Future Climate Change Research and Observations: GCOS, WCRP and IGBP Learning from the IPCC Fourth Assessment Report (AR4)

Survey Summary

(based on pre-workshop survey)

DRAFT Version 1.5

24 August 2007

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[Executive Summary to be added]

1. Background: Learning from IPCC Assessments

The IPCC's periodic assessments of the causes, impacts and possible response strategies to climate change are the most comprehensive and up-to-date reports available on the subject, 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). It has received unprecedented attention by policymakers, scientists, industry, and the general public.

Taking the opportunity to derive maximum benefit from the lessons learnt from the AR4 for their respective future strategy,

- The Global Climate Observing System Programme (GCOS; co-sponsored by WMO, IOC/UNESCO, UNEP, and ICSU);
- The World Climate Research Programme (WCRP, co-sponsored by WMO, IOC/UNESCO, and ICSU); and
- The International Geosphere-Biosphere Programme (IGBP, sponsored by ICSU)

initiated a process whereby key scientists involved in the AR4 made recommendations as to how these three international programmes could better address key gaps and uncertainties in research and observations that currently hinder our ability to understand, mitigate and adapt to human-induced climate change.

2. Key gaps, uncertainties and deficiencies in climate research and observations

The challenges facing our community have been (tentatively) grouped into four categories:

- Gaps in AR4: Knowledge, Interpretation, General Appraisal;
- Climate and Earth System Modelling;
- Impacts, Adaptation, and Risk;
- Regionalising Model Projections/Downscaling.

These have been designed to aid future research and observation priority setting. The process used to determine key issues is explained in full in Appendix 2 and summarized here.

Every key gap, uncertainty and deficiency ("gap") listed in this section has immediate and serious implications for policy and societal response. These are given below each issue.

It must be stressed that the gaps listed below, along with major reasons for these gaps, their consequences and possible actions to remedy them (see Appendix 2) are not exhaustive. The Technical Summaries of the AR4 WG I and II reports provided the full list of gaps (Appendix 3) that was used in the survey prior to the workshop. The following list reflects the level of importance of these gaps attributed by respondents to the survey, and may therefore have a bias towards the science fields covered by the respondents. As these statements are quotes, some may concepts that are not immediately self-explanatory.

2.1. Gaps in AR4: Knowledge, Interpretation, General Appraisal

Uncertainty in aerosol-cloud interaction and associated indirect radiative effects
Negative consequences:
- Large uncertainty in GCMs and in estimating climate sensitivity
- Uncertainty in prediction of regional precipitation

Uncertainty in radiative forcing, for example due to insufficient quantification of land-surface properties and land-atmosphere interactions
Negative consequences:
- Lack of confidence in attributing some climate change phenomena/modelling results to anthropogenic influences; not understanding feedbacks a key problem of climate models
- Land-use changes have large impact on regional climate, and on adaptation options
- Land-use changes and l-a interactions crucial to better understand carbon cycle

The causes of recent changes in the growth rate of atmospheric methane are not well understood
Negative consequences:
- Understanding of methane forcing essential, since a key GHG
- Risk of possibly large methane releases in the future unclear

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
Negative consequences:
- Major uncertainties in quantifying the anthropogenic contribution to sea level rise
- Very much needed for initializing coupled atmosphere-ocean models; also in view of estimating decadal variability
- Little confidence in the regional distribution of sea-level rise

Insufficient understanding of the carbon cycle, including future feedbacks
Negative consequences:
- Limited understanding of response of land surface CO2 uptake under temperature change; may result in additional warming due to positive feedback
- Important for developing policies for addressing climate change - for example in allocating credit for human intervention

2.2. Climate and Earth System Modelling

(Global needs for observations, for evaluation, for improvement, and for impact studies)

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

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

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 major impacts on societies in coastal zones
- Major challenge to project the pathway for future sea-level change: start and end points are quite well-known, its the shape of the curve in between that is not well-known, and glacier dynamics are clearly crucial in making these projections

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

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

Our understanding of the likely future impacts of climate change is hampered by lack of knowledge regarding the nature of future changes, particularly at the regional scale and particularly with respect to precipitation changes and their hydrological consequences on water resources, and changes in extreme events, due in part to the inadequacies of existing climate models at the required spatial scales

See 'precipitation' item above

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

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

Large area long-term field studies are required to evaluate observed impacts of climate change on managed and unmanaged systems and human activities

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

It is important to understand how close we are to tipping points and thresholds for natural ecosystems such as the Amazon rainforest

Negative consequences:

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

2.3. Impacts, Adaptation and Risk

(Encompassing biodiversity, human health, water cycle, agriculture…)

Additional scenarios are required to describe the future evolution of the world under different and widely-ranging assumptions about how societies, governance, technology, economies will develop in future

Negative consequences:

Inadequate representation of future world scenarios

Existing research* [on vulnerability and adaptation] *has emphasized the global scale, and studies, which are disaggregated to the regional/local scale are urgently needed

Negative consequences:

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

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

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" [WG II Report, Ch20]

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

Negative consequences:

Limited knowledge about costs of impacts, adaptation costs and benefits, especially in developing countries

2.4. Regionalising Model Projections/Downscaling

(Future projections at the regional scale; relation to adaptation and policy)

Attribution at regional scales and over timescales 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

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

Additional scenarios are required at the regional and local scales appropriate for impacts analysis, allowing adaptation to be incorporated in climate change impacts estimates

Negative consequences:

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

3. Priorities for climate change research (WCRP and IGBP)

As with the key gaps and uncertainties in section 2, the following ‘priorities’ emerged from the survey conducted for this 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 move adequately fast to combat the consequences of greenhouse warming.

3.1. Overall priorities

Climate change research entered a new and different regime with the publication of the IPCC 4th 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?’ Climate change researchers cannot hide behind the “need to improve models/observations” any longer. 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.

3.1.1. 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.

3.1.2. 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.
- Until and unless ENSO, PDO, NAO and AMO 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. I.e. it is not just the forecast but the confidence and uncertainty that are just as much a key.
- 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: organize 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 No3/2007) 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.

3.2. Specific priorities

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

3.2.1. 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.
- 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 large chunk of projection uncertainty; mesh cloud-resolving models into AOGCM
- Improvement in understanding of global hydrological cycle under greenhouse (rainfall, evaporation and clouds), 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

3.2.2. Bio-geochemical research

- Establishing the likelihood of Amazon die back 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

3.2.3. Feasibility of tackling research challenges

[The following items are somewhat complementary to those listed in sections 3.2.1 and 3.2.2.]

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, 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 modeling
- Systematic analysis of feedback strengths (AR4 Chapter 9 is 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 emission and temperature rise
- Higher resolution, inclusion of stratosphere, chemical processes, low resolution paleo modeling
- Precipitation measurements, combined with improvements in assimilation methods and reanalysis techniques
- Better representation of soil C 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 paleo modelling including stadial transitions, model verification of ice cores, paleo data assimilation
- Studies that incorporate more regional detail, better C-cycle, permafrost, CH4 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 CO2 and CH4 concentrations
- AOGCM with full cloud resolving models

4. Priorities for climate observations (GCOS)

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?”.

4.1. Among all observations

- Maintain current satellite radiance and earth radiation budget climate data records which includes surface sensing channels. With the NPOESS demanifest this is under threat.
- Full implementation of the GSN, infilling with 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 re-analysis 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 (8a)
- 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

4.2. GCOS Essential Climate Variables

4.2.1. Priority and impact on IPCC and UNFCCC requirements

- List of ECVs is adequate and highly relevant
- 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 (rivers discharge, ice caps, biomass) and sub-surface ocean ECVs (temp, salinity, acidity) seem to be most important for UNFCCC esp. wrt the Nairobi Work Programme

4.2.2. Adding or removing 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 NO3 (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

4.2.3. 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
- Creation of sufficient collocation databases as to remove ambiguity in our monitoring activities across the full suite of ECVs
- High resolution paleo modeling, also on regional scales, including stadial transitions; model verification of ice cores; paleo data assimilation

5. Institutional or Technical Infrastructure Improvements

5.1. 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 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 FP), to ensure that expertise is retained, and to give better security/quality of life to individual researchers

5.2. 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.

6. Suggestions for Future IPCC Assessments

While the IPCC AR4 has been immensely useful in laying the groundwork for this paper, many responses to the survey suggested changes in the IPCC's mode of operation in view of possible future assessments. The call for suggestions in this regard was supported by the IPCC Secretariat. It is hoped that the following suggestions provide useful points for discussion.

- AR5 should not play out as AR4 and TAR; from a WG1 perspective, Special Reports on ice sheets and on the climate carbon-cycle feedback should be planned in 2-3 years. But more importantly the WG structure should be revised, probably by merging WG1 and WG2 and closer interaction with WG3. They cannot continue to function basically in isolation.
- Maybe the WGII Report should be broken down into a series of regional and/or sectoral reports
- Start the SYR team at least a year earlier while there was time for it to influence some of the Working Group reports
- Future IPCC reports must be more focused, shorter, timely and more solution-oriented. We absolutely need a complete re-think, since the IPCC was designed 20 years ago when the problem was less well understood and political acceptance more fragile
- In general we were too conservative in AR4 WG1. For example, expressing an abrupt cessation of the MOC by 2100 as 'very unlikely' is not giving policymakers, or people in general, the information in a form that they can understand. It is equally statistically correct to say that "there may be as much as a 10% likelihood of an abrupt cessation of the MOC by 2100", which portrays the information in a more meaningful manner for risk anaylsis. So risk analyses more closely linked to WG1 projections are required.
- Construct the AR5 on the Synthesis model, rather than the 3 separate disciplines in the Working Group model - this way people with very different understandings of science and policy problems and with very different world views would have time to work together to fashion real progress on interdisciplinary, policy-oriented questions from governments. The current SYR is already very late in the game for such integrative understanding and thus is a difficult venue to accomplish interdisciplinary integration in the allotted time
- 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 disaggregated working groups model used so far, since the latter is not very effective at integration of conflicting paradigmatic views of the world when scientists with very different frameworks largely meet at SYR after it is too late to really modify the disciplinary reports based on emerging interdisciplinary knowledge
- Suggest a single observation AR on 5 year repeat cycle (but with yearly online updates), and modelling updates and assessment on a 2-3 year update basis to be more in tune with actual science understanding. This mechanism would lose the generalness of the exercise, but improve its relevance

- The 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 1, 2 and 3 within IPCC
- A lot of skeptics are recruited from the geological and physics community - how can they be integrated in the IPCC-process
- An AR5 is probably needed, around 2013 to allow for sufficient advance since AR4. The separation of the observations aspects into several chapters in AR4 was necessary and the same structure should be used in AR5, so long as full collaboration between Chapters is maintained. We need to monitor the trajectory of climate change to assess whether we are heading into a danger-zone
- Maintain ongoing interactions across the communities that populate the disciplinary working groups--like the CWT (Core Writing Team) of the Synthesis report at the moment--post IPCC with a bit less stress to make a report and more time to learn from each other how to do integrative research to answer key questions like those posed above
- More use of probabilistic projections - rather than the use of ranges and individual model results
- Concerted engagement in the AR5 process of major fossil fuel industries who might represent lobby groups that are purported to be holding some governments back from more concerted action?

7. Conclusions

The scientists involved with AR4 have served the climate community with great distinction and have again produced assessments of high quality and authority. The WCRP and IGBP coordinate much of the science that underpins their assessments and this Survey shows that both are keen to understand how their work can be improved. The requirements developed by GCOS have been well received and respected and have taken GCOS to a different level. AR4, however, will change the demand toward impacts and adaptation, at a time when investment in sustained climate observations is probably declining rather than increasing. The community will need to make clear that the science and observations that underpin WG1 assessments is far from done, but moving to a different plane. WG2 is providing additional challenges.

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Appendix 1

Links between GCOS, WCRP, IGBP, and the IPCC

The Intergovernmental Panel on Climate Change (IPCC)[1] was set up jointly by the World Meteorological Organization and the United Nations Environment Programme to provide an authoritative international statement of scientific understanding of climate change. The IPCC's periodic assessments of the causes, impacts and possible response strategies to climate change are the most comprehensive and up-to-date reports available on the subject, and form the standard reference for all concerned with climate change in academia, government and industry worldwide.

At its first session, the IPCC was organised into three Working Groups. The current remits of the three Working Groups are for Working Group I to examine the scientific aspects of the climate system and climate change; Working Group II to address vulnerabilities to, impacts of and adaptations to climate change; and Working Group III to explore the options for mitigation of climate change. The three previous assessment reports were produced in 1990, 1996 and 2001.

A1.1. GCOS, WCRP, IGBP and the IPCC

A1.1.1. GCOS

GCOS is a long-term, user-driven operational system capable of providing the comprehensive observations required for,

- Monitoring the climate system,
- Detecting and attributing climate change,
- Assessing impacts of, and supporting adaptation to, climate variability and change,
- Application to national economic development, and
- Research to improve understanding, modelling and prediction of the climate system.

GCOS builds upon, and works in partnership with, other existing and developing observing systems and their advisory bodies toward meeting the needs for climate. GCOS addresses the total climate system including physical, chemical and biological properties, and atmospheric, oceanic, terrestrial, hydrologic, and cryospheric components.

Since its inception in 1992, close links existed between the GCOS Steering Committee, the GCOS Science Panels, and the IPCC. In 2002, the GCOS programme held a workshop with key IPCC contributors to the Third Assessment Report (2001), then focusing solely on the adequacy of the global climate observing system. This workshop was vital for the completion of the GCOS Second Adequacy Report (2003)[2] and the GCOS Implementation Plan (2004)[3].

A1.1.2. WCRP

The First IPCC Assessment (FAR) concluded that it was certain that *"emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases"* (notably carbon dioxide), with model simulations using emission scenarios projecting warming into the future. WCRP's significance to FAR lay in the identification of key scientific uncertainties: the control of greenhouse gases by the Earth's systems; cloud radiative processes, precipitation and evaporation; ocean transport and storage of heat; and ecosystem processes.

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1 http://www.ipcc.ch/

2 *The Second Report on the Adequacy of the Global Observing System for Climate in Support of the UNFCCC*, GCOS-82), April 2003 (WMO/TD-No 1143). http://www.wmo.int/pages/prog/gcos

3 *Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC*, GCOS-92, October 2004 (WMO/TD-No. 1219).

In the IPCC Second Assessment Report (SAR) issued in 1995, WCRP contributions again included observational datasets and metrics from model intercomparison projects. A major accomplishment was that the results from the Atmospheric Model Intercomparison Project (AMIP) enabled a detailed assessment of the model-simulated climate variables. Datasets on clouds and land-surface proved useful in the verification and calibration of climate models. A highlight of SAR was the conclusion that the "*balance of evidence suggests a discernible human influence on global climate"*. The paper providing the basis for this key finding received the 1998 International Norbert-Gerbier Mumm Award and included several WCRP-associated scientists.

The Third Assessment, issued in 2001, received significant inputs from the WMO/UNEP Assessment on Ozone Depletion (1999) and WCRP's project on Stratospheric Processes And their Role in Climate (SPARC). SPARC led the initiative on the attribution of the observed stratospheric cooling trends to ozone depletion and long-lived greenhouse gas increases (recognized by the 2003 International Norbert Gerbier-Mumm Award) and on radiative forcings originating from the stratosphere, used by some TAR models. The hallmarks of the TAR were the far-reaching conclusions: "*an increasing body of observations gives a collective picture of a warming world"; "emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that are expected to affect the climate"; "natural factors have made small contributions to radiative forcing over the past century";* and *"there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities*".

The AR4 demonstrates how climate research has grown and matured. For example, the joint IGBP-WCRP Coupled Carbon Cycle Climate Model Intercomparison Project (C4MIP) experiment was the source of the very worrying positive carbon feedback with global warming. IGBP, WCRP and GCOS would benefit from tighter focus towards solving scientific issues arising out of IPCC assessments, as suggested in responses to the survey held ahead of the Sydney workshop.

A1.1.3. IGBP

Links between IGBP and IPCC are…

A1.2. Learning from the IPCC AR4: The Sydney 2007 Workshop

The joint GCOS-WCRP-IGBP workshop "Future Climate Change Research and Observations: GCOS, WCRP and IGBP Learning from the IPCC Fourth Assessment Report" has been a unique opportunity to benefit from the experience of key IPCC AR4 authors and other contributors, and the lessons learnt from writing the AR4. The workshop has been designed to provide input to the future strategies of the three international programmes, while highlighting key gaps and deficiencies in worldwide climate research and climate observations. In order to provide input to these topics ahead of the discussion at the meeting itself, all participants, as well as all Coordinating Lead Authors of IPCC Working Groups I and II, were invited to complete a survey. The survey mainly asked for prioritization and possible remedy options to the key gaps and deficiencies laid down in the Technical Summaries of the WG I and II reports. 33 replies were received[4].

Version 1.4 of this paper is largely based on the results from this survey.

[4] As of 20 August 2007; Responses related to IPCC AR4 (multiple answers possible): WGI CLA: 7, WGI Other: 11, WGII CLA: 5, WGII Other: 5, Other: 4, No relation: 4

Appendix 2

Reasons, Consequences and Possible Solutions to Prioritized Key Gaps and Uncertainties in the AR4 related to WG I and II

Key gaps, uncertainties and deficiencies ("gaps") listed below, along with major reasons for these gaps, their consequences and possible actions to remedy them, are not exhaustive. The Technical Summaries of the AR4 WG I and II reports provided the full list of gaps that was used in the survey prior to the workshop. The following list reflects the level of importance of these gaps attributed by respondents to the survey, and may therefore have a bias towards the science fields covered by the respondents. Some statements are quotes that may not always be self-explanatory.

A2.1. Working Group I: The Physical Science Basis

[Quote from WG I Report Preface]
The Working Group I report focuses on those aspects of the current understanding of the physical science of climate change that are judged to be most relevant to policymakers. It does not attempt to review the evolution of scientific understanding or to cover all of climate science. Furthermore, this assessment is based on the relevant scientific literature available to the authors in mid-2006 and the reader should recognize that some topics covered here may be subject to further rapid development.

A feature of recent climate change research is the breadth of observations now available for different components of the climate system, including the atmosphere, oceans, and cryosphere. Additional observations and new analyses have broadened our understanding and enabled many uncertainties to be reduced. New information has also led to some new questions in areas such as unanticipated changes in ice sheets, their potential effect on sea level rise, and the implications of complex interactions between climate change and biogeochemistry.

In considering future projections of climate change, this report follows decisions made by the Panel during the AR4 scoping and approval process to use emission scenarios that have been previously assessed by the IPCC for consistency across the three Working Groups. However, the value of information from new climate models related to climate stabilization has also been recognized. In order to address both topics, climate modelling groups have conducted climate simulations that included idealized experiments in which atmospheric composition is held constant. Together with climate model ensemble simulations, including many model runs for the 20th and 21st centuries, this assessment has been able to consider far more simulations than any previous assessment of climate change.

The IPCC assessment of the effects of climate change and of options for responding to or avoiding such effects, are assessed by Working Groups II and III and so are not covered here. In particular, while this Working Group I report presents results for a range of emission scenarios consistent with previous reports, an updated assessment of the plausible range of future emissions can only be conducted by Working Group III.
[End of quote from WG I Report Preface]

Uncertainty in aerosol-cloud interaction and associated indirect radiative effects (item 1a in the survey based on the AR 4 WG I report's Technical Summary, 1c)

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

Major impacts:
- 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) + better representation in GCMs

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

Relevant GCOS panels, networks, ECVs: AOPC; GAW, BSRN; cloud properties, aerosol properties, water vapour
Relevant WCRP activities: GEWEX, AC&C

Uncertainty in radiative forcing, for example due to insufficient quantification of land-surface properties and land-atmosphere interactions (1f, 3a, see also 4c, 4g)

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

Major impacts:
- Lack of confidence in attributing some climate change phenomena/modelling results to anthropogenic influences; not understanding feedbacks a key problem of climate models
- Land-use changes have large impact on regional climate, and on adaptation options
- Land-use changes and l-a interactions crucial to better understand carbon cycle

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 modeling) in the present day needed; they are important metrics for the reliability of the “drivers” implemented in AOGCMs (taking as a past example ICRCCM run by WCRP/DOE)
- 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 where the issue is (1) one of scale, i.e., likely to be addressed by simply increasing resolution, (2) where need to go back and develop new parametrisations, e.g., convective processes and where (3) more physical process understanding/data is required before (2) can be achieved, e.g., soil moisture and land use feedbacks

Relevant GCOS panels, networks, ECVs: AOPC, TOPC, WG LSA; GAW; land cover, carbon dioxide, methane, other GHGs, ERB
Relevant WCRP activities: WOAP; GEWEX, ACC, Monsoons

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 (4c, 4g, see also 1f, 3a)

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

Major impacts:
- Not understanding feedbacks a key problem of climate models

Possible solutions:
- Constrain radiative forcing (see 1f, 3a)
- Link cloud-resolving models to AOGCM
- Improve parameterization of convection processes

- Reduce uncertainties in cloud feedbacks, e.g., through collaborative efforts between cloud feedback models and a comparison 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:

- Once model metrics are developed, what is one going to do with them? Is one going to exclude from future IPCC AR results models that do not achieve certain thresholds for these metrics? Or weigh the results of models that give good metrics? Is a good reproduction of recent climate a good indicator of a good projection of future climate?
- Identify where the issue is (1) one of scale, i.e., likely to be addressed by simply increasing resolution, (2) where need to go back and develop new parametrisations, e.g., convective processes and where (3) more physical process understanding/data is required before (2) can be achieved, e.g., soil moisture and land use feedbacks

Relevant GCOS panels, networks, ECVs: AOPC; all, in particular cloud properties
Relevant WCRP activities: WGCM, CLIVAR, ACC

The causes of recent changes in the growth rate of atmospheric methane are not well understood (1d).

Major reasons:

- Lack of understanding of fundamental (biogeochemical) processes

Major impacts:

- Understanding of methane forcing essential, since a key GHG
- Risk of possibly large methane releases in the future unclear

Possible solutions

- Set up 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 modeling 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

Relevant GCOS panels, networks, ECVs: AOPC; GAW; methane
Relevant WCRP activities: AC&C; SPARC

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 (2e, 3c, 3e, 7a)

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

Major impacts:

- 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 Tmin, Tmax, mean sea-level pressure) observations routinely, not just for GCOS stations; develop global extremes datasets and indices for validation
- Proper funding for state-of-the-art reanalyses would probably 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 (Held and Soden, 2006, J

Climate, Allen, Ingram, Stainforth Nature 2002, compared with Wentz et al, Science 2007) need to be sorted out
- 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)

Relevant GCOS panels, networks, ECVs: AOPC; GSN, WWW GOS; precipitation
Relevant WCRP activities: GEWEX, Extremes, ACC

Limitations in ocean sampling imply that decadal variability in global heat content, salinity, and sea level changes can only be evaluated with moderate confidence (2o, 2q); 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 (3g)

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); Recent years : inhomogeneities between different sensors (e.g., XBT and ARGO)

Major impacts:
- Major uncertainties in quantifying the anthropogenic contribution to sea level rise
- Very much needed for initializing 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 modeling (assimilation of existing T,S data in OCGMs)
- Stimulate development of new in situ technology, such as gliders, to observe the deep ocean

Linked issues:
Need a focused programme to resolve this issue, including observations and modeling (e.g., inclusion of shelf ice and glaciers in AOGCM)
Relevant GCOS panels, networks, ECVs: OOPC; GOOS; XBT, ARGO; ocean variables
Relevant WCRP activities: CLIVAR; Sea Level; WGSF; Decadal

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 (2f)

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

Major impacts:
- 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 and network coverage

Relevant GCOS panels, networks, ECVs: OOPC; GOOS; XBT, ARGO; ocean variables
Relevant WCRP activities: CLIVAR, GEWEX; Extremes; Monsoons

Attribution at regional scales and over timescales 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 (3b, 3f)

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

Major impacts:
- 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 caught?
- Continued efforts to acquire and analyze 4D datasets of climate variables; more sensitivity/intercomparison studies of climate models, maybe with idealized settings

Relevant GCOS panels, networks, ECVs: mostly those directly relevant for adaptation
Relevant WCRP activities: WGCM; Decadal; WGNE

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 (4n, 8b)

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

Major impacts:
- 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 major impacts on societies in coastal zones
- Major challenge to project the pathway for future sea-level change: start and end points are quite well-known, its 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 modeling and experimental (observations) community. CliC and SCAR are proposing to organize 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, and increased sea levels)
- Explore coupling of ice sheets into GCMs for long-term feedbacks
- Find thresholds for abrupt changes in (a) ice sheets, (b) MOC; try to find hints in palaeorecord (see also 9e)

Relevant GCOS panels, networks, ECVs: GTN-G, GTN-P, ice sheets, sea ice, sea level
Relevant WCRP activities: CliC; Sea Level; WGCM

Insufficient understanding of the carbon cycle, including future feedbacks (4m)
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 die back) (see 2e, 3c, 3e)
- GCM models that include land-surface feedbacks have as yet not been cognizant of the multitude of ecosystem feedbacks - hence the needs for a more comprehensive earth-system view incorporating ecological feedbacks

Major impacts:
- Limited understanding of response of land surface CO2 uptake under temperature change; may result in additional warming due to positive feedback
- Important for developing policies for addressing climate change - for example in allocating credit for human intervention

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

Relevant GCOS panels, networks, ECVs: AOPC, OOPC, TOPC; all carbon-related variables
Relevant WCRP activities: AC&C; ACC

A2.2. Working Group II: Impacts, Adaptation and Vulnerability

The WG2 report has deficits for two reasons: (i) poor downscaling and (ii) the lack of a coherent methodology for impact study. WCRP/GCOS will propose a strategy to greatly improve the downscaling in their input to UNFCCC SBSTA - see papers in preparation for Sept 2007.

Additional scenarios are required to describe the future evolution of the world under different and widely-ranging assumptions about how societies, governance, technology, economies will develop in future (5a)
Major reasons:
- The SRES scenarios have some limitations. They assume convergence, despite recent tendencies of increasing income gaps between wealthy and poor countries, regions and households
- Limitations in modeling (all aspects)
- Need better linkage of climate applications to socio-economic data

Major impacts:
Inadequate representation of future world scenarios
Possible solutions:
- Deploy other scenario options:

The Global Scenarios Group set of scenarios includes characterisations in which institutions and governance as we know them persist with minor reform; 'barbarization' scenarios consider futures in which "absolute poverty increases and the gap between rich and poor …[and] national governments lose relevance and power relative to trans-national corporations and global market forces…" (Gallopin et al. 1997: 29-33); 'great transitions' scenarios contain story-lines in which sustainable development becomes an organising principle in governance
- Reduce uncertainties in possible trends in societal, economic, and technological change with or without climate change, and incorporate these in scenarios

Relevant GCOS panels, networks, ECVs: none? mostly those directly relevant for adaptation
Relevant WCRP activities: ACC; AC&C

Additional scenarios are required at the regional and local scales appropriate for impacts analysis, allowing adaptation to be incorporated in climate change impacts estimates; (5b, 5c, 8a)
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

Major impacts:

- 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 2 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 ICM framework has been useful for climate change adaptation in the coastal areas and for islands, it needs to be improved to include the new knowledge that is coming out of communities recovering from tsunamis and make future coastal communities to be more resilient.

Relevant GCOS panels, networks, ECVs: ClimDev Africa; ECVs: mostly those directly relevant for adaptation

Relevant WCRP activities: WGCM; ACC; Sea Level

Existing research* [on vulnerability and adaptation] *has emphasized the global scale, and studies, which are disaggregated to the regional/local scale are urgently needed (6b)

Major reasons:

- Lack of linking between IPCC WGs
- Previous studies focused more on temperature rising and impact, and less on stabilizing emissions

Major impacts:

- Still very limited interest on climate change by national policy makers; regional and local information may provide greater incentives to national policy makers.
- Vulnerabilities to climate change depend considerably on specific geographic, sectoral, and social contexts. Therefore, global estimations of damages avoided 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 and then assess what impacts under what emission level with temperature rising
- 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 disaggregated 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.

Relevant GCOS panels, networks, ECVs: none? mostly those directly relevant for adaptation
Relevant WCRP activities: WGCM; WGNE; Extremes

Large area long-term field studies are required to evaluate observed impacts of climate change on managed and unmanaged systems and human activities (8a)

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 up to the decadal at least
- Lack of knowledge – particularly for the southern hemisphere - of what relevant datasets already exist

Major impacts:
- 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, Australia 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 not favoured because a) they are expensive b) inherently do not provide quick results and c) funders feel they can get convincing looking reports on the question involved based on models with flashy graphical outputs.
Relevant GCOS panels, networks, ECVs: none? mostly those directly relevant for adaptation
Relevant WCRP activities: WOAP; AC&C; Decadal

It is important to understand how close we are to tipping points and thresholds for natural ecosystems such as the Amazon rainforest (9e)

Major reasons:
- Lack of fundamental understanding
- Insufficient linkage of climate applications to socio-economic data

Major impacts:
- 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, Sahel, Siberia (permafrost)
- Observation in regional and local scales on possible impact systems and sectors; Experiments on relative affected systems and sectors

Linked issues:
I think "tipping points" are real in specific systems, but we rarely know precisely where they are and even a mild aggregation smears it out so I don't like that framing, rather prefer the notion of vastly increasing the numbers of key vulnerabilities and their magnitudes with increases in global mean temperature, rather than some fictitious threshold below which all is fine and above all is disaster - a pretty non-credible framing in my view
Relevant GCOS panels, networks, ECVs:
Relevant WCRP activities: GEWEX; Sea Level; Monsoons

Our understanding of the likely future impacts of climate change is hampered by lack of knowledge regarding the nature of future changes, particularly at the regional scale and particularly with respect to precipitation changes and their hydrological consequences on water resources, and changes in extreme events, due in part to the inadequacies of existing climate models at the required spatial scales (7a)

See 'precipitation' item under WG I

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 SD and vice versa (10a)

Major reasons:

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

Major impacts:

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" [WG II Report, Ch20]

Possible solutions:

- Determine both the factors that constraint and/or contribute to this synergy
- Raise "climate awareness" of policy makers at national, regional and local levels; policy and governance are critical in "mainstreaming" climate change
- Vulnerability studies (9a); Better integration of social, human and physical change

Linked issues:

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.

Relevant GCOS panels, networks, ECVs:

Relevant WCRP activities: links are primarily to ESSP joint projects, and to START

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 (11b)

Major reasons:

Insufficient application of climate analyses to societal needs; linkage of climate applications to socio-economic data

Major impacts:

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--generalizers--to see what "rules" might emerge at more than local scales

Linked issues:

- More work needed to fund this research, since external funding of indigenous capacity is usually not sustained
- Cost of climate change is important because not every decision maker understand that adapting or mitigating impacts of climate change need investment

Relevant GCOS panels, networks, ECVs:

Relevant WCRP activities: GEWEX; Sea Level; Monsoons

Appendix 3

Key Gaps and Uncertainties in the AR4 related to WG I and II

The following lists are based on the Technical Summaries of Working Groups I and II contributions to the AR4. More details on specific research and observation needs can be found in the respective chapters of the reports.

Working Group I: The Physical Science Basis

1) CHANGES IN HUMAN AND NATURAL DRIVERS OF CLIMATE

a) The full range of processes leading to modification of cloud properties by aerosols is not well understood and the magnitudes of associated indirect radiative effects are poorly determined.
b) The causes and radiative forcing due to stratospheric water vapour changes are not well quantified.
c) The geographical distribution and time evolution of the radiative forcing due to changes in aerosols during the 20th century are not well characterized.
d) The causes of recent changes in the growth rate of atmospheric methane are not well understood.
e) The roles of different factors increasing tropospheric ozone concentrations since pre-industrial times are not well characterized.
f) Land-surface properties and land-atmosphere interactions that lead to radiative forcing are not well quantified.
g) Knowledge of the contribution of past solar changes to radiative forcing on the time scale of centuries is not based upon direct measurements and is hence strongly dependent upon physical understanding.

2) OBSERVATIONS OF CHANGES IN CLIMATE

Atmosphere and Surface

a) Radiosonde records are much less complete spatially than surface records and evidence suggests a number of radiosonde records are unreliable, especially in the tropics. It is likely that all records of tropospheric temperature trends still contain residual errors.
b) While changes in large-scale atmospheric circulation are apparent, the quality of analyses is best only after 1979, making analysis of, and discrimination between, change and variability difficult.
c) Surface and satellite observations disagree on total and low-level cloud changes over the ocean.
d) Multi-decadal changes in daily temperature range (DTR) are not well understood, in part because of limited observations of changes in cloudiness and aerosols.
e) Difficulties in the measurement of precipitation remain an area of concern in quantifying trends in global and regional precipitation.
f) 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.
g) The availability of observational data restricts the types of extremes that can be analyzed. The rarer the event, the more difficult it is to identify long-term changes because there are fewer cases available.
h) Information on hurricane frequency and intensity is limited prior to the satellite era. There are questions about the interpretation of the satellite record.
i) There is insufficient evidence to determine whether trends exist in tornadoes, hail, lightning and dust-storms on small scales.

Snow, Ice and Frozen Ground

j) There is no global compilation of in-situ snow data prior to 1960. Well-calibrated snow water equivalent data are not available for the satellite era.
k) There are insufficient data to draw any conclusions about trends in the thickness of Antarctic sea ice.
l) Uncertainties in estimates of glacier mass loss arise from limited global inventory data, incomplete area-volume relationships, and imbalance in geographic coverage.
m) Mass balance estimates for ice shelves and ice sheets, especially for Antarctica, are limited by calibration and validation of changes detected by satellite altimetry and gravity measurements.
n) Limited knowledge of basal processes and of ice shelf dynamics leads to large uncertainties in the understanding of ice flow processes and ice sheet stability.

Oceans and Sea Level

o) Limitations in ocean sampling imply that decadal variability in global heat content, salinity, and sea level changes can only be evaluated with moderate confidence.
p) There is low confidence in observations of trends in the meridional overturning circulation.
q) Global average sea level rise from 1961–2003 appears to be larger than can be explained by thermal expansion and land ice melting.

Paleoclimate

r) Mechanisms of onset and evolution of past abrupt climate change and associated climate thresholds are not well understood. This limits confidence in the ability of climate models to simulate realistic abrupt change.
s) The processes and degree to which ice sheets retreated in the past, and the rates of such change, are not well known.
t) Knowledge of climate variability over more than the last few hundred years in the Southern Hemisphere and tropics is limited by the lack of paleoclimatic records.
u) Differing amplitudes and variability observed in available millennial-length Northern Hemisphere temperature reconstructions, as well as the relation of these differences to choice of proxy data and statistical calibration methods, still need to be reconciled.
v) The lack of extensive networks of proxy data for temperature in the last 20 years limits understanding of how such proxies respond to rapid global warming and of the influence of other environmental changes.

3) UNDERSTANDING AND ATTRIBUTING CLIMATE CHANGE

a) Confidence in attributing some climate change phenomena to anthropogenic influences is currently limited by uncertainties in radiative forcing, as well as in uncertainties in feedbacks and in observations.
b) Attribution at scales smaller than continental and over timescales 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.
c) There is less confidence in understanding of forced changes in precipitation and surface pressure than there is of temperature.
d) The range of attribution statements is limited by the absence of formal detection and attribution studies, or their very limited number, for some phenomena (e.g., some types of extreme events).
e) Incomplete global data sets for extremes analysis and model uncertainties still restrict the regions and types of detection studies of extremes that can be performed.
f) Despite improved understanding, uncertainties in model-simulated internal climate variability limit some aspects of attribution studies. For example, there are apparent discrepancies between estimates of ocean heat content variability from models and observations.
g) Lack of studies quantifying the contributions of anthropogenic forcing to ocean heat content increase or glacier melting together with the open part of the sea level budget for 1961–2003 are among the uncertainties in quantifying the anthropogenic contribution to sea level rise.

4) PROJECTIONS OF FUTURE CHANGES IN CLIMATE

Model Evaluation

a) A proven set of model metrics comparing simulations with observations, that might be used to narrow the range of plausible climate projections, has yet to be developed.
b) Most models continue to have difficulty controlling climate drift, particularly in the deep ocean. This drift must be accounted for when making assessments of many oceanic variables.
c) Models differ considerably in their estimates of the strength of different feedbacks in the climate system.
d) Problems remain in the simulation of some modes of variability, notably the MJO, recurrent atmospheric blocking, and extreme precipitation.
e) Systematic biases have been found in most models' simulations of the Southern Ocean that are linked to uncertainty in transient climate response.
f) Climate models remain limited by the spatial resolution that can be achieved with present computer resources, by the need for more extensive ensemble runs, and by the need to include some additional processes.

Equilibrium and Transient Climate Sensitivity

g) Large uncertainties remain about how clouds might respond to global climate change.

Global Projections

h) The likelihood of a large abrupt change of the MOC beyond the end of the 21st century cannot yet be assessed reliably. For low and medium emission scenarios with atmospheric greenhouse gas concentrations stabilized beyond 2100, the MOC recovers from initial weakening within one to several centuries. A permanent reduction of the MOC cannot be excluded if the forcing is strong and long enough.
i) The model projections for extremes of precipitation show larger ranges in amplitude and geographical locations than for temperature.
j) The response of some major modes of climate variability such as ENSO still differs from model to model, which may be associated with differences in the spatial and temporal representation for present-day conditions.
k) The robustness of many model responses of tropical cyclones to climate change is still limited by the resolution of typical climate models.
l) Changes to key processes which drive some global and regional climate changes are poorly known (e.g.,. ENSO, NAO, blocking, MOC, land-surface feedbacks, tropical cyclone distribution).
m) The magnitude of future carbon cycle feedbacks is still poorly determined.

Sea Level

n) 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.
o) The sensitivity of ice sheet surface mass balance (melting and precipitation) to global climate change is not well constrained by observations and has a large spread in models. There is consequently a large uncertainty in the magnitude of global warming which, if sustained, would lead to the elimination of the Greenland ice sheet.

Regional Projections

p) In some regions there has been only very limited study of key aspects of regional climate change, particularly with regard to extreme events.
q) AOGCMs show no consistency in simulated regional precipitation change in some key regions (e.g., northern South America, northern Australia and the Sahel).
r) In many regions where fine spatial scales in climate are generated by topography, there is insufficient information on how climate change will be expressed at these scales.

Working Group II: Impacts, Adaptation and Vulnerability

5) IMPACTS UNDER DIFFERENT ASSUMPTIONS ABOUT FUTURE DEVELOPMENT PATHWAYS

Most AR4 studies of future climate change are based on a small number of studies using SRES scenarios, especially the A2 and B2 families. This has allowed some limited, but incomplete, characterization of the potential range of futures and their impacts
Scenarios are required:

a) to describe the future evolution of the world under different and widely-ranging assumptions about how societies, governance, technology, economies will develop in future;
b) at the regional and local scales appropriate for impacts analysis;
c) which allow adaptation to be incorporated into climate change impacts estimates;
d) for abrupt climate change such as the collapse of the North Atlantic Meridional Overturning Circulation, and large sea level rises due to ice sheet melting;
e) for beyond 2100 (especially for sea level rise).

Increasingly, climate modellers run model ensembles, which allow characterization of the uncertainty range for each development pathways. Thus, the impacts analyst is faced with very large quantities of data to capture even a small part of the potential range of futures.

f) Tools and techniques to manage these large quantities of data are urgently required.

6) DAMAGES AVOIDED BY DIFFERENT LEVELS OF EMISSIONS REDUCTION

a) Very few studies have been carried out to explore the damages avoided, or the impacts postponed, by reducing or stabilizing emissions, despite the critical importance of this issue for policymakers.
b) Existing research has emphasised the global scale, and studies, which are disaggregated to the regional and even local scale are urgently required.

7) CLIMATE SCIENCE-RELATED RESEARCH NEEDS

Two of the most important requirements identified relate to research in climate change science, but have been clearly identified as a hindrance to research in impacts, adaptation and vulnerability:

a) The first is that our understanding of the likely future impacts of climate change is hampered by lack of knowledge regarding the nature of future changes, particularly at the regional scale and particularly with respect to precipitation changes and their hydrological consequences on water resources, and changes in extreme events, due in part to the inadequacies of existing climate models at the required spatial scales.
b) The second relates to abrupt climate change. Policymakers require understanding of the impacts of such events as the collapse of the North Atlantic Meridional Overturning Circulation. However, without a better understanding of the likely manifestation of such events at the regional scale, it is not possible to carry out impacts assessments.

8) OBSERVATIONS, MONITORING AND ATTRIBUTION

a) Large area long-term field studies are required to evaluate observed impacts of climate change on managed and unmanaged systems and human activities. This will enable improved understanding of where and when impacts become detectable, where the hotspots lie, and why some areas are more vulnerable than others. High quality observations are essential for full understanding of causes, and for unequivocal attribution of present-day trends to climate change.
b) Timely monitoring of the pace of approaching significant thresholds (such as abrupt climate change thresholds) is required.

9) MULTIPLE STRESSES, THRESHOLDS AND VULNERABLE PEOPLE AND PLACES

It has become clear in the AR4 that the impacts of climate change are most damaging when they occur in the context of multiple stresses arising from the effects, for example, of globalization, poverty, poor governance and settlement of low-lying coasts. Considerable progress has been made towards understanding which people and which locations may expect to be disproportionately impacted by negative aspects of climate change. It is important to understand

a) what characteristics enhance vulnerability,
b) what characteristics strengthen the adaptive capacity of some people and places, and
c) what characteristics pre-dispose physical, biological and human systems to irreversible changes as a result of exposure to climate and other stresses.
d) how systems can be managed to minimize the risk of irreversible changes
e) how close we are to tipping points and thresholds for natural ecosystems such as the Amazon rainforest
f) what positive feedbacks would emerge if such a tipping point is reached.

10) CLIMATE CHANGE, ADAPTATION AND SUSTAINABLE DEVELOPMENT

The AR4 recognized that synergies exist between adaptive capacity and sustainable development, and that societies which are pursuing a path of sustainable development are likely to be more resilient to the impacts of climate change.

a) 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.
b) Further understanding of adaptation is likely to require learning-by-doing approaches, where the knowledge base is enhanced through accumulation of practical experience.

11) THE COSTS OF CLIMATE CHANGE, BOTH THE COSTS OF THE IMPACTS AND OF RESPONSE (ADAPTATION AND MITIGATION)

a) Only a small amount of literature on the costs of climate change impacts could be found for assessment. Debate still surrounds the topic of how to measure impacts, and which metrics should be used to ensure comparability.
b) The literature on 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.

Better understanding of the relative costs of climate change impacts and adaptation allows policymakers to consider optimal strategies for implementation of adaptation policies, especially the amount and the timing.

Appendix 4

GCOS Essential Climate Variables[5]

Essential Climate Variables that are both currently feasible for global implementation and have a high impact on UNFCCC and IPCC requirements

Domain	Essential Climate Variables
Atmospheric (over land, sea and ice)	**Surface:** Air temperature, Precipitation, Air pressure, Surface radiation budget, Wind speed and direction, Water vapour. **Upper-air:** Earth radiation budget (including solar irradiance), Upper-air temperature (including MSU radiances), Wind speed and direction, Water vapour, Cloud properties. **Composition:** Carbon dioxide, Methane, Ozone, Other long-lived greenhouse gases[6], Aerosol properties.
Oceanic	**Surface:** Sea-surface temperature, Sea-surface salinity, Sea level, Sea state, Sea ice, Current, Ocean colour (for biological activity), Carbon dioxide partial pressure. **Sub-surface:** Temperature, Salinity, Current, Nutrients, Carbon, Ocean tracers, Phytoplankton.
Terrestrial[7]	River discharge, Water use, Ground water, Lake levels, Snow cover, Glaciers and ice caps, Permafrost and seasonally-frozen ground, Albedo, Land cover (including vegetation type), Fraction of absorbed photosynthetically active radiation (fAPAR), Leaf area index (LAI), Biomass, Fire disturbance, Soil moisture[8].

[5] The Second Report on the Adequacy of the Global Observing Systems for Climate in Support of the UNFCCC, GCOS-82, April 2003 (WMO/TD No. 1143). http://www.wmo.int/web/gcos/gcoshome.html

[6] Including nitrous oxide (N_2O), chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF_6), and perfluorocarbons (PFCs).

[7] Includes runoff ($m^3 s^{-1}$), groundwater extraction rates ($m^3 yr^{-1}$) and location, snow cover extent (km^2) and duration, snow depth (cm), glacier/ice cap inventory and mass balance ($kg\ m^{-2} yr^{-1}$), glacier length (m), ice sheet mass balance ($kg\ m^{-2} yr^{-1}$) and extent (km^2), permafrost extent (km^2), temperature profiles and active layer thickness, above ground biomass (t/ha), burnt area (ha), date and location of active fire, burn efficiency (%vegetation burned/unit area).

[8] Recognized as an emerging ECV

Appendix 5

List of Acronyms