Regional Environmental Change: Human Action and Adaptation

What does it take to meet the Belmont Challenge?

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Preliminary report of an ad hoc ICSU panel

August 2010

Preface

In late 2009 the Belmont Forum, a group of major funders of international global change research, invited the International Council for Science (ICSU) to conduct an analysis of the international research capability required to respond to the challenge of delivering knowledge to support human action and adaptation to regional environmental change. This challenge was named the Belmont Challenge and requires regional and decadal prediction, advanced observing systems and the integration of the social sciences.

To address this task, ICSU set up a panel consisting of 15 international experts with Guy Brasseur as the chair (Annex 1). While the panel members served in their personal capacity, the report was able to benefit from, and build upon, the collective wisdom of a large community with which they interact. The analysis draws on the existing synthesis and assessment products of the broader scientific community, the experiences and strategic plans of the global change programmes[1] and other related international and national activities, and many peer-reviewed papers. This report summarizes the panel's findings.

The report has undergone extensive peer review. Inputs were sought from relevant ICSU bodies and other organizations. Nevertheless, the scale of the task and the limited time available did not permit a comprehensive analysis of all issues; consequently, the report should be regarded as a preliminary analysis. Indeed, one of the outcomes of the analysis is the realization that the details of the Belmont Challenge itself need to be better specified, and further studies on a number of important areas are needed.

Initially, the starting point and thus the focus of the Belmont Challenge was: 'to deliver knowledge to support Human Action and Adaptation to Regional Environmental Change'. It was recognized that decadal prediction would be an essential first step in this process, but after some consultation, particularly with external reviewers and the Belmont Forum, it was decided to expand the analysis to include mitigation. To some extent this is reflected in the structure of the report and the fact that coverage of areas is somewhat uneven.

While this report was being drafted by ICSU, parallel work was being conducted by the Belmont Forum to detail the Belmont Challenge, in the form of a white paper. Unfortunately, the timing was such that the panel could not take full account of this work. Despite these limitations, we nevertheless hope that the report will be a useful starting point for addressing the Belmont Challenge, since it represents an important component of a complete Earth system research agenda.

In 2008 ICSU initiated an Earth System visioning exercise that has defined five grand challenges for global sustainability research, with concrete scientific questions under each of the challenges. Some of the visioning outcomes cover elements set out in the Belmont Challenge. Although this analysis and the visioning process are two independently designed processes, the overlap in the priorities identified only serves to underline their importance.

Partly due to the overlap, there has been some confusion, within the research community, about the two parallel processes. While the visioning process was mandated by the ICSU General Assembly in 2008 to outline options for an overall framework for global environmental change research, the present report is an analysis requested by the funders and should not be regarded as an implementation plan for the visioning process, although the discussions and suggestions of the analysis may provide useful inputs to the ongoing visioning process.

[1] DIVERSITAS, an International Programme of Biodiversity Science; International Geosphere-Biosphere Programme (IGBP); International Human Dimensions Programme on Global Environmental Change (IHDP); World Climate Research Programme (WCRP); and Earth System Science Partnership (ESSP).

This report is the culmination of contributions from many organizations and individuals. In addition to the panel members and the contributors listed in Annex 1, many others have played an important role. On behalf of ICSU, I would like to express very sincere thanks to the dozens of reviewers whose advice and recommendations have served to significantly improve the report. A special thank you goes to Guy Brasseur, and to Mel Shapiro who assisted the chair of the panel in a most efficient and effective way. NSF provided financial support to the project. Colleagues from the Belmont Forum also provided useful information about the articulation of the Belmont Challenge and feedback to earlier versions of the report.

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Executive Summary and Recommendations

In June 2009, the US National Science Foundation (NSF) and the UK Natural Environment Research Council (NERC) led a meeting in Belmont, Washington DC, attended by representatives of several of the world's major global change research funding agencies and the International Council for Science (ICSU). These agencies, supporting basic and applied research in Earth system science, identified a challenge for the international scientific community to *develop and deliver knowledge in support of national and international government action to mitigate and adapt to global and regional environmental change with an emphasis on regional hazards.* This challenge is hereafter referred to as the *Belmont Challenge*. In response, a panel was assembled by ICSU. It was tasked to assess the willingness, readiness and capacity of the international research community to respond to the Challenge and to address issues related to the integration of weather, climate, ecosystem, energy, health, agriculture, engineering and social science research, emphasizing near-term (year-decade), as well as medium-term (20 years) options, challenges, and approaches to the needed level of international activity. This requires a dialogue between stakeholders (political, economic and social actors, either as individuals, groups or organizations), and natural and social scientists.

The environmental problems facing today's society cannot be overcome by a single nation or a single scientific discipline. Responding to these challenges demands highly coordinated and collaborative research and service agendas. The panel proposes a research agenda to provide the scientifically based information needed by local, national and international decision makers, as they take actions for the benefit of society and environmental sustainability. This agenda will mobilize the full spectrum of scientific disciplines. Reducing vulnerability and increasing resilience to environmental stress is a unifying goal of the diverse communities involved in these issues.

The panel highlights the need for the development and implementation of:

- Integrated tools for analysis, prediction and projection in support of the capability of environmental management to identify and respond to hazards, risks and vulnerability, and to develop mitigation and adaptation strategies. A major challenge is to develop integrated Earth system analysis and prediction systems, including the characterization of regional vulnerability and risks.
- More effective use of physical and societal observations to improve global-to-regional environmental analysis and prediction.
- Information/communication tools and facilities that provide authoritative and easily accessible information to policy makers and decision makers.
- Capacity-building strategies in both developing and developed countries, as well as scientific partnerships between institutions from different geographic regions of the world.

The panel recognizes the urgent need to:

- **Coordinate efforts and enhance the support** required to address the needs of a sustainable environment and the needs of society. The challenge is to integrate environmental and developmental issues that have often been addressed independently in past decades.
- **Facilitate the dialogue between scientists, decision makers and the general public** to support decisions and actions at the forefront of society's needs.
- **Encourage natural and social scientists to work together** to ensure that environmental observations, analyses, predictions and services most effectively meet the needs of society.
- **Maintain and expand access to, and use of, the current global observing and monitoring systems** through coordinated databases and develop assimilation procedures to achieve the maximum benefit.

- **Respond to society's increasing demand for detailed information** at the regional and local scales. This requires sector-relevant information that includes observations, analyses, high-resolution projections/predictions at timescales from days to decades.

The panel established the following priorities to address the Belmont Challenge:

- **Develop Earth system knowledge:** Building on past successes, mobilize existing research teams and networks to develop and deliver the knowledge required to address pressing global to local environmental and societal issues, with the support of funding agencies and national and international programmes.
- **Facilitate the communication of knowledge to decision makers:** Identify the objectives and means for effective translation and communication of scientific knowledge for targeted sectors and regions in order to realize the intended benefits from the application of such knowledge.
- **Nurture the next generation of experts:** Invest in training scientists and associated staff through fellowships and research grants, emphazing scientific challenges at the interface of natural and human systems.

The panel recommends the following actions by the funding agencies:

1. **Establish an international research and educational network for Earth system science.**
2. **Promote the development of the human capital** required to address the Belmont Challenge.
3. **Establish multi-national interdisciplinary and transdisciplinary teams** that promote a dialogue with decision makers to identify the key environmental and societal issues that regions are facing.
4. **Encourage diverse approaches** for the analysis of multi-stressors, responses and feedback processes affecting the physical, chemical, biological and social systems in selected regions particularly prone to human perturbations and environmental change.
5. **Develop and coordinate advanced experimental, observational, and computational facilities** that address the Belmont Challenge and provide support for the operational and maintenance costs of these facilities.
6. **Develop integrated Earth system models** with global and regional capability that provide predictions and projections of the evolution of the Earth system, including weather, climate and other environmental changes, the occurrence of natural and human-induced extreme events, as well as the impacts of these changes on ecosystems and human society.
7. **Conduct a study focusing on issues associated with the integration of natural and social sciences.**
8. **Address issues related to the vulnerability and adaptability of human societies** to environmental change and risks affecting vulnerable regions, as well as the economic and environmental impacts of potential mitigation and adaptation strategies.
9. **Initiate partnerships between nations** to draw on their collective scientific and societal expertise; support the special research and infrastructure needs of developing countries.

1. Introduction

There is emerging interest within national academic research funding agencies to coordinate their support for international and interdisciplinary Earth system research. In June 2009, the US NSF and the UK NERC led a meeting of principals of several of the world's major global change research funding agencies and ICSU, in Belmont, Washington DC. Participants at the Belmont meeting agreed on the need for an improved forum for dialogue between research funding agencies and the scientific community represented by ICSU, and for a coordinated process for early-phase engagement on global environmental change research strategies and priorities. As a result, a new high-level forum, called the Belmont Forum, was established, with the aim of identifying strategic priorities for international collaboration.

This meeting established the *Belmont Challenge*, with a focus on *Regional Environmental Change: Human Action and Adaptation.* It aims at delivering knowledge to support human action and adaptation to regional environmental change. Responding to this challenge requires regional and decadal prediction, advanced observing systems and inclusion of social sciences. The objective is *to develop and deliver knowledge in support of national and international government action to mitigate and adapt to global and regional environmental change and its associated regional hazards.*

Regional and decadal-scale monitoring, projections, and adaptation and mitigation strategies are urgently required by decision makers for priority issues such as: coastal zones; water cycle and water resources; ecosystem services and food security; carbon cycling, including ocean acidification; deforestation; land use and soils; and the most vulnerable societies. Research in these areas is central to the provision and utilization of environmental information services for decision-support to governments, business and society at large.

ICSU was charged by the Belmont Forum to conduct an analysis of international research willingness and capability to take action, with a focus on solvability of problems, infrastructure and personnel needed to meet the Belmont Challenge. Responding to the Belmont Challenge will require major advances in the prediction of integrated and comprehensive daily-to-seasonal-to-decadal changes, to improve the utilization and development of observing systems, and to accelerate the integration of natural, engineering, health and socio-economic sciences. There is also a need to build upon existing globally coordinated multidisciplinary, interdisciplinary and transdisciplinary efforts to achieve this objective (see the box on the next page for definitions).

In response to the Challenge, ICSU convened a panel of international leading experts charged with:

- Assessing the willingness, readiness and capability of the international research community to respond to the Belmont Challenge, and provide recommendations for action.
- Addressing issues related to the integration of weather, climate, ecosytem, energy, health, agriculture, engineering and social science research at the regional level.
- Focusing both on the near-term (year-decade) and on the medium-term (20 years) challenges and approaches at the required level of international activity.
- Identifying impediments and how to overcome them.

- Discussing adaptation and mitigation science needs.
- Fostering the necessary collaborative interdisciplinary research activities among international partners.

The primary objectives of the Belmont Challenge are to determine:

- how to address major scientific issues related to environmental changes at the interface between natural and human systems; and
- how to use the resulting knowledge for assessments of impacts, adaptation, vulnerability and the management of associated risks.

Research during the last decades of the 20th century, and into the 21st century, has focused on environmental diagnostics and predictions. The additional focus in the first decades of the 21st century has been to integrate strategies for socio-economic development and environmental sustainability.

Delivering environmental information requires that the issues at the forefront of society's needs be identified. There is an urgency to expand the environmental change research arena by addressing research challenges that mobilize the full spectrum of disciplines, theories and methodologies. We must ensure that individuals and communities participate in the development of research agendas to address social, political and economic problems. Science should provide the basis to assist governments in informing and warning their citizens of impending changes to the environment on daily-to-seasonal-to-decadal timescales, so that actions can be taken to reduce risks, alleviate impacts and benefit from opportunities.

The Belmont Challenge places an emphasis on enhancing the contributions of the *social sciences* to research in global environmental change. This requires that leaders of the social science community engage in all areas related to the agenda of the Belmont Challenge. It is important that social scientists, from the outset, be part of the broader agenda that includes engaging with physical observation, analysis and modeling systems. It is equally important that methods used in the social sciences be understood and appreciated by other scientific communities involved.

The panel recommends that ICSU, in cooperation with the International Social Science Council (ISSC), convene a panel to specifically address the issue of integrating natural and social sciences.

Definitions

Regional Change: Change that occurs over a usually continuous segment of a surface or space often recognized through some common natural or cultural characteristics. A region can cover: a large, almost continental area (e.g. the Asian Monsoon region); a somewhat smaller, though still multi-national area (e.g. the Mediterranean region); or a small area within a country (e.g. the southwestern United States). Understanding the interplay between neighbouring regions and the Earth as a whole is a vital part of understanding the behaviour of the Earth system.

Environmental change: Change that affects different aspects of the social-ecological system including changes in weather, climate, hydrology, ice cover, ecosystems, land-cover and land-use, biodiversity, biogeochemical cycles, chemical composition of air and water, environmental services, etc.

Multidisciplinary: A range of disciplines working on the same problem or question, but with the implications that there are limited or no interactions among these disciplines.

Interdisciplinary: Many disciplines strongly interacting, sharing concepts and approaches, and developing new integrated approaches that span disciplines. Approaches are interdisciplinary when they focus primarily on the integrated system, not only on its components.

Transdisciplinary: Transdisciplinary science refers to research that cuts across social and natural sciences, and includes at least five constitutive features: problem-oriented, beyond disciplinarity, practice-oriented, participatory and process-oriented.

2. Readiness of the Community

The panel discussed the readiness of the community to undertake necessary steps in response to the Belmont Challenge. Most stakeholders (e.g. policy makers and decision makers in diverse socio-economic sectors) concur that *integrated* information is required to develop and implement mitigation and adaptation strategies that more effectively respond to the regional manifestations of global environmental change. However, at present, government frameworks are not always optimally suited to fully respond to the challenges resulting from environmental change. Requirements for advanced weather, climate and other environmental services for diverse socio-economic and environmental sectors focus on time scales ranging from daily-to-decadal, with a strong emphasis on issues that arise at the regional scale.

Scientists are cognizant of their responsibility to address interdisciplinary, global-to-regional issues. However, some believe that their research is primarily guided by fundamental disciplinary challenges and secondarily by societal requirements for scientific information.

Both disciplinary- and societal-driven research are required. There will be important new insights of direct relevance to environmental issues from fundamental basic research, as well as from research defined by society. Intellectual excitement is essential for creativity and innovation. Addressing large complex and intellectually challenging problems requires an institutional framework.

The Belmont Challenge calls for new intellectual and structural approaches. In the past, scientific research was often initiated because it was academically challenging, and secondarily to address a pressing societal issue. The Belmont Challenge calls for an approach in which major cooperative research initiatives are developed from a dialogue between scientists and stakeholders; it is not clear whether the entire research community is fully ready for such an approach. On a positive note, many academic institutions are currently restructuring their curricula to engage in the interdisciplinary and transdisciplinary research needed to solve complex problems that society is facing. There is a growing community within academia, including within the student population, that is engaging in interdisciplinary research of societal relevance.

The *physical-climate, climate-impact and resilience-adaptation-vulnerability* research communities—which, historically, have been separate —must expand their coordination and collaboration. Funding agencies must be encouraged to establish strategic visions that draw these three communities closer together. The physical-climate and the climate-impact communities use, primarily, an approach based on scenario-driven sector impact models, while the resilience-adaptation-vulnerability research community adopts an approach in which climate change is treated as one of the many interacting stresses. These contributions to the Belmont Challenge will be of central importance, since its approach is aligned with what managers at local and regional scales need. Methodologies for impact–vulnerability–adaptation studies should be further developed. Reducing vulnerability and increasing resilience to environmental stress should be a goal for society, including the scientific communities involved. It should be recognized, however, that regional aspects should be developed with a global perspective in mind. Indeed, regional studies must take into account both regional manifestations and impacts of global changes in order to accurately represent the behaviour of the regions of interest.

In past decades, scientific assessments (e.g. those conducted by the Intergovernmental Panel on Climate Change, IPCC) have been important avenues for initiating dialogue between the scientific community and political and economic actors. In the future, these assessments in addition to presenting a critical and expert synthesis of the work conducted by the scientific community, will have to better address broader issues of importance to society.

Addressing the Belmont Challenge requires that a broad range of weather, climate, biogeochemical, geochemical and socio-economic information be collected, coordinated, archived and disseminated. The panel highlights the need for comprehensive and easily accessible databases and for integrated analysis and prediction systems. It notes that:

- Large amounts of Earth system data are available. However, expanded databases are required, e.g. for: surface and ground-water hydrology; oceans; health; public vulnerability/response; and impacts on human and socio-economic activities, and on ecosystems.
- All environmental data should be made openly available to all research users.
- The use of advanced weather and climate data assimilation and prediction systems to combine the best aspects of both data and models (e.g. accuracy and consistency, respectively) is an important aspect of advancing the use and value of multidisciplinary information.
- There is a need to improve long-term, high spatial and temporal resolution observations and predictions that seek to capture extreme environmental and societal events.
- Prediction models need to be tailored to address the integrated science issues posed in the Belmont Challenge. Developing high-resolution global-to-regional Earth system analysis and prediction models, that account for natural as well as human-driven processes, will most effectively be accomplished by strong cooperation between academic, government and risk-management (e.g. insurance) institutions.

3. Impediments

3.1. Funding Structure

In general, academic funding tends to remain mostly structured along traditional disciplines and the level of development of co-designed programmes is less than optimal, e.g. in terms of integration between natural and social sciences. Several attempts have been made by different agencies to develop cross-cutting initiatives. It is increasingly common to see solicitations for proposals by funding agencies that transcend a given discipline.

Co-designed programmes (social and natural sciences) and funding schemes should be developed and coordinated at the local, national and international levels. To complement existing programmes in either natural or social science, the participation of the ongoing international programmes, which have acquired experience in linking different national research communities, would be useful. To be successful, co-designed international projects require long-term scientific commitment and support. Current funding is not optimally structured to address long-term research needs, such as those required to address the Belmont Challenge.

Today's environmental issues are often related to the vulnerabilities and opportunities of specific regions. In some nations, there is a need for enhanced support of scientific research by regional/local governments. Regional authorities should be involved in integrated studies—on subjects such as water, extreme natural events, food and health—in their region.

3.2. Educational Systems

Important initiatives have been taken by the research community to facilitate research and education at the intersection of disciplines. However, many universities continue to emphasize traditional topics and approaches. Specifically, PhD students should be encouraged and supported to address multidisciplinary or interdisciplinary problems. They should also be encouraged to supplement their initial PhD education with post-doctoral training in other disciplines, within natural or social sciences or outside (e.g. humanities).

Students often believe that it is difficult to develop a successful career without a strong specific disciplinary focus. However, there are clear exceptions, for example, geography, anthropology and economics. Similarly, natural scientists are often reluctant to engage in the socio-economic integration and application of their science. The present reward/recognition system at most universities is not sufficiently conducive to what is required to meet the Belmont Challenge.

Some academic institutions have recently established inter-disciplinary, multi-departmental research institutes that focus on climate and social-ecological issues, and developed Earth system science undergraduate and PhD programmes that provide opportunities to address the Belmont Challenge. The introduction of curricula linking natural sciences, engineering and socio-economics (e.g. economics of environmental change, risk management) should be encouraged.

The education system should encourage post-doctoral researchers to expand their interdisciplinary engagement. Academic and governmental institutions should develop interdisciplinary visiting programmes with international and multi-cultural participation.

Addressing the Belmont Challenge requires a strong engagement with universities and the research branches of operational agencies. The interplay of environmental issues with engineering should be enhanced.

3.3. Infrastructure and Facilities

The infrastructure to address environmental issues, especially at the regional scale, has often been developed separately by the natural science and socio-economic communities, and government service providers. Today, information provided by these communities and providers needs to be integrated into a single framework. This task is a major challenge, since the vocabulary, methodologies and approaches adopted by the different communities differ significantly. In certain cases, the lack of spatial disaggregation of environmental and economic data are incompatible with the needs of natural scientists. For example, trace gas emissions compiled by official authorities in different countries are often provided as single values for the entire country, while environmental models require highly spatially resolved geographic distributions of these emissions.

Monitoring environmental conditions is important to assess the vulnerability of societies and to develop mitigation and adaptation strategies. In order to support long-term monitoring activities, there is a need for better cooperation between agencies that fund research—across the spectrum from basic research through to operational research. Progress would be made if the funding for essential observing systems were successfully transitioned from project-based research funding to ongoing operational funding. A major challenge in sustaining and updating observational capabilities is to demonstrate their effectiveness and impacts (e.g. on research, analysis, data assimilation, forecasting). Currently, only a small fraction of available observations are used for research and operation due to a variety of issues, including lack of access, restrictions by some nations, inconsistency in processing and documenting the different products, complexity of the algorithms used, difficulty in use and interpretation by non-experts, and lack of training.

Integrated environmental studies utilize information produced by different research and operational institutions. The panel believes that there is inconsistent support provided to enable integration of data and to check data quality. While there is sufficient work in some areas (due to sufficient support), existing work is insufficient in others. For example, there is an important issue that arises regarding the units of analysis when integrating natural science and social science efforts. While social science data are almost always collected in terms of political/administrative units (e.g. census tracts, municipalities, provinces, nations), natural science data are usually collected based on regular spatial intervals (e.g. a grid of 5 km). A major challenge for all of us, therefore, will be to find a way to harmonize the resultant data sets. In many instances, access to existing data remains limited by restrictive information-sharing policies. Environmental data acquired by public funds should be accessible to scientists. In addition, international programmes should play a major role in evaluating the consistency of related data sets and in producing and evaluating unified data sets that incorporate the data products from multiple providers. Initiatives should be taken to develop visualization of data with emphasis on data and systems that are accessible to non-specialists.

Finally, the panel highlights that the development of a family of Earth system prediction models—that include a representation of physical, chemical and biological details at global-to-regional scales with sufficiently high spatial resolution—cannot be achieved without access to dedicated supercomputing facilities. Even though much support has been provided for the installation of supercomputing systems by some countries, challenging problems require even more powerful machines. For example, models that resolve clouds, hurricanes and strong precipitation, urban air quality, surface hydrology, local environmental conditions and ecosystem status, require development of and access to much more powerful machines. Grid and cloud computing are playing an increasingly important role in many disciplines; these approaches will be particularly useful in fostering collaborative research in Earth system research. Their development should be encouraged.

4. Road Map to Address the Belmont Challenge

The panel proposes a road map to facilitate the implementation of the Belmont Challenge by considering the identification of issues and the approaches needed to address these issues.

4.1. Identifying key issues

In order to identify the key issues within the Belmont Challenge, it is crucial to improve the dialogue between the scientific community and the diverse stakeholder communities, especially at the regional level. There is a need for an iterative, interactive process, involving both communities engaging in dialogue to identify and analyze issues and questions (originating from this dialogue), and to determine their significance. At the same time, scientists should engage in dialogue among the disciplines in order to develop responses to the needs of society. Ultimately, the identification of the key issues should involve both stakeholders and scientists.

Discussions conducted at the international level, often involving stakeholders, have identified important research questions to be addressed for better management of planetary resources. In its early definition of the Belmont Challenge, a few near-to-mid-term foci were identified:

1. coastal zones in the 21st century: ecosystems, people, commerce and security;
2. water quality and water resources: availability and distribution;
3. sustainable carbon-based economy, including ocean acidification, deforestation, land use and soils; and
4. the most vulnerable societies, with low-response capacity and with high societal vulnerability to environmental changes.

Other issues will be raised through the dialogue with stakeholders. Here, the participation of social scientists (e.g. economists, political scientists, sociologists and psychologists) will be crucial. Illustrative examples of issues that need to be addressed by these communities of scientists are provided in the box on the following page. A broad engagement of social scientists—from different communities and different regions of the world—is necessary to identify not only the specific social science questions that the Belmont Challenge raises but also the social science perspectives that must be brought to bear on the full range of priorities identified—predictions and observations included.

Illustrative example: Broad societal issues for the Belmont Challenge

A key challenge is to understand the roots of human behaviour as it pertains to human-environment interactions. It is important to understand how and when major behavioural changes occur.

Within this framework, some of the focus should be on:

- top-down approaches featuring public policy making and implementation;
- bottom-up approaches featuring the role of social movements;
- the role of institutions and, more specifically, governance systems;
- decision-making under uncertainty, including the roles of rules of thumb and heuristics (educated guess, intuitive judgment or common sense) and the role of local or traditional knowledge, as well as religious or spiritual beliefs; and
- human security, specifically options available to individuals and communities to stop, to mitigate or to adapt to environmental change and related social vulnerabilities, and their capacities to do so.

4.2. Addressing the issues

Responding to the Belmont Challenge will require that the scientific community: (i) enhance its understanding of the multiple stressors affecting the environment, their combined impacts and feedbacks, as well as the vulnerability of ecosystems and society; (ii) better quantify the rates of change, the controlling factors and feedbacks at relevant spatial and temporal scales; and (iii) assess the environmental and societal consequences of mitigation and adaptation strategies. These issues will be addressed by:

- Developing and evaluating the next-generation of Earth system models coupled to observations.
- Developing a diagnostic and projective capability for societal and ecological vulnerability.
- Developing decision-support tools to map out how policy decisions affect future environmental and societal changes.

These issues require more effective use and further development of four elements:

1. observation and monitoring systems;
2. analysis and prediction systems;
3. information and communication tools; and
4. capacity building capability.

1. Elements of global and regional environmental and socio-economic observation systems and data management

The *first element* is the development of more effective uses of existing observations. The research community will need to define and advocate for additional *observation* and *monitoring information* systems to respond to the Belmont Challenge. The focus should be on observations that characterize the dynamics of a region, e.g. weather and climate variations and trends, extremes, vulnerabilities of both social systems and ecosystems, and societies as drivers of change and at risk from change. This will include different aspects of environmental and socio-economic evolution, e.g. extreme weather and other disasters, fires and air pollution, as well as economic and social benefits and impacts. The panel recommends that a few regional pilot projects be initiated in selected societally and environmentally vulnerable regions. Attention should be given to natural and human drivers of change and subsequent responses. Opportunities to use existing and future observation platforms (e.g. in space, or on aircraft, ships or land) as well as using dedicated platforms, should be fully exploited.

Examples of information needed from observation and monitoring systems

- Regional and local information on forcing and response, e.g. land cover and water resources.
- Environmental parameters with high spatial/temporal resolution, to be able to describe the frequency and spatial distribution of extreme events.
- Socio-economic data, including systematic mapping and assessments of costs associated with disasters at global, regional and local scales. These data should be obtained with consistent methodologies for assessment of natural hazards proceeding from the probability of their occurrence and recurrence and using empirical, statistical, and deterministic approaches to enable estimates of hazard potential, affected areas and impact duration.

2. Integrated Earth system analysis and prediction systems

Earth system science integrates observations, research, monitoring and prediction of the most probable evolution of the Earth system in response to natural forces and human activity. It synthesizes, integrates and assimilates *in situ* airborne and space-based Earth observations, together with human-dimension information, into comprehensive and consistent four-dimensional descriptions of the evolving Earth system. Such analyses form the basis for projections/predictions by dynamic Earth system models, e.g. ensemble prediction models, regional coupled models, statistical and neural network models. Dynamic downscaling will meet some of the user-needs at local and regional scales for socio-economic, agro-meteorology, human health, policy, resource, threat, risk and adaptation-mitigation applications.

The *second element* is the development of integrated regional *modeling tools* for analysis and projection/prediction, in support of environmental management (risks, vulnerability and adaptation) and provision of information. Here, priorities are the development and evaluation of a hierarchy of models, and their use to diagnose and analyze the past evolution of environmental and socio-economic systems, to predict the future state and to characterize vulnerability and risks. This requires the development of a hierarchy of Earth-system models with regional capability that includes a representation of coupled physical, chemical and biological processes. High resolution multi-model (ensemble) simulations for different scenarios should be performed. A wide range of environmental issues need to be considered, including climate change, flooding, droughts, tropical cyclones, sand and dust storms, winter storms, land-use changes, overexploitation of marine resources, loss of biodiversity, ocean acidification, lake eutrophication, air and water pollution, toxins, invasive species, and perturbation of biogeochemical cycles. The focus of these modelling studies should be on trends, abrupt changes and the probability of occurrence of future extreme events.

Some important considerations are improving the skill for prediction on daily-to-inter-annual timescales, and assessing decadal-to-centennial predictability limits and the predictive skills of models. This requires that predictive skills be investigated for past variability and change. The relationship between information required for model initialization and subsequent predictive skill should be addressed. Since decadal predictions of high-impact local events are still over the horizon and any information from such predictions is likely to be probabilistic, scenario-based projections will remain a useful approach as input to decision-making. Here, scenario development and analysis should be developed as a tool for structuring interdisciplinary discussions at the regional level, taking into account the global context in which regional changes take place. Clearly, the new generation of models should take the human dimension into consideration. The panel emphasizes that a decision-information system regarding hazards, risks and responses will benefit from advanced data assimilation systems coupled to high-resolution models.

The panel believes that the long-term goal is the *development of integrated Earth system analysis and prediction systems*. By fully engaging with the relevant disciplines and communities, it will be possible to develop integrated observing, analysis and prediction systems that address coupled atmospheric, land, ice, biosphere and oceanic components and their future evolution under severe human-related stress.

To accelerate progress in this area, the following recommendations are made:

- Accelerate collaboration between the meteorological, oceanographic, hydrological, ecological, and climate communities, and share methodologies and software, e.g. model-to-observation software, diagnostics packages.
- Converge internationally on a limited number of appropriate models that will be developed by a large, interdisciplinary community of scientists.
- Develop and assess decadal prediction systems as extensions to existing seasonal forecasts systems.
- Concentrate investments in high-performance computing that will allow a rapid increase of resolution for forecasting systems through improvements in the representation of physical, chemical and biological processes.
- Encourage investments in observing systems and implement the transition of research findings into operational services, particularly in the case of ocean observations.
- Secure new funding for historical Earth system re-analysis and re-forecast activities.

Another important challenge is the development of a *prediction/projection capability for the characterization of vulnerability and risk* (personal, health, economic) and response strategies (resilience, insurance). Here, key research questions are: How vulnerabilities (e.g. population, infrastructure, economic activity and livelihood, health) can best be determined and portrayed in a way that provides the critical information required by policy makers and decision makers? How can appropriate adaptation measures best be identified, evaluated and prioritized? Who and what are the people and places most at risk and why? And, how might the risks change with time?

It will be important to consider models at various scales, able to run multiple scenarios and ensembles in order to get a probabilistic distribution of results. As model simulations become available, uncertainties will have to be quantified to the maximum extent possible. The differences in the uncertainties coming from the different models will have to be addressed through model-model and model-data inter-comparisons.These model results will support future international assessment activities.

Illustrative example: Towards a seamless weather, climate and Earth system prediction system

1. Advances in the representation of physical processes (e.g. tropical convection, atmosphere/ocean/land/ice interactions, aerosols, cloud microphysics and radiation, boundary layer turbulence) and their interactions with the global circulation will lead to more skilful predictions of regional to global weather and climate. This success will translate into socio-economic applications for improving early-warning systems for weather- or climate-induced hazards. Applications could be for agriculture, the water cycle and its management, or health—particularly in regions affected by monsoons.
2. Advances in coupled data assimilation are a prerequisite for long-range weather and climate predictions. Historically, data assimilation research and its applications have focused mostly on the requirements of operational short- to medium-range weather forecasts. The next generation of assimilation and re-analysis projects will have to integrate information provided by climate, weather and Earth system research programmes.
3. An important requirement is to build satellite missions and implement planned ones that provide long-term capability for process studies, data assimilation and prediction.
4. High-performance computing and archive centres will be required to enable efficient numerical modeling, advanced experimental design, improved data processing and distribution of data (including relevant socio-economic information and analysis).

3. User-Interface: Environmental service in support of informed decision making

The *third element* is to develop *information/communication tools*, or more generally *integrated Earth system knowledge platforms* to provide scientific results to stakeholders and specifically to policy makers and decision makers/managers. Here, it is important to advance the two-way communication system between science and society. Information must be objective and easily accessible. New media and communication technologies are very important tools and they should be fully exploited. Direct dialogue with stakeholders is an important component of a communication system. Working with information providers and disseminators, including teachers and journalists, should be encouraged. Communication should emphasize the probability of occurrence of key parameters that are badly needed by policy makers and decision makers/managers.

It is necessary to integrate stakeholder consultation with research across a wide range of Earth science disciplines, engage the private sector, and to do so in partnership with various national efforts. One important element is to identify the stakeholder needs for Earth system observation and prediction products. Recently, national leaders, investors, business leaders and policy makers have begun to seek strategies to help prepare for the adverse and beneficial impacts of environmental change on business, industries, local communities and entire nations. Unfortunately, decision makers are not yet fully provided with the information needed to develop cost-effective strategies to reduce vulnerabilities, such as:

- the probability of various types of climate change happening in a particular geographic region from seasons to decades;
- the vulnerability of various natural and human systems in this geographical region to environmental changes; and
- the costs and benefits of strategies to reduce vulnerability.

The establishment of a Global Framework for Climate Services[2] provides an opportunity for developing bridges between research, operations and society. The Framework must integrate knowledge on multi-stressors affecting social and ecological systems and the complex feedbacks that exist between different components of the Earth system. Hence, the Framework will provide information as an extension of current national meteorological and hydrological services. They must embrace the physical climate system, biogeochemistry and socio-economic sciences. This approach presents research, personnel and capacity challenges across the disciplines. The service function should remain coupled to research. The focus should be on impacts, vulnerability and adaptation.

Providing information on the global and regional environment that specifically supports human action and adaptation to environmental change requires that research funding agencies and their constituencies coordinate closely with operational funding agencies.

[2] The decision to establish a Global Framework for Climate Services was made during the High Level Segment of the World Climate Conference 3 in Geneva, 31 August–4 September 2009. More information on the Framework can be found at: http://www.wmo.int/wcc3/declaration_en.php

Illustrative example: Towards the quantification of human and economic risks associated with environmental changes

- Develop products (observation and model) on a regular basis, tailored to users' needs, including those for specific regions and sectors.
- Run models responsively for multiple scenarios in ensembles to provide uncertainty estimates.
- Develop data delivery systems to provide results to users.
- Include socio-economic information so human and economic costs of risks and impacts can be characterized and/or estimated.
  - Modeling of risk requires the integration of natural and socio-economic sciences—how to do best is a key research question. Risk assessment and modeling, and the provision of evidence-based scientific advice require natural and social scientists to collaborate. Modeling of risk requires the development of holistic models incorporating natural processes, infrastructure, societal factors and human behaviour.
- Support extensive multi-disciplinary quantitative analysis of model outputs, especially to identify potential unintended consequences of changes.
  - Development of risk models, which can incorporate both quantitative and qualitative information will allow for the comparative analysis of different approaches towards risk reduction. Scientists undertaking this research should work closely with local communities and authorities so that science is integrated into societal concerns and policy development.
- Provide comparative analysis and integrative approaches that analyze the context and related risks, vulnerabilities and projected impacts from both the top-down (i.e. downscaling) and bottom-up (i.e. critical thresholds approach)—resulting in additional research insights and benefits for users.
- Communicate uncertainty in forecasts and risk assessments to decision makers and the public—this is a challenging task, for which drawing on local indigenous knowledge systems will help.
- Address decision making in governance and society—political, economic, social factors. Identify key obstacles/barriers to urban adaptation to environmental change, including knowledge gaps, human and financial resources and institutional capacity.

4. Capacity Building

The *fourth element* is to develop a *capacity building strategy*. Such a strategy will apply to both developing and developed countries, with particular attention to the needs of the societies under greatest stress. Capacity building requires a sustained approach. This can be facilitated by education programmes, especially in developing countries, as well as supporting infrastructure—especially for data delivery, archiving, and visualization. Extensive opportunities should be provided for scientists from developing countries to visit leading institutions around the world—to share experiences and help build a global scientific community. Opportunities should be created for early career scientists, especially those from developing countries, to work alongside established scientists (e.g. on field campaigns and assessments). Two-way partnerships between scientists and institutions from developed and developing countries should be established.

5. Instruments and Suggested Initiatives

The panel concludes this report with suggestions to facilitate the implementation of activities that respond to the Belmont Challenge, recognizing that many of these ideas are presently under consideration by the scientific community. In particular, the recent ICSU-led visioning process—to develop a holistic strategy for global sustainability research—is exploring options for a new institutional framework to meet the five grand challenges that have been identified as part of the visioning process. The following suggestions, which should build on the experiences and capacities from the existing global environmental change programmes and activities, may also provide useful inputs to the ongoing visioning process.

5.1. International Research and Educational Network for Earth System Science (IRNESS)

Create an International Research Network for Earth System Science (IRNESS) with access to state-of-the-art facilities, including interdisciplinary databases and high-capacity supercomputing. This network of centres will host staff and visiting scientists, develop a strong interdisciplinary focus towards integrated Earth system science and support regional initiatives. Its agenda will be broad and highlight integrated, interdisciplinary aspects of environmental sciences (physical climate system, social-ecological system). It will focus on regional and global environmental issues, including: climate change; land use/cover changes; chemical pollution; loss of biodiversity; human health under environmental stress; adaptation and mitigation policies; and international negotiations. It will be accessible to scientists from around the world. The network will facilitate an international programme that brings together the knowledge needed to support dialogue that contributes to adaptation measures and environment management. The network will build upon existing academic and government agency centres and will include virtual components linking participating institutions. The centres will be connected through modern telecommunication facilities. The network will offer training classes for scientists and other stakeholders and will offer a post-doctoral programme and a senior visitor programme.

Develop an international doctoral programme for interdisciplinary Earth system science. Support and expand existing initiatives that attract students from different disciplines and from around the world. Within a network of universities and other research institutions, the programme would provide an international Earth system curriculum that would bridge natural and social sciences. In addition, it would organize summer schools, where students from all around the world could be exposed to and exchange perspectives on issues and their impacts in different regions.

5.2. Pilot Studies

Conduct interdisciplinary pilot studies in selected regions with the purpose of developing mitigation and adaptation strategies to natural and human-induced environmental changes. Such studies should be coordinated by scientists from the region and should be regarded as regional Earth system integrated studies.

6. Conclusions

The environmental problems facing today's society cannot be overcome by a single nation or a single scientific discipline. Responding to these adversities demands highly coordinated and collaborative research and operational service agendas. The proposed agenda in this report will lead to the provision of the scientifically based information needed by local, national and international decision makers as they take actions for the benefit of society and environmental sustainability.

The panel concludes with the following requirements:

- At a time of globalization, environmental and development issues need to be addressed at the international level. Countries, as well as agencies within individual countries, need to increasingly work together to coordinate and support research required to address global societal needs. The challenge is to integrate in a single framework environmental and economic issues that have been largely addressed separately in past decades.
- An integral component of the Belmont Challenge is to develop and maintain a two-way dialogue between scientists, policy makers and the general public by which scientists provide answers that are pertinent to the questions posed by society.
- It is important to maintain and expand the access and the use of the current global observing and monitoring systems, to coordinate databases and to develop assimilation procedures with the purpose of gaining maximum benefit from these observations. It is equally important to contribute to the development of new observing systems, both physical and societal.
- Society increasingly requests detailed regional and site-specific information. Earth system models should provide high-resolution predictions at the timescales of days-to-seasons-to-decades; this requires the next generation of prediction models to achieve a higher degree of useful predictive skill and to represent high-resolution processes, such as weather and surface hydrology changes and their interactions with socio-economic activities at seasonal to decadal time scales.
- The most advanced and powerful dedicated supercomputing facilities are required to resolve key high-resolution physical, chemical and biological processes as well as human activities and treat the full complexity of these issues.
- It is important to expose a new generation of natural and social scientists to environmental observations, analyses and predictions and to communicate the excitement and challenge of integrating complex Earth system processes into daily-to-decadal weather and climate predictions.

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