FUTURE CLIMATE CHANGE RESEARCH AND OBSERVATIONS:

GCOS, WCRP AND IGBP LEARNING FROM THE IPCC FOURTH ASSESSMENT REPORT

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ARC NESS	Australian Research Council Research Network for Earth System Science
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GCOS	Global Climate Observing System
Greenhouse 2007	
ICSU	International Council for Science
IOC	Intergovernmental Oceanographic Commission
IGBP	International Geosphere-Biosphere Programme
IPCC	Intergovernmental Panel on Climate Change
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NSW	New South Wales Government
UCC	Australian Universities Climate Consortium
UNEP	United Nations Environment Programme
WCRP	World Climate Research Programme
WMO	World Meteorological Organization

Future Climate Change Research and Observations: GCOS, WCRP and IGBP Learning from the IPCC Fourth Assessment Report

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Executive Summary

Learning from the authors of the IPCC Fourth Assessment Report and its findings to help guide future strategies for climate change observations and research was the key objective of a workshop organised jointly by the Global Climate Observing System (GCOS), the World Climate Research Programme (WCRP), and the International Geosphere-Biosphere Programme (IGBP) in Sydney, Australia, 4-6 October 2007.

Some 66 IPCC authors and other experts associated with the three international programmes discussed some fundamental climate change observation and research needs and challenges, based on gaps and uncertainties identified by IPCC Working Group I (The Physical Science Basis), and Working Group II (Impacts, Adaptation and Vulnerability) in their latest assessments. The starting point for this evaluation was the results of a survey of IPCC AR4 authors' and contributors' views on gaps and shortcomings identified in the most recent assessment.

In a sequence of plenary and break-out sessions, the workshop looked specifically at the gaps in observations and basic science raised by the IPCC, and at deficiencies in the way information about climate change can be used for estimation of impacts, design of adaptation measures, and assessment of vulnerability, particularly on the regional scale. Among numerous issues that limit our confidence in projections of climate change are our poor understanding of ice-sheet behaviour and its implications for sea-level rise, and gaps in knowledge about the hydrological and carbon cycles. Participants also agreed that vulnerability of regions and societies to climate change should be considered when framing future climate change research strategies and needs for additional observations.

The workshop also made suggestions on the research necessary to improve performance of regional climate change models. Better connections between global circulation models and regional models were identified as a major field of necessary action, as well as the need for enhanced cooperation between the climate modelling community and those involved in climate change impact assessment and response. In general, more rigorous validation of these models with observations of "essential climate variables" (considered feasible for global observation, and essential for IPCC and UNFCCC needs[1]) is required. Obtaining appropriate data to test regional models, including impact models, is a significant challenge however, particularly for developing countries. Research into regional climate change could benefit from the model intercomparison expertise built over many years in WCRP and IGBP – most recently refined in the Coupled Carbon Cycle Climate Model Intercomparison Project (C4MIP).

[1] *Second Report on the Adequacy of the Global Observing Systems for Climate in Support of the UNFCCC (GCOS-82, WMO/TD-No. 1143)*

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Future Climate Change Research and Observations: GCOS, WCRP and IGBP Learning from the IPCC Fourth Assessment Report

1. Introduction: Learning from the IPCC

1.1 Purpose of the Workshop

The purpose of the Workshop jointly organised by the Global Climate Observing System (GCOS), the World Climate Research Programme (WCRP), and the International Geosphere-Biosphere Programme (IGBP) in Sydney, Australia, 4-6 October 2007, was to learn from the authors of the IPCC Fourth Assessment Report and its findings to help guide future strategies for climate change observations and research. The recommendations from the Workshop were for consideration by the scientific/steering committees of the three international programmes, especially related to how to address the gaps and uncertainties in climate change science identified in the most recent IPCC assessment.

1.2 Background

The IPCC's periodic assessments of the state of understanding of causes, impacts, vulnerabilities and possible adaptation and mitigation strategies to climate change are the most comprehensive and widely-agreed surveys available on these subjects, and form the standard reference for all concerned with climate change in academia, government and industry worldwide. Many hundreds of international experts contributed to the IPCC Fourth Assessment Report (AR4). The Working Group reports and their summaries have received unprecedented attention by policymakers, scientists, industry, and the general public. The award of the 2007 Nobel Peace Prize to the IPCC (jointly with Al Gore Jr) recognises the outstanding impact of the IPCC.

The World Climate Research Programme (WCRP) and the International Geosphere-Biosphere Programme (IGBP) coordinate much of the evolving research that is assessed in IPCC reports. The observing systems which make up the Global Climate Observing System (GCOS) provide the long-term, high-quality climate data records and products that underpin climate change research, assessment and forecasting; the observational requirements for GCOS (including the 'Essential Climate Variables') are closely aligned with the needs identified by the IPCC and UNFCCC.

Taking the opportunity to derive maximum benefit from the lessons learnt from the AR4 for their respective future strategy, the scientific/steering committees of

- GCOS (co-sponsored by WMO, IOC, UNEP, and ICSU),
- WCRP (co-sponsored by WMO, IOC, and ICSU), and
- IGBP (sponsored by ICSU)

initiated a process whereby key scientists involved in the AR4 could review key gaps and uncertainties in research and observations that currently hinder our ability to detect, describe, understand, forecast, mitigate and adapt to climate change. The scientists also made recommendations for consideration by the scientific/steering committees of the three international programmes as to how to address these gaps and uncertainties. Consequently, this Report focuses on what is *not known* about climate change and on the barriers to improve our knowledge, rather than what is known; it furthermore tries to highlight key gaps and urgent needs in current research programmes and observing systems. It is also important to note that the IPCC considers climate change to include both natural and human-induced effects, since societies are affected by both.

It was envisaged that the steps in this process should be:

- A survey involving all IPCC AR4 WG I and WG II lead authors and Workshop participants, based on key gaps and deficiencies[2] identified in the IPCC AR4, leading to a survey summary paper circulated before the Workshop;
- A three-day Workshop during which the key gaps in the IPCC AR4 and those raised in the survey were debated, leading to this Workshop Report, circulated to all participants, projects, working groups and panels associated with the three programmes;
- Consideration of this Report by the GCOS, WCRP and IGBP steering committees, projects working groups and panels as part of their respective processes for identifying needs and priorities for future climate change research and observations.

This Report is structured following the topics discussed at the Workshop, and the survey-based analysis of shortcomings in the material assessed by IPCC WG I and WG II (summarized in boxed text throughout the Report, and in Appendix B). The Report deals with Climate Change Prediction Capabilities for Adaptation, Identifying Vulnerability through Assessment of Impacts, Adaptation and Risk, some key Science Issues underlined by the Workshop, Regionalisation of Climate Models, and finally the issues of Interfacing Climate Change Science with Policy and the Expression of Uncertainty. In the final section, the Report reflects ideas raised by Workshop and survey participants' for consideration by the IPCC regarding its mode of operation for future climate change assessments. Appendix A contains a factual account of the discussions and presentations at the Workshop.

Throughout the Report, some potential agents for follow-up action (including but not limited to those represented at the workshop) have been identified, while recognizing that other agents who have not been identified in this Report will also have an important contribution to make.

Inset into the text are boxes which are based on the pre-Workshop survey, listing some of the shortcomings identified in material assessable for IPCC AR4, and quoted responses from the survey. These boxes appear as follows:

EXAMPLE BOX

SHORTCOMING IDENTIFIED in ASSESSABLE MATERIAL FOR IPCC AR4:
[IPCC AR4 identified limitation or shortcoming]

SURVEY RESPONSES:
- Major reasons for this material not being assessable by IPCC AR4;
- Negative consequences of this;
- Possible solutions for this;
- Linked issues.

1.3 Identifying Emerging Climate Change Science Needs

Strengthening basic climate science for better understanding of fundamental processes in the complex climate system remains crucial, since it provides the foundation for better science on climate change impacts, adaptation and mitigation. Climate models continue to exhibit many uncertainties and deficiencies, and the development of improved models must be accompanied by a sustained, high-quality climate data record, which requires maintenance of long-term observational networks and systems. Actions to ensure this record and to move within 5-10 years towards a comprehensive global observing system for climate (underpinning all application areas, including climate change research) have been defined by the community in the GCOS Implementation Plan[3]. This Plan has been endorsed at the climate policy level (all Parties to the UNFCCC) and at the technical level (e.g., all GCOS co-sponsors, including WMO). Research planning for physical components of the climate

[2] *As given in the Technical Summaries of the IPCC Fourth Assessment WG I and II Reports (for full reference see Appendix B).*
[3] *Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (GCOS-92, 2004)*

system is guided by the WCRP Strategic Framework[4]. Correspondingly, the research strategy on the interactions between biological, chemical and physical processes and interactions with human systems is described in the IGBP Science Plan and Implementation Strategy[5]. This Report aims to further strengthen these plans and identify weaknesses revealed by the IPCC AR4.

The IPCC AR4 has significantly increased the demand for climate change science (research and observations) and increased the emphasis on impacts, adaptation and mitigation. This society and policy-driven need unfortunately arises at a time when investment in sustained climate observations, detailed climate change analysis, understanding the knowledge demands of decision-makers and validated climate predictions has not kept pace with the urgent and increasing demand for information. In this context, this Report identifies and discusses some of the challenges to meet the needs for research and observations that underpin approaches to both mitigation of and adaptation to climate change.

The Workshop and the preceding four-month process undertaken by the GCOS, WCRP, and IGBP Secretariats have resulted in recommendations for:

- Guiding principles for setting future strategic priorities in climate change research, including a mechanism for a rolling review of climate change research priorities, based on societal needs;
- Urgent needs for climate research, and needs for enhanced observations in addition to those described in the GCOS Implementation Plan.

Concerning the guiding principles**,** the Workshop provided recommendations for GCOS, WCRP, and IGBP in setting and updating future climate change research and observation needs. They include:

- Addressing the key science areas needed to further understanding of the climate system, and improving predictive capability;
- Including consideration of vulnerability in framing climate change research and observations;
- Ensuring effective links between global/regional modellers, and the communities involved in the assessment of impacts, adaptation and vulnerability;
- Ensuring the development of climate predictions for the next 10-30 years to complement longer-term projections;
- Addressing the need to effectively communicate uncertainty estimates for all information provided;
- Ensuring continuity of the climate record while incorporating new requirements derived from the research community.

The critical importance of societal needs and the requirement for the research community to address these needs more effectively was raised several times in the Workshop. A possible mechanism for the rolling review of climate change research priorities discussed during the Workshop is described in Section 3. In there, Fig. 1 describes a potential link between society-relevant climate change issues, activities required to address these issues, and related policy responses.

During the Workshop, it became clear that many of the urgent needs identified in the IPCC AR4 are already included within existing plans of GCOS, WCRP and IGBP, and these existing plans remain essential to the advancement of climate science. It is important to note that this Workshop, in addressing urgent needs, did not detail all the observation and research activities that are well-established; recommendations in this Report should therefore not detract from the value of these unmentioned activities. The emerging climate change science needs that were identified and detailed do include some already implicit in existing plans, as well as additional challenges.

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[4] *WCRP Strategic Framework 2005-2015 (WCRP-123, 2005)*

[5] *IGBP Science Plan and Implementation Strategy (IGBP Report No. 55, 2006)*

The urgent needs addressed at the Workshop include:

- Identification of regions where society is most vulnerable to climate change ("climate hot spots");
- Identification of thresholds beyond which potentially "dangerous" changes (to society) will occur ("climate tipping points")
- An authoritative set of information at the scales relevant for adaptation policy;
- Better understanding of ice-sheet dynamics;
- Impacts, adaptation and vulnerability communities' needs for research and observations, and addressing these needs based on current capabilities and prospects;
- Better regional information on past and future climate change;
- Methodologies to define, determine and communicate uncertainties and limitations in regional observations and model products in a context-sensitive manner;
- Quantification of radiative forcing due to aerosols and clouds by comprehensive model-model and model-observation comparisons;
- Better understanding of the hydrological cycle, especially convection and precipitation processes;
- Ensuring sustained observations of the oceans and the land surface;
- Continuity of key satellite missions for climate;
- Ensuring analysis, reanalysis and reprocessing of all climate data, with attention to observing system changes.

It was also noted that ongoing research and observations should provide the scientific basis for a climate information service for decision-makers.

Further recommendations and greater detail can be found in the relevant chapters.

Note that the issues discussed in this Report largely reflect the science fields covered by Workshop participants, the discussions at the Workshop, and responses to the pre-Workshop survey. This Report is thus not exhaustive. Those aspects of climate change science that were inadequately discussed need further attention.

2. Understanding and Predicting Climate Change for Adaptation

2.1 Building an Information Base for Adaptation

The climate will continue to change substantially from human activities over the next several decades, so that adaptation will be essential. An imperative and essential first step is to provide the scientific basis for a *climate information system* that informs decision-makers about what is happening and why, and what the immediate prospects are.

Aim: The proposed climate information system should include:

- Observations which ideally should come from observing systems that satisfy the GCOS Climate Monitoring Principles and address at least the Essential Climate Variables;
- a performance-tracking system;
- effective data access, management and stewardship; the analysis and reanalysis of observations and derivation of products;
- assessment of past climate change and its attribution, including likely impacts on human- and eco-systems;
- prediction of near-term climate change over several decades;
- longer term projection to 2100 and beyond;
- mechanisms to respond to decision-makers and other users.

Recommended Activities (potential lead agents: GCOS, WCRP):

- Collect data on changes in climate and on external forcings;

- Attribute the reasons for these changes and uncertainties. Note that any attribution activity is fundamentally about the science of climate predictability, including the predictability of climate variability (e.g., ENSO, seasonal variability), as well as long-term climate change (indeed, understanding and attributing past climatic conditions would seem to be a prerequisite to making any climate prediction). The central goal is to understand the causes of observed climate variability and change, including uncertainties, and to be able to 1) use this understanding to improve model realism and forecast skill and 2) to communicate this understanding to users of climate information, including the general public;

- Attribution should include research to determine the extent to which recent conditions could have been predicted, given the state of conditions at the lower boundary of the atmosphere, such as the observed sea-surface temperatures (SSTs), soil moisture, and snow cover. More broadly, it should also seek to explain the evolution and current status of the Earth system, including those factors that have served to determine the current pattern of SSTs and soil moisture. With improved models comes the ability to attribute climate events that could not be attributed in the past.

Individual researchers may have understanding and capabilities far ahead of what is given in consensus assessments. Accordingly, both attribution steps should take account of model shortcomings and should employ empirical (e.g., statistical) evidence, which can be more compelling. This effort will require significantly expanded computer resources for ensemble simulations and for simulations that have sufficient resolution for regional-scale climate attribution (e.g., droughts, hurricanes, floods).

The development of this climate information system potentially takes on, in a more operational framework, a key part of what is currently done as part of the IPCC assessment process. There are many research questions on how to develop such a system, and what such a system must include in order to be viable. GCOS and WCRP could play a major role in addressing these issues, noting that this would require adequate new funding.

The related follow-on activities described below aim to improve climate models and their initialization fields, to allow for credible ensemble predictions that cover the next ~30 years.

2.2 Confronting Models with Observations

It is desirable to confront models with a variety of observational evidence in order to interpret observed historical changes in the climate system, and to have confidence in projections of future change. The AR4 demonstrated that there is now a relatively good understanding of the causes of surface temperature changes observed over the 20th century on both global and continental scales. Our understanding of temperature change on these scales is such that we are able to attribute their causes with relatively high confidence. In fact, to quantify the contributions to observed change of the main external influences that are thought to have influenced climate over the past century. However, our ability to interpret change in most other impact-relevant variables (such as circulation change, precipitation change, and changes in extremes of various types) remains much more limited. Detection and attribution research provides one model metric (amongst others) with which to assess the skill of models in representing the climate system.

More generally, the AR4 revealed a pressing need to develop and apply a set of community-accepted model metrics that can be used to weigh the many different models contributing to the large ensembles

Recommended Activities (including potential lead agents):

Run ensemble simulations of historic 20th century climate using combinations of forcings and individual forcings (time frame of a possible fifth assessment report, coordinated by WGCM). Amongst other things, these simulations would provide initial fields for predictions for several decades into the future (see Section 2.3)

1. Focussed experimentation with climate models, including the use of protocols such as CFMIP (Cloud Feedback MIP) and Transpose AMIP (Atmospheric Model Intercomparison Project) , that is designed to isolate the causes of specific and persistent model biases at the process level (by 2015, coordinated jointly by WGCM (WCRP Group on Coupled Modelling), WGNE (WCRP Group on Numerical Experimentation));

2. Develop a collection of objective climate model metrics, agreed upon by the modelling and user communities, designed to reveal the models' ability to:
   - Simulate the annual cycle;
   - simulate climate variability as observed during the 20th century, including the main modes of climate variability, on scales from hours (diurnal) to decadal;
   - simulate the mean 20th century climate and its evolution (as a boundary forcing problem);
   - produce short-term weather predictions across a number of individual cases (i.e., an initial value problem);
   - predict the short-term evolution of the climate system over the satellite period (i.e., as an initial value /boundary forced decadal prediction problem);
   - simulate the features of the longer-term historical evolution of the climate system as estimated from palaeoclimatic datasets of, for example, the last millennium, the last glacial maximum, or the mid-Holocene (~6000 years before present).

SHORTCOMING IDENTIFIED in ASSESSABLE MATERIAL FOR IPCC AR4:
Limitations in ocean sampling imply that decadal variability in global heat content, salinity, and sea level changes can only be evaluated with moderate confidence; Lack of studies quantifying the contributions of anthropogenic forcing to ocean heat content increase, together with the open part of the sea level budget for 1961–2003

SURVEY RESPONSES:
Major reasons:
- Lack of understanding of fundamental processes
- Temporal/spatial coverage of observations; observing technology; data access
- Past decades: poor 3-D spatial coverage of temperature (T) and salinity (S); in recent years : inhomogeneities between different sensors (e.g., XBT and ARGO)

Negative consequences:
- Major uncertainties in quantifying the anthropogenic contribution to sea level rise
- Insufficient initialization of coupled atmosphere-ocean models, also in view of estimating decadal variability
- Little confidence in the regional distribution of sea-level rise

Possible solutions:
- Generation of homogeneous, well-calibrated global/regional sea level datasets (from satellites and *in situ*), with more systematic treatment of the biases, supported by sustainable reference measurements (e.g., use of several sources of independent information on steric sea level change); more research on the origin of regional variability and decadal fluctuations of ocean heat content
- Lack of global information on land water storage effects (of climate and anthropogenic origin) on sea level change
- Ensure ARGO network is maintained at the present density or greater and yields homogeneous data for >50 years
- Via ocean modelling (assimilation of existing T,S data in OCGMs)

2.3 Decadal Climate Prediction for Adaptation Decision Support

Running atmospheric general circulation models (GCMs) with specified sea-surface temperatures has often produced improved understanding of past climate anomalies. For instance, the Sahel drought and the "Dust Bowl" period of drought in the United States in the 1930s can be simulated in this way. It is essential to have the patterns of SSTs around the globe simulated accurately, and it is clearly not possible to make corresponding predictions without first initializing ocean properties and other key climate parameters. The extent to which accurate initialization leads to predictability is not yet clear, but there is sufficient predictive skill available to be useful for, e.g., adaptation.

On a 30-year time frame, climate predictions are effectively insensitive to the details of long-lived greenhouse gas emissions scenarios (because all follow essentially the same trajectory in this time frame). Hence, this aspect can be largely removed from considerations here. However, forecasts on this time frame would be exceedingly valuable. Therefore, climate (change) predictions are needed to provide information on a 0-30 year time scale, and they must be accompanied by estimates of uncertainty (via ensemble runs; the impact of volcanic eruptions remains an issue) and estimates of sensitivity to errors in model initial conditions. Such an exercise would also lead to improved models through regular testing against data, as noted above.

The results would have direct applications where impacts and adaptation considerations operate on the spatial and temporal scales of predictability (decadal, 1000's km, intermediate ocean), including factors such as living marine resources, ice-sheets, sea level, and meridional overturning circulation of the ocean. This activity would feed directly into the need to provide boundary conditions for downscaling and adaptation-science relevant projections, resulting in probability distributions for all fields of interest.

Recommended Activities (potential lead agents: WCRP, IGBP, IHDP, DIVERSITAS, GCOS):

1. Carry out model experiments to quantify predictability and test processes relevant to models; undertake systematic errors/model intercomparisons;

2. Assemble, quality-check, reprocess and reanalyse datasets relevant to decadal prediction
   - Sea level and heat content data highest priority; SST;
   - Salinity data, particularly for high-latitudes;
   - Intermediate-deep ocean data, with emphasis on Southern Ocean, Northern Pacific;
   - Sea ice;
   - Soil moisture, precipitation, and other hydrological variables;
   - Tropical cyclones;
   - Surface winds.

3. Define experimental framework:
   - Multiple runs with high resolution – ensemble 1;
   - Many runs with lower resolution, same/similar initial conditions – ensemble 2;
   - Different start times, such as 1960, 1980, 2005 to assess how much predictability arises from initial conditions versus boundary forcing;
   - Several models – multi-model ensemble;
   - Different models but with the same initial conditions;
   - Reanalysis, for understanding errors, processes, systematic errors.

4. Testing – metrics
   - Systematic tendencies e.g. in heat content, sea level – signal;
   - Modes of variability – PDO, El Niño, MJO, SAM, NAO, etc. – relative skill;
   - Integrated measures – strength of gyres, sea level.

5. Diagnostics: Inferred Extremes
   - environmental conditions/indices as indicators of Tropical Cyclones (SST gradients);
   - El Niño related extremes;
   - Storminess indices related NAO, etc.;
   - Blocking.

6. Operational attribution, as given above.

3. Identifying Vulnerability through Assessment of Impacts, Adaptation and Risk

URGENT NEEDS:

- Identification of an authoritative set of information needs for adaptation policy;
- Identification of the research and observation needs of the impacts, adaptation and vulnerability communities, and addressing these needs based on current capabilities and prospects;
- Identification of regions where society is most vulnerable to climate change (“climate hot spots”) for better-targeted regional adaptation (see Section 5).

Anthropogenic changes in the composition of the atmosphere have committed humankind to climate change impacts over at least the next two to three decades. Therefore, addressing the issue of adaptation has now become a matter of urgency. Adaptation will involve the investment of significant financial and human resources, and require effective engagement with decision-makers in government, industry and other sectors. Collectively, the community will have to decide where to make such investments. Impact and adaptation studies and their interpretation in terms of risk for societies broaden the scope of data and process knowledge required by incorporating, for example, a wider variety of environmental and human variables. The resulting complexity needs to be reduced through wide agreement on a limited set of key variables which are most relevant for the development of effective adaptation measures by decision-makers (see Section 3.1).

One option is to frame climate research from the perspective of vulnerabilities, which are a product of the sensitivity (or response function) of societies and ecosystems to particular climate changes, the anticipated exposure to these changes, and the adaptive capacity of the system or region being impacted.

Vulnerabilities can be derived from both top-down or bottom-up methodologies:

- Top-down: Starts with the development of harmonized scenarios used in climate and other models to derive potential impacts (this requires new scenarios (see Section 3.2) and response functions (see Section 3.3));
- Bottom-up: Recognises that there are other stresses on societies besides climate change, and relies on an engagement of eventual users and decision-makers (this requires sub-global approaches (see Section 3.3)).

SHORTCOMING IDENTIFIED in ASSESSABLE MATERIAL FOR IPCC AR4:
Synergies exist between adaptive capacity and sustainable development of societies, and further research is required to determine the factors which contribute to this synergy, and how policies to enhance adaptive capacity can reinforce sustainable development, and vice versa

SURVEY RESPONSES:
Major reasons:
- Insufficient application of climate analyses to societal needs
- Challenge to transfer experience gained in adapting to climate variability to adaptation to climate change (thereby selecting sustainable pathways)

Negative consequences:
- Unnecessary disconnect between policies related to sustainable development, and policy measures related to adaptation, since "actions to cope with the impacts of climate change and promote sustainable development share such common goals and determinants as access to resources (including information and technology), equity in the distribution of resources, stocks of human and social capital, access to risk sharing mechanisms, and abilities of decision-support mechanisms to cope with uncertainty" (AR4 WG II Report, Chapter 20)

Possible solutions:
- Determine both the factors that constrain and/or contribute to this synergy

Both top-down and bottom-up methodologies have their advantages. Their implementation requires an intensive dialogue between the research and systematic observation communities with users engaged in both methodologies (encompassing all activities in Fig. 1). Existing mechanisms and institutions need to be engaged, some of which may not yet be actively dealing with climate change issues, and appropriate capacity needs to be built. Maximum benefit will be gained by focusing on an array of regions that encompass diverse sensitivities to climate change and different social systems.

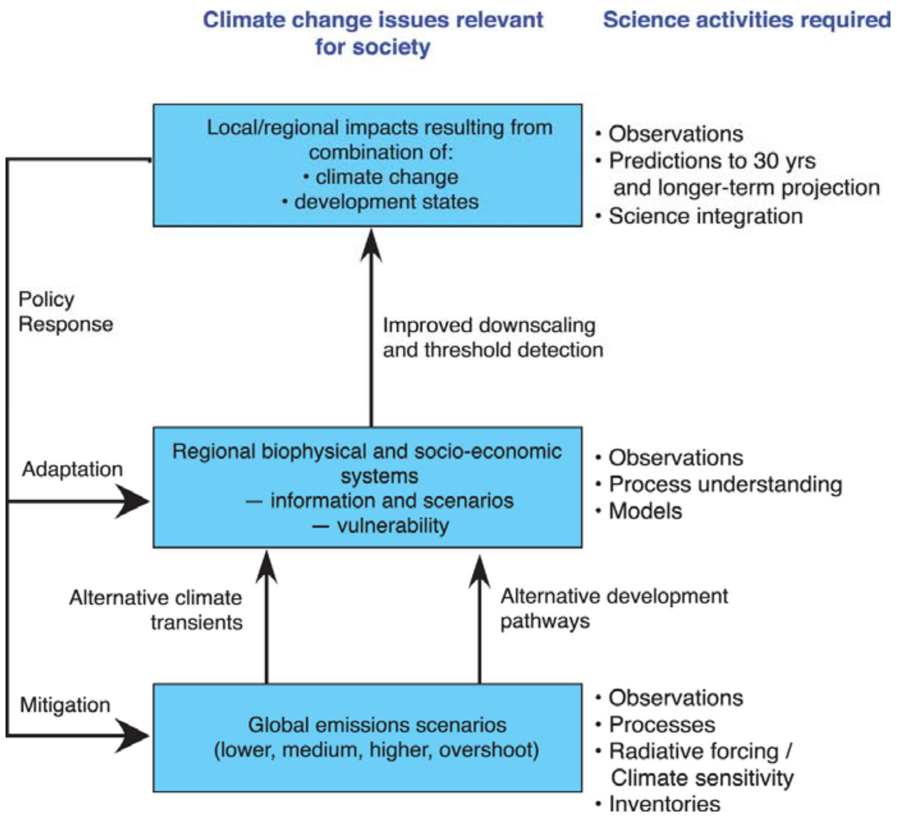

Fig. 1: Society-relevant climate change issues (boxes), science activities required to address these issues (right), and policy responses (left).

3.1 Understanding and Informing the Adaptation Process

3.1.1 Defining User Needs

Rationale: Much effective adaptation to climate change is at the local and regional scale, and information provided in order to plan for adaptation has to be tailored appropriately. Current approaches to adaptation science are generally case-specific and confound autonomous and planned adaptation.

While it is not argued that there can be a single set of universal indicators, contextual diversity and detail pose a challenge, e.g. differences in adaptive capacity to cope with climate change impacts among nations. Experience suggests that a limited set of information will support the majority of decisions in most places; this could significantly improve decision-making over the next few years, recognising that there will be additional local needs that become clearer over time. The time is now ripe to define an authoritative set of information measures, but this requires a systematic dialogue in order to obtain general agreement.

Vulnerability of regions and societies to the impact of climate change provides a possible framework to enhance the dialogue between urgent needs for climate science and relevant policy issues (shown schematically in Fig. 2).

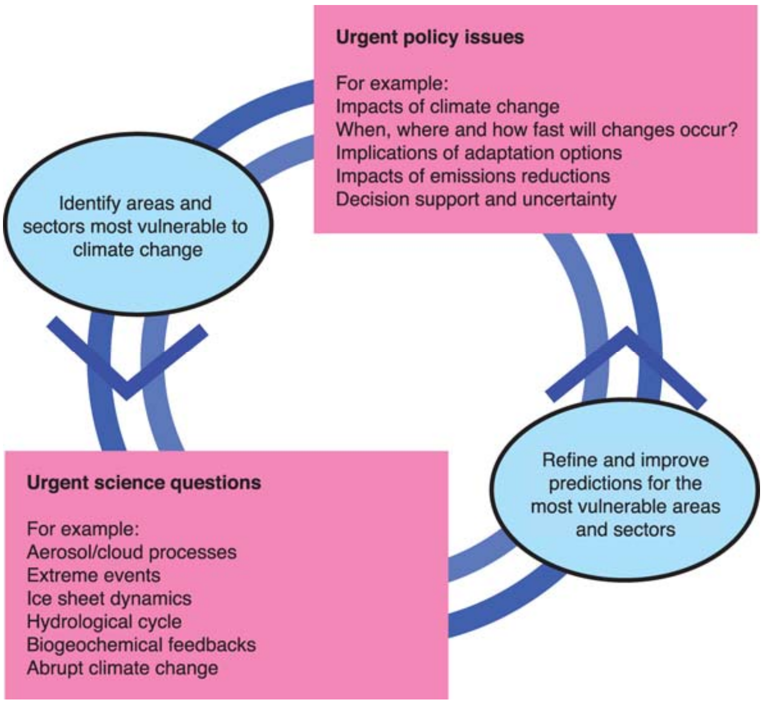

Fig. 2: Using vulnerability of regions and sectors to climate change as a possible framework to link urgent science questions with societal concerns.

Collation, systematisation and generalisation of a series of local case studies covering a diversity of climatic, environmental and socio-economic contexts is therefore required. An increasing understanding of what determines and supports human adaptive capacity is also required; this knowledge will emerge from these local case studies, but can also be supported by analyses of historical adaptation to environmental change. Results emerging from these analyses will help to prioritise the authoritative set of adaptation indicators.

Aim: To define an agreed and authoritative set of information needs, including the assessment of scientific and technical capabilities (see Section 2), through a structured dialogue, and to improve understanding of adaptation capacity. This will define what indicators and information will be needed to support adaptation in response to vulnerability.

Recommended Activities (potential lead agents: ESSP, with links to IHOPE, for dialogue; GCOS with ESSP and adaptation/vulnerability community for observations):

Identify and move towards an authoritative set of information needs for adaptation. The first steps are:

- Take a few well-studied case sectors (e.g., coastal zones, Asian mega-deltas, subsistence farms, urban centres, small islands, polar regions) with broad geographical representation, and establish a dialogue between the human dimension community and the research and observation community to a) establish a framework of classes of decisions to be made, b) identify a core set of common data needs, and c) determine how these must be communicated. These data needs should reflect both national-scale policy concerns, and more local sectoral management needs;
- Determine the datasets/variables required to detect, understand and monitor vulnerable systems and changes in these systems – including both biophysical and human dimensions measures – and assess the adequacy of existing observing systems to address these needs (see e.g., Sections 2 and 4.6);
- Assess what additional mechanisms are needed to ensure data accessibility, generation of user-tailored products and analyses derived from these systems;
- Produce short and long-term recommendations to IGBP, WCRP and GCOS on observational needs, with vulnerability as a focusing concept;
- Note that enhanced (geophysical) observations are often, but not necessarily needed in the areas of highest vulnerability, e.g., in the case of more detailed observations of ice sheets (which are required in order to better predict sea-level change and its impact on vulnerable low-lying coastal areas);
- Infer past human adaptive capacity to climate by combining historical datasets with palaeo-environmental data (with commensurate biophysical and socioeconomic data);
- Establish a system for monitoring autonomous and planned adaptation as it occurs and evolves over time.

SHORTCOMING IDENTIFIED in ASSESSABLE MATERIAL FOR IPCC AR4:
Large area long-term field studies are required to evaluate observed impacts of climate change on managed and unmanaged systems and human activities

SURVEY RESPONSES:
Major reasons:
- Temporal/spatial coverage of observations: high-quality observations essential for full understanding of causes and attribution of present-day trends to climate change; to validate the models that are used for prediction, and to provide initial conditions for climate prediction on scales at least up to the decadal
- Lack of documentation and access to – particularly for the southern hemisphere – of what relevant datasets already exist

Negative consequences:
- Lack of understanding of where and when impacts become detectable, where the hotspots lie, and why some areas are more vulnerable than others

Possible solutions:
- Need for regional, long-term monitoring and field studies, particularly in vulnerable (hot spot) areas of Asia, Africa, Latin America and small islands, based on rigorous risk assessment
- Increased investment into remotely-sensed observations of temperature, humidity, clouds, altimetry, gravity and trace gases; *in situ* observations of the oceans and on land

Linked issue:
- Long-term ecological and agricultural field studies are generally

The process identified in the first step needs to be iterative in the long term, and could form the basis of an ongoing two-way dialogue between policy and science about what kind of information is needed for adaptation, and what research and observations can provide.

3.1.2 Filling the Gaps in Observed Impacts

Rationale: The Summary for Policymakers of the IPCC WG I states that warming of the climate system is now unequivocal. For policymakers, it is important to understand whether and how this warming is affecting physical, natural and human systems. Working Group II of the Fourth IPCC Assessment Report went some way towards making this connection but could not be conclusive, partly because of lack of data coverage (see also Section 2). The next phase of data collation should attempt to begin to account for autonomous or planned adaptation, potentially by comparing results from regions with different adaptive capacities.

Aim: Obtain and improve access, and analyse with respect to warming trends, time series for physical and natural variables (a) from outside Europe and North America, and (b) of human activities and socio-economic conditions.

Recommended Activities (potential lead agents: GCOS, IGBP, IHDP):

- Search for, document and make accessible datasets in areas of low data coverage (see map in Chapter 1 of AR4 WG II). Combine this search with mentoring and capacity building;
- Analyse these new datasets to enhance understanding of observed impacts of climate change on selected natural systems. This would enable improved detection and attribution of climate change impacts and understanding of whether the rate of climate change impacts is accelerating or is faster than was given in the Third IPCC Assessment Report (TAR). This work would also improve the evaluation of relevant impact models;
- Develop, test and apply techniques for attributing climate change impacts.

3.2 Needs for Harmonised Scenarios and More Interdisciplinary Engagement

The current IPCC SRES[6] scenario approach is based on a series of greenhouse gas emission scenario storylines ("narratives") making a range of assumptions about future energy use, land use and other human activities which are then implemented in integrated assessment models. This results in a strong quantitative approach that allows calculation of concentrations, radiative forcing and climate change. The resulting projected trends in CO_2 concentrations and climate are used to estimate impacts, which, in turn, are used to identify adaptation options and their effectiveness. By comparison, the current impacts and vulnerability assessments are based on a plethora of different socio-economic and environmental (including climatic) baselines combined with different scenario approaches. Often, these assessments do not use the range of SRES scenarios. Additionally, different downscaling methodologies, periods and spatial and temporal resolutions are used. This makes the comparison between different studies extremely difficult. Only very few studies (e.g., Advanced Terrestrial Ecosystem Analysis and Modelling (ATEAM)) have developed a systematic approach to applying scenarios for different sectors. An additional limitation of SRES applications is that many impact, adaptation and vulnerability studies do not consider the impacts on and vulnerabilities of societies and ecosystems implied by the scenario storylines themselves.

The Millennium Ecosystems Assessment (http://www.millenniumassessment.org/en/index.aspx) has used a different, more qualitative scenario approach. Their scenarios were developed for evaluating different approaches to managing ecosystem services, based on narratives. These narratives proved essential in

SHORTCOMING IDENTIFIED in ASSESSABLE MATERIAL FOR IPCC AR4:
Existing research* [on vulnerability and adaptation] *has emphasized the global scale, and studies, which are disaggregated to the regional/local scale, are urgently needed

SURVEY RESPONSES:
Major reasons:
- Lack of linking between IPCC Working Groups
- Previous studies focused more on temperature rising and impact, and less on stabilizing emissions

Negative consequences:
- Still very limited interest on climate change by national policymakers; regional and local information may provide greater incentives to national policymakers
- Vulnerabilities to climate change depend considerably on specific geographic, sectoral and social contexts. Therefore, global estimations of avoided damages are not reliable
- Research on vulnerabilities and adaptation potentials of human systems has lagged behind research on physical environmental systems

Possible solutions:
- Provide estimates of damages avoided by different levels of emissions reduction at key geographic and sectoral scales (e.g., city, industry, transportation), including more reliable cost estimates
- Collaborative research between scientists from the north and the south
- Link stabilizing emissions to temperature rise; assess the impacts for different emission levels
- Studies on the critical importance of reducing or stabilizing emissions are especially relevant at the national and local levels – we require a more accurate understanding of the constraints to curbing emissions given by such factors as the speed (30 to 50 years) at which new technologies can be designed and deployed
- Need multi-scale, multi-disciplinary and multi-institutional studies with a hierarchy of models designed by advanced cooperative meetings of all significant players – more like the IPCC SYR model than the disciplinary working groups model used so far

Linked issues:
- Develop financial thresholds regarding the insurability of climate change impact risks
- Vulnerability and adaptation have frequently been analyzed in isolation from other stressors (e.g., air pollution, human-induced water scarcity) from which climate variability and change are but one

[6] *SRES: Special Report on Emissions Scenarios, the terms of reference of which call for the use of multiple models, seeking inputs from a wide community as well as making scenario results widely available for comments and review.*

translating the coarse global drivers towards regional and local drivers in a consistent way.

These examples show that there is a large need for consistent guidelines for applying a harmonized set of scenarios, including baselines and policy scenarios. The advantage of using harmonized scenarios will be the urgently-needed comparability and consistency between studies for different sectors, regions and periods. This will allow for a comprehensive synthesis of impacts, vulnerabilities and adaptation options.

An additional, increasingly urgent need is to facilitate the engagement of a wider range of research disciplines in the assessment of vulnerability, impacts and adaptation. The scope and character of climate science, with its particular focus on the modelling of future change and the intrinsic uncertainties that this entails, often appears complex, unfamiliar and/or inaccessible to other as-yet unengaged disciplines. This applies at varying levels across the broad domain of social sciences, with their interest in understanding the impacts of climate change on livelihoods, social stability, community functioning, population displacement, conflict situations, wellbeing, health and survival.

Recommended Activities (potential lead agents: ESSP and IGBP-AIMES):

- Address the need for consistent guidelines for applying a harmonized set of scenarios;
- Facilitate the engagement of a wider range of research disciplines in the assessment of vulnerability, impacts and adaptation; one component of this should be an effort to build reference scenarios in order to ensure consistency between the climate and impacts, adaptation and vulnerability assessments.

3.3 Quantifying Impacts and Vulnerability

3.3.1 Quantifying Impacts

Rationale: For effective adaptation and mitigation activities and related policy-making, reliable information on the nature of climate change impacts is required, including for example timing and magnitude. Integrated Assessment Models must contain appropriate climate impact response functions based on this information.

Aims:

- The ability to better quantify climate change impacts over time, e.g., precipitation changes (cf. Figs. TS3 & 4 in the AR4 WG II report); in order to do this, a wider range of response functions as a function of the magnitude and rate of climate change need to be defined;
- Response functions are also needed in Integrated Assessment Models, including economic integrated assessments. For this, reasonable estimates of response functions at regional as well as global scales are needed;
- Ability to estimate economic costs and benefits of adaptation and mitigation options, including the cost of no action;
- Response functions should, where possible, incorporate understanding of thresholds.

Recommended Activities (potential lead agents: IGBP, Diversitas, IHDP, WHO, as well as many international bodies such as FAO (for response functions) and GCOS (for datasets)):

- Define the range of processes for which response functions are needed (e.g., number of species at risk, area of reef lost, number of people with water and food security);
- Define a core set of international metrics related to what might be concerns about “dangerous” climate change’ (see AR4 WG II Table 19.1 and the set of metrics and categories behind this), supplemented by metrics of interest to nations. This definition requires a dialogue between the science and policy communities. It is worth noting that some of the emerging factors will be important not only in the context of impacts, but also for feedbacks to the climate system;

- Understand the processes by which individual changes are taking place, in order to determine whether regional responses can be generalised. Studies will be needed to fill in the response functions that are not well known, starting from reviewing what is known;
- Build adequate datasets to extrapolate from regions with good data and knowledge, to global responses with regional resolution. This requires well-defined, readily-available data and metadata;
- Better quantify climate change impact on a regional scale in the context of emission scenario storylines. These impacts need to be made sector-specific, and need to contain information to enable determination of equity.

SHORTCOMING IDENTIFIED in ASSESSABLE MATERIAL FOR IPCC AR4:
The literature on costs of impacts, adaptation costs and benefits is limited and fragmented. It focuses on sea level rise and agriculture, with more limited assessments for energy demand, water resources and transport. There is an emphasis on the US and other OECD countries, with only a few studies for developing countries

SURVEY RESPONSES:
Major reasons:
- Insufficient application of climate analyses to societal needs; linkage of climate applications to socio-economic data

Negative consequences:
- Limited knowledge about costs of impacts, adaptation costs and benefits, especially in developing countries

Possible solutions:
- Improve support for research that transcends boundaries, particularly in developing countries, including social and human sciences
- Multi-scale, multi-disciplinary, multi-institutional research with stakeholders, governments and business getting together using case studies to focus the work and inviting good theoreticians (generalists) to see what "rules" might emerge at more than local scales

Linked issues:
- More resources needed to fund this research, since external funding of indigenous capacity is usually not sustained

3.3.2 Quantifying Vulnerabilities

Aggregate analyses synthesize climate change impacts and vulnerabilities in an internally consistent manner, using relatively comprehensive global indicators or metrics (often expressed in US dollars, or changes in vegetation cover). This enables direct comparisons of impacts among sector systems and regions, and with other costs due to, e.g., environmental problems and emission control measures. However, disaggregated analyses provide impact and vulnerability assessment tailored to regional or sectoral specifics. Integrated Assessment Models provide a means of structuring the enormous amount of and often conflicting data available from disaggregated studies.

Rationale: Beyond the global-scale approach to addressing vulnerability, the need for aggregating on regional and national scales is recognised since different societies have different value judgements about what is perceived as vulnerable. Analyses at regional and national levels are needed, as well as bottom-up global aggregates built up from these (cf. current top-down global analyses, see Section 3 above).

Aim: Identify and quantify vulnerabilities globally over time with ‘regional’ resolution, engaging at the national level to obtain some ‘bottom-up’ understanding of values, but also provide tools for nations to assess their internal vulnerabilities.

Recommended Activities (potential lead agent: IHDP, in conjunction with ESSP projects):

- Develop globally appropriate measures for defining vulnerability hotspots, including both climatic and non-climatic factors, building on existing work (e.g., criteria in AR4 WG II report Table 19.1);
- Collate the data; identify vulnerabilities;
- Provide disaggregated data to countries; identify key vulnerability hotspots from each country and the metric of vulnerability.

4. Science Issues Underlined by the Workshop

While our understanding of the climate system and of climate changes improved considerably from the IPCC TAR to the AR4, critical gaps in aspects of climate research and climate observations remain. Gaps in scientific knowledge are discussed in detail in the AR4 WG I report. Here, the consideration is limited to deficiencies that lead to fundamental uncertainties in climate predictions/projections, in particular where these deficiencies inhibit determination of climate change impacts on societies. This framework requires not only a good understanding of and ability to forecast the “mean climate state” but also the possibility of the occurrence of high-risk, low-probability events, many of which relate to non-linear responses in the climate system.

In this context, key goals of climate research and observations remain to advance understanding of:

- What happened in the past?
- What is happening now?
- How to provide the most accurate estimate of the range of future climatic conditions, from seasonal to decadal to centennial and longer, regionally?

Basic climate science needs to continue to be developed (and be taken to a higher level of support) since climate models continue to exhibit a number of uncertainties and deficiencies, as highlighted in this section. The development of improved models must be accompanied by a sustained, high-quality climate data record.

4.1 Abrupt Climate Change

Abrupt climate change is defined as a large-scale change in the climate system that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades, and causes substantial disruptions in human and natural systems.

This summary considers progress in understanding four types of abrupt change that stand out in the palaeoclimate record as being so rapid and large in their impact that if they were to occur, they would pose clear risks to society in terms of our ability to adapt. These are: (i) rapid change in ice sheets and hence sea level; (ii) widespread and sustained changes to the hydrological cycle (see Section 4.2); (iii) abrupt change of the Atlantic meridional overturning circulation (AMOC); and (iv) rapid release to the atmosphere of methane trapped in permafrost and on continental shelves.

New palaeoclimate reconstructions have been developed that reveal and provide greater understanding of patterns and mechanisms of past abrupt climate change in the ocean and on land. These past changes demonstrate clearly that the climate system can and has reached points where change proceeds suddenly and non-linearly (“abrupt”). Further, new observations are revealing unanticipated rapid dynamical changes of ice sheets and ice shelves and are challenging our understanding about the processes that are contributing to these changes.

4.1.1 Ice Sheets

Recent rapid changes on the margins of the Greenland and West Antarctic ice sheets show an acceleration of flow and thinning of outlet glaciers, with some ice stream velocities increasing more than twofold. Some of these accelerations closely followed the reduction or loss of ice shelves which were brought on by atmospheric or oceanic warming.

This degree of acceleration and thinning was not predicted by the models *a priori*, and how much it scales with rising surface air and ocean temperatures is very uncertain. Regions likely to be sensitive to future rapid changes in ice volume are those where melt water is lubricating the base of the ice sheet or where ice is grounded well below sea level, such as the West Antarctic Ice Sheet, or large outlet glaciers in Greenland, like the Jakobshavn Isbrae.

This issue is addressed extensively in Section 4.5, where recommendations for research and observations are made.

4.1.2 Atlantic Meridional Overturning Circulation (AMOC)

The IPCC AR4 stated that the strength of the AMOC will very likely decrease over the course of the 21st century in response to increasing levels of greenhouse gases in the atmosphere, with a best-estimate decrease of 25%. However, it is very unlikely that the AMOC will undergo an abrupt transition during the course of the 21st century, and it is unlikely that the AMOC will collapse beyond the end of the 21st century because of global warming. The chances and consequences of this high impact/low probability event need to be better understood.

Recommended Activities (potential lead agent: WCRP):

- Establish and maintain long-term baseline reference networks for ocean quantities, particularly in the North Atlantic;
- Place a major effort on ocean data assimilation and now-casting;
- Improve resolution of ocean model components in global comprehensive models;
- Investigate ocean mixing processes and their parameterisation in coupled climate models;
- Explore parameter space of global models and search for possible thresholds.

4.1.3 Methane Release

An abrupt release of methane to the atmosphere appears very unlikely, but it is likely that climate change will accelerate the pace of persistent emissions from both hydrate sources and wetlands. Existing models suggest that wetland emissions could double in the next century, and this could be an underestimate primarily because of uncertainties in the evolution of northern hemisphere wetlands as climate changes. Acceleration of chronic release from hydrate reservoirs is expected, but its magnitude is difficult to estimate.

A lack of understanding about the fundamental drivers controlling atmospheric methane concentrations is demonstrated by recent decreases in the growth rate of atmospheric methane, which were not predicted and that are not understood. It is unclear if this observation is caused by errors in estimated emissions and/or by in-atmosphere processes. Better understanding of how emissions might change and how atmospheric and ecological processes affect atmospheric concentrations is needed.

> *SHORTCOMING IDENTIFIED in ASSESSABLE MATERIAL FOR IPCC AR4:*
> ***The causes of recent changes in the growth rate of atmospheric methane are not well understood.***
>
> *SURVEY RESPONSES:*
> Major reasons:
> - Lack of understanding of fundamental (biogeochemical) processes
>
> Negative consequences:
> - Lack of understanding of methane as a key GHG
> - Risk of possibly large methane releases in the future unclear
>
> Possible solutions
> - Establish and maintain long-term baseline reference networks for methane with appropriate global coverage (including data harmonization)
> - Process level studies, combined with long-term observations, with comprehensive physical and chemical modelling to understand the variations in present-day; uncertainty analyses from emissions to tropospheric chemical reactions to the spatially-dependent concentrations; this to be followed by parameterizations applicable in biogeochemical-climate models
>
> Linked issues:
> - Space-based observation of some atmospheric constituents may be poorer in the next decade than in the current one

Recommended Activities (potential lead agents: WCRP, IGBP)

- Maintain and strengthen long-term baseline reference networks for methane with appropriate global coverage, including data harmonization, such as the WMO/Global Atmosphere Watch Global Atmospheric Methane Monitoring Network;
- Initiate process level studies, combined with long-term observations, with comprehensive physical and chemical modelling to understand the variations in present-day methane levels:
    - Include uncertainty analyses from emissions to tropospheric chemical reactions to the spatially-dependent concentrations;
    - Establish parameterizations applicable in biogeochemical-climate models;
- Ensure continuation of satellite-based observations of methane and other chemical constituents that control atmospheric methane concentrations, such as from the IASI[7] and SCIAMACHY[8] instruments.

[7] IASI: Infrared Atmospheric Sounding Interferometer (on the EUMETSAT METOP satellite launched in 2006)

4.2 Detecting and Predicting Changes in the Hydrological Cycle, including Extremes

Water supply, too much or too little, is the result of changes and variation in the hydrological cycle. The hydrological cycle varies on time scales ranging from minutes to centuries and longer, and is spatially highly heterogeneous. Increased understanding on all time and space scales is important, but for the immediate future (next five years) there is a window of opportunity from new satellite observations in particular, to better understand the changing nature of the high frequency supply-side component of the hydrological cycle over land, the storage component of water over land, and the low-frequency supply-side component of the water balance over the oceans. A major starting point is developing the datasets and harmonizing them with model simulations on appropriate time scales to understand better how the supply side of the hydrological system affects water storage, surplus, and ocean salinity.

4.2.1 Improving Precipitation Observations, Products and Modelling

Precipitation is the general term for rainfall, snowfall, and other forms of frozen or liquid water falling from clouds. Precipitation is intermittent, and the character of the precipitation when it occurs depends greatly on temperature and the weather situation. Precipitation varies from year to year and over decades, and changes in amount, intensity, frequency and type (e.g., snow versus rain) all matter for the environment and society. The characteristics of precipitation are just as vital as the amount for soil moisture, stream flow, extremes, erosion, urban flooding, human health, and water quality. Evidence is building that human-induced climate change is changing precipitation and the hydrological cycle, and in particular the extremes. Precipitation is obviously a critical variable in terms of societal needs and environmental impacts, and how it changes is critical for water management, agriculture, hydroelectric power, wildfire fighting, and many other uses.

Observational needs: For the reasons outlined above, observations and datasets of precipitation are required at high spatial and temporal resolution. In climate models, the typical time step is on the order of 20 minutes, the shortest meaningful time interval is about an hour due to numerical noise. In the real world, also, it is desirable to not just sample instantaneous rates that might apply very locally to a single cell of a cloud, but to get values more representative of the whole cloud (i.e. at a spatial scale of the order 1-5 km or larger). Scaling principles (e.g., fitting a Gamma or Log-normal distribution) allow estimates of hourly rates from instantaneous estimates from space or radar observations which may be calibrated by ground-based observations.

Accordingly, an achievable goal is to encourage and develop *hourly observations of precipitation at a horizontal resolution of the order 100 km (threshold) to 1 km (target)* and encourage their use in evaluating models. The diurnal cycle provides one way to assess frequency, intensity and onset of precipitation in models and observations, and allows the assessment of the full probability distribution and especially of precipitation extremes. In turn, how these quantities change and relate to other variables, such as water vapour, atmospheric stability, and temperature, are valuable diagnostics for the understanding of processes.

Global hourly precipitation is feasible: Many observations of precipitation already exist, but many data are not shared, and the development of comprehensive analyses has proven difficult (precipitation products available from the Global Precipitation Climatology Centre provide a valuable contribution to the community). Yet, further synthesis of the data and the resulting products would be a huge benefit for water management decisions and many other applications.

At present, precipitation in routine reporting is often given in 6-hourly accumulations. Further, attention to coordinated, calibrated hourly observations is needed, with real-time data sharing. A strategy for a global hourly precipitation product needs to be developed. Over land it should include recording rain gauges, hourly observations, radar measurements, and satellite-based observations where practicable. Over the oceans, the main observations come from space using combinations of geostationary and polar orbiting satellite instruments. In the future, coordinated satellite

[8] *SCIAMACHY: Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (on the ESA ENVISAT satellite launched in 2002)*

measurements from the Global Precipitation Mission will help enormously. Much more attention needs to be given to hardened *in situ* precipitation measurement during severe weather events, especially as more observing systems are automated.

In the framework of the European ENSEMBLES project, daily gridded fields of precipitation and temperature at 25 km resolution have been developed for observational purposes and for model validation, providing a valuable initiative in this area (see Section 4.6).

Recommended Activities (potential lead agents: WMO, GCOS, CGMS International Precipitation Working Group, GEWEX Hydrometeorology Panel):

- Change reporting practices (e.g., by national meteorological services) to include hourly precipitation in synoptic reports;
- Develop a strategy for a global hourly precipitation product with at least 100 km horizontal resolution (with 1 km resolution as ultimate target), possibly starting with demonstration products in Europe and North America.

SHORTCOMING IDENTIFIED in ASSESSABLE MATERIAL FOR IPCC AR4:
Difficulties in the measurement of precipitation, as well as in the understanding of forced changes in precipitation, remain an area of concern in quantifying trends in global and regional precipitation, and assessment of their likely impacts

SURVEY RESPONSES:
Major reasons:
- Poor spatial coverage of observations; low data quality; observation technology deficits
- Model skill in representing precipitation substantially lower than, e.g., for temperature

Negative consequences:
- Precipitation, daily weather extremes, and soil moisture are all high impact climate variables; “water is the key issue related to climate impacts”
- Decadal variability of precipitation on continental scale grossly underestimated in most coupled models, even though the interannual variability is about right

Possible solutions
- Better observing technology, including at sea; better data access: require all countries to provide access to all daily precipitation (and T(min), T(max), mean sea-level pressure) observations routinely, not just for GCOS stations; develop global extremes datasets and indices for validation
- Better funding for state-of-the-art reanalyses would help considerably, combined with better observational data; clarify whether reanalysis datasets are adequate yet for the study of (precipitation) extremes
- Basic understanding of precipitation response also needs to take place. For example, disagreements between theoretical expected responses of rainfall need to be resolved
- Model evaluation of precipitation needs to go beyond looking at mean fields. For example, model results need to be evaluated regionally against high-frequency precipitation data, looking at issues such as daily precipitation rates and fraction of precipitation falling from convective versus large scale systems (e.g., versus TRMM data)

Models: In models, it is also desirable to accumulate hourly precipitation data, rather than the common practice of daily or monthly amounts. Analysis of the diurnal cycle, probability distributions, and extremes then becomes straightforward. Model evaluations (global and regional) to date tend to overestimate precipitation occurrence, with insufficient intensity, and with premature onset of precipitation. These deficiencies indicate fundamental problems in the physics of models (notably convective parameterizations).

Recommended Activities (potential lead agents: WCRP, GCOS):

- Improve the understanding of the observed occurrence of extreme precipitation events and changes seen in global and regional climate modelling, through improved techniques to monitor and analyse small-scale extreme precipitation events

As discussed in Section 5, advances in downscaling and regionalization of models will allow for more accurate representation of the frequency, intensity and trends in extreme events, such as heavy precipitation. The limitations of such forecasts and recommendations for resolving them are also discussed there.

4.2.2 Information on Components of the Hydrological Cycle (Soil moisture, Water vapour)

Soil Moisture: Datasets on effective soil moisture that can be used to constrain terrestrial models remain largely unavailable. Space-based capabilities to observe top-soil moisture (e.g., from ASCAT[9]) and full moisture content (including ground water from GRACE[10]) have become available, and provide, in combination with existing *in situ* soil moisture profile measurements, for the first time an

[9] *ASCAT: Advanced Scatterometer (on the EUMETSAT METOP satellite, launched in October 2006)*
[10] *GRACE: Gravity Recovery and Climate Experiment, twin satellites launched March 2002 to measure Earth’s gravity field.*

opportunity to better understand the storage side of the water balance. Similar challenges are encountered for measurements of latent and sensible heat – they are unlikely to be available for model evaluation at climate modelling scales in the next decade. However, with some effort, several key datasets could feasibly be collated which would help in constraining the global hydrological cycle

SHORTCOMING IDENTIFIED in ASSESSABLE MATERIAL FOR IPCC AR4:
Records of soil moisture and streamflow are often very short, and are available for only a few regions, which impedes complete analyses of changes in droughts

SURVEY RESPONSES:
Major reasons:
- Temporal/spatial coverage of observations; observing technology
- Data quality

Negative consequences:
- Inability to close the water budget and to fully understand hydrological feedback
- Soil moisture is a key variable to predict the impact of extreme precipitation events and droughts

Possible solutions
- Enhance research on remote sensing of soil moisture variations, e.g., through GRACE and follow-on missions
- Reinforce international monitoring and data assimilation programs
- Better data access, exchange and network coverage

Recommended Activities (potential lead agent: WCRP/GEWEX):

- Make best use of soil moisture observations for land-surface water balance analyses, including region-specific analyses, with a special focus on integrating these measurements to derive this important missing component of land-surface water balance;
- Further develop observations of soil moisture (both remotely sensed top-soil indicators and deeper soil moisture profiles from *in situ* measurements).

Atmospheric Water Vapour: Changes in atmospheric water vapour are a key component on the supply side of the water balance. Today, new observations exploiting Global Positioning System signals (surface and space-based), space-based micro-wave observations, and existing *in situ* measurements of water vapour provide an opportunity to better understand the changing character of water vapour and precipitation.

Recommended Activity (potential lead agents: GCOS, WCRP/GEWEX):

- Since no single system can provide a full profile of water vapour over spatially comprehensive scales, a concerted effort to best integrate these data for the analysis of water vapour over both land and ocean needs to be undertaken

4.2.3 Ocean Component

Ocean Salinity as a "Rain Gauge": Space-based observations using active radars and microwave measurements provide new opportunities to resolve changes in precipitation over the ocean that can be cross-validated with changes in salinity, which is now much better monitored. The IPCC AR4 stated that zonal changes of precipitation over the ocean could not be resolved, a key component related to our understanding of the hydrological cycle. However, IPCC AR4 gives an illustration of the changing global-scale distributions of salinity in the world's oceans. Large-scale, coherent trends in salinity are observed for 1955 to 1998, and are characterized by a global freshening in sub-polar latitudes and a salinisation of shallower parts of the tropical and subtropical oceans. Freshening is pronounced in the Pacific, while increasing salinities prevail over most of the Atlantic and Indian Oceans. These trends are consistent with changes in precipitation, and with inferred larger water transport in the atmosphere from low latitudes to high latitudes, and from the Atlantic to the Pacific.

Issues: Spatial and temporal observations of ocean salinity are currently not sufficient, for example in the Southern Ocean. Some issues in the current measurements include instrumental biases, a lack of deep-water salinity data (particularly at high latitudes), insufficient global data analyses and incomplete coverage of surface ocean salinities.

Recommended Activities (potential lead agents: GOOS, GCOS):

- Maintain strong quality control of Argo[11] salinity profiles and surface salinity data from the Ships of Opportunity Programme (SOOP);
- Develop strategies for obtaining salinity data for the whole water column;

[11] *ARGO: a network of 3,000 underwater robots that monitor profiles of oceanic temperature and salinity*

- Promote reanalyses of the temporal changes in salinity.

4.2.4 Overarching Recommendations

Overarching Recommended Activities (potential lead agents: GCOS, WCRP/GEWEX):

Assemble and harmonize the following datasets, and develop a holistic view on the global hydrological cycle:

- Precipitation probability distributions based on high-frequency observations;
- New observations of soil moisture (both remotely-sensed top-soil indicators, and deeper soil moisture profiles from *in situ* measurements);
- Continental-scale runoff from river gauge data;
- Changes in the large-scale hydrological cycle and its relation to ocean salinity.

4.3 Land Surface Processes, the Carbon Cycle and Biogeochemical Feedbacks

The terrestrial and ocean environments are the two key players in the Earth's carbon cycle. The oceans currently store 37% of the carbon dioxide emissions (AR4 WG I, Chapter 7). There is concern that the oceans' capacity to store carbon is reducing (AR4 WG I, Chapter 5). From an Earth system modelling point of view, the parameterization of land surface processes is a weakly modelled component of global climate models. Terrestrial environments host the bulk of the biosphere and most of the human population; radiation, energy, momentum, water and carbon cycles are intimately coupled through living processes (notably photosynthesis and respiration) in land-based ecosystems; and this is where much of the economic activities, most of the impacts of climate change, as well as all adaptation and mitigation measures take place. Better process modelling and understanding of feedbacks in the carbon cycle will require a denser and more evenly distributed network of sustained *in situ* observations of carbon on land, in the oceans and in the atmosphere.

4.3.1 Carbon Cycle Models and Feedbacks

Some of the key limitations of global climate models as well as areas where significant progress may be possible in a relatively short period include the understanding and parameterization of:

- the surface radiation and water balance in GCMs, and their impact on carbon cycle feedbacks;
- the uptake and release of carbon dioxide, over both continents and oceans.

Significant advances can be expected through the effective assimilation of satellite products and ocean data.

SHORTCOMING IDENTIFIED in ASSESSABLE MATERIAL FOR IPCC AR4:
It is important to understand how close we are to tipping points and thresholds for natural ecosystems such as the Amazon rainforest

SURVEY RESPONSES:
Major reasons:
- Lack of fundamental understanding of sensitivity of carbon uptake and release to changing climate
- Insufficient linkage of climate applications to socio-economic data

Negative consequences:
- Like feedbacks, this new area is critical to our predictive capability, with potential large surprises and key to sustainable development

Possible solutions:
- Modelling experiments, driven by long-term monitoring programs in the Amazon and Sahel regions, Siberia (permafrost)
- Observations in regional and local scales on possible impact systems and sectors; Experiments on relative affected systems and sectors

C4MIP[12] simulations have documented large uncertainties in model approaches to carbon cycle feedbacks. These cast doubts on the understanding of the response of soil carbon pools and primary production to increasing surface temperature, and on the effectiveness of knowledge and model representation of the CO_2 fertilization effect. In the ocean, critical processes include stratification (which influences the carbon uptake rate), large-scale changes in patterns of ocean warming, and acidification. The net effect of these factors on the biological carbon pump is unknown.

[12] *C4MIP: Coupled Carbon Cycle Climate Model Intercomparison Project.*

Recent research, not available for AR4, suggests that atmospheric concentrations of CO_2 are now increasing faster than previously, the causes being faster increase in the use of fossil fuels, cessation of the long-term trend of increasing carbon efficiency of economies, and decreasing sink strength of the oceans. This may imply a reduction of the effectiveness of the ocean sink.

Carbon models currently disagree significantly with each other in uptake and emission rates and often do not match the available empirical evidence. Atmospheric concentration measurements are too sparse to adequately constrain global or regional-scale inversion models.

Further progress in simulation models will require a better understanding of fundamental processes, both over land and in the ocean, such as:

- Understanding of CO_2 fertilization of terrestrial biota, including acclimation; understanding why the land carbon sink continues to grow in parallel with CO_2 emissions;
- Ocean acidification and its effect on the net carbon flux into sea water;
- Temperature response of net primary productivity (NPP) and ecosystem carbon stocks, nitrogen cycling and soil decomposition, and soil moisture availability.

Such advances will require a combination of field and modelling studies, as well as more comprehensive observations and field manipulation studies interpreted within a sound theoretical framework.

4.3.2 Carbon Cycle Observations

Components of a carbon flux observing system already exist in Europe, the United States, Japan, and parts of the Atlantic and Pacific Oceans. Issues with data continuity and consistency persist, since these systems are largely based on short-term research efforts, and often operated without common measurement protocols, data management and, for the land, complementary routine monitoring of carbon stocks. Continuation and expansion of measurements of CO_2 concentrations and other carbon cycle tracers in the atmosphere is vital. The impending launch of satellites sensors to observe the global carbon cycle, especially the atmospheric reservoir, could provide a quantum leap in our ability to diagnose the evolution of this cycle at global and regional scales.

SHORTCOMING IDENTIFIED in ASSESSABLE MATERIAL FOR IPCC AR4:
Insufficient understanding of the carbon cycle, including future feedbacks

SURVEY RESPONSES:
Major reasons:
- Insufficient ability to separate the natural and human contributions to carbon stock change
- Regional biases in models (e.g., in precipitation) could provide critical limitations on projecting carbon cycle changes (e.g., resulting in tropical forest dieback)
- Most GCMs include some land-surface parameterizations but few ecosystem feedbacks. A more comprehensive Earth-system view is urgently required

Negative consequences:
- A limited understanding of uptake CO_2 by land surfaces under temperature and precipitation change may hide unknown feedbacks
- Important for developing policies for addressing climate change - for example in allocating credit for human intervention

Possible solutions:
- Closer liaison between terrestrial carbon cycle scientists and GCM modellers

Effective soil moisture (see Section 4.2.2) is currently difficult to measure, while sensible and latent heat fluxes at the surface can only be measured at a limited number of FLUXNET sites. Data from these sites would be very valuable to evaluate, combined with satellite and observations, in order to constrain models. Nevertheless, significant progress has been achieved and further developments can be expected in the following areas:

- Continental-scale runoff, to help constrain the water balance;
- FAPAR and other vegetation properties, to help constrain the carbon balance;
- Albedo (NIR and visible) and skin temperature, to help constrain the surface energy balance;
- CO_2 and other trace gas concentrations, to help constrain the climate change forcing;
- Global systematic observations of ocean colour and associated geophysical variables.

Efforts should be pursued to evaluate and assimilate these datasets in appropriate models, as well as to exploit such resources in other downstream applications. Care must be taken in the assimilation process: for example, recent research results show inconsistent radiation budgets within models if measurements (field-based, remotely-sensed) of vegetation properties, such as FAPAR, are directly assimilated. Such remote sensing observations must be analyzed in terms of effective variables, which can then be consistently assimilated in models. Retrieving or comparing such effective variables to field observations requires detailed information on the 3D structure of the environment.

Detailed specifications on key geophysical variables needed for systematic observation of the carbon cycle, as well as the projects and institutions charged with implementing these observations are provided in the Integrated Global Carbon Observations (IGCO) Theme Report[13] as well as in the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC[14].

4.3.3 Urgent Needs in Carbon Cycle Research

The carbon observing and modelling communities should aim to (1) drastically reduce existing differences between estimates of carbon stocks and fluxes on a global and regional basis, and over a multi-year period and (2) explain the stability of their long-term trend in "airborne fraction" of emitted CO_2. Considerably more attention should also be given to the standardization of measurement protocols from field stations and from space.

Recommended Activities (potential lead agents: WCRP, IGBP, GCOS):

- Accelerate the creation of global collections of quality-controlled carbon data;
- Create joint meetings of experimenters and general circulation modellers (including biogeochemical cycles) to understand the radiation, water, nitrogen and carbon cycles in land systems, and to improve the representation of these cycles in GCMs and biogeochemical cycle models;
- Accelerate the collection of data on biogeochemical variables including ocean carbon content, ocean alkalinity, pH and pCO_2;
- Develop improved use of multiple constraints in general circulation models (including Bayesian techniques);
- Monitor and assess the effectiveness of carbon management policies on global atmospheric GHG levels, including attribution of sources and sinks by region and sector;
- Progress the standardization and harmonization of field observation protocols.

4.4 Aerosol-Cloud Interactions and Radiative Forcing

URGENT NEED:

- Better quantification of radiative forcing due to aerosols–cloud interactions through comprehensive model-model and model-observation comparisons, including enhanced observations from all platforms

4.4.1 Scientific Relevance and Importance

In the AR4, several of the climate models did not have representation of the anthropogenic aerosol-cloud interactions and thus of the aerosol indirect forcing. Globally averaged, the net radiative effect of aerosols is negative (i.e., contributes to cooling at the surface) and is estimated to have a magnitude of about 75% of the forcing due to the CO_2 increase since pre-industrial times. About 60% of this is forcing via aerosol-cloud interactions, which is also the most uncertain of the anthropogenic forcings. There is a critical need to improve the understanding of the processes (e.g., aerosol transport, convective processes, cloud formation and dissipation) leading to this forcing, represent them reliably in climate models and thus simulate the interactions accurately to better quantify the anthropogenic influence on climate.

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[13] *http://ioc.unesco.org/igospartners/Carbon.htm*
[14] *http://www.wmo.int/pages/prog/gcos/Publications/gcos-92_GIP.pdf*

This is important both in the context of 20th century climate change due to human activity, as well as for future climate projections under specific scenarios. A principal challenge in this research problem is the spatial and temporal inhomogeneity of the different species of aerosols, which makes it difficult to quantify their distributions, forcing and impacts.

SHORTCOMING IDENTIFIED in ASSESSABLE MATERIAL FOR IPCC AR4:
Uncertainty in aerosol-cloud interaction and associated indirect radiative effects

SURVEY RESPONSES:
Major reasons:
- Lack of understanding of fundamental processes
- Insufficient model parameterizations
- Lack of observations and data quality

Negative consequences:
- Large uncertainty in GCMs and in estimating climate sensitivity
- Uncertainty in prediction of regional precipitation

Possible solutions:
- Ground-based, balloon-based and aircraft-borne column measurements, and collocating measures of clouds, aerosols and soil moisture from satellites such as CALIPSO
- Improved process research (eventually including ice clouds), on a more global scale than GEWEX does now; high-resolution regional modelling (e.g., in low shallow clouds) and better representation in GCMs

Linked issues:
- Volcanic forcing uncertainty, solar variability inadequately addressed

4.4.2 Availability of New Data

A crucial test involves the comparisons of model-simulated variables against observations, e.g., aerosol and cloud microphysical properties. The scope of the observational data to understand the relevant processes and evaluate model simulations has increased significantly in the past few years, greatly enabling future climate science assessments to take advantage of this facility. The datasets include observations from newly-launched satellites, airborne field campaigns, ground-based stations and ships.

4.4.3 Model-model and Model-observation Comparisons

In the wake of AR4, modelling centres have now begun to include interactive aerosol chemistry schemes and thus aerosol-cloud interactions in the climate models. The opportunity thus is ripe for systematically examining models which incorporate this effect through both model-model and model-observation comparisons. The variables that can be examined include aerosol optical depth, cloud optical depth, cloud fraction, drop effective radius, and radiative fluxes at the top of the atmosphere and the surface. The comparisons should be performed under a wide range of conditions e.g., near source regions, downwind of sources such as continental aerosol plumes transported across coastlines and interacting with low clouds, and remote pristine regions.

Recommended Activities (potential lead agents: WCRP, IGBP, GCOS):

- Model-model and model-observation comparisons should be coordinated under combined WCRP-IGBP auspices. It is estimated that an initial phase of the comparisons described above can be accomplished over the next 2 years, thus being of direct benefit for future climate change assessments;
- More detailed evaluations of the models enable more accurate inputs into successive climate assessments. The initial comparison exercise could reveal the need for additional observations (e.g., on aerosol chemical composition) to further constrain models.

4.4.4 Separation of Direct and Indirect Forcing

Aerosol radiative impacts are generally separated into the “direct” effect (i.e., how aerosols interact directly with radiation) and the “indirect” effects (i.e., how aerosols affect cloud reflectivity, extent and lifetime, thereby affecting Earth’s radiative balance). This separation implicitly assumes that aerosols are “activated” at a threshold relative humidity, above which they nearly instantaneously grow into cloud droplets. However, observations have shown that some aerosols may depart from this conceptual picture and instead there may be a continuum of states, from the dry aerosol state to mixtures to “very hydrated aerosol” and eventually to ”small cloud droplet”. Thus, models and analyses need to account for the possibility of such continua in capturing the total (direct and indirect) aerosol effects.

From an observational standpoint, serious difficulties arise in quantifying and separating direct and indirect effects. The finite time and spatial resolution of measurements – in particular those from satellites, which typically have a resolution of several to tens of kilometres – means that a single data point may contain clear air, as well as aerosols in various hydration states, and clouds. Interpretation of partly-cloudy pixels is extremely problematic, in turn affecting the quantification of the indirect effect. Much of the planet is covered by broken clouds, giving rise to the possibility of biases in interpretations. The resulting uncertainties pose a limitation to the verification of model simulations.

Recommended Activities (potential lead agents: WCRP, IGBP):

- New datasets, e.g., CALIPSO/CloudSat, and high-resolution cloud models should be taken advantage of to determine to what degree there is a continuum between hydrated aerosol (direct effect) and cloud droplets (indirect effect). Quantification of the different elements would provide an important step towards the quantification of the total aerosol effect;

- A robust, critical analysis needs to be undertaken to determine how assessment of the indirect effect from satellite data is affected by biases, brought on due to uncertainties in the interpretation of partially cloudy pixels in the analysis, and how this contrasts with samples of cloud-free and cloud-filled pixels (which may miss samples of very hydrated aerosols).

SHORTCOMING IDENTIFIED in ASSESSABLE MATERIAL FOR IPCC AR4:
Models differ considerably in their estimates of the strength of different feedbacks in the climate system; the response of clouds to global climate change is particularly uncertain

SURVEY RESPONSES:
Major reasons:
- Lack of understanding of fundamental processes
- Inadequate model parameterization of processes; model resolution issues (e.g., when accommodating poorly-parameterized small-scale processes)
- Response of tropical low clouds particularly uncertain

Negative consequences:
- Not understanding feedbacks a key problem of climate models

Possible solutions:
- Better observations of clouds, e.g., using CloudSat
- Constrain radiative forcing
- Link cloud-resolving models to AOGCM
- Improve parameterization of convection processes
- Reduce uncertainties in cloud feedbacks, e.g., through collaborative efforts between cloud feedback model intercomparison project (CFMIP) and the GEWEX cloud system study (GCSS)
- Develop a proven set of model metrics (before including them in a future IPCC assessment), e.g., through working groups, comparing for feedbacks, to be validated from observations; use perturbed parameter ensembles to indicate sensitivity and spread feedbacks

Linked issue:
- What will be the use of model metrics, particularly with respect to future climate change assessments?
- Identify where the issue of model performance is (1) scale, i.e., likely to be addressed by simply increasing resolution, (2) parameterization, e.g., convective processes (3) more physical process understanding/data is required before (2) can be achieved, e.g., soil moisture and land use feedbacks

4.4.5 Regional Field Campaigns to Connect to Global Impacts

Many of the parameters needed to constrain the direct and indirect effects are not currently measured, and focused field campaigns – to date – have not been able to provide a clear picture of the magnitude of, in particular, the aerosol indirect effect(s). Due to the large number of variables that control cloud properties, and the large variability from region to region that these different control factors play, a “best guess” value for the global aerosol indirect effect may not be feasible in a five year time frame, given limited resources. However, the objective of framing better estimates of the uncertainty of the indirect, and thereby the total aerosol, effect can be attained.

Recommended Activities (potential lead agents: WCRP, IGBP, GCOS):

- Design an experiment, involving the broad community, which would allow the determination of whether the very large indirect effect given by some models can be observed in reality;
- Undertake the experiment in areas where large aerosol indirect effects are expected;
- Support the experiment by field campaigns in a few key regions, reflecting different climatological conditions,

leading to improved quantification of the indirect effect, which in turn would lead to more reliable estimates of the total aerosol effect and the net anthropogenic forcing.

4.5 Ice-sheet Dynamics and Sea-level Rise

URGENT NEED:

- Better understanding of ice-sheet dynamics is required

Recommended Activity (potential lead agents: WCRP CliC, GCOS):

- Support a major effort to develop ice-sheet models on a par with current models of the atmosphere and ocean. Particular effort is needed with respect to the modelling of ocean/ice shelf interactions, of surface mass balance from climatic information, and of all of the forces which drive ice motion

Sea-level rise is a major emerging concern from the IPCC AR4 and from more recent projections. Indeed, recent observations indicate that sea levels are rising more rapidly than the IPCC AR4 central model projections, and instead fall at the upper end of the projections, even when including the uncertain contributions from land-based sources of ice. As a result, there is significant concern that future projections of sea-level rise may be underestimated, as indicated by simple statistical models.

Coastal extreme sea-level events, e.g., due to storms and surges in particular, have a significant impact on vulnerable coastal populations, and events of a given height will become more frequent and events more severe as sea levels rise. However, the specific relationship between coastal impacts and sea-level rise is still poorly understood. Multi-disciplinary studies are crucially needed for better understanding of coastal responses to multiple forcing (sea-level rise, extreme events, compaction of sediments and reduction in supply of sediments, coastal currents and winds) and their impacts on vulnerable coastal populations.

The record of past changes in ice volume provides important insight to the response of large ice sheets to climate change. Palaeoclimatic data records demonstrate that there is a strong inverse relation between atmospheric CO_2 and global ice volume. Sea-level rise during the deglaciation period averaged 10-20 mm/yr, with large “meltwater fluxes” producing sea-level rise rates exceeding 40 mm/yr (4m/century) lasting several centuries, clearly demonstrating the potential for ice sheets to cause rapid and large sea-level changes.

There are uncertainties in all components contributing to present-day sea-level rise: ocean thermal expansion for both the upper ocean and the deep ocean, contribution from glaciers and ice caps, potentially large future contributions from the ice sheets and very poorly constrained contributions from changes in terrestrial storage. At the moment the greatest concern is related to the possibility of a rapidly growing contribution from the ice sheets, particularly the Greenland Ice Sheet and the West Antarctic Ice Sheet.

As noted in Section 4.1, recent observations have shown rapid changes at the margins of the Greenland and West Antarctic Ice Sheets through increasing flow rates and decreasing ice thickness. Most of these glacier accelerations closely followed reduction or loss of ice shelves induced by atmospheric or oceanic warming,

SHORTCOMING IDENTIFIED in ASSESSABLE MATERIAL FOR IPCC AR4:
Models do not yet exist that address key processes that could contribute to large rapid dynamical changes in the Antarctic and Greenland ice sheets that could increase the discharge of ice into the ocean

SURVEY RESPONSES:
Major reasons:
- Lack of fundamental understanding
- Insufficient temporal and spatial coverage of observations
- Disinterest until very recently – with the belief that ice sheets would not respond quickly to GHG-induced warming

Negative consequences:
- Dynamical changes to ice sheets have the potential to induce rapid sheet disintegration, with the potential for very significant sea level rises – identified as the single greatest uncertainty in sea level projections in the AR4, with negative consequences on societies in coastal zones
- Major challenge to project the pathway for future sea-level change: start and end points are quite well-known, it is the shape of the curve in between that is not well-known, and glacier dynamics are clearly crucial in making these projections

Possible solutions:
- Intensify observational efforts (observations of ice sheets, glaciers, e.g., through field experiments and future satellite missions such as IceSat II and GRACE-2); better coordination of field research in Greenland among EU and US partners
- Upgrade existing polar observing networks to provide instantaneous data transfer via satellite links for model verification, process studies, and monitoring
- A major initiative is needed to bring together the modelling and experimental (observations) community. CliC and SCAR are proposing to organise such workshops with the aim to include the dynamics of ice sheets in Earth system and predictive models. Polar regions are missing basic long-term climate measurements, in particular the remote regions of Greenland and Antarctica. The long-term component of projects within the IPY should be fostered to the extent possible. WCRP (in partnership with others) should commission a white paper and initiate a number of specific studies of the Greenland Ice sheet and the West-Antarctic Ice Shelf
- Intensify modelling efforts (modelling of e.g., ice sheet response to increased percolation of melt water, increased basal lubrication)
- Explore coupling of ice sheets into GCMs for long-term feedbacks
- Find thresholds for abrupt changes in ice sheets

implying a causal connection that is not currently represented in models.

The interaction of warm waters with the periphery of the large ice sheets represents one of the most significant possibilities for abrupt change in the climate system. Mass loss through oceanic melting and iceberg calving accounts for more than 95% of the ablation from Antarctica and 40-50% of the ablation from Greenland. Future changes in ocean circulation and ocean temperatures will produce changes in basal melting, but the magnitude of these changes is not modelled in the current generation of climate models.

Current ice-sheet models lack proper representation of the physics involved in the processes that modern observations suggest are potentially the most important in causing an abrupt loss of ice and thus sea-level rise. Emphasis should be given to launching a new initiative in support of a committed ice-sheet modelling effort aimed at addressing these shortcomings and thereby providing significant improvement in predicting future sea-level rise.

Recommended Activities (potential lead agents: WCRP, GCOS):

1) Long-term initiative: Development of next-generation ice-sheet models that include all relevant processes needed to access future climate-induced ice sheet and sea-level change, and in particular the non-linear response of ice sheets to climate change. This effort will likely take at least five years, given adequate resources and manpower, and thus needs to be started as soon as possible. This initiative should be led by the WCRP Climate and Cryosphere (CliC) project, in collaboration with groups from ISMASS[15], SCAR[16] to join and support the initiative. It is therefore recommended to:

- Organise a workshop in the near future to bring ice-sheet modellers and experimentalists together to highlight the issues, assess the current status (including the potential for rapid change), and identify guidelines for implementation of this initiative;

- Utilize the Ice, Cloud, and land Elevation Satellite (ICESat) laser and, once launched, CryoSat-2 radar altimeter satellites – complemented by aircraft altimetry – to survey changes in the surface topography of the ice sheets. Based on experience gained therein, develop suitable follow-on satellites for deployment in order to assure a contiguous data record;

- Sustain satellite observations of the time-varying gravity field from GRACE[17] and plan for an appropriate follow-on mission with finer spatial resolution to contribute to estimating changes in ice-sheet mass.

2) Short-term initiative: In order to assess potential future changes in ice sheets and sea-level rise, we recommend a shorter term community initiative designed to use process studies, observations, and syntheses to obtain a consensus on the possible non-linear responses of ice sheets to climate change, including their influences on rates of sea-level rise. It is recommended to:

- Support field, theoretical and computational investigations of processes beneath ice shelves and beneath glaciers, especially near to the grounding lines of the latter, with the goal of understanding recent increases in mass loss;
- Survey changes in ice-sheet topography using satellite radar (e.g., Envisat and Cryosat-2) and laser (e.g., ICESat) altimeters, and plan follow-on laser-altimeter missions, including a wide-swath altimeter;
- Sustain aircraft observations of surface elevation, ice thickness, and basal characteristics, to ensure that such information is acquired at high spatial resolution along specific routes, such as glacier flow lines, and along transects close to the grounding lines;
- Maintain climate networks on ice sheets to detect regional climate change and calibrate climate models;

[15] ISMASS: Ice-Sheet Mass Balance and Sea Level project of the SCAR Global Change Programme (SCAR GCP)
[16] SCAR: Scientific Committee for Antarctic Research, an inter-disciplinary committee of the International Council for Science (ICSU)
[17] GRACE: Gravity Recovery and Climate Experiment, twin satellites launched March 2002 to measure Earth's gravity field.

- Utilize existing satellite interferometric SAR (InSAR) data to measure ice velocity, and develop and implement an InSAR mission to sustain observations of flow rates in glaciers and ice sheets.

To resolve the differences between model projections and the observed rate of sea-level rise, more synergy is needed between sea-level modelling and observations. Continuity of satellite and *in situ* (e.g., ARGO) observing systems for measuring sea-level change and the processes responsible for the observed changes, need to be strongly reaffirmed.

Recommended Activities (potential lead agents: WCRP, GCOS):

- Measurements relevant to understanding sea-level rise (i.e. satellite altimetry – ongoing and overlapping Jason quality missions[18]) and *in situ* observations from tide-gauges fitted with GPS receivers should be maintained;
- With the initial implementation of Argo complete, the array needs to be maintained and extended into the ice-covered oceans using new technologies;
- More synergy is needed between sea-level modelling and observations;
- The design (and implementation) of a deep ocean observing system is of high priority.

A detailed report of priorities for improving sea-level rise projections is available at http://wcrp.wmo.int/AP_SeaLevel.html.

4.6 Ensuring the Observational Record for Climate

Multi-decadal observational datasets of climate variables commonly show unresolved and sometimes clearly unphysical drifts and discontinuities, even following attempts at homogenization. Examples include atmospheric temperatures from the sequence of MSU[19] instruments and from radiosondes, sub-surface ocean temperatures from ocean cruises, expendable bathythermographs and Argo floats; satellite cloud products or satellite-derived snow cover and sea-ice cover. These inconsistencies make it difficult to make unequivocal statements on climate trends and their causes, or on the capabilities of models to reproduce past changes.

Whenever more becomes known about the properties of historic data and how to retrieve the climate signal from them, reprocessing of data is required. The requirements for reprocessing climate data records have been recognised by GCOS in its Implementation Plan and have been stressed also by WCRP through its Observation and Assimilation Panel (WOAP). In response, Space Agencies and the WMO Space Programme have developed the Global Satellite Inter-Calibration System (GSICS) and are developing an implementation plan for a global network of Regional/Specialised Satellite Centres for Climate Monitoring (R/SSC-CM). These will be part of a processing chain for the production of Fundamental Climate Data Records and derived satellite products for Essential Climate Variables (ECVs), as illustrated in Fig. 3.

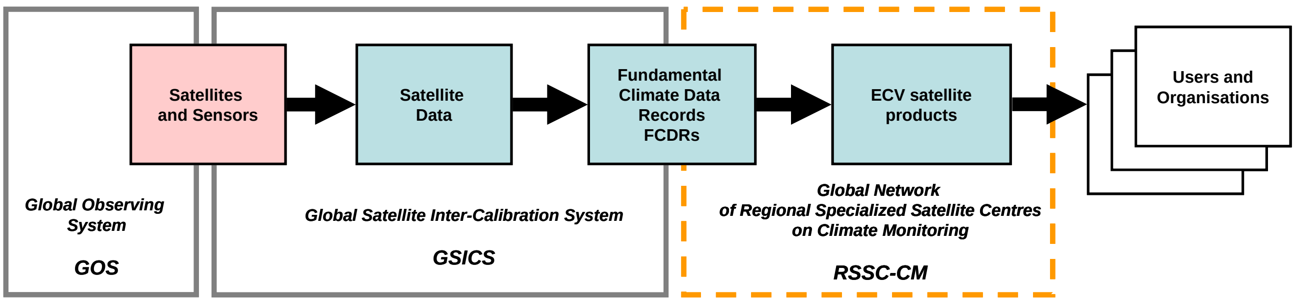

Fig. 3: Role of the R/SSC-CM Global Network in sustained satellite-based climate monitoring

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[18] *Jason: a satellite to observe and monitor ocean dynamics (intra-seasonal to inter-annual changes, mean sea level, tides); a follow-on to high accuracy altimeter service, provided since 1992 by TOPEX/POSEIDON.*

[19] *MSU: Microwave Sounding Unit satellite instrument*

Recommended Activity (potential lead agents: GCOS and WCRP):

- Provide scientific guidance to on-going satellite data reprocessing efforts for appropriate ECVs

While GSICS has been established to facilitate the reprocessing and harmonization of satellite data, there is no such formal system for *in situ* measurements. Inadequate or unproven datasets need to be flagged, and there needs to be a process for formal recognition of datasets. At all reprocessing stages, the data must be fully archived along with the final datasets, allowing full transparency, and enabling new techniques for homogenising datasets.

Recommended Activity (potential lead agents: GCOS and WCRP):

- To aid future climate change assessments, it is necessary to assign some form of formal dataset maturity index, reflecting the scientific value of any dataset. Criteria may include: Dataset availability; audit trail; publication history; code availability; accessibility of support, update frequency and latency, number of users

For many types of satellite data, conversion to geophysical parameters can introduce artificial time-varying biases. So it is often better to compare model equivalents of the measured quantity with the direct measurements, than to convert the measurements to the model's geophysical variables. There already exist various satellite data simulators for climate models, for example the simulators for ISCCP[20] and Cloudsat[21], and the various fast radiative transfer models for radiance simulations, e.g., for HIRS[22] and SEVIRI[23]. It is feasible to archive an agreed set of satellite-equivalent variables from climate model simulations to be used as a performance metric in future assessments.

Recommended Activity (potential lead agent: WCRP):

- Support the archiving of satellite data-equivalent measures for future model runs, to facilitate unambiguous comparison of satellite data and model output

A sustained global observing system is the foundation for all climate studies. The climate community needs an integrated set of global, atmospheric, oceanic, and terrestrial observing systems for climate monitoring, model validation, and initializing climate forecast models. It is critical that we now commit to sustaining these observations, so that future generations will have the tools necessary to resolve questions about long-term trends in climate observations.

However, the potential contribution of satellites to monitor the GCOS ECVs in the future is under threat. For example the contribution of the NPOESS[24] system to climate monitoring has been significantly degraded by cost constraints. As of late 2007, the eliminated sensors include those used to determine the Earth's radiation budget, solar irradiance (total and spectrally resolved), a passive microwave imager for lower tropospheric water vapour, aerosol optical properties, and sea-surface topography.

Recommended Activity (potential lead agents: GCOS and WCRP):

- Continue to advocate for climate monitoring sensors on the NPOESS satellite to be reinstated, and to maintain and add relevant sensors on other satellite platforms

Contingency plans for gaps in the climate record must be developed to cover, for example, instrument failure. For some ECVs, such as solar irradiance, a gap cannot be filled, but for other ECVs, it may be possible to bridge gaps with other measurements. Such measurements must be of sufficient quality, accuracy and sampling to act as a transfer standard. *In situ* reference observing networks leveraging on existing or partially completed networks of reference sites taking multiple measurements of many different variables will be an important element of any future observing network. Implementation of these reference networks is of high priority to ensure the value of future

[20] *ISCCP: International Satellite Cloud Climatology Project*
[21] *Cloudsat: NASA satellite launched in April 2006*
[22] *HIRS: High-Resolution Infrared Radiation Sounder (launched by NOAA)*
[23] *SEVIRI: Spinning Enhanced Visible and Infrared Imager (launched by EUMETSAT on Meteosat-8)*
[24] *NPOESS: National Polar Orbiting Environmental Satellite System (NOAA/NASA/US Dept of Defense)*

observations. For example, the GCOS Reference Upper Air Network (GRUAN), aiming at reference atmospheric profile measurements of several ECVs, is now in the process of being established.[25]

Recommended Activity (potential lead agent: GCOS):

- Continue to design and advocate the setting up of reference networks, and promote their widespread use in dataset construction and climate monitoring

Climate change science is ill-served by a number of issues, such as:

- restrictive data policies and shortness of digitized records in many countries;
- the lack of resources to adequately homogenize the data (surface and upper-air records, involving most of the GCOS ECVs).

There is a clear need to encourage both a standard for metadata archival and to promote homogeneity of the basic data. This work is essential for reanalysis[26] projects, especially for radiosonde and surface data before the satellite era.

SHORTCOMING IDENTIFIED in ASSESSABLE MATERIAL FOR IPCC AR4:
Uncertainty in radiative forcing, for example due to insufficient quantification of land-surface properties and land-atmosphere interactions

SURVEY RESPONSES:
Major reasons:
- Lack of understanding of fundamental processes
- Lack of observation data, including historical data

Negative consequences:
- Limited confidence in attributing some climate change phenomena or modelling results to anthropogenic influences; not understanding or including feedbacks in climate models
- Inability to understand or predict the impact of changes in land cover or land use on regional climate and adaptation options

Possible solutions
- Carry out sensitivity/feedback analyses using a large number of GCM and meso-scale (not too regional) model studies, for example with a variety of land use forcings, e.g., from peat and tropical ecosystems
- Much more focus in WCRP and IGBP on verification of the influences (singly and combined) upon the radiation budget (via measurements and modelling) in the present day needed; they are important metrics for the reliability of the "drivers" implemented in AOGCMs
- Generation of climate-quality datasets ("Climate Data Records") through long-term, continuous monitoring, and reprocessing of historical datasets, for key parameters such as land surface and aerosols
- Continuous, homogeneous datasets on total and spectrally resolved TOA radiance needed; expansion of the radiation monitoring networks at ground level

Linked issue:
- Identify (1) where the issue is scale (can be addressed by increasing resolution, (2) where new parameterizations are needed (convective processes) and (3) where more physical process understanding or observations are required before (2) can be achieved, e.g., soil moisture and land use feedbacks

In many countries, records have only been digitized since the 1950s or 1960s. Digitizing the earlier data is important for extending datasets for impact studies, and can also be used in the upcoming Extended Reanalyses, which are planned to extend back to the 1890s using surface data alone. This effort is considerable and therefore best done in a distributed manner, as individual countries should possess the required metadata to enable the necessary dataset adjustments. This work also requires common standards and coordination, through the Working Group on Observational Datasets for Reanalysis of AOPC and WCRP, for example. If the availability of the full surface instrumental record cannot be improved, it will be essential for future climate change assessments to hold regional workshops, where, for example, updated, homogeneous indices of extremes[27] can be exchanged, as was done before the IPCC AR4.

As an example of what is possible, the EU ENSEMBLES project has collected daily temperature, precipitation and pressure data from most European meteorological services. These are being used to develop daily gridded fields at 25 km resolution for model evaluation and gridded 'extremes' analysis and will be used in many national impact studies. Note however that only the gridded products can be made available for scientific use as some of the raw station data are subject to restricted distribution. In addition, some raw datasets have not been made available in the first place and impose a limitation on the gridded fields.

Recommended Activity (potential lead agents: GCOS and WMO):

- Reaffirm to and advocate with national meteorological services the importance of both data and metadata access and use for understanding climate change and likely impacts

Building on the success of recent atmospheric and ocean reanalyses, and on ongoing improvements in datasets and methods of atmospheric and oceanic data assimilation, additional information can be obtained from global observations of the last 50 years by constructing coupled atmosphere/ ocean/sea-ice reanalysis systems. There are also plans to run surface-data-only reanalyses for over a

[25] GCOS Reference Upper-Air Network: Justification, requirements, siting and instrumentation options (GCOS-112, April 2007)
[26] Reanalysis is the use of a fixed model to assimilate and analyse historical data consistently through the historical record.
[27] See for example http://hadobs.org : HadEX .

century. Particular attention is required to account for the gross time-varying changes in the historical observing system.

Recommended Activities (potential lead agents: GCOS and WCRP, especially the GCOS/WCRP Working Group on Observational Datasets for Reanalysis):

- Promote the creation of coupled ocean-atmospheres reanalyses for the last 50 years, and support new reanalysis efforts using improved input datasets and assimilation systems;
- Promote use of recently available reanalysis data for Earth System science;
- Increase the accessibility of current and future atmosphere-ocean reanalysis products;
- Encourage meteorological services to make more of their digital archives available without restrictions on use.

5. Regionalising Model Projections/Downscaling

URGENT NEEDS:

- Better regional information on past and future climate change;
- Develop methodologies to define, determine and communicate uncertainties and limitations of regional climate science.

In addition to improvements in fundamental knowledge about the climate system at regional scales, there is an overarching need to make observational data and model output more directly relevant to addressing policy-relevant issues (cf. Sections 2 and 3). Decision support requires that information be provided at the appropriate scale – decisions are by nature made primarily at the local to regional scale. The coarse grid-spacing of GCMs does not resolve many of the features critical to, for example, water resource management (e.g., small-scale variations in precipitation in mountainous regions) nor do they resolve many extreme events (e.g., thunderstorms, tornadoes). Increased acceptance that some degree of climate change is inevitable is now coupled with increasing demand from communities, industry and governments for reliable climate information at high resolution and with accurate extremes. There must, therefore, be development in regionalizing climate information, principally through downscaling. Such climate information is critically dependent upon access to high-quality historical climate records, and so greater effort is needed to secure past climate observations and to ensure that observing systems are in place to obtain climate data at regional scales.

5.1 Credibility Issues

Policy decisions on climate mitigation and adaptation are proceeding with less than complete information. In the context of this immediate need, one critical question is how to produce credible regional information while recognizing and communicating associated uncertainties. Credibility refers to establishing relative confidence in the model response to external forcing on spatial scales commensurate with the needs of policy makers. This will require consideration of policymakers' needs and how to best characterize and communicate uncertainties. In turn, such interactions with policy makers will help to set appropriate research questions and priorities.

The question of credibility has particular relevance in the developing world context, where limitations in data availability, computational resources and experience using climate information increases the challenge of establishing confidence in and usability of

SHORTCOMING IDENTIFIED in ASSESSABLE MATERIAL FOR IPCC AR4:
Attribution at regional scales and over time scales of less than 50 years is limited by larger climate variability on smaller scales, by uncertainties in the small-scale details of external forcing and the response simulated by models, as well as uncertainties in simulation of internal variability on small scales, including in relation to modes of variability

SURVEY RESPONSES:
Major reasons:
- Lack of fundamental understanding; poor modelling skill; insufficient temporal/spatial coverage of observations
- Data quality, access
- Mechanisms of internal variability not well known
- Models are not adequately tested

Negative consequences:
- Regional attribution of climate change and variability limited, compromising regional projections; e.g., current projections do not have coupled ice sheet models included in the climate models; detrimental effect on the design of adaptation measures
- Limited assessment of the causes of extremes and large anomalies

Possible solutions
- Need for better understanding of internal variability at different scales
- More theoretical approach needed: Is detection on regional scale at all possible, or are we chasing something which cannot be isolated?
- Continued efforts to acquire and analyze 4-D datasets of climate variables; more sensitivity/intercomparison studies of climate models, maybe with idealized settings

regional information, including projections. In addition, many countries facing these challenges coincide with areas particularly problematic for model performance (e.g., tropical processes). This is an issue which cannot be simply solved by increasing model resolution (even though this is important). Finally, an enhancement in regional modelling research will provide capacity building (e.g., expertise, training, networking) for local researchers conducting regional studies.

Specific issues that arise with regard to this issue are:

User needs: Our conceptions of regional knowledge requirements and where efforts to enhance credibility are targeted must be negotiated with local/regional decision and policy makers in order for our research to have relevance for the management of risk. It is important to determine the mismatch in scale, where present, between user needs and what can be provided by both models and observations, as specified in particular contexts. Regional approaches can help to bridge the gap (by removing the spatial resolution barrier) between so-called "top-down" and "bottom-up" approaches, at a minimum allowing exploration of integration across these two approaches. (*Links to recommendation 3 below*)

Uncertainty: Defining uncertainty in a given context and with regard to given methodologies is an important aspect of establishing credibility. Once the dimensions of uncertainty are defined, major research activities remain in how to characterize, quantify, and communicate uncertainty efficiently. (*Links to recommendation 2 below*)

Model quality: In order to enhance model quality and, where appropriate, reduce uncertainty, verification standards need to be developed. This includes model application in past climates. Some of the key questions relevant to these issues are: When is a model 'good enough' for providing policy-relevant information? In a given context, how do we define 'good enough'? Does this vary across contexts? (*Links to recommendation 1 below*)

Data needs: Better utilization of existing "traditional" observations is clearly needed, but in the study of regional climate, data rescue from non-traditional sources (e.g., newspapers, historical societies, local councils) is vital. Relevant data are often fragmented; some are in private hands or used to generate income; and some government data have not been digitized or are otherwise not made available freely. It is important to be creative in filling data gaps in data sparse regions such as, for example, the polar regions and Pacific Islands. (*Links to recommendation 4 below*)

Along with the analysis of observations and process-based research, developing regional climate information from global models using dynamical or statistical downscaling is a common tool currently being used to generate high resolution climate change information, with regard to attribution of past change, understanding the processes that lead to change, and projecting future change. To facilitate developments in this area, the implementation of programmes that focus on well-defined regions based on decisions rather than natural boundaries, and that integrate activities that more typically would occur across the range of global programmes (WCRP, IGBP, IHDP, etc) will deliver results more effectively. START, for example, has valuable experience here. This is not just good practice for developed-world applications; it also supports activities in the developing world. (*Links to recommendation 3 below*)

Regional reanalyses: In the last decade, the reanalysis methodology has revolutionized many aspects of climate research. Use of state-of-the-art data assimilation systems, the highest quality observations, and high resolution regional models can be used to derive the best estimate of the evolution of regional climate. Such reanalyses support the development and evaluation of regionalization approaches, supply crucial input to impacts models that need to be verified using 20th century realizations, and test understanding of the response of decision processes. (*Links to recommendation 1 below*)

5.2 Climate Extremes

The importance of – and difficulties associated with – understanding and being able to predict trends in the occurrence of extreme precipitation events was discussed in detail in Section 4.2.1. Similar arguments apply to the occurrence of other climate extremes. Because such events often occur on small spatial scales and on time frames on the order of hours (rather than weeks), higher resolution models are needed for viable predictions. However, as noted in Sections 4.1 and 4.4, there are considerable technical issues that currently limit the accuracy of such models.

To have value, any prediction must have an error estimate associated with it. Further, it is also important to have metrics by which to quantify model improvement. While many regional projects do currently include some level of verification, there is a need for agreed standards such that different projects can be compared in a meaningful way and that overall progress in the field of downscaling can be achieved. Dealing with these problems is especially difficult since the occurrence of extreme events introduces statistical uncertainties, requiring large ensembles to reduce these uncertainties. (*Links to recommendation 1 below*)

Some extreme events can be explicitly resolved by regional models, and in these cases, care is needed in ensuring that statistical samples of regional models are long enough to be reliable for trend analysis. Other finer-scale events of economic importance, such as flash floods and tornadoes, cannot realistically be resolved and there is a need to support the modelling effort with careful statistical analysis of the relationship between model-scale features and extreme events. (*Links to recommendation 6 below*)

5.3 Terrestrial Processes

Regionalisation is aimed at providing information at the land surface, including coastal areas, where human systems interact with natural ecosystems. This requirement means that there are particular needs for monitoring, analysing and predicting terrestrial processes. Natural ecosystems, agriculture and forestry have been studied deeply in recent years. However, urban systems represent a rapidly growing sector of human and environmental interactions which are affecting biophysical and biogeochemical interactions and feedbacks with the climate system. For assessing the impacts on coastal megacities and ecosystems, regional datasets of sediment compactions, loss of sediment supply and sea-level rise are important. In addition, social processes driving urban expansion are not well understood, nor are they accounted for in regional and global models. (*Links to recommendation 5 below*)

The prediction of future human impacts and drivers to changes in land use and land cover need support by regional climate science. To support future analysis and prediction at the required scales, it will be important to develop regional datasets of key variables associated with land use and land cover change. Comparison between regions and transferability of techniques will depend upon consistent harmonisation of strategies across models; e.g., integrated assessment models, Earth system models, impacts models etc. Agreed standards for use and quality control of higher resolution datasets need to be developed. Datasets include digital elevation models, coastlines (all processes), streamflow, groundwater, land use and land cover. (*Links to recommendation 5 below)*

The water cycle is complex in both urban and rural systems. The interactions between groundwater, surface water and the atmosphere are not well represented in models (see Section 4.2), and not at all for urban systems. The interactions between clouds, precipitation and aerosols are not well understood or characterised in models (see Section 4.4). Modelling quality and water quality, including accounting for biogeochemical interactions and feedbacks within the climate system is vital for adaptation studies at regional scales.

5.4 Methodological Issues

Data Needs: Statistical downscaling models depend fundamentally on regional-scale data quality. At the same time, global and regional models have biases, which may lead to unrealistic regional climate features. High quality, high resolution and complete data are needed in order to inform statistical approaches and to confirm error reductions in models. (*Links to recommendations 1, 4 and 8 below*)

Global models: The results from regional models will be unreliable if the boundary conditions provided by a driving global model are in error or out of phase. However, regional models themselves also have limitations (e.g., cloud physics, urban processes). To optimize regional predictability estimates, we need to improve both global and regional models and the interface between them. Further, accurate surface boundary conditions will take best advantage of predictability that may arise from surface conditions. (*Links to recommendations 3 and 9 below*)

Statistical methods: The statistical characteristics of both local data and high resolution model output are often complex. Appropriate and robust statistical methods are needed for extremes, extrapolation, and downscaling, and these methods will need to be suitable for providing information of utility to decision-makers. (*Links to recommendation 6 below*)

Science capacity: Methodologies should be developed in view of the computational limitations in developing countries and countries with economies in transition. For example, it is reasonable to assume that short integrations, driven by lateral boundary conditions from global models, can be performed in order to explore the impact of future climate scenarios on the development of regional synoptic systems that are relevant to the local climate including extremes. (*Links to recommendation 6 below*)

Recommended Activities (including potential lead agents):

1. Support research to evaluate regional climate models, including the development of regional reanalyses and support of the development of model performance metrics; (*potential lead agent: WCRP*)
2. Develop methodologies to define, determine and communicate uncertainties and limitations to regional observations and model products in a context-sensitive manner; (*potential lead agents: WCRP, WCP through WMO, UNFCCC SBSTA*)
3. Implement new and strengthen existing regionally-based integrated programmes that have the potential to deliver better decisions with regard to climate change adaptation and mitigation more effectively; (*potential lead agent: ESSP*)
4. Develop and enhance national and regional observational networks and data rescue activities that provide data on the same scale as the required downscaling activity, including collection, archiving and access. The data requirements encompass physical, chemical and biological datasets. (*potential lead agent: WMO*)

Additional recommendations (including potential lead agents):

5. Develop and enhance international standards for key high-resolution terrestrial datasets, specifically: digital elevation models, streamflow, ground water, land cover, and urban development; (*potential lead agents: GCOS/GTOS*)
6. Improve understanding of the observed occurrence of extreme events in global and regional climate models; develop techniques

SHORTCOMING IDENTIFIED in ASSESSABLE MATERIAL FOR IPCC AR4:
Additional scenarios are required at the regional and local scales appropriate for impacts analysis, allowing adaptation to be incorporated in climate change impacts estimates

SURVEY RESPONSES:
Major reasons:
- Temporal/spatial coverage of observations: high-quality observations essential for full understanding of causes and attribution of present-day trends to climate change
- Lack of knowledge – particularly for the southern hemisphere – of what relevant datasets already exist
- Model resolution: a key scale is the city one, especially now when 50% of the population lives in cities, and urbanization has become a pervasive phenomenon

Negative consequences:
- Shortcomings in impact analyses, with implications for adaptation
- Limited understanding of vulnerability, also caused by lacking knowledge of adaptive capacity

Possible solutions:
- Enhanced observations on regional scales; higher spatial resolution climate scenarios, such as 25 km×25km, 5km ×5km or even 1×1km, are highly required, they could help generate “near true” impacts
- Much broader set of scenarios of emissions and other disturbances essential for a risk-management framework that the Plenary has insisted that WG II use, and thus we need some probabilistic estimation of scenarios
- Undertake scenarios of prototype cities and their climate relevant development trajectories based on economic, social, ecological and institutional resilience
- Capacity building for regional and local scientists, through fellowships and workshops
- Involve from the very beginning both natural and social scientists in identifying and - if possible - estimating key feedbacks between adaptation practices (e.g., snow making) and other key relevant processes (e.g., increase GHG emissions).

Linked issues:
- Regional downscaling and impacts are very important for adaptation and reasons for concern that motivate mitigation
- The distributional effects of impacts--equity--across regions, sectors (e.g., crops or plants reaction to different temperatures and moisture) and groups is critical to assessing what is "dangerous" and not apparent here
- Need more information on adaptive capacity (from governments) to assess vulnerability; “climate change must be seen in the context of development”
- Tsunamis should be included in climate change adaptation as they undermine the coping capacity of coastal communities; while the Integrated Coastal Management framework has been useful for climate change adaptation in the coastal areas and for islands, it needs to be improved to include new knowledge that is coming out of communities recovering from tsunamis, in order to make future coastal communities more resilient

to monitor and analyse small-scale extreme events such as tornadoes and hail; *(potential lead agents: WCRP, GCOS).*

7. Support the robust investigation of potential linkages between integrated assessment models, Earth system models and regional models (*potential lead agent: IGBP*)
8. Provide ongoing key ocean and terrestrial observations, e.g., ARGO, satellite-based, to support simulations of regional climate on seasonal to decadal time scales; (*potential lead agents: GCOS/GOOS*)
9. Develop innovative underpinning algorithms (nesting approaches, nudging, adaptive grids) and initial value and boundary value techniques to support investigations of regional detection, attribution, and predictability. (*potential lead agent: WCRP*)

6. Interfacing with Policy: Defining and Communicating

While mainly covering climate change research and observation issues per se, the Workshop also reaffirmed the importance of effective communication of scientific results related to climate change, in particular the communication of associated uncertainties. The AR4 highlighted the need to assess and communicate uncertainty well – all three Working Group reports provided detailed explanations on the treatment and representation of uncertainties. These are particularly relevant in the context of risk management, as elaborated in the following section. In addition, scientists at the Workshop and survey respondents provided ideas for consideration by the IPCC when defining the timing, structure and content of future climate change assessments, summarized in Section 6.2.

6.1 Expressing Uncertainty in the Context of Risk Management

One of the eventual purposes of the research and observation activities canvassed in this Report is to inform policymakers about climate change. Policy must, of course, make judgments about numerous social and political uncertainties in addition to those emerging from science. The scientific uncertainties thus need to be communicated in ways which are as explicit and transparent as possible.

Risk management, using the classical definition of risk as the product of probability and consequence, is most rationally applied when uncertainties are characterized consistently, and when the "fat tails" of the probability distribution, that include outcomes with potentially high consequences for society, are included.

6.1.1 Characterizing Uncertainty

The term "uncertainty" implies anything from confidence just short of certainty to informed guesses or speculation. Lack of information obviously results in uncertainty, but often, disagreement about what is known or even knowable is also a source of uncertainty. Some categories of uncertainty are amenable to quantification, while other kinds cannot be expressed sensibly in terms of probabilities. Uncertainties arise from factors such as linguistic imprecision, statistical variation, measurement error, variability, approximation, subjective judgment, and disagreement. These problems are compounded by the global scale of climate change, but local scales of impacts, long time lags between forcing and response, low-frequency climate variability that exceeds the length of most instrumental records, and the impossibility of before-the-fact experimental controls. Moreover, because climate change and other complex, socio-technical policy issues are not just scientific topics but also matters of public debate, it is important to recognise that even good data and thoughtful analysis may be insufficient to dispel some aspects of uncertainty associated with the different standards of evidence and degrees of risk aversion/acceptance that individuals participating in this debate may hold.

Examples of Sources of Uncertainty [28]

Problems with data
1) Missing components or errors in the data
2) "Noise" in the data associated with biased or incomplete observations
3) Random sampling error and biases (non-representativeness) in a sample

Problems with models
4) Known processes but unknown functional relationships or errors in the structure of the model
5) Known structure but unknown or erroneous values of some important parameter
6) Known historical data and model structure, but reasons to believe that parameters or model structure will change over time
7) Uncertainty regarding the predictability (e.g., chaotic or stochastic behaviour) of the system or effect
8) Uncertainties introduced by approximation techniques used to solve a set of equations that characterize the model

Other sources of uncertainty
9) Ambiguously defined concepts and terminology
10) Inappropriate spatial/temporal units
11) Inappropriateness of/lack of confidence in underlying assumptions
12) Uncertainty due to projections of human behaviour (e.g., future consumption patterns, or technological change), which is distinct from uncertainty due to "natural" sources (e.g., climate sensitivity)

In dealing with uncertainty in science or the policy arena, typically, two options are available: 1) bound the uncertainty, or 2) reduce the effects of uncertainty. The first option is to reduce the uncertainty through data collection, research, modelling, simulation techniques, etc. This is characteristic of normal scientific study. The objective is to overcome the uncertainty; in other words, to make known the unknown. However, the daunting magnitude of uncertainty surrounding global environmental change, as well as the need to make decisions before the uncertainty is resolved make the first option a goal, but one rarely achieved. That leaves policymakers an alternative: to manage uncertainty rather than master it. Thus, the second option is to integrate uncertainty directly into the policy-making process, often known as "risk management" in health, investment and strategic defence decision-making circles.

The emphasis on managing uncertainty rather than mastering it can be traced to work on resilience in ecology. Resilience refers to the ability to recover from a disturbance, without compromising the overall health of the system.

6.1.2 Guidance on Uncertainties

Attempts to achieve more consistency in assessing and reporting on uncertainties are just beginning to receive increasing attention. However, the scientific complexity of the climate change issue and the need for information that is useful for policy formulation present a large challenge to researchers and policymakers alike – it requires both groups to work together towards improved communication of uncertainties. The research community must also bear in mind that readers often assume for themselves what they think the authors believe to be the distribution of probabilities when the authors do not specify it for themselves. For example, integrated assessment specialists may have to assign probabilities to alternative outcomes (even if only qualitatively specified by natural scientists) since many integrated assessment tools require estimates of the likelihood of a range of events in order to calculate efficient policy responses. Moss and Schneider (2000) argued that it is more rational for experts to provide their best estimates of probability distributions and possible outliers than to have novice users make their own determinations. In particular, a guidance paper on uncertainties for the IPCC Third Assessment Report – the essence of which was adopted in the IPCC Fourth Assessment Report – recommends developing an estimate of a probability distribution based on the documented ranges and distributions in the literature, including sources of information on the key causes of

[28] From Moss, R.H. and S.H. Schneider (2000): Uncertainties in the IPCC TAR: Recommendation to lead authors for more consistent assessment and reporting. In Pachauri, R., T. Taniguchi, and K. Tanaka (eds.) (2000): Guidance Papers on the Cross Cutting Issues of the Third Assessment Report of the IPCC, pp. 33-51. IPCC Secretariat c/o World Meteorological Organization, Geneva, Switzerland.

uncertainty. An assessment should include a measure of the central tendency (if appropriate) of the distribution as well as a characterization of the end points of the range of outcomes, possible outliers, and the likelihood of outcomes beyond the end points of the range. Truncating the estimated probability distribution should be avoided, since this narrows the range of described outcomes, excludes outliers ("fat tails") that may include "surprises" and thus does not convey to potential users a representation of the full range of uncertainty associated with the estimate. It is inappropriate to combine different distributions into one summary distribution if this obscures differences between two (or more) "schools of thought". Representing the full distribution has important implications regarding the extent to which the analysis accurately conveys uncertainties.

A projected range is a quantifiable range of uncertainty situated within a population of possible futures that cannot be fully identified. The limits of this total range of uncertainty are unknown, but may be estimated subjectively. The inner range represents a "well-calibrated" range of uncertainty based on documented literature. The wider range of uncertainty represents a "judged" range of uncertainty based on expert judgments, which may not encompass the full range of uncertainty given the possibility of cognitive biases, such as overconfidence. New information, reliable and comprehensive empirical data in particular, may eventually narrow the range of uncertainty by falsifying certain outlier values.

6.1.3 Aggregation and the Cascade of Uncertainty

A single aggregated damage function or a "best guess" climate sensitivity estimate is a very restricted representation of the wide range of beliefs available in the literature or among lead authors, particularly since these estimates rely on a causal chain that includes several different processes. The resultant aggregate distribution might have very different characteristics than the various distributions that comprise the links of the chain of causality[29]. Thus, poorly managed projected ranges in impact assessment may inadvertently propagate uncertainty. The process in which uncertainty accumulates throughout the process of climate change prediction and impact assessment has been variously described as a "cascade of uncertainty" or the "uncertainty explosion". The cascade of uncertainty implied by coupling the separate probability distributions for the quantification of greenhouse gas emissions and the biogeochemical cycle in order to arrive at greenhouse gas concentrations needed to calculate radiative forcing, climate sensitivity, climate impacts and valuation of such impacts into climate damage functions has yet to be produced in the literature. If an assessment is continued through to economic and social outcomes, even larger ranges of uncertainty can be accumulated. The cascade of uncertainty will produce a range of possible outcomes, rather than best guesses. Therefore, decision-makers will be put in a position of managing the competing risks of their policy options using information that offers probability distributions for future events, but does not offer certainty about any one of those outcomes.

6.1.4 Using Probability Distributions to Evaluate Climate Impacts and their Consequences

Many recommendations to policymakers related to climate impacts and their consequences are based on point estimate values – that is, results that are derived from a series of "best guesses". This point estimate method fails to account for the wide range of plausible values for many parameters. Similarly, output from a single model run does not display all the information available nor does it offer sufficient information to provide the insights needed for well-informed policy decisions. Clearly, the use of probabilistic information, even if subjective, provides a much more representative picture of the broad views of the experts as well as a fairer representation of costs which, in turn, allow better potential policy insights. Policymaking via risk-management practices in the business, health and security sectors is often based on hedging against low probability but high consequence outcomes. Regardless of how risk-prone or risk-averse the individual decision-maker is, the characterization and range of uncertainties of the information provided by decision analysis tools must be made explicit

[29] *Modified from: Jones, R.N. (2000): Managing uncertainty in climate change projections: Issues for impact assessment. Climatic Change 45(3-4): 403-419.*

and transparent[30]. Thus, any climate policy analysis that represents best guess point values or limited (i.e., “truncated”) ranges of outcomes restricts the ability of policymakers to make strategic hedges against such risky outlier events. The end result of any set of integrated assessment modelling exercises will be, as always, the subjective choice of a decision-maker, but a more comprehensive analysis with uncertainties in all major components explicitly categorized and displayed will hopefully lead to a better-informed choice. In a highly interdisciplinary enterprise like the integrated assessment of climate change, it is necessary to include a wide range of possible outcomes along with a representative sample of the subjective probabilities that knowledgeable assessment groups believe accompany each of those possible outcomes.

It is then essential to link all assessed confidences and likelihood estimates to a quantitative scale negotiated by assessment teams and reviewers, in order to have consistent use of terminology like “high confidence” or “unlikely”. Vague and undefined language like “great uncertainty” or “cannot be excluded” or “is not definitive” can have very different quantitative interpretations and is best avoided to prevent misinterpretations. For example, the subjective probability of something being “not definitive” can vary by orders of magnitude.

Finally, risk assessment and management based on scientific findings need to be fully transparent. It is essential to provide a “traceable account” that describes the reasons for adopting a particular probability distribution, including important lines of evidence used, standards of evidence applied, approaches to combining/reconciling multiple lines of evidence, explicit explanations of methods for aggregation, and critical uncertainties.

6.2 Views on Future IPCC Assessments

While the IPCC AR4 has been immensely useful in laying the groundwork for this Report, many responses to the pre-Workshop survey and discussions at the Workshop raised ideas for consideration by the IPCC regarding its mode of operation for any possible future assessments. The call for ideas in this regard was supported by the IPCC Secretariat. It is hoped that the following ideas provide useful points for discussion. Although it was recognised that future comprehensive assessments are probably needed, it was felt it should not be until around 2013 to allow for sufficient advance since AR4. Some responses indicated a need for more focused, shorter, timely and more solution-oriented reports.

The most strongly supported structural suggestions included:

- Risk analyses more closely linked to WG I projections are required:
    - Need multi-scale, multi-disciplinary and multi-institutional studies with a hierarchy of models designed by advanced cooperative meetings of all significant players, following the example of the IPCC Synthesis Report model rather than the disciplinary working groups model used to date;
    - Try to formulate conclusions from the AR4 WG I in terms of risk assessments;
    - More use of probabilistic projections (on a sound scientific basis) rather than the use of ranges and individual model results;
- Concerted engagement with a wider set of user/stakeholder groups in future assessments;
- Construct future climate change assessments on the Synthesis model, rather than on the model with three separate Working Groups. The current SYR of AR4 is late in the process for such integrative understanding and thus is a difficult venue to accomplish interdisciplinary integration in the allotted time;
- Start the SYR team at least a year earlier, allowing for it to influence some of the Working Group reports;

[30] *Moss, R. and S.H. Schneider (1997): Characterizing and Communicating Scientific Uncertainty: Moving Ahead from the IPCC Second Assessment, in Hassol, S.J. and J. Katzenberger (eds), Elements of Change 1996, Aspen Global Change Institute, Aspen, Colorado, pp. 90-135.*

- Special Reports on ice sheets and on the climate carbon-cycle feedback could be planned in 2-3 years;
- Create and sustain ongoing interactions across the communities that populate the disciplinary working groups:
  - A top priority is to involve from the very beginning both natural and social scientists in an integrated framing and assessment of climate issues, which have been so far separately addressed by Working Groups I, II and III;
  - The core Writing Team of the Synthesis report could be maintained after release of a possible fifth assessment report, allowing for more time to learn from each other how to do integrative research to answer key questions;
  - The WG II Report could be broken down into a series of regional and/or sectoral reports.

Improving the relevance of IPCC assessments was also discussed, giving rise to many ideas about specifics. However, GCOS, WCRP and IGBP may also be able to respond to some of these suggestions:

- Online updates of key research/observational issues;
- Updates and assessments on a 2-3 year basis, or as appropriate, in areas of significant improved scientific understanding; and
- Monitoring the actual trajectory of climate change to assess whether key developments (such as possible approaching of "tipping points", or an increased potential for abrupt climate change) should be urgently brought to the attention of the policy and user/stakeholder communities.

7. Conclusions

In the context of increased recognition of our changing climate, researchers and those responsible for climate observations recognise that there is an increasing demand by decision-makers for climate change information required for adaptation and the assessment of impacts and vulnerability. Improving climate models and observations continues to be of great importance and at the same time there is a requirement to underpin an increasing range of user/stakeholder needs. Guidance about decisions on adaptation is often being demanded faster, and with greater detail than research can deliver and than the observing system can support. It was in this context that the three international climate programmes, the Global Climate Observing System (GCOS), the World Climate Research Programme (WCRP) and the International Geosphere-Biosphere Programme (IGBP), set the goals for the "Future Climate Change Research and Observations: GCOS, WCRP and IGBP Learning from the IPCC Fourth Assessment Report" Workshop.

The future interplay of societal and scientific aspects of climate change includes the need to identify and understand the important processes that control climate, and how these processes interact with broader community issues. The AR4 clearly illustrated that the need for improving process-level understanding is still great for many important areas in the climate system. In other words, it underlined that there are many urgent gaps to fill. Models are needed that both accurately and precisely describe these processes; observations of sufficient detail and scope are required to improve models and to ensure that the processes themselves can be elucidated, predicted and projected.

Now that the IPCC has been so successful in convincing society about the reality of anthropogenic climate change, there is an urgent demand at the highest political level for better information to underpin mitigation and adaptation decisions in order to "do something about it". From the point of view of the global programmes for climate research and observations, this illustrates the need for rapidly improving our observational data base, our understanding and our models for prediction of future climate change and of framing our efforts more consciously around the concepts of risk, vulnerability, impacts and adaptation. The participants of the workshop expressed the desire that the kinds of assessment currently being done in the different IPCC working groups be done with greater coordination – and that the international observation and research communities themselves should frame efforts in ways that stimulate this coordination. There was a clear desire to enable the communities researching impacts, adaptation and vulnerability and the climate research and observation communities to develop relevant and linked research and observational strategies. If successful, this would help provide new and important evidence for any future IPCC assessment that would be better aligned with the questions of societal relevance that are now being asked with greater frequency and urgency.

The Workshop recommended guiding principles for considerations by GCOS, WCRP, and IGBP for setting and updating future climate change research and observation needs. They include:

- Addressing the key science areas needed to further understanding of the climate system, and improving predictive capability;
- Including consideration of vulnerability in framing climate change research and observations;
- Ensuring effective links between global/regional modellers, and the communities involved in the assessment of impacts, adaptation and vulnerability;
- Ensuring the development of climate predictions for the next 10-30 years to complement longer-term projections;
- Addressing the need to effectively communicate uncertainty estimates for all information provided;
- Ensuring continuity of the climate record while incorporating new requirements derived from the research community.

These principles could be used to guide how and where to expend resources in terms of process studies, and in which key areas to strive for increased model and observational resolution. Needs for climate science could undergo a rolling review process, considering (1) needs of decision-makers and the impacts, adaptation and vulnerability communities and (2) actual climate science capabilities and prospects (research and observations). In this way, international programmes would address process-level gaps in understanding of climate such that the most vulnerable areas are comprehensively investigated. This kind of framing requires a greater dialogue between researchers from all three programmes and with stakeholders. Similar principles apply to ensure the traditional IPCC working groups work more closely together – the Workshop suggested ideas for consideration in any future IPCC assessments.

Appendix A

AGENDA, WORKING GROUPS and MEETING NOTES

Meeting Notes

4 October 2007
The workshop was opened at 9.00am by John Church (WCRP), who thanked all participants for coming to Sydney and stressed that the meeting was concentrating on gaps and deficiencies in the science assessed in the IPCC Fourth Assessment Report. He added that the meeting was intended to give GCOS, WCRP and IGBP guidance on how to address these gaps in their future planning.

In their welcoming statements, Thomas Rosswall (ICSU) and Robin Batterham (Australian Academy of Technological Sciences and Engineering) emphasized the significance of the event for the three international programmes, and for the further advancement of climate science. Geoff Love (Bureau of Meteorology, representing the WMO) welcomed all participants and noted that scientific gaps were particularly apparent in the Reports of IPCC Working Group II and III. Both Love and Neville Smith (representing the IOC) recalled the urgent need for a more integrated view on climate science, encompassing all IPCC Working Groups. For the evolution of the IPCC and possible future climate change assessments, Renate Christ (IPCC) stressed the importance of recommendations emanating from this event and thanked the organisers for IPCC's involvement in its preparation.

In the following, the Directors of GCOS, WCRP and IGBP programmes presented key results of the survey conducted prior to the workshop (see Appendix B), and possible implications for their respective programmes.

Ann Henderson-Sellers (WCRP) highlighted as key research issues the predictive skill of climate change models, its relation to the ability of models to simulate observations, and the question of weighing models based on model metrics in order to optimize multi-model ensemble predictions of, in particular, regional climate change. She quoted some research priorities given by the survey, and stressed that climate change science was by no means "done", as demonstrated by many deficiencies in the prediction of regional climate extremes, such as floods and droughts. Given that climate change was happening now, she advocated the development of climate change research emergency priorities centred on improved regional science and prediction, the ability to issue society-relevant high-risk warnings, and enhanced participation of climate change science in the business sector.

Kevin Noone (IGBP) presented research foci and linkages of the IGBP programme with other global change programmes, such as those represented in the Earth System Science Partnership. He then posed a set of integrative questions that required collaboration between scientists from different programmes and communities, such as on the oxidative state of the atmosphere, oceans and freshwater systems. He highlighted areas which have been characterized as "tipping points" in the climate system, since change in the physical and biogeochemical properties of these areas could occur on relatively short time scales ("abrupt climate change").

David Goodrich (GCOS) reiterated key questions for this workshop from the perspective of climate observing systems, and noted that changes in the observing system in order to address emerging needs should not jeopardize the maintenance of long-term, homogeneous time series of climate data for all climate applications. He stressed that the main goal from a GCOS perspective was to learn from the IPCC Fourth Assessment report, and what new developments had become apparent since the IPCC Third Assessment Report. The workshop would constitute one source of input to a comprehensive GCOS progress report to be submitted to the UNFCCC SBSTA in 2009. Examples for key needs for observing systems identified in the survey were the maintenance of Earth radiation budget measurements, access to high-resolution daily precipitation data, and the completion of the ocean observing system. Dr Goodrich closed with survey-based suggestions for new Essential Climate Variables and further more general issues raised, e.g. the need for reprocessing and reanalysis of key climate datasets.

Discussions at the workshop were held in a sequence of plenary and break-out sessions. Break-out Task Groups had designated co-chairs responsible for screening the survey results relevant to their Group, chairing the discussions, reporting results back to plenary, and leading their group's contribution to the Workshop Report. To facilitate the work of Task Groups, specific guidelines had been prepared ahead of the workshop. In the following, all Task Group co-chairs introduced their group and outlined key points of discussion:

Thomas Stocker (University of Bern) and Ulrich Cubasch (FU Berlin) introduced their Task Group concerned with "Gaps in AR4: Knowledge, Interpretation and General Appraisal" by commenting on the structure of the AR4, particularly the thematic choice of chapters in the report, which had a strong influence on the content and spin of the document. In their group, key science issues requiring further attention were discussed, such as uncertainties in "tipping points" of the climate system, the development of long-term emissions scenarios, uncertainties in radiative forcing, carbon cycle feedbacks and the long-term natural variability in ocean variables.

Venkat Ramaswamy (NOAA) and Phil Jones (University of East Anglia) focussed discussions in their group on global needs for observations, evaluation, improvement and impact studies in the context of climate and Earth system modelling. They specifically highlighted practical steps to better know the connection of these global needs to improved regional projections as well as to other priorities for climate research and systematic observation.

Mark Stafford-Smith (CSIRO) and Lucka Kajfez-Bogataj (University of Ljubljana) introduced key topics of discussion for the Task Group "Impacts, Adaptation and Risk", namely the urgent need for: (1) additional scenarios that describe the future evolution of the world, (2) a stronger focus of vulnerability assessments down to the regional scale, (3) better exploration of the links between adaptive capacity and the sustainable development of societies, and (4) cost-benefit analyses of adaptive measures in light of climate change impacts. As an overarching need, they advocated for prioritising climate science around its relevance to policy and management responses to climate change.

In Task Group 4, Amanda Lynch (Monash University) and Paul Mason (University of Reading) focussed on aspects of improving the spatial resolution of climate models to a regional scale, and issues and initialization and validation of these models using observational data.

In the discussion after the initial presentations by the Task Groups, participants called for closer involvement of users of climate information for impacts and adaptation measures, especially from developing countries, but also noted that these users were not represented among participants at this Workshop. The need for regional observations to properly verify regional climate change predictions using observations was emphasized, given that global models were largely not able (and designed) for providing reliable information on a regional scale.

In a series of plenary talks, lead authors from IPCC Working Group I and II provided their perspectives on the AR4 report:

Kevin Trenberth (NCAR; WG I) highlighted uncertainties and gaps in atmospheric modelling and observations, such as insufficient homogeneity of the long-term climate record, especially from space-based instruments, and the need for internationally-coordinated reprocessing of these records. Coordinated reanalyses of datasets was equally required to fully understand trends in the climate record. He also stressed the urgent and continuing need for better access to high-resolution (time and space) *in situ* observations, e.g. of precipitation, and advocated for reference-type networks providing observations of highest quality. As to regional climate change, Trenberth argued that full understanding of the changes in modes of climate variability (e.g., PDO, NAO, …) was required to better address regional climate change.

Nathan Bindoff (University of Tasmania and CSIRO; WG I) focussed on key research questions in the area of oceanic climate change, namely global-scale temperature and salinity changes, regional-scale changes, understanding of the ocean carbon cycle, and sea-level changes. Bindoff stressed the need for sustained observations of the oceans (both *in situ* and satellite-based), timely access to the data, and enhanced multi-disciplinary research in order to address the totality of ocean changes and impacts of these changes.

Research in the area of terrestrial coupling and biogeochemistry was the subject of Colin Prentice's (University of Bristol; WG I) presentation. On the whole, coupling strengths between the land surface and the atmosphere was poorly understood and therefore inadequately represented in models, he said. He informed the meeting about the large range of carbon feedback effects, and advocated for an international strategy to better understand these effects, including the maintenance of long-term observation datasets. In his view, dedicated case studies in the area of terrestrial climate change were very useful for directly address major questions about climate change.

In his talk, Koni Steffen (University of Colorado Boulder; WG I) focussed on climate change in the cryosphere, and more specifically on: changes in the cryospheric contribution to past and present sea-level rise; recent insights into the change of mass balance of the Greenland and Antarctica ice sheets, including model inadequacies in explaining them; and changes in Arctic sea-ice cover. In his conclusion, he highlighted some key uncertainties as to the future prediction of cryospheric change and possible way to remedy them.

Linda Mearns (NCAR; WG II) introduced the role of high-resolution climate scenarios for impacts and adaptation research. She presented different aspects of regional modelling and challenged the added value of higher-resolution models and scenarios for impacts and adaptation studies in different areas, such as agriculture and water management. In her view, the choice of emission scenarios was the dominant source of uncertainty in climate projections. More research into the relative contribution of uncertainties from global and regional climate models was needed, as well as better socio-economic information at higher spatial resolution.

Roger Jones (CSIRO; WG II) informed the group on issues in the area of impacts, adaptation and vulnerability in the context of the AR4. As key gaps, he highlighted poor downscaling of regional climate change models, and the lack of a coherent methodology for impact studies. One item of discussion in WG II had revolved around whether uncertainties in model predictions needed to be further reduced by better science, or needed to be managed appropriately by decision-makers. Jones stressed that in order for science to be policy-relevant, consistent framing of uncertainties was crucial, for example when mapping key climate change impacts as a function of warming. He presented different approaches to assessing vulnerability (top-down versus bottom-up) as well as alternative ways to communicate risks and uncertainties. He also highlighted key research questions related to adaptation, and an approach to framing adaptation in the societal context in the light of different climate change projections and world scenarios.

On behalf of Patricia Romero-Lankao (NCAR; WG II), Kathy Hibbard (NCAR) presented a case study on adaptation to climate change in the urban environment. Underlying the case for cities to be at the centre of adaptation measures (population centres, centres of greenhouse gas emissions), she informed the meeting of existing adaptation frameworks, deficiencies in regional modelling to address urban needs, and the fragmentation of vulnerability assessment approaches in cities. Romero-Lankao focussed on examples of causal loops exacerbating urban vulnerability, such as land markets and policies that foster the settling of population in risk-prone areas. She also showed examples for urban planning decision that accounted for projected climate change impacts, although in general, little knowledge existed on adaptation practices at the city level.

In the following session, views on the future direction of IPCC, and on research and observation needs for future climate change assessments were discussed.

Renate Christ (IPCC Secretariat) briefly reviewed IPCC history including past IPCC assessments and reports, and stressed the will on the part of policymakers up to the highest level to act now, based on scientific evidence provided by the IPCC. For future assessments, she reflected upon possibilities to change the structure of IPCC as suggested by the pre-Workshop survey, e.g. in terms of focus and timing of its assessments. Within the Working Group model, better integration of the groups was required. Christ concluded her talk with some key science and policy questions that were highlighted in the AR4, for consideration by Workshop participants.

Stephen Schneider (Stanford University) covered aspects of risk management and risk assessment to address vulnerabilities in the context of the AR4. He presented seven criteria for defining and assessing key vulnerabilities: magnitude, distribution, timing, persistence and reversibility, likelihood and confidence, potential for adaptation, “importance” (perceived, objective) of the vulnerable system. In his view, climate change science should support risk assessments (consequence times probability) as a function of alternative policy choices, and explained different types of errors in decision-making (“false positive” (Type I) leading to squandered resources, versus “false negative” (Type II) leading to unmitigated damages). He conceded that the quantification of climate change impacts remained in many cases difficult because of large uncertainties involved. In closing, he stressed the importance of “fat tails” of probability density functions, e.g. for describing global mean temperature change, and their relevance for responsible risk management.

Gerry Meehl (NCAR) addressed the issue of climate change modelling questions that arose from the AR4, focussing on (1) better decadal predictions (“near term”, i.e. for the next 20-30 years), especially on regional scales, (2) the size and nature of carbon cycle feedbacks in the climate system, (3) adaptation and mitigation scenarios. Meehl explained a set of experiments to develop a new class of long-term scenarios (“reference concentration pathways”), based on stabilized emission levels. Ongoing discussions in the modelling community are leaning towards four reference pathways defined by effective radiative forcing in 2100, including an unmitigated case, one case assuming low mitigation, and two cases of medium mitigation. He also made suggestions as to additional data needs (oceans, carbon cycle, ice sheets) and to details of future coordinated modelling experiments.

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In a sequence of plenary and break-out sessions, participants discussed in more depth the topics raised by the Task Group co-chairs, by the survey, and in presentations in plenary, and prepared draft text for inclusion into the Workshop Report.

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In the morning, Task Groups finalized their work and in part re-organised their composition as felt appropriate.

Back in plenary, Adrian Simmons (ECMWF; AOPC Chair), Ed Harrison (NOAA; OOPC Chair) and Han Dolman (VU Amsterdam; TOPC Chair) briefed participants on the status of work in the three domains (atmosphere, oceans, terrestrial) of the global climate observing system (GCOS), based on the Second Adequacy Report and the GCOS Implementation Plan. They stressed the need to maintain and enhance the long-term observational record for climate, concentrating on Essential Climate Variables and using all platforms. Further, the continuing need for reprocessing and reanalyzing of historical datasets in order to better understand climate variability and change was emphasized. The evolution of the observing system was crucially dependent on considering new developments in climate science, as highlighted in the AR4 and the survey preceding the Workshop.

In the afternoon, Martin Manning (IPCC TSU WG I) raised some points for discussion related to priorities for future IPCC assessments: (1) Science should remain policy-relevant, (2) What frameworks existed or needed to be developed for cross-disciplinary science, (3) What frameworks existed or needed to be developed for developing country participation in the process, and (4) What could be done in the context of the Workshop? As for policy relevance, he raised the need for more interdisciplinary and timely science input for decision-making, which could possibly be addressed by a comprehensive climate information system. Better cross-disciplinary science could be enabled by better integration of climate change models and impact models, and the use of reference scenarios as an organizing principle. Better self-organisation of the community behind impacts, adaptation and vulnerability would greatly simplify this task. International organisations and conventions, such as UNFCCC, IPCC and WMO, should foster developing country participation in the assessment process, for example building on experience gained in START. Manning also offered his thoughts on possible outcome of the Workshop and implementation of its recommendations, for example the trade-off between gradual shifting of existing organisational structures versus an entirely new initiative.

Roberto Acosta Moreno (UNFCCC) gave an update on current activities in the framework of the UNFCCC, including preparation for the 13th Conference of the Parties in Bali, Indonesia. He stressed that adaptation and mitigation now received comparable levels of attention by the Convention. Acosta reviewed the status of UNFCCC decisions in the area of systematic observation and research and emphasized the major role of climate research and observations in the SBSTA Nairobi Work Programme on Impacts, Vulnerability and Adaptation to climate change.

Buruhani Nyenzi (WMO) gave an brief overview of the planning status for the World Climate Conference-3, sponsored by WMO. This conference will be hosted by WMO in Geneva in 2009, with a focus on seasonal to interannual climate predictions and their benefits to society. Planning was well underway, and would consider the lessons learnt from the IPCC AR4 and the recommendations from the Workshop.

Nebojsa Nakicenovic (IIASA and TU Vienna) briefed the group on latest developments in the context of IPCC Working Group III. Since the SRES scenarios had been developed ten years ago, a revisit was needed based on the latest scientific findings. WG III had conducted a broad literature review and noted that in the meantime, (1) the span of greenhouse gas emission scenarios had change little, but radiative forcing was better constrained (e.g., aerosol effects), (2) expected maximum world population in the 21st century was at an estimated 13-16b – 2b less than previously expected, (3) some changes in the policy context had occurred, (4) new literature on new approaches to mitigation (e.g., the concept of regional burden-sharing etc.) was available. As mentioned by Gerry Meehl, future mitigation scenarios were concentrating on different stabilization levels. WG III had formed a consortium which elaborated further on these scenarios. Now, the process of identifying modelling groups that would provide runs for the next assessment using these scenarios had started. Another year was probably needed to provide additional information regarding these scenarios (e.g., related to the spatial distribution of emissions, full documentation, socio-economic drivers behind the scenarios). A report on these issues was under development and would be widely distributed.

John Church (WCRP), John Zillman (GCOS) and Carlos Nobre (IGBP) thanked all participants for their active participation and their hard work during the Workshop. They expressed their confidence that the recommendations given by the group would be of great value in shaping the future strategy of GCOS, WCRP and IGBP, and formally closed the Workshop at 5.45pm.

Agenda

Thursday 4 October 2007

1. Registration 08:30 – 09:00

2. Opening (Chairs: J. Church, C. Nobre, J. Zillman) 09:00 – 09:45

   2.1 Welcome
   - T. Rosswall (ICSU)
   - R. Batterham (Australian Academy of Technological Sciences and Engineering)
   - G. Love (representing the WMO)
   - N. Smith (representing the IOC)

   2.2 IPCC Opening Address (R. Christ)
   2.3 Local arrangements (W. Steffen, with P. Holper, M. Hopkins)
   2.4 Expectations of the workshop, approval of the agenda and acknowledgements of sponsors (Chairs)

3. Gaps, uncertainties and deficiencies (Survey Results) 09:45 – 10:30
   (A. Henderson-Sellers, K. Noone, D. Goodrich)

Tea Break: Greenhouse 2007 ***10:30 – 11:00***

4. Creating Workshop Task Groups 11:00 – 12:20
   (Chair: A. Henderson-Sellers)

   4.1 Group 1: Gaps in AR4: Knowledge, Interpretation, General Appraisal
   (T. Stocker/U. Cubasch)
   4.2 Group 2: Climate and Earth System Modelling (V. Ramaswamy/P. Jones)
   (Global needs for observations, for evaluation, for improvement, and for impact studies)
   4.3 Group 3: Impacts, Adaptation, and Risk (Mark Stafford-Smith/L. Kajfez-Bogataj)
   (Encompassing biodiversity, human health, water cycle, agriculture…)
   4.4 Group 4: Regionalising Model Projections/Downscaling (A. Lynch/P. Mason)
   (Future projections at the regional scale; relation to adaptation and policy)

   4.5 Plenary Discussion

5. IPCC AR4: Perspectives

   5.1 IPCC WG I: The Physical Science Basis (Chair: M. Manning) 12:20 – 13:00
   5.1.1 Atmospheric Modelling and Observations (K. Trenberth)
   5.1.2 Oceanic Climate Change (N. Bindoff)

Lunch with Greenhouse 2007 ***13:00 – 14:00***

   5.1 IPCC WG I (*cont'd*) 14:00 – 14:40
   5.1.3 Terrestrial Coupling and Biogeochemistry (C. Prentice)
   5.1.4 Cryospheric Climate Change (K. Steffen)

   5.2 IPCC WG II: Impacts, Adaptation, and Vulnerability (Chair: J. Palutikof) 14:40 – 15:20
   5.2.1 High-resolution climate scenarios for impacts and adaptation research (L. Mearns)
   5.2.2 Impacts and Vulnerability (R. Jones)

Tea Break with Greenhouse 2007 ***15:20 – 15:50***

	5.2 IPCC WG II (*cont'd*) 5.2.3 Adaptation Case Study: Urban Settlements (P. Romero-Lankao)	15:50 – 16:10
	5.3 Research and Observation Needs for Future IPCC Assessments (Chair: J. Stone)	16:10 – 17:25
	5.3.1 General Perspectives (R. Christ) 5.3.2 Risk Assessment and Risk Management (S. Schneider) 5.3.3 Modelling Scenarios (G. Meehl) *(Summary of 'The Netherlands' meeting)*	
6.	Instructions/Guidance for Task Groups (A. Henderson-Sellers, K. Noone, D. Goodrich)	17:25 – 18:00
	[N.B.: Task Groups meet in the evening]	
	Greenhouse 2007 Conference Dinner	

Friday 5 October 2007

7.	Questions from/Guidance to Task Groups (Plenary)	08:30 – 08:45
8.	Work in Task Groups [N.B.: Select/confirm group rapporteurs]	08:45 – 11:00
	Tea break with Greenhouse 2007	***11:00 – 11:30***
9.	Work in Task Groups *(cont'd)*	11:30 – 12:50
	Lunch break with Greenhouse 2007 [N.B.: Task Group chairs meet with workshop organisers at lunch]	***12:50 – 13:50***
10.	First report of Task Groups (Plenary) • Check status quo • Possible re-composition of groups	13:50 – 14:30
11.	Continue work in Task Groups	14:30 – 17:00
12.	Plenary discussion: Reports from Task Groups	17:00 – 18:00
	[N.B.: Task Groups meet in the evening]	
	Workshop sponsored Dinner at Casa di Nico (19:00)	

Saturday 6 October 2007

	[N.B.: DRAFT WORKSHOP REPORT AVAILABLE FOR PARTICIPANTS]	
13.	Panel & Plenary discussion (Chair: W. Steffen):	08:30 – 09:00
14.	Additional Time for Discussion/Cross-fertilization in Task Groups	09:00 – 10:30
	Tea break (Workshop sponsored)	***10:30 – 11:00***

15.	Panel & Plenary discussion (Chair: M. Manning): Priorities for future IPCC assessments	11:00 – 12:30
	Lunch (Workshop sponsored)	***12:30 – 14:00***
16.	Task Groups Finalize Report Components for GCOS (observations) and WCRP and IGBP (research)	14:00 – 15:30
	Tea break (Workshop sponsored)	***15:30 – 16:00***
17.	Round Table & Plenary discussion (Chair: D. Goodrich): Workshop lessons learned for GCOS, WCRP and IGBP *(Review draft workshop report; individual last words)*	16:00 – 17:00
18.	Plenary discussion (Chair: K. Noone): Future climate research and observation priorities for GCOS, WCRP and IGBP	17:00 – 17:30
20.	Workshop closing and final remarks (Chairs: J. Church, C. Nobre, J. Zillman, K. Lambeck)	17:30 – 18:00

Appendix B

SUMMARY of PRE-WORSKHOP SURVEY: URGENT NEEDS FOR CLIMATE CHANGE RESEARCH AND OBSERVATIONS, BASED ON KEY GAPS AND UNCERTAINTIES IDENTIFIED FROM THE IPCC FOURTH ASSESSMENT REPORT (WG I and II)[31]

1. Urgent needs for climate change research

The following 'urgent needs' emerged from the survey conducted prior to the Workshop. While they are unlikely to be either complete or even constitute a unanimous list, they can be seen to represent gaps that clearly have a detrimental impact on our current understanding and on our ability to adequately address the consequences of greenhouse warming.

1.1. Overall needs

Climate change research entered a new and different regime with the publication of the IPCC Fourth Assessment Report (AR4). There is no longer any question about 'whether' human activities are changing the climate; instead research must tackle the urgent questions of: 'how fast?'; 'with what impacts?'; and 'what responses are needed?' In many cases, answers are now being demanded faster than, and at higher resolutions than, research can deliver. It is essential for the climate change research community to be transparent and honest about what it can (and cannot) deliver and how (if ever) current inadequacies can be resolved.

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1.1.1. Policy

There are policy issues that climate change research must reach, such as

- Monitoring the trajectory of climate change to assess whether we are heading into a danger zone and how fast/where;
- Examining policy-driven questions to learn to understand how others see the world and what scientists need to do to help resolve such non-science priorities;
- Rolling reassessment building on what works, discarding what is weaker and revisiting with governments and stakeholders their priority needs;
- Establishing metrics of transient change impacts to detect and monitor the most likely (best predicted) changes of importance for rapid adaptation response;
- Assisting in determining what adaptation measures are needed beyond current coping capacity;
- Providing pathway options to obtain thresholds like the 2^{o}C limit goal of the EU;
- Fuller understanding of the carbon-cycle and stabilizing emissions levels of GHG;
- Increasing confidence in the relationship between stabilizing emission and temperature rise.

1.1.2. Research

There are serious inadequacies now that concern climate change research including:

- The rush to emphasize regional climate does not have a scientifically sound basis;
- Prioritize the models so that weaker ones do not confuse/dilute the signals;

[31] See (1) IPCC (2007) : Summary for Policymakers. In : Climate Change 2007 : The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 19-91 (Technical Summary); and (2) IPCC (2007) : Summary for Policymakers. In : Climate Change 2007 : Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 23-78 (Technical Summary).

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- Until and unless ENSO, PDO, NAO and AMOC etc. can be predicted to the extent that they are predictable, regional climate is not a well defined problem. It may never be. If that is the case then we should say so. Therefore, it is not just the forecast but the confidence and uncertainty that are just as important;
- Climate models need to be exercised for weather prediction, there are necessary but not sufficient things that can best be tested in this framework, which is just beginning to be exploited;
- The response of models to a single transient 20th century forcing construction. The factors leading to the spread in the responses of the models over the 20th century can then be better ascertained, with forcing separated out thus from the mix of the uncertainty factors. AR4 missed doing this owing essentially to the timelines that were arranged;
- Adding complexity to models, when some basic elements are not working right (e.g., the hydrological cycle) is not sound science. A hierarchy of models can help in this regard;
- More attention to basic model flaws: without doing so, future IPCC ARs will look very similar each time, and many resources would be wasted;
- Improve decadal predictability: organise in WCRP and work together with GCOS;
- Better reanalysis and data recovery/homogenization in general will help with many items;
- We need much more reliable social and economic data in order to understand the links between development and climate – preferably at a country level;
- Socio-economic feedbacks – in other words linking (in a coherent way) the forcing scenarios used to run projections to plausible futures of population, fossil fuel use, technology etc. IPCC has done a very poor job of linking these to date;
- A framework presenting a unified picture of the future emissions' scenarios across the IPCC Working Groups I, II and III and thus the entire climate community has been defined in the 'Aspen Statement' (WCRP Informal Report No. 3/2007) facilitated by the modelling groups of WCRP and IGBP. Among the important recommendations is the need to have an integrated effort to produce past-to-future emissions of aerosols and ozone precursors that would ensure the use of consistent and documented data relevant to communities working on climate, carbon, aerosols and chemistry;
- Understanding and attributing climate change: try to answer questions such as 'how many Cat 4 tropical cyclones impacting the Gulf Coast in a year is a climate change? Or how many over 40C periods of 20 days in Europe is due to increase in GHGs?' Posing topics in this format would relate better to e.g., "application of climate analyses to societal needs, linking climate applications to socio-economic data" (G&I in the list of research & observation needs).

It is clear that climate change will remain a risk management problem for the foreseeable future. However, the more we can constrain distribution functions of important process variables or outcomes like climate sensitivity or damages the better will be humanity's chances of adaptation. The cleverer we are in the design, the sooner we constrain the potential for some really "dangerous" outcomes that cannot currently be ruled out with less than 10% chances.

1.2. Specific needs

Tackling the resolution problem properly is seen to be very important and not easy – consider massive increment in computer resources, which should enable immediate improvement in space and time scale so we can evaluate whether greatly increasing resolution does (as promised) solve many climate projection problems or not.

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1.2.1. Atmospheric and ocean research

- Thorough understanding of the physics and dynamics of the Greenland and Antarctic ice sheets, with a view to predicting sea-level rise within 20% for a specified change in climate over the ice sheets;
- Simulation of the main modes of variability in each of the main oceans: ENSO and PDO in Pacific, THC, MOC and AMO in Atlantic, monsoons in Indian Ocean. Replicating relative changes over the past 50 years is essential and is an initial value problem for the oceans;
- Re-evaluation of the projections for sea-level rise, reduction of uncertainties in sea-level change, aiming for a consensus rather than a lot of publications criticizing AR4;

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- Constrain radiative forcing as much as possible (aerosols, clouds, land surface, …);
- Reducing cloud feedback uncertainties, because these are the cause of most of the uncertainty in forcing and model response and therefore a majority of projection uncertainty; mesh cloud-resolving models into AOGCMs;
- Improvement in understanding of global hydrological cycle (rainfall, evaporation and clouds) under increase of greenhouse gas level, since a) the hydrological cycle is critical for estimating radiation budgets, but is poorly measured and b) rainfall and evaporation are of such critical importance to human affairs.

1.2.2. Bio-geochemical research

- Establishing the likelihood of Amazon forest dieback creating a CO_2 source (instead of a sink);
- Links between land use/cover change and GHG emissions;
- Bringing the carbon cycle models (including methane) to a level comparable with the physical climate change models and fully incorporate them (i.e. reducing carbon cycle feedback uncertainties);
- Reducing climate sensitivity.

1.2.3. Feasibility of tackling research challenges

Participants to the survey made many recommendations for action. Overarching recommendations included, for example, “better (2-way) dialogue between climate modellers/data providers and users (both academic/research and wider stakeholder community), and similarly, better dialogue between research/stakeholder communities in developed/developing countries.” There were also many overlaps with observational priorities (see Section 4.6 in the main text, not repeated here). This section only highlights the “do immediately” and the “tough and long-term” challenges.

Immediate action is feasible and strongly recommended for:

- (Deep) ocean and ice-sheet changes: both observations and improved modelling;
- Systematic analysis of feedback strengths (AR4 WG I Chapter 9 is a weak and often vague attempt at this);
- Global reprocessing of observations to standards of multiple variables;
- More reliable assessment of ocean heat content variability and trends on global, hemispheric and ocean-basin scales, by digitizing remaining manuscript sub-surface and surface data and carefully homogenizing all available data;
- Clarify relationship between stabilizing emissions and temperature rise;
- Higher resolution, inclusion of stratosphere, chemical processes, low resolution palaeoclimate modelling;
- Precipitation measurements, combined with improvements in assimilation methods and reanalysis techniques;
- Better representation of soil carbon dynamics in GCMs.

Tough and long-term research challenges (to do within 10-15 years from now):

- Develop Earth system models that include atmosphere, biosphere, ocean, land and cryosphere not only at the process level but interacting with each other on regional as well as global scales;
- Climate scientists to work more closely with scientists that develop mitigation options;
- Complete an incremental evolution of current climate models to Earth system models, with more efforts on sensitivity studies;
- High resolution palaeoclimatic modelling including stadial transitions, model verification of ice cores, palaeoclimate data assimilation;
- Studies that better incorporate regional details, the carbon cycle, permafrost, CH_4 etc.;
- Rolling reassessment building on what works, discarding what is weaker and revisiting with governments and stakeholders what are priority needs. Meanwhile no monitoring programs should be dropped without careful examination of what would be lost when the record simply stopped;
- Biogeochemical processes directly affecting CO_2 and CH_4 concentrations;
- AOGCM with full cloud resolving models.

2. Urgent needs for climate observations

The list of Essential Climate Variables (ECVs) was defined in the GCOS Second Adequacy Report (2003), after close consultation with key IPCC authors of the TAR. They provide a priority list of climate variables targeted for global observation. Taking advantage of the AR4 to re-examine the adequacy of the ECVs allows GCOS to stay abreast of scientific and technological development since 2003, and to ask questions such as “is the set of variables correct?”, “are the ECVs properly measured”, “what are implications of the list of ECVs for future observing systems?”.

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2.1. Among all observations

- Maintain current satellite radiance and Earth radiation budget climate data records, which include surface sensing channels. With the NPOESS demanifest this is under threat;
- Full implementation of the GSN, addition of remote ocean island sites as feasible;
- i) Ensure a year’s overlap between successive satellite systems for sounding atmospheric temperature and water vapour; ii) Establish the proposed Global Reference Upper Air Network (GRUAN), ensuring collaboration with the Global Space-based Inter-Calibration System (GSICS); iii) Complete and maintain the GCOS Upper Air Network., particularly ensuring that all GUAN stations in the tropics function fully and yield homogeneous data;
- Precipitation (also hourly and daily records);
- Because of the important role radiation plays in the climate system, operation of the Baseline Surface Radiation Network (BSRN) is critical to assess the radiative feedback and an independent and direct measure of global warming; international and national support is needed to continue these baseline measurements;
- Reprocess of satellite records of climate variables: especially hurricanes (intensity, size, duration, track; need integrated measures not point values), clouds, top-of-atmosphere radiation, sea-surface temperature, sea ice, precipitation, snow cover extent and thickness, ocean winds and surface fluxes;
- Ensure ARGO network is maintained at the present density or greater and yields homogeneous data for >50 years;
- Water resources: streamflow, soil moisture, particularly in developing countries;
- Ice sheets, ice volumes in relation to understanding sea-level rise;
- Spatially complete datasets of climate extremes (perhaps from high-resolution reanalysis initiatives), especially those associated with temperature, rainfall, tropical cyclones and sea level;
- Development of high-resolution (e.g., 25/50 km) daily gridded datasets of surface parameters for use in model evaluation and IAV studies. i.e., equivalent of the ENSEMBLES 25 km daily product for Europe for other assessment regions;
- More formal assessment of the structural uncertainties inherent in the datasets, for example through a “maturity index”, which otherwise regularly cause false findings to be published in high quality journals; efforts ongoing at NOAA to create such an index;
- Add additional observation issues of impacts on ecosystem, agriculture and water in the weather observation system;
- Digitization of historical data, better data access ensured by governments’ data policies;
- CDR (Climate Data Records) development, also making use of new kinds of data (GPS-RO) and improved model resolution;
- Carry out climate quality reanalyses;
- Climate OSSEs for capturing optimal climate observing system;
- Coordinate national aircraft campaigns with international research partners and *in situ* observations, including instrumentation of commercial airliners.

2.2. GCOS Essential Climate Variables

2.2.1. Priority and impact on IPCC and UNFCCC requirements

- List of ECVs is adequate and highly relevant;

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- Atmosphere Surface: 1) temperature, 2) water vapour, 3) precipitation. (water vapour given high priority because a) it affects heat stress and vegetation and radiative transfers; and b) it may not be as reliably measured as precipitation at present and therefore needs more work);
- Upper-air: 1) temperature, 2) water vapour;
- Ocean surface: 1) sea-surface temperature, 2) sea level;
- Sub-surface: 1) temperature 2) salinity 3) carbon;
- Precipitation (combined with improvements in assimilation methods and reanalysis techniques), GHGs, biomass;
- Atmospheric composition is critical, and needs to be expanded and turned into reference networks;
- Terrestrial by far, since so under-developed; list needs to be prioritized by current status;
- Selected terrestrial ECVs (river discharge, ice caps, biomass) and sub-surface ocean ECVs (temperature, salinity, acidity) seem to be most important for UNFCCC especially with respect to the Nairobi Work Programme.

2.2.2. Adding or removing Essential Climate Variables

- ECV list looks adequate [many responses];
- Before more ECVs are added to the list, concrete plans need to be made concerning how to take care of the current ones; prioritize?
- Add stratospheric temperature;
- Add UV part of solar radiation;
- Evaporation/Evapotranspiration is an unusual omission. A useful ‘second order’ list might include climate phenomena with associations to extreme events (e.g., tropical cyclones, thunderstorms, hail, lightning). The ECV are weak in data for impacts and adaptation;
- Include under radiation budget “including upwelling and down welling long wave radiation";
- Include under terrestrial "Class A pan evaporation" with associated radiation, VPD and wind-speed measurements;
- Remove “(including MSU radiances)” from the atmospheric list; MSU is a specific instrument;
- Why are some atmospheric variables split into surface and upper-air, and some listed under composition, without specifying whether the composition variables are surface or upper-air?
- Carbon and nutrient fluxes from land to ocean missing – needs DOC (Dissolved Organic Carbon), DIC (Dissolved Inorganic Carbon), POC (Particulate Organic Carbon) and NO_3 (Nitrate) of riverine inputs to ocean;
- More details on ice sheets and soil moisture (2);
- Sea-ice thickness and snow thickness on sea ice are crucial climate parameters and missing;
- Land surface skin temperature to consider adding;
- Include under terrestrial ,"soil C stocks to 30cm depth";
- Species changes hardly mentioned, yet they are among the prime key vulnerabilities;
- There are now information products that must be derived from these variables that are important.

2.2.3. Feasibility of sustained observation now and/or within 5-10 years

- If it is not feasible to observe within 5-10 years then it should not be an ECV;
- Energy budget is really worrisome; we should have had 20 years of ERBE type data by now- this would have told us about cloud feedback and climate sensitivity. Availability of a reliable long-term measurement is questionable. This combined with accurate ocean heat uptake data would really help constrain the big-picture climate change outcome, then we can work on the details;
- Observation of all the atmospheric and oceanic physical quantities is feasible and sustainable now;
- High resolution observations for certain key regions would be desirable;
- Sustainability of ocean altimetry is a major concern;
- Large-scale long-term climate monitoring from space (satellite) is not guaranteed for the coming decade because of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) debacle;

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- Creation of sufficient collocation databases as to remove ambiguity in our monitoring activities across the full suite of ECVs;
- High resolution palaeoclimatic modelling, also on regional scales, including stadial transitions; model verification of ice cores; palaeoclimatic data assimilation.

3. Institutional or Technical Infrastructure Improvements

3.1. Climate Research

- Problems identified, now we now need to direct our science towards the "solutions";
- There is a strong need to promote merging of IGBP and WCRP and revitalizing the international framework for climate science;
- There are too many committees and working groups and way too much time spent on liaising between 'partners'; simplify the international committee structure, reducing unnecessary overlap and complexity;
- “Human-ware” is very much a depleted commodity, especially younger scientists having the urge and motivation to delve into the climate problems. This rarely gets mentioned as a serious point; make the science of modelling more attractive to good young scientists. In part this requires less 'publish or perish' management as model development is inevitably not a paper generator;
- Merge the efforts of CLIVAR and GEWEX into an 'operational' international climate observing and analysis network of national agencies;
- Building and promoting a climate information service as an outgrowth of the annual issue of the Bulletin of the American Meteorological Society annual climate report, led by NCDC in NOAA, for instance. In many ways this involves transitioning research to operations, but operations in a climate service;
- Climate change has not been addressed as a security (or military) threat. If it were then very high risk, low probability events would be given much higher priority – need to provide policy makers with more information about likelihood, and potential significance of abrupt climate change;
- Better IT infrastructure and use: higher communication bandwidths, exploitation of new computer technology (GRID, e-conferencing, video-conferencing, etc) allowing more equitable access to data, models, expertise;
- Improved continuity and planning of funding (e.g., EU Framework Programme), to ensure that expertise is retained, and to give better security/quality of life to individual researchers.

3.2. Climate Observations

- Raise the profile of small volunteer groups such as Ocean Observing Panel for Climate (OOPC) and associated panels (AOPC) that are doing such careful work. All the glitz associated with EOS – what did it achieve except distracting a lot of people from useful but underappreciated work;
- Much more international coordination of terrestrial methodologies and observation networks;
- Realization by nations of the need for *in situ* and remote sensing observational data on a sustained basis. A basic understanding of this need must somehow be brought to the attention of policymakers and budget keepers so that long-term observations are continued on behalf of all humankind to ensure a truly long-term period into the future. GEO has not been able to achieve this;
- There needs to be identified organisation in Europe to fund climate observations globally in partnership with US and others;
- Establishment of a robust and global trust fund to be administered on behalf of sustained *in situ* climate observations in all developing nations, and permanent regional centres for implementing and maintaining climate observations. The locations and functions of these centres should be determined by, not only geopolitical considerations, but also by critical observation needs and the nature and extent of the vulnerabilities to climate change;
- Make reference quality observations dedicated to climate monitoring and adhering to the GCOS climate monitoring principles; promulgate these principles in realm of weather;
- Better coherence among implementation agencies (e.g., NMHSs) and the setters of targets/priorities (e.g., GCOS, UNFCCC). WMO could do this as it’s a 'better conversation' issue;
- Actual implementation of the institutional and infrastructural items identified in the GCOS Implementation Plan, including its Satellite Supplement.

Appendix C

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Appendix D

Glossary of Acronyms

AIMES	ANALYSIS, INTEGRATION AND MODELLING OF THE EARTH SYSTEM
AMOC	ATLANTIC MERIDIONAL OVERTURNING CIRCULATION
ANU	AUSTRALIAN NATIONAL UNIVERSITY
AOPC	ATMOSPHERIC OBSERVATION PANEL FOR CLIMATE
AOGCM	ATMOSPHERE-OCEAN GENERAL CIRCULATION MODEL
AR4	IPCC FOURTH ASSESSMENT REPORT
ASCAT	ADVANCED SCATTEROMETER (EUMETSAT)
C4MIP	COUPLED CARBON CYCLE CLIMATE MODEL INTERCOMPARISON PROJECT
CALIPSO	CLOUD-AEROSOL LIDAR AND INFRARED PATHFINDER SATELLITE OBSERVATIONS
CFMIP	CLOUD FEEDBACK MODEL INTERCOMPARISON PROJECT
CGMS	COORDINATION GROUP FOR METEOROLOGICAL SATELLITES
CliC	CLIMATE AND CRYOSPHERE PROJECT (WCRP)
CLIVAR	CLIMATE VARIABILITY AND PREDICTABILITY PROJECT (WCRP)
CSIRO	COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANISATION (AUSTRALIA)
DIVERSITAS	INTERNATIONAL PROGRAMME OF BIODIVERSITY SCIENCE
ECMWF	EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS
ECV	ESSENTIAL CLIMATE VARIABLE (AS DEFINED BY GCOS SECOND ADEQUACY REPORT (GCOS-82))
ENSO	EL NINO SOUTHERN OSCILLATION
ENVISAT	ENVIRONMENTAL SATELLITE (ESA)
ERBE	EARTH RADIATION BUDGET EXPERIMENT (NASA)
ESA	EUROPEAN SPACE AGENCY
ESSP	EARTH SYSTEM SCIENCE PARTNERSHIP
EU	EUROPEAN UNION
EUMETSAT	EUROPEAN ORGANISATION FOR THE EXPLOITATION OF METEOROLOGICAL SATELLITES
FAO	FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
FAPAR	FRACTION OF ABSORBED PHOTOSYNTHETICALLY ACTIVE RADIATION
GCM	GENERAL CIRCULATION MODEL
GCOS	GLOBAL CLIMATE OBSERVING SYSTEM
GEO	GROUP ON EARTH OBSERVATIONS
GEWEX	GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (WCRP)
GHG	GREENHOUSE GAS
GOOS	GLOBAL OCEAN OBSERVING SYSTEM
GOS	GLOBAL OBSERVING SYSTEM (WMO)
GPS	GLOBAL POSITIONING SYSTEM
GRACE	GRAVITY RECOVERY AND CLIMATE EXPERIMENT
GRUAN	GCOS REFERENCE UPPER-AIR NETWORK
GSICS	GLOBAL SPACE-BASED INTERCALIBRATION SYSTEM
GSN	GCOS SURFACE NETWORK
GTOS	GLOBAL TERRESTRIAL OBSERVING SYSTEM
GUAN	GCOS UPPER AIR NETWORK
HIRS	HIGH RESOLUTION INFRARED RADIATION SOUNDER (NOAA)
IASI	INFRARED ATMOSPHERIC SOUNDING INTERFEROMETER (EUMETSAT)
IAV	IMPACTS, ADAPTATION AND VULNERABILITY (CLIMATE CHANGE)
ICESat	ICE, CLOUD AND LAND ELEVATION SATELLITE (NASA)
ICSU	INTERNATIONAL COUNCIL FOR SCIENCE
IGBP	INTERNATIONAL GEOSPHERE-BIOSPHERE PROGRAMME
IHDP	INTERNATIONAL HUMAN DIMENSIONS PROGRAMME
IHOPE	INTEGRATED HISTORY OF PEOPLE ON EARTH
IIASA	INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
IOC	INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION (OF UNESCO)

IPCC	INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE
IPY	INTERNATIONAL POLAR YEAR 2007-2008
ISCCP	INTERNATIONAL SATELLITE CLOUD CLIMATOLOGY PROJECT
ISMASS	ICE-SHEET MASS BALANCE AND SEA LEVEL PROJECT OF THE SCAR GLOBAL CHANGE PROGRAMME
METOP	METEOROLOGICAL OPERATIONAL POLAR SATELLITE
MIPAS	MICHELSON INTERFEROMETER FOR PASSIVE ATMOSPHERIC SOUNDING
MJO	MADDEN-JULIAN OSCILLATION
MSU	MICROWAVE SOUNDING UNIT SATELLITE INSTRUMENT (NOAA)
NAO	NORTH ATLANTIC OSCILLATION
NCAR	NATIONAL CENTER FOR ATMOSPHERIC RESEARCH (USA)
NCDC	NATIONAL CLIMATIC DATA CENTER (USA)
NIR	NEAR INFRARED SPECTRAL RANGE
NMHS	NATIONAL METEOROLOGICAL AND HYDROLOGICAL SERVICE
NOAA	NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (USA)
NPOESS	NATIONAL POLAR-ORBITING OPERATIONAL ENVIRONMENTAL SATELLITE SYSTEM
NPP	NET PRIMARY PRODUCTIVITY
OCGM	OCEAN GENERAL CIRCULATION MODEL
OECD	ORGANIZATION FOR ECONOMIC COOPERATION AND DEVELOPMENT
OOPC	OCEAN OBSERVATIONS PANEL FOR CLIMATE
OSSE	OBSERVING SYSTEM SIMULATION EXPERIMENT
PDO	PACIFIC DECADAL OSCILLATION
R/SSC-CM	REGIONAL SPECIALIZED SATELLITE CENTRES FOR CLIMATE MONITORING
SAM	SOUTHERN ANNULAR MODES
SAR	SYNTHETIC APERTURE RADAR
SBSTA	SUBSIDIARY BODY FOR SCIENTIFIC AND TECHNOLOGICAL ADVICE (UNFCCC/COP)
SCAR	SCIENTIFIC COMMITTEE ON ANTARCTIC RESEARCH
SCIAMACHY	SCANNING IMAGING ABSORPTION SPECTROMETER FOR ATMOSPHERIC CARTOGRAPHY (ESA)
SEVIRI	SPINNING ENHANCED VISIBLE AND INFRARED IMAGER (EUMETSAT)
SOOP	SHIP OF OPPORTUNITY PROGRAMME
SRES	IPCC SPECIAL REPORT ON EMISSION SCENARIOS
SST	SEA-SURFACE TEMPERATURE
START	GLOBAL CHANGE SYSTEM FOR ANALYSIS, RESEARCH AND TRAINING
SYR	IPCC SYNTHESIS REPORT
TAR	IPCC THIRD ASSESSMENT REPORT
THC	THERMOHALINE CIRCULATION
TOPC	TERRESTRIAL OBSERVATION PANEL FOR CLIMATE
TOPEX/POSEIDON	OCEAN SURFACE TOPOGRAPHY ALTIMETER EXPERIMENT (NASA/CNES)
TRMM	TROPICAL RAINFALL MEASURING MISSION (NASA/JAXA)
TSU	IPCC TECHNICAL SUPPORT UNIT
UNEP	UNITED NATIONS ENVIRONMENT PROGRAMME
UNFCCC	UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE
UV	ULTRAVIOLET
WCP	WORLD CLIMATE PROGRAMME (WMO)
WCRP	WORLD CLIMATE RESEARCH PROGRAMME
WG	WORKING GROUP (IPCC FOURTH ASSESSMENT REPORT)
WGCM	WCRP GROUP ON COUPLED MODELLING
WGNE	WCRP GROUP ON NUMERICAL EXPERIMENTATION
WHO	WORLD HEALTH ORGANIZATION
WMO	WORLD METEOROLOGICAL ORGANIZATION
WOAP	WCRP OBSERVATION AND ASSIMILATION PANEL
XBT	EXPENDABLE BATHYTHERMOGRAPH

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