groups including their advantages and limitations;
2. Advance the science of attribution of impact-relevant climate change, such as attribution of changes on regional scales, in precipitation and extremes, and of events; as well as the science of the attribution of impacts of climate change, such as on ecosystems, cryosphere, human health, agriculture, etc. Consideration will also be given to the attribution of specific weather events;
3. Improve the understanding of the role that may be played by confounding influences in attribution studies, including internal variability of climate and of the systems, and other factors such as land-use change, other natural and anthropogenic forcings including aerosols, pollution, invasive species, human management, etc.;
4. Expand coverage of data and studies to include more regions and more systems, particularly in the tropics and the Southern Hemisphere, and in developing countries;
5. Develop a better understanding across the two working groups at an early stage in the development of the AR5, thereby improving the process of synthesis.

Steering Group

Thomas Stocker (WGI Co-Chair)
Dahe Qin (WGI Co-Chair)
Chris Field (WGII Co-Chair)
Vicente Barros (WGII Co-Chair)

A scientific steering committee with broad representation is being formed.

Timing: 14-16 September 2009, immediately before planned IPCC Bureau Meeting

Duration: 2.5 to 3 days

Location: Geneva (tbc)

Participants

About 40 participants in total, with broad international representation. It is proposed that 16 journeys for experts from developing countries and economies in transition including WGI and WGII Vice-Chairs are allocated as part of the line item “expert meetings related to the AR5” in the already agreed IPCC Trust Fund budget for 2009.

Expertise

Detection and attribution of climate change and of the impacts of climate change;
additional expertise: climate observations and modelling, cryosphere, hydrology, terrestrial ecosystems, marine ecosystems, coastal zones, agriculture, human health, etc.

Annex 2: Programme

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

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

PROGRAMME

Monday, 14 September 2009

08:00	**Registration** ***(Salle B Foyer)***
09:00	**Welcome Address (Michel Jarraud, Secretary-General, WMO)** ***(Salle B)***
09:10	**Introduction/Background (Barros/Field/Qin/Stocker)**
PLENARY SESSION I: The Scientific Background of Detection and Attribution (Chair: Dahe Qin)	
09:30	**Keynote Presentation:** ***Towards Detection and Attribution of Impact-Relevant Climate Change: The WG1 Perspective*** **(Gabriele Hegerl)** [20 min presentation + 10 min discussion]
10:00	**Keynote Presentation:** ***Detection and Attribution of Climate Change Impacts: A Perspective from WG2*** **(Christopher Field)** [20 min presentation + 10 min discussion]
10:30	**General Discussion**
10:45	**Break** ***(Salle B Foyer)***
PLENARY SESSION II: Specific Topics in Detection and Attribution (Chair: Vicente Barros)	
11:15	***Detection and Attribution Related to Anthropogenic Climate Change in the Atmosphere from a Global Perspective*** **(Peter Stott)** [10 min presentation + 10 min discussion]
11:35	***Detection and Attribution of Anthropogenic Climate Change in the World's Oceans*** **(David Pierce)** [10 min presentation + 10 min discussion]
11:55	***Detection and Attribution Related to Anthropogenic Climate Change in the Cryosphere from a Global Perspective*** **(Wilfried Haeberli)** [10 min presentation + 10 min discussion]
12:15	***Human-Modified Temperatures Induce Species Change*** **(Terry Root)** [10 min presentation + 10 min discussion]
12:35	**General Discussion**
13:00	**Lunch** ***(WMO Cafeteria)***
14:00	**Introduction of Break-Out Groups and Good Practice Guidance Paper (Stocker and Field)** ***(Salle B)***

BREAK-OUT GROUPS – Part A	
14:20	**BOG1: Extremes [Chair: Fredolin Tangang; Rapporteur: Sari Kovats]** ***(Room 7 Jura)*** **BOG2: Global Scale [Chair: José Moreno; Rapporteur: Camille Parmesan]** ***(Room 8 Jura)*** **BOG3: Regional Scale [Chair: Serge Planton; Rapporteur: Gino Casassa]** ***(Salle B)***
16:00	**Break** ***(Salle B Foyer)***
16:30	**Reports from Part A Break-Out Groups (BOG Chairs)** ***(Salle B)***
PANEL SESSION	
16:50	***A Unified Framework for Detection and Attribution in AR5?*** **[Panelists: Myles Allen, Cynthia Rosenzweig, Stephen Schneider, Hans von Storch; Chair: David Wratt]** ***(Salle B)***
18:20	**Adjourn**
18:30	**Welcome Reception: WMO Cafeteria Reception Area**

Tuesday, 15 September 2009

08:30	**Summary Day 1; Introduction Day 2 (Kristie Ebi and Pauline Midgley)** ***(Salle B)***
PLENARY SESSION III: Specific Topics in Detection and Attribution (Chair: Christopher Field)	
08:40	***The Contribution of Climate and CO_2 Changes to the Observed Increase in Vegetation Productivity Over the Past Three Decades*** **(Shilong Piao)** [10 min presentation + 10 min discussion]
09:00	***Detection and Attribution of Anthropogenic Climate Change and Ocean Acidification: Impacts on Marine Ecosystems from a Global Perspective*** **(Ove Hoegh-Guldberg)** 10 min presentation + 10 min discussion]
09:20	***Detection and Attribution of Changes in Tropical Cyclones from a Global Perspective*** **(Thomas Knutson)** [10 min presentation + 10 min discussion]
09:40	***Detection and Attribution Related to Anthropogenic Climate Change: Facilitating Information Exchange*** **(David Karoly)** [10 min presentation + 10 min discussion]
10:00	**General Discussion**
10:45	**Break**
BREAK-OUT GROUPS – Part A Continued	
11:15	**BOG1: Extremes [Chair: Fredolin Tangang; Rapporteur: Sari Kovats]** ***(Room 7 Jura)*** **BOG2: Global Scale [Chair: José Moreno; Rapporteur: Camille Parmesan]** ***(Room 8 Jura)*** **BOG3: Regional Scale [Chair: Serge Planton; Rapporteur: Gino Casassa]** ***(Salle B)***
13:00	**Lunch** ***(WMO Cafeteria)***
14:00	**Reports from Part A Break-Out Groups (BOG Chairs)** ***(Salle B)***
14:30	**Forming of Part B BOGs (Barros/Field/Qin/Stocker)**
BREAK-OUT GROUPS – Part B	
14:40	**BOG1: Methods and Definitions [Chair: Francis Zwiers; Rapporteur: Dáithí Stone]** ***(Room 7 Jura)*** **BOG2: Data and other Requirements [Chair: Matilde Rusticucci; Rapporteur: Guy Midgley]** ***(Room 8 Jura)*** **BOG3: Forcing Factors and Confounding Influences [Chair: Linda Mearns; Rapporteur: Phil Jones]** ***(Salle B)***
16:00	**Break**
BREAK-OUT GROUPS – Part B Continued	
16:30	**BOG1: Methods and Definitions [Chair: Francis Zwiers; Rapporteur: Dáithí Stone]** ***(Room 7 Jura)*** **BOG2: Data and other Requirements [Chair: Matilde Rusticucci; Rapporteur: Guy Midgley]** ***(Room 8 Jura)*** **BOG3: Forcing Factors and Confounding Influences [Chair: Linda Mearns; Rapporteur: Phil Jones]** ***(Salle B)***
18:00	**Reports from Part B Break-Out Groups (BOG Chairs)** ***(Salle B)***
18:30	**Adjourn**

Wednesday, 16 September 2009

08:30	**Summary Day 2; Introduction Day 3 (Gian-Kasper Plattner)** ***(Salle B)***
BREAK-OUT GROUPS: Drafting of Bullets/Outline for Good Practice Guidance Paper	
08:40	**BOG1: Methods and Definitions [Chair: Francis Zwiers; Rapporteur: Dáithí Stone]** ***(Room 7 Jura)*** **BOG2: Data and other Requirements [Chair: Matilde Rusticucci; Rapporteur: Guy Midgley]** ***(Room 8 Jura)*** **BOG3: Forcing Factors and Confounding Influences [Chair: Linda Mearns; Rapporteur: Phil Jones]** ***(Salle B)***
10:00	**Reports from Part B Break-Out Groups (BOG Chairs)** ***(Salle B)***
10:30	**Break**
SESSION IV: Good Practice Guidance Paper (Chair: Thomas Stocker)	
11:00	**Plenary Approval of Executive Summary of Guidance Paper**
12:45	**Closing Remarks and Next Steps (Barros/Field/Qin/Stocker)**
13:00	**End of Meeting**

Annex 3: Extended Abstracts

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* *Speaker*

Detection and Attribution of Climate Change Impacts: A Perspective from WG2

Christopher Field

Co-Chair, IPCC WGII, Carnegie Institution, USA

Detection and attribution of climate change impacts can be defined and used in a way that completely parallels the well-developed applications for the physical climate system. With this set of definitions, detection refers to statistical confidence in the identification of a change in a biological or physical process. Attribution refers to statistical confidence in assigning responsibility to anthropogenic climate change. In this usage, the emphasis is on connecting the impact with the anthropogenic component of climate change. Several kinds of evidence are potentially relevant for supporting this conclusion. These include consistency with climate model experiments that reconstruct the historical record, coherent temporal and spatial patterns, and lack of sensitivity to natural variability. Studies that have taken this approach to attribution are foundational in the body of evidence that the anthropogenic component of climate change has already had measureable effects.

A larger set of attribution studies focus on analytical approaches to linking biological or physical impacts to changes in temperature or precipitation, without the emphasis on causation by the anthropogenic component of climate change. While such studies are less relevant to building the case for anthropogenic causation, they may be as useful or even more useful for developing projections of future impacts, including projections that capture the uncertainties in both the climate projections and the sensitivity of the impacts.

These two classes of attribution studies, one focused on unambiguous assignment to anthropogenic climate change and one directed at quantifying the effect of climate changes, independent of their cause, often identify different targets, are typically based on different criteria, are intended for different purposes, and play different roles in the agenda for future research. As the emphasis in impacts research continues to move toward providing the information to support good decisions about complicated, multi-stressor settings, it will be increasingly important to insure that attribution research maintains a focus broader than case studies with the strongest prospects for clear signatures of anthropogenic climate change. Careful work on impacts linked to fingerprints for anthropogenic climate change will continue to be valuable. So will studies that focus on questions that may not provide such clear answers, for example, studies attributing physical and biological responses to regional changes in climate, to changes in precipitation, to changes in extremes, or to factors that involve interacting parts of the climate system or interactions between climate and other processes.

Detection and Attribution Related to Anthropogenic Climate Change in the Cryosphere from a Global Perspective

Wilfried Haeberli

Geography Department, University of Zurich, Switzerland

The cryosphere on earth is close to melting conditions. As a consequence, climate-related changes in snow and ice can be spectacular and well recognisable even for a broad public. Together with information from deep ice cores, widespread knowledge about the reduction of arctic sea ice or about the worldwide shrinking of mountain glaciers indeed constitutes a fundamentally important component of the now-existing awareness with respect to anthropogenic climate change.

Early detection strategies are among the primary goals of snow and ice monitoring in global climate-related observing systems (GCOS 2009). Criteria considered in such detection strategies are (a) rates of change and acceleration trends, (b) present conditions in relation to pre-industrial variability ranges and (c) spatial patterns of change as compared to modelled climatic scenarios. The following briefly mentions the most prominent cryosphere indications with their signal characteristics (detection of change, attribution with respect to causes and impacts) as related to climate change (cf. IGOS 2007, the overview in UNEP 2007 and a summary of most recent research on key aspects of cryosphere change by UNEP 2009).

Continental ice sheets:
Greenland and Antarctica are important drivers in the climate system. Slow changes in their mass balance and flow are complex and relate to centennial to millennial time scales, making attribution to causes difficult. Modern altimetry and gravimetry technologies are now strongly improving detection possibilities at shorter (decadal) time scales. This is especially important in view of possible ice-sheet instabilities from recent flow acceleration of outlet glaciers with beds far below sea level and corresponding surface draw down of large catchment areas. Attribution to impacts primarily relates to long-term sea level rise and atmosphere/ocean circulation.

Probably the clearest and most significant cryospheric information on past climate change is from ice core analysis in Antarctica and Greenland. Especially high resolution GHG and isotopic ice core records reaching 105 to 106 years back in time are fundamental for detection/documentation of past climate changes and for attribution of corresponding causes. They clearly show the extraordinary level of modern GHG concentrations and contain quantitative evidence from the past about possible anthropogenic effects.

Borehole temperature profiles in cold firn/ice provide independent checks on records of isotopic temperature proxies and reflect changes in atmospheric (annual) temperatures. If more systematically monitored (change of temperature at depth with time) and analyzed (numerical modelling of heat diffusion and flow effects), they would be important for detecting and attributing atmospheric warming as compared to conditions over very long time periods in the past.

Sea ice:
Via its albedo effects and its influence on the formation of deep ocean water, sea ice relates to the climate system with important interactions and feedbacks. The continued decrease in Arctic sea ice extent, age and volume and especially the sudden shrinking to a new record low in 2007 is probably the most dramatic recent change in the Earth's cryosphere, taking place at a rate which by far exceeded the range of previous model simulations. Sea ice around Antarctica shows little change – a fact, which is still not fully understood. Continued sea ice monitoring is a key element of detection strategies for global climate change.
Attribution to causes is complex as the development is influenced by higher air and ocean temperatures and by particular ocean circulation patterns (acceleration of the transpolar drift in the case of the arctic ocean). The development of the arctic sea ice is of great

concern, because attribution with respect to impacts involves aspects of highest global importance such as global albedo and ocean circulation as well as navigation through the NW- and NE passages.

Glaciers and ice caps:
The shrinking of mountain glaciers and (smaller) ice caps is among the clearest and most easily understood evidence in nature for rapid climate change at a global scale and, hence, constitutes a key element of detection strategies for global climate change. Especially mountain glaciers are considered to be “unique demonstration objects” concerning ongoing climate change. Mass balance monitoring shows a striking acceleration of loss rates since the mid 1980s. Glacier extent (length, area) may have reached “warm” limits of pre-industrial (Holocene) variability ranges and is far out of equilibrium conditions at many mid- and low-latitude sites.

Attribution to atmospheric (summer) temperature rise as a primary cause is relatively safe as air temperature not only relates to all energy balance factors but also to rain/snowfall and hence accumulation. Complications are due to variable englacial temperature conditions (cold, polythermal, temperate firn/ice) and strong feedbacks (positive: albedo, elevation/ mass balance; negative: adjustment of geometry, debris cover). Attribution to impacts involves landscape changes, runoff seasonality, hazards (lake outburst floods, slope instability) and erosion/sedimentation cascades (debris flows, river load, lake filling etc.). Modern satellite-based glacier inventories with digital terrain information (SRTM, global ASTER DEM since 2009) now enable documenting and modelling large glacier ensembles in entire mountain ranges.

Ice shelves:
The rapid disintegration and collapse of ice shelves in the Antarctic Peninsula and the almost complete disappearance of the Canadian ice shelves on Ellesmere Island are well-documented changes. The anticipated progression of ice-shelf collapse towards colder parts of Antarctica forms a key element of cryospheric detection strategies.

Complex air/ocean/ice interactions make attribution to exact causes difficult but “warming” as a general cause appears to be evident. Attribution to impacts concerns high-latitude marine ecosystems, the stability of outlet glaciers and ice streams in Antarctica and with this indirectly long-term sea level.

Permafrost:
Perennially frozen ground at high latitudes is an important feedback element in the climate system (CH_4, surface drainage, vegetation). Important information on rising ground temperatures as compared to historical conditions can be derived from changing subsurface temperatures and from heat flow anomalies in deep boreholes. Observed changes in active layer thickness must be complemented by measurements of subsidence from thaw settlement in ice-rich materials and so far do not show clear trends. In both cases, attribution to climatic causes is complicated by multiple interactions of frozen ground with vegetation, snow and surface water. Attribution to impacts involves large terrestrial ecosystems and living conditions (water resources, infrastructure, hazards) at high latitudes and high altitudes.

Lake and river ice:
The duration of ice on lakes and rivers is an indicator of winter and lowland conditions, complementing summer/altitude evidence from mountain glaciers. Shortening of the season with lake and river ice in wide northern regions can be generally attributed to “winter warming” effects. Highly complex influences from short-term weather patterns (wind, precipitation/snow fall) and limnological conditions (water circulation, groundwater influx, lake turnover, etc.) make attribution to exact causes and modelling difficult. Trafficability and ecosystem evolution are primary aspects of attribution to impacts.

Ice patches/miniature ice caps:
Important climatic information exists from cold/old ice patches/miniature ice caps not usually described in cryosphere overviews (Farnell et al., 2004; Haeberli et al., 2004). Dating of organic matter from disappearing ice patches shows that ice (and summer air temperature?) conditions without precedence during the past 5 to 8 millennia have now been reached in sub-arctic and alpine regions. Detection and attribution need improvement.

Snow cover:
With its large area, small volume and

correspondingly extreme spatio-temporal variability, snow is a "nervous interface" between the atmo-, litho-, cryo-, hydro- and biosphere. In fact, snow cover is an important feedback in the climate system rather than an ideal indicator of change. Observed trends (decreasing spring snow extent in the northern hemisphere) point to some effects from warming but remain vague. Attribution to impacts concern many parts of the climate systems – especially cryosphere components and the water cycle.

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Towards Detection and Attribution of Impact-Relevant Climate Change: The WG1 Perspective

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Detection and attribution serves two purposes: Demonstrating that changes in external forcing (for example, greenhouse gas increases) have in fact influenced observed changes in climate, or caused impacts; and estimating the contribution that the forcing made to the observed changes. The concepts of climate change *detection* and *attribution* were defined in attribution chapters in previous IPCC reports (Mitchell et al., 2001; Hegerl et al., 2007). *Detection* is defined as "the process of demonstrating that climate has changed in some defined statistical sense, without providing a reason for that change" (Glossary WG1). Therefore, the first question asked about observed changes is, how significantly different are these from variability generated within the climate system. This requires an estimate of the variability generated within the climate system (or impact system) on the timescales considered, usually decades or longer. In climate research, these estimates often originate from climate models that are run without changes in external forcing. However, the results are far more credible if the variability in models compares well with that recorded in long instrumental data and proxy reconstructions.

Attribution "of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence" (see Glossary). As noted since the SAR (Santer et al.*,* 1996), unequivocal attribution would require controlled experimentation with our climate system. Since that is not possible, in practice attribution is understood to mean demonstration that a detected change is "consistent with the estimated responses to the given combination of anthropogenic and natural forcing" and "not consistent with alternative, physically-plausible explanations of recent climate change that exclude important elements of the given combination of forcings" (Mitchell et al., 2001). Information about the expected responses to external forcing, so called 'fingerprints', is usually derived from simulations by climate models, although the use of simple or conceptual models is possible as well. The consistency between an observed change and the estimated response to a forcing can be determined by estimating the amplitude of a 'fingerprint' from observations and then assessing whether this estimate is statistically consistent with the expected amplitude of the pattern from a model. If the response to a key forcing, such as greenhouse gas increases, is also distinguishable from that to other forcings, this strengthens confidence in the attribution assessment. Often, results are based on multiple regression of observations onto several fingerprints representing climate responses to different forcings, and in many cases, the estimate involves a metric that increases the signal-to-noise ratio by suppressing internal climate variability, see appendix of Hegerl et al., 2007). Results vary between variables and scales:

Global scale *surface temperature* is recorded by an instrumental record of 150 years and reconstructed from palaeo data over several centuries. Both compare well with climate model simulations if driven with estimates of external forcing (see Figure 1; Hegerl et al., 2007 and references therein), even on the scale of large regions. This comparison, attribution studies and physical energy considerations led to the assessment that it 'is extremely unlikely (<5%) that the global pattern of warming during the past half century can be explained without external forcing'. Results from fingerprint studies show that the response to greenhouse gases can be well separated from that to other forcings, and that the recent warming requires a significantly positive and substantial response to greenhouse gas forcing, irrespective of the model used and robust to a variety of technical choices. The fingerprint does not require significant rescaling to match the observed change. All this led to the assessment that 'greenhouse gas forcing has very likely caused most of the observed global warming over the recent 50 years'. Results for individual continents for the same timeframe show that 'it is likely that there has been a substantial anthropogenic contribution to surface temperature increases over every continent except Antarctica'. Antarctica is now covered as well (Gillett et al., 2008). However, for impacts, results on smaller regions and seasonal temperatures will be needed.

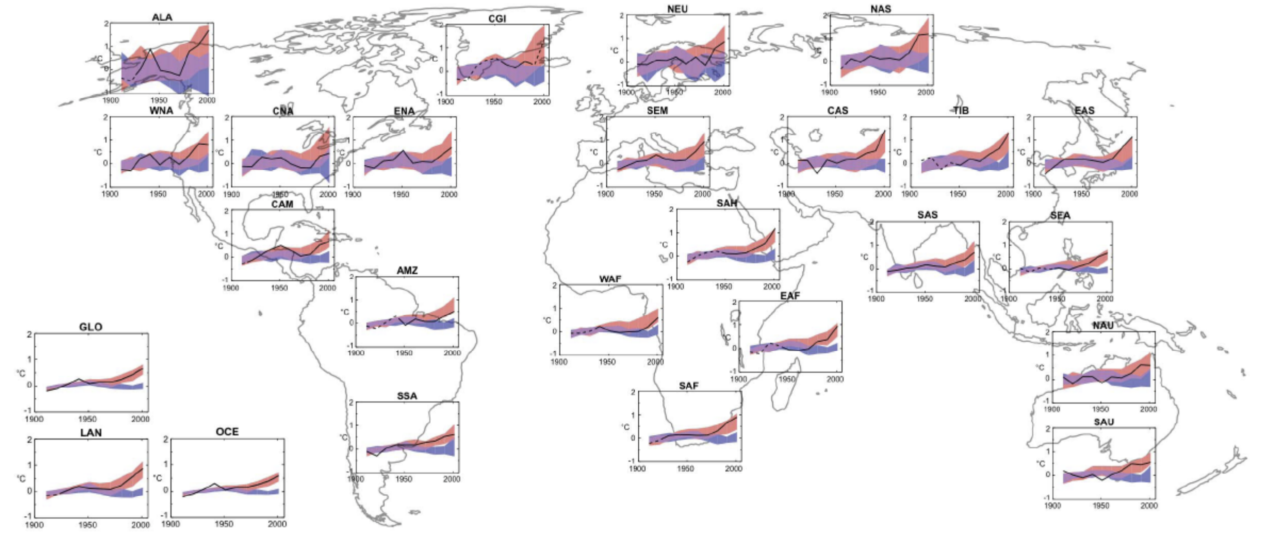

Figure 1. Comparison of multi-model dataset 20th century multi-model simulations containing all forcings (red shaded regions, 90% range) and containing natural forcings only (blue shaded regions) with observed decadal mean surface temperature changes 1906-2005. All details see Hegerl et al., 2007. Units: ºC

Changes in precipitation are more ambiguous: The signal-to-noise ratio for precipitation is lower, precipitation datasets are more uncertain than temperature datasets, and no reliable long-term dataset is available over oceans (see Zhang et al., 2007). Climate model variability is smaller than instrumentally recorded variability, particularly in the tropics. Nevertheless, recent zonal changes in precipitation show significant contributions from anthropogenic fingerprints to the observed changes, which are distinguishable from the response to natural forcing even when the estimate of internal variability is inflated (Zhang et al., 2007). However, the magnitude of the observed change is larger (significantly so) than that of the multi-model mean fingerprint, raising questions about instrumental data and climate model realism. *Climate extremes*, such as daily maximum temperature, drought, precipitation extremes and storminess are subjects of active research and still remain uncertain and challenging.

When attempting to attribute climate change relevant for impacts, difficulties arise that may be similar to those in attributing impacts: Often, information is needed on scales that are comparable to or smaller than present climate model resolution. At the gridpoint scale, the energy cascade from smaller to larger scales no longer works in climate models, and variability originates from strongly parameterized processes. Competing external influences may play a role that are small globally, but can be considerable regionally, such as land use change. Options that may help to bridge the scales include use of regional models and inference from larger scales to smaller scales (Christidis et al., 2009). A further difficulty arises when no end-to-end modelling framework is available for attribution (for example, as is still the case for tropical cyclones). Then, the ability is limited to estimate the contribution to observed changes from greenhouse gas increases (Zwiers and Hegerl, 2008). On the other hand, full end-to-end approaches are not available for many problems, particularly if plagued by short records, limited process understanding, and difficulty in quantifying confounding factors. Nevertheless, the information contained in results where, for example, part of the link from forcing to impact response is conceptual in nature, is very useful. Thus, concise, exact, and intuitively understandable language needs to be crafted that helps express this range of attribution results.

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Detection and Attribution of Anthropogenic Climate Change and Ocean Acidification: Impacts on Marine Ecosystems from a Global Perspective

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The accelerating changes in the composition of the atmosphere have resulted in rapid changes to the physical and chemical nature of the world's oceans. Ocean temperatures have risen by 0.1 °C (0–700 m) over the past 40 years, resulting in changes to ocean structure, circulation and volume. At the same time, the steady acidification of the ocean by increased atmospheric carbon dioxide has resulted in a pH change of 0.1 units in the surface layers of the ocean since 1750 (Ch5, WG1, IPCC 2007; Key et al., 2004). Long-term records from sediments, coral skeletons and other archives suggest these changes are unique in the last thousand if not million years.

There is substantial evidence that changes to the physical and chemical nature of the ocean has already had important consequences for ocean ecosystems. Increasing sea temperatures have resulted in heat-related impacts on ecosystems such as coral reefs, and changes to the distribution of organisms as different as plankton and polar bears. Sea ice habitats, home to vast ecosystems, are vanishing. The growing stabilisation of parts of the ocean (especially within ocean gyres) has impacted the nutrient dynamics of surface waters, leading to the expansion of oligotrophic (low nutrient) areas. Stabilisation of the ocean has also driven decreased oxygenation of deeper habitats, as water column turnover has slowed. The rise in atmospheric carbon dioxide has also caused the steady acidification of the ocean, which in turn has resulted in a precipitous decrease in the carbonate ion concentration. These changes to ocean chemistry are reducing the ability of marine organisms to produce skeletons and shells, with consequences for the sustainability of carbonate-dominated ecosystems such as coral reefs, pelagic productivity and oceanic carbon pumps.

At the heart of the detection and attribution of these changes is the veracity with which we can assign specific changes within ocean ecosystems to climate change and ocean acidification. In order to demonstrate a strong case for these changes being driven by greenhouse gas concentrations, this paper will partially focus on the specific case of coral reef ecosystems (Hoegh-Guldberg et al., 2007).

Coral reefs provide habitat for at least 25% of all marine species, despite only occupying 0.1% of the Earth's surface. They are also critically important for at least 500 million people who live in coastal areas around the world. These people look to the coral reefs for food, resources and services such as coastal protection. Beginning in 1979, however, mass coral bleaching events began to occur across the tropical regions. These vast ecological impacts are caused by temperature anomalies which are only 1–2 °C above the long-term summer temperature, resulting in the breakdown of the mutualistic symbiosis that exists between coral and dinoflagellates (also known as zooxanthellae). This symbiosis provides abundant energy and ultimately underpins the ability of reef building corals to precipitate large amounts of calcium carbonate for their external skeletons. Over time, calcium carbonate builds up to provide the 3-dimensional complexity of coral reefs, which is critical for providing habitat to over 1 million species of marine organisms and ultimately resources to millions of people worldwide.

One of the most compelling pieces of evidence that mass coral bleaching can be attributed to global warming is that there are no scientific reports of mass coral bleaching prior to 1979, despite the fact that these events are highly visible to even the amateur observer (Figure 1A).

In addition to this, a large number of studies have confirmed that small increases in sea temperature are all that is needed to trigger mass coral bleaching. Corals that bleach are more susceptible to disease and death, with mortalities often claiming 50-100% of corals on a reef. Given the fact that coral reefs take at least 15 years to recover, the increased frequency of mass coral bleaching is expected to result in the loss of reef building corals over time. In line with this, a recent study (Bruno and Selig, 2007) has demonstrated that coral populations in the Western Pacific and South-East Asian regions have undergone contractions of their coral communities at about 1 to 2% of per year since the early 1980s. This change has occurred on reefs close to heavily populated coastlines as well as areas in which few people live, suggesting that global are supposed to local (e.g. pollution, overfishing) factors are responsible for these changes.

The detection of the changes that are occurring within marine ecosystems such as coral reefs as result of ocean acidification has been more difficult. While there have been a large number of laboratory studies on the impact of declining carbonate ion concentrations on the calcification of a wide range of organisms from algae to corals (Kleypas and Langdon, 2006), detection of the impacts in the field has been elusive and confounded by the potential influence of other factors. Despite these problems, two studies published earlier this year report major changes in the calcification rate of corals which appear to be novel within the 400 year coral core records examined. In a comprehensive study of 328 coral records from 69 reefs within inshore and offshore sites across the Great Barrier Reef, De'ath et al. (2009) reported 14.2% decline in calcification since 1990. While it is hard to attribute this change solely to ocean acidification, it is significant that the same amount of change was detected in areas that were warming at different rates (e.g. inshore versus offshore).

The detection of the biological responses of coral reefs to recent changes benefits from an understanding of the past conditions under which coral reefs have developed. This allows detected changes to be distinguished from natural variability. Conservative estimates of the variation in the sea temperature and carbonate ion concentration for typical coral reefs over the past 420,000 years reveal that current conditions for coral reefs are well outside those that coral reefs have experienced over this long period (Figure 1C) (Hoegh-Guldberg et al., 2007). Importantly, these changes have exceeded the ability of coral reefs to keep up with what are essentially unprecedented rates of change, and place coral reef ecosystems on a trajectory which will soon (within 30-50 years) exceed the temperature and carbonate ion thresholds that are known to exist for corals as atmospheric carbon dioxide approaches 450 ppm. Developing similar insights for other marine ecosystems is less well developed but must be a priority for future detection and attribution projects.

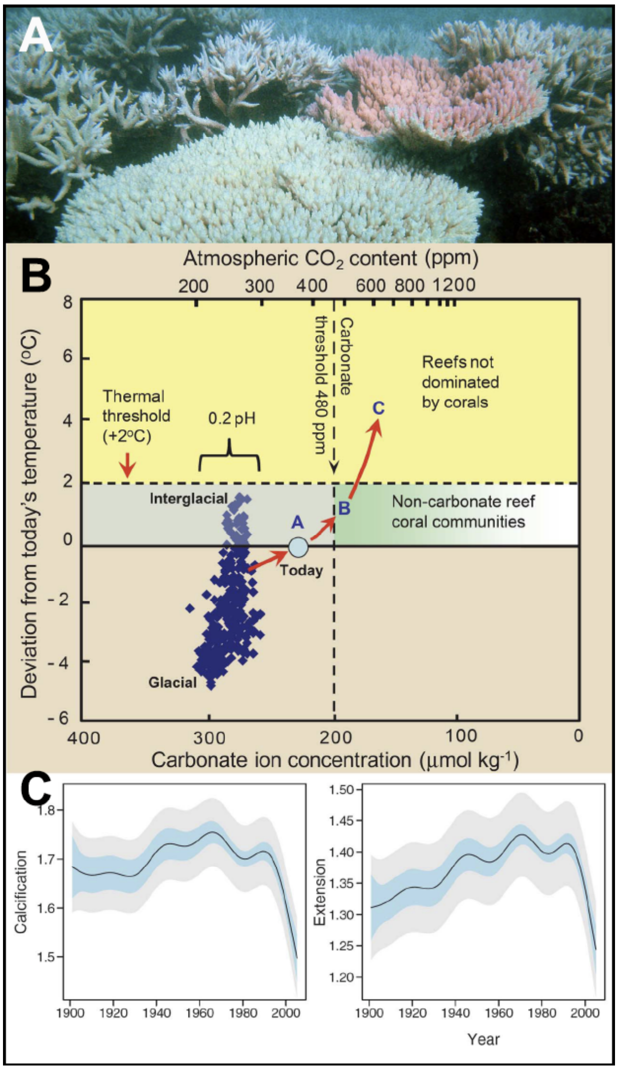

Figure 1. A. Coral bleaching on the southern Great Barrier Reef (February, 2006); B. Water temperature and carbonate ion concentrations for a typical coral reef over the past 420,000 years (full details, see Hoegh-Guldberg et al., 2007); C. Coral calcification and skeletal extension over the past 100 years on the Great Barrier Reef – section of record presented by De'ath et al. (2009).

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Detection and Attribution Related to Anthropogenic Climate Change: Facilitating Information Exchange

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There are a number of activities that can facilitate enhanced information exchange between scientists involved in different aspects of detection and attribution related to anthropogenic climate change and improve the relevant chapters in the Fifth Assessment Report (AR5). Some of them are already underway, such as holding this Expert Meeting and the preparation of the concise "Good Practice Guidance Paper on Detection and Attribution" to serve as a reference document for detection and attribution reporting in WGI and WGII. Others are needed as part of the development of the AR5, including selection of appropriate Lead Authors, Contributing Authors, and Reviewers to provide important links between the two WGs and the encouragement of open communication between the relevant author teams.

Expert Meeting on Detection and Attribution Related to Anthropogenic Climate Change This meeting will be an important step in developing greater consistency and coherence of terminology used for detection and attribution in WGI and WGII, and better understanding of the methods used by the two working groups including their advantages and limitations.

Good Practice Guidance Paper on Detection and Attribution This will serve as a reference document for detection and attribution reporting in WGI and WGII. It will contain agreed terminology and usage, and will serve the scientific community and stakeholders when it comes to the interpretation and application of statements in WGI and WGII documents.

Author Teams for the WGI and WGII Chapters It will be important to select author teams, both Lead Authors and Contributing Authors, who have relevant expertise across the two WGs and who are interested in better understanding and applying the range of methods used across the two WGs. It may not be appropriate to have the same person as a Lead Author in chapters in both WGI and WGII, due to the time and writing commitments involved. However, it will be helpful to have a small number of Lead Authors from the relevant chapters in each WG also involved as Contributing Authors in the chapter for the other WG and supported to attend one or more Lead Author meetings in that other WG. While CAs normally don't attend LA meetings, this would be very helpful in developing better coherence between the chapters in the two WGs. In addition, all LAs from the relevant chapters in each WG should be Reviewers for the chapter in the other WG.

Supporting Open Communication Between the Author Teams This will be greatly assisted by the joint LAs and CAs described above, but will also need support for the participation of some relevant CAs at LA meetings. It will also be vital to share draft chapters and sections of chapters between the author teams from the two WGs as early as possible, before they are available for Expert and Government Review. Delays or difficulties in sharing draft chapters will lead to less consistency and coherence between the relevant chapters.

Role of the TSUs The TSUs have very important roles in supporting the author teams and open communication between the WGs. Some changes in the LA meetings and the invitation of cross-WG LAs and CAs to LA meetings should be encouraged.

Improvements in the Science Improved information exchange between scientists involved in different aspects of detection and attribution will lead not only to better WG chapters but also to advances in the application of D&A science to new and interesting areas, through better methods, improved data coverage, and improved cross-disciplinary understanding.

Detection and Attribution of Tropical Cyclones from a Global Perspective

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Despite some findings suggesting a human influence on tropical cyclone activity, detection and attribution remains elusive. A significant hurdle is the quality of existing tropical cyclone historical records, which, although most complete in the Atlantic basin, contain significant data homogeneity issues and limited record lengths in all basins. Taking into account such data limitations, it remains uncertain whether past changes in tropical cyclone activity have exceeded the variability expected from natural causes. In this paper, several key findings that have suggested significant long-term trends or possible anthropogenic influence on tropical cyclone activity are examined.

One key finding to consider is the record of Atlantic hurricane power dissipation (Emanuel 2007), which is strongly correlated with tropical Atlantic SST on multi-year time scales. If this statistical relation holds generally, such that it also applies to the local Atlantic SST warming associated with the global-scale warming due to greenhouse gases, then a dramatic ~300% increase in power dissipation is projected by a statistical extrapolation of that relation to the late 21st century (Vecchi et al., 2008). Additionally, in that case, the attribution of tropical Atlantic SST warming in recent decades to anthropogenic forcing (Gillett et al. 2008) would, via indirect attribution, also imply an attribution of a hurricane activity increase to anthropogenic forcing. However, existing dynamical models do not support this interpretation, as they project much smaller late 21st century changes in Atlantic hurricane power dissipation and other metrics than would be obtained by statistical extrapolation based on local tropical Atlantic SST (Vecchi et al., 2008). Therefore, the dynamical models also weigh against the notion of a detectable human influence on Atlantic hurricanes at this time.

A second important line of evidence is the long-term (~130 year) record of Atlantic tropical cyclone counts. In the original HURDAT data set, this record shows a very large (~100%) increase since 1900, and the changes are correlated on long time scales with the warming of the tropical Atlantic SST (Holland and Webster, 2007; Mann and Emanuel, 2006). However, recent studies (Vecchi and Knutson, 2008; Landsea et al., 2009) indicate that significant numbers of non-landfalling storms were probably missed in the earlier decades prior to the satellite era (~1965) due to limited ship traffic. After correcting for such an estimate of missing storms, the latter studies find that the upward trends since 1878 are largely removed and are no longer significant. While another study (Mann et al. 2007) used climate indices to estimate missing storms and found a smaller adjustment than Vecchi and Knutson (2008), their method uses tropical Atlantic SST as a key predictor, and thus does not provide a clear independent assessment of whether the statistical relation between tropical Atlantic SST and tropical cyclone numbers observed in recent decades also holds for century-scale trends.

A third important line of evidence is a satellite-based reconstruction of tropical cyclone intensities, which is global in extent, and extends back to 1981. This record has been homogenized by using satellite data uniformly across different basins and in different years to minimize the impact of observing practices on long-term trends. In an early use of this dataset, the Kossin et al. (2007) study raised questions about the quality of the observed "Best Track" intensity data in a number of regions, especially outside of the Atlantic and NE Pacific. This was one piece of evidence that led researchers to question earlier reported findings by Webster et al. (2005) of large increasing trends in strong tropical cyclone numbers (Category 4-5) in all basins since the mid 1970s. An updated version of the satellite-based dataset was subsequently used to document an apparent increase in the intensities of the strongest tropical cyclones (upper quantiles of the intensity distributions) globally (Elsner et al., 2008). The intensification signal, while present in globally aggregated statistics since 1981, is most strongly present in the Atlantic basin. But in that basin, longer-term records for other tropical cyclone metrics suggest that trends computed since 1981 are not representative of longer-term trend behavior. Aside from the Atlantic, the basins with the next most significant signals are the Indian Ocean basins, but the homogenized data there have important limitations and required substantial adjustments due to changes in satellite view angles over time. Thus, due to the short length of reliable records and the limited information about internal variability levels of intensity metrics in various basins, we do not yet conclude that a long-term climate change has been detected in tropical cyclone intensities.

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The Contribution of Climate and CO_2 Changes to the Observed Increase in Vegetation Productivity Over the Past Three Decades

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Terrestrial net primary production (NPP) has been a central focus of ecosystem science in the past several decades because of its importance to the terrestrial carbon cycle and ecosystem processes, as well as to food and fiber production. Previous observational and modeling studies have documented that terrestrial photosynthetic activity has increased over the past 2-3 decades (Boisvenue and Running, 2006). Using a satellite-based model of NPP, Nemani et al. (2003) inferred that global NPP increased by 0.34% yr^{-1} over the past two decades. NPP in China increased by 18% over the period 1982-1999 (Piao et al., 2005), which is larger than that in North America (8% during 17 years) (Hicke et al., 2002). This increase over the Northern Hemisphere (NH) has been confirmed by the multi-year normalized difference vegetation index (NDVI) derived from the satellite sensor (Zhou et al., 2001).

There has been much debate about the cause of such a significant increase in vegetation activity. For example, Ahlbeck (2002) employed statistical analysis methods to demonstrate that the increase in atmospheric CO_2 concentration was the primary driving force for enhanced vegetation growth, while Kaufmann et al. (2002) suggested that the greening of northern region was chiefly driven by rising temperature. More recently, Lucht et al. (2002) found that temperature change alone largely explained the vegetation greening trend in the boreal region. Concurrently increased precipitation is also suggested as a possible cause for the increase in vegetation productivity over China and USA (Piao et al., 2005; Nemani et al., 2002). More recently, radiation quality changes, i.e., an increase in the diffuse fraction of global radiation has also been suggested as a driving force of the increase in vegetation activity.

There is little doubt that many environmental factors affect vegetation dynamics. The real question is that how much each major factor contributes to the observed signals. In this study, we use a mechanistic terrestrial carbon model ORCHIDEE and relevant data sets to investigate the spatial patterns of mechanisms controlling current enhanced vegetation activity over the last three decades.

In the first analysis, we will discuss the mechanisms for the increase in leaf area index (LAI) in the Northern Hemisphere since the 1980s. Our results indicate that changes in climate and atmospheric CO_2 likely function as dominant controllers for the greening trend during the study period. At the continental scale, atmospheric CO_2, temperature, and precipitation account for 49%, 31%, and 13% of the increase in growing season LAI, respectively, but their relative role is not constant across the study area. The increase in vegetation activity in most of Siberia is associated with warming, while that in central North America is primarily explained by the precipitation change. The model simulation also suggests that the (spatial) regression slope between LAI and temperature increases with soil moisture, but decreases with temperature. This implies that the contribution of rising temperature to the current enhanced greening trend will weaken or even disappear under continued global warming.

In the second analysis, we will show spatio-temporal change in global NPP and its driving factors. Our modeling results also suggest that global NPP increased with an average increase rate of 0.4% yr^{-1} from 1980 to 2002. At global scale, such an increase seems to be primarily attributed to the increase in atmospheric CO_2 concentration, and then to precipitation change. In response solely to atmospheric CO_2 change, the modeled global NPP increased by about 6%, accounting for 80% of the increase in the simulation that consider changes in all factors. Current precipitation change is an important factor responsible for enhanced vegetation productivity in the Southern Hemisphere (South of 20°S) and tropical region, where precipitation change alone has led to significant increase in annual NPP by about 0.26% yr^{-1} and 0.15% yr^{-1}, respectively. Although NPP in boreal region increases with rising temperature, it is likely that the rise in temperature alone does not benefit to vegetation NPP in temperate and tropical ecosystems, due to soil moisture limitations. Our results also suggest that the contribution of land use change to the increasing trend of global NPP over the last two decades may be limited.

In the last analysis, we will discuss uncertainties of our modeling simulation results through comparing with the results derived by other four different ecosystem models (HyLand, LPJ, SDGVM, and TRIFFID).

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Detection and Attribution of Anthropogenic Climate Change in the World's Oceans

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1. Introduction

Searching for an anthropogenic warming signal in the World's Oceans is compelling because 84% of the warming over the last half century has gone to heat the oceans (Levitus et al. 2000), the oceans are not subject to urban heat island effects, and the transfer of heat to the deep ocean sets the time lag between increases in greenhouse gases (GHG) and surface temperatures.

There are also challenges with a detection and attribution (D&A) study of ocean temperatures. Climate models show pronounced drift in this quantity, which must be removed. Recent work has shown systematic biases in ocean temperature measurements, which have contaminated the observed signal (e.g., Gouretski and Koltermann, 2007). Third, there is extreme sampling variability in the oceans, as well as systematic biases (the polar regions are less sampled during winter).

Despite these challenges, D&A on ocean temperature changes is rewarding since it can potentially reveal the three-dimensional signal of penetration of heat into the World's Oceans. In this work we briefly sketch out how the above-mentioned challenges were approached, and what the final result of a D&A analysis of ocean temperatures shows.

2. The Problem of Ocean Drift

Current coupled ocean-atmosphere climate models show substantial drift in the subsurface ocean's heat content (Figure 1a). In 20th century runs, the drift is often comparable to the anthropogenic warming rate. Clearly, the net ocean surface radiation imbalance in most control runs is of the same order as the additional radiative forcing due to GHGs and aerosols in the late 20th century. Nevertheless, control runs are used based on a low rate of surface temperature change rather than a small net surface radiation imbalance. The oceans have a ventilation timescale of *O*(1000 yrs), so multi-millennium control runs would be required to reach equilibrium. Even so, there is little understanding of what multi-century drift is expected due to natural climate variability, and so we cannot reject a model based solely on its ocean temperature drift.

We assume that the same model drift would obtain from the anthropogenically forced runs, which typically branch off from the control run. We calculate the anthropogenic "signal" as the difference between the drifting mean temperature in the control run (low-passed to remove noise) and that found in the anthropogenic run, taken the same model year. This means model control runs must overlap forced runs, which reduces the number of usable CMIP3 models.

3. Biases in observed ocean temperatures

In Barnett et al., 2001, the most notable disagreement between models and observations was an observed peak in the 1970s. Subsequent work examined whether a fluctuation of this magnitude could be simulated (AchutaRao et al., 2006), and asked if models underpredict natural variability. If the latter, model noise profiles would be wrong to use in a D&A study.

More recent work has demonstrated that it was actually the observations that were erroneous, rather than the models (e.g., Gouretski and Koltermann, 2007). With a more accurate calibration of the drop rate in XBTs, the peak in the 1970s largely goes away, but the decadal trend remains. This controversy was reminiscent of a more recent one, where it was reported that the surface oceans had cooled, which also turned out to be an instrumentation error (Willis et al., 2007). However, although corrected ocean temperatures are now available, there has been no comprehensive revisit of the ocean heat content D&A using the large number of models now available.

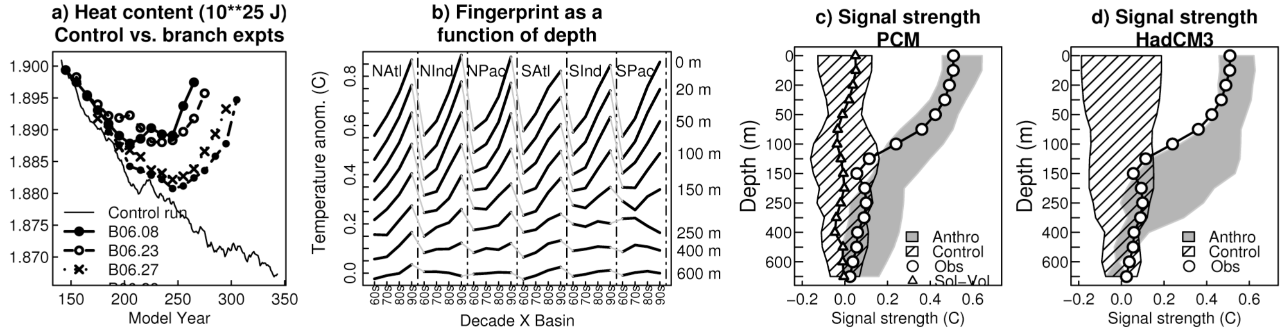

Figure 1. a) Ocean heat content in the control run (solid line) and anthropogenically forced historical runs branched off from the control run (dashed lines). b) Model fingerprint of warming as a function of depth, for the concatenated decades and basins. c) and d) Signal strength as a function of depth for PCM and HadCM3.

4. Sampling Issues

The tremendous year-to-year variability in ocean sampling, along with the secular increase over the decades, poses special challenges (e.g., AchutaRao et al., 2006, Lyman and Johnson, 2008). We sidestep these issues by only sampling the model at the same locations and times as the observations. This is important because the change in sampling itself has a robust effect on the mean temperature anomaly. This sampling strategy poses some technical problems for low-pass filtering the control run, as we wish to filter out changes in ocean temperatures, not changes in the sampling mask. Our technique for doing this is described in Pierce et al., 2006, Appendix A.

5. The fingerprint of ocean warming

Following Barnett et al. (2005), we form a concatenated space-time fingerprint of ocean warming for four decades (1960s-90s) in 6 ocean basins (north and south Atlantic, Indian, and Pacific oceans). Decadally averaging reduces high-frequency noise. The fingerprint could be constructed to include vertical (depth) information as well, but we choose to form a separate fingerprint at each level and then analyze how the detectability varies with depth. Figure 1b shows the fingerprint as a function of depth. The peak to peak amplitude of the warming signal drops from 0.25 °C in the surface layers to less than 0.1 °C at 400 m. At depth, differences between the basins become more pronounced; convection carries the warming signal to greater depths in the actively convecting basins (North and South Atlantic).

6. Anthropogenic signal strength

At each level, we project the observed temperature anomalies $T(\mathbf{z})$ onto the model fingerprint $F(\mathbf{z})$ to calculate the anthropogenic signal strength S:

$$S = (F \cdot T)/\|F\|$$

where **z** is the concatenated space-time axis. We choose to normalize by *F* to retain units of Celsius, which are more easily understood by most people, and so that the projection can be sensibly compared in amplitude to the observed warming. A D&A result that finds a large mismatch in strength between model-predicted and observed change is unconvincing.

The signal strength as a function of depth for the two models we used, PCM and HadCM3, are shown in Figures 1c and 1d, respectively. The cross hatched regions show the 90% confidence interval of the signal strength in the long control run; the white dots are the observed signal strength; and the grey regions are the signal strengths in the anthropogenically forced runs. A clear D&A result is obtained in the upper part of the water column, consistent with our understanding of how the increase in greenhouse gasses and aerosols affect the ocean's surface heat fluxes.

7. Conclusion

Detection and attribution of ocean temperatures has some unique challenges related to climate model drift, the extreme sampling variability, and systematic biases in measurements. However the ocean warming signal is robust enough over the past 40 years (~0.3 °C in the surface layers) that a clean and highly significant D&A result is found in the ocean's upper layers (above 100 m). At deeper levels, the picture depends on the particular ocean basins considered; the North and South Atlantic, with their active convection, carry the warming signal to depths of 400 m or more, while no such signal is detectable in the Pacific Ocean.

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Human-Modified Temperature Induce Species Changes

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One of the main conclusions of the Third Assessment Report from Working Group II was that plants and animals around the globe were showing consistent patterns of detecting regional warming (2001b.) Using species to attribute of the regional warming to humans was not yet possible because the needed modeling still needed to be done. This was in part due to a perceived mismatch of scales; the scale at which robust modeled temperatures could be obtained from GCMs was assumed to be dramatically larger than the small scale at which most ecological studies occurred.

In 2005, Root and co-authors were able to attribute to humans the regional warming species detected at various locations throughout the northern hemisphere. The data used for this investigation came from 30 different studies occurring at a total of 42 different study areas. Included were 145 species that exhibited significant shifts in their spring phenology. Of these studies 83 provided actual temperature data for the study site and over the time period of the study. The strength of the associations between the actual temperature trends with the species trends were measured by correlations, and a frequency distribution of the 83 correlation coefficients was generated (Figure 1). This distribution provided the baseline information to which similar information obtained from modeled data could be compared.

Modeled temperature data were needed to quantify the strength of the associations between those modeled and actual temperatures. By doing this we were able to establish "...the most likely causes for the detected change with some defined level of **confidence**" (WGI definition of attribution in 2001a, and 2007 with emphasis added).

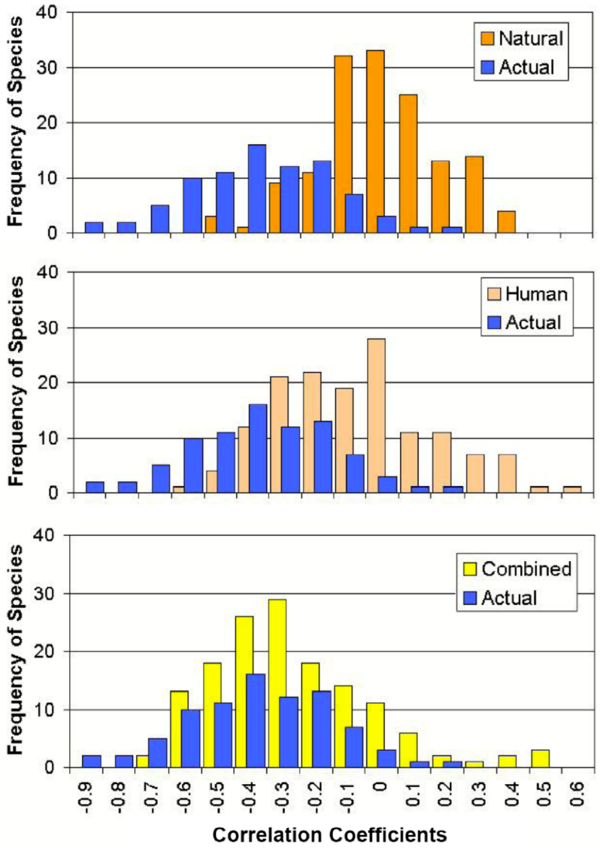
We used the HadCM3 GCM to derived three types of modeled temperatures: using only natural forcing, using only human forcing and using a combination of these forcing. An ensemble of four averaged runs for each forcing was used. These modeled temperature data were obtained for each grid box containing a study site. The season was defined as March, April and May, while the specific years included in the modeled data were tailored to match those of the particular species observed at the study site. The various studies ranged from 11 to 97 years, having a mean of 28 years. For each study site, the strength of the associations between the species trends and each of the three modeled temperatures were measured by deriving the correlation coefficients. (This work would have been significantly strengthened by using additional models, which is what we are now in the process of doing.)

We derived frequency distributions of correlation coefficients for each type of forcing. Each of these frequency distributions was then compared to that obtained using the actual temperatures (Figure 1). The stronger the overlap between the frequency distributions of a given modeled temperatures with that of the actual temperatures, the more variability is explained by the particular modeled temperatures (Figure 1).

If the associations between species trends and temperature data were random, we would expect the frequency of the species' correlation coefficients to be normally distributed around zero, which is roughly what we find when temperatures are modeled using natural forcing (Figure 1 top panel); the median correlation coefficient is 0.004. The frequency distribution of the correlation coefficients between species' data and temperatures modeled with only human forcing (Figure 1 middle panel) produces a less random pattern (median of -0.09). Finally, the frequency distribution of correlation coefficients between species' data and temperatures modeled with combined forcing (Figure 1, bottom panel) is strongly skewed to the left—a median of -0.31—due to the strongly negative phenological response.

The caveats for this type of investigation are many. For example, unpredictable factors, such as actual chaotic weather fluctuations, introduce stochasticity in climate models;

missing factors, such as land-use change, prevent the models from reflecting all influences on species; unavoidable approximations occur in the models; warming is not the only factor influencing phenological traits; and field observations are not without errors.



Despite the caveats, the observed spring phenological traits of plants and animals are most closely associated with HadCM3 temperatures modeled with both natural and human forcing. When taking separately, the association using only human forcing was stronger than that of only natural alone. These results provide strong quantitative evidence of attribution: humans are contributing to changing regional temperatures, which in turn are associated with changes in wild species. Consequently, climatic changes modeled at the grid-box scale and observed changes in wild species, are highly likely to be forced to a considerable degree by human emissions of greenhouse gasses and aerosols. In addition, these findings provide strong evidence that the HadCM3 GCM model has discernible predictive ability at the grid-box scale; the modeled temperature trends appear quantitatively similar to the actual temperature trends experienced by wild species.

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Detection and Attribution of Anthropogenic Climate Change in the Atmosphere from a Global Perspective

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The IPCC WGI Fourth Assessment Report (IPCC, 2007) came to a more confident assessment of the causes of global temperature change than previous reports and concluded that "most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations". It also concluded that "discernible human influences now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes and wind patterns. Since then, warming over Antarctica has also been attributed to human influence, and further evidence has accumulated attributing a wider range of climate changes to human activities. Such changes are broadly consistent with theoretical understanding, and climate model simulations, of how the planet is expected to respond.

The AR4 presented strong evidence that recent multi-decadal trends in global near-surface temperatures were very unlikely to have been caused by natural internal variability or natural external forcings from changes in solar output and explosive volcanic eruptions. Since then, the fact that neither 2007 or 2008 has broken the record for warmest year in the instrumental record has been used by some to claim that global warming has stopped or slowed down. However papers by Easterling and Wehner (2009) and by Knight et al. (2009), have demonstrated that decade long trends with little warming or cooling are to be expected under a sustained long-term warming trend, as a result of multi-decadal scale internal variability. These results underscore the importance of understanding the effects of variability, in addition to external drivers of climate.

Detection of the anthropogenic and natural fingerprints of near-surface temperature change has enabled robust observationally constrained quantification of the contributions of different forcings to global temperature trends and likely ranges of future warming, assuming particular emissions scenarios (Stott et al, 2006). By including multiple climate models to provide estimates of the uncertainty in response patterns, more comprehensive estimates of attributable changes are obtained (Christidis et al, 2009).

Theoretical understanding of how the hydrological cycle is expected to respond to anthropogenic warming is broadly consistent with what climate models predict and the changes observed to date. It is expected that the there should be a roughly exponential increase with temperature of specific humidity (Allen and Ingram, 2002) and anthropogenic influence has been detected in surface humidity (Willett et al, 2007) and in lower tropospheric moisture content (Santer et al., 2007), consistent with theoretical expectations. Global precipitation is expected to be constrained by the global energy budget (Allen and Ingram, 2002) and an anticipated consequence of moisture flux and transport changes is that wet regions should become wetter and dry regions drier (Held and Soden, 2006). An analysis of observed and modelled trends averaged over latitudinal bands has shown that anthropogenic forcing has had a detectable influence on observed changes in mean precipitation (Zhang et al., 2007). While these changes cannot be explained by internal climate variability or natural forcing, the magnitude of change in the observations is greater than simulated. This could indicate that climate models underestimate the real world's hydrological cycle sensitivity to global warming, although further analyses are required to determine whether this is the case. Further evidence that climate model could be under-sensitive come from the cryosphere, where few model simulations show trends in sea ice extent of comparable magnitude to observations (Stroeve et al., 2007).

Most formal detection and attribution analyses of sea level pressure have been restricted to individual seasons (e.g., Gillett et al., 2005) and while these studies all detected the influence of external forcing, none of them were able to separately detect the effects of anthropogenic and natural influences. A recent study (Gillett and Stott, 2009) analysed all 4 seasons and was the first to detect anthropogenic response independently of the natural response.

A framework has been developed for attributing individual extreme events in which the change in the probability of an extreme event under current conditions is calculated and compared with the probability of the event if the effects of particular external forcings, such as due to human influence, had been absent (Allen, 2003). It has been applied to show that the probability of seasonal mean temperatures as warm as those observed in Europe in 2003 had very likely at least doubled as a result of human influence (Stott et al, 2004). Attributing causes to changes in the frequency and intensity of hurricanes remains very controversial. While two studies (Santer et al., 2006; Gillett et al, 2008) have shown that human-caused changes in greenhouse gases are the main driver of the observed 20th-century increases in sea surface temperatures in the main hurricane formation regions of the Atlantic and the Pacific, the importance of the anthropogenic increase in sea surface temperature in the cyclogensis region for past and future changes in hurricane activity is still poorly understood (Vecchi and Soden, 2007).

The most robust attribution statements are to be expected when anthropogenic fingerprints as simulated by models are consistent with theoretical understanding and are detected in the observed record when internal variability and natural forcings of climate are also taken into account. While robust fingerprints are likely to be global in nature, their manifestation could have important regional differences, as is the case for surface precipitation. It will be important to evaluate confidence in the regional characteristics of such attributable changes. Attribution analyses of the hydrological cycle, the cryosphere and of circulation changes have shown evidence for models underestimating observed rates of change, although further work is needed to determine whether this is indicative of climate model deficiencies in representing an increasing rate of climate change.

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Annex 5: Bibliography

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