THE WORLD CLIMATE RESEARCH PROGRAMME ACCOMPLISHMENT REPORT

WCRP
World Climate Research Programme

Foreword

Past successes for future progress

We are pleased to share with you this achievement report that captures the progress made by the World Climate Research Programme (WCRP)* and its Core Projects since publication of the previous report in 2009. During this period, the WCRP leadership and network of affiliate researchers focused their efforts on: (a) coordinating international climate research, modelling and prediction in support of the priorities identified by WCRP sponsors and stakeholders; (b) developing a future research strategy and priorities in response to the rapidly emerging needs for science-based climate information for decision-making, in close consultation with the international science community; (c) participating actively in major international initiatives such as Future Earth: Research for Global Sustainability (ICSU); the Global Framework for Climate Services (WMO) and the Integrated Framework for Sustained Ocean Observations (UNESCO-IOC), to assist in identifying the required observations, modelling and research priorities for the ensuing decade; and (d) establishing a vigorous capacity-development initiative to train the next generation of scientists and research networks at the global and regional levels.

The scientific excellence and objectivity promoted by WCRP during the past three decades, the extensive network of international scientists affiliated with its four Core Projects and WCRP's unique contributions to the field of climate science are the hallmarks of WCRP that are also expected in the future.

This report highlights the progress made in international coordination by WCRP and in cooperation with its sister programmes in developing high-quality, climate-data records, especially from space-based observing systems, developing a comprehensive set of model simulations of centennial and decadal Earth/climate system projections, and coordinating major international reanalysis activities worldwide. These efforts together will provide, for the first time, an unprecedented volume of data and information to be used in climate/Earth system research, international science-based policy assessments, such as the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, international adaptation planning and risk-management studies, water-resources and food-production analysis and assessments and evaluation of alternative energy and transportation planning, to name but a few.

For the first time, these activities extend the range of climate simulations and resulting information from centennial to decadal and seasonal timescales, and from global to regional level to meet the needs of decision-makers dealing with climate-risk management, adaptation planning and impacts and vulnerabilities assessment. WCRP is also facilitating major efforts with its partner national and international organizations to evaluate these products based on past and present observational records in order to build greater confidence in future projections.

A major WCRP focus during this period was on understanding the characteristics of extreme weather/climate events, with emphasis on observations, research and modelling for developing near-real-time detection of such events and attribution of their causes to mitigate and/or ameliorate their impacts on people, ecosystems and the world economy. Some notable activities include international coordination of observations, research and modelling of: (a) meteorological and hydrological droughts and establishment of an international drought information portal for the global sharing of available knowledge and best practices; (b) regional sea-level change and impacts on coastal systems and communities; and (c) expanding the development of climate/weather extreme indices to include factors such as precipitation and temperature for use in agricultural practices and water-resources management.

WCRP organized a major Open Science Conference (OSC) on the occasion of its 30th anniversary in October 2011 to assess the current state of knowledge of climate

*WCRP is sponsored by the World Meteorological Organization (WMO), the International Council for Science (ICSU) and the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO).

variability and change; consult with the international community of experts to identify the most urgent scientific issues and research challenges; and to ascertain how WCRP can best facilitate the research and partnerships required to make greater progress in the seamless prediction of the Earth's climate system across space- and timescales during the coming decades. The OSC confirmed that the WCRP focus on prediction of the Earth's climate system and the role of human beings remain valid objectives today, along with the WCRP strategic priority of an enhanced focus on climate research that is of direct value and benefit to society. The overall theme of the Conference was "Climate science in service to society" to allow a more effective dialogue between climate information and knowledge developers (i.e. the research community) and the decision-makers wrestling with difficult adaptation, mitigation and risk-management issues. The outcomes of the presentations and discussions of the Conference are being used to identify the research priorities for WCRP and its four major international projects in the ensuing decades.

A major emerging theme from the Conference was the need for "actionable" science. While decision-makers – including water providers, farmers, insurance companies, oil exploration companies and many more – need climate and other scientific information to guide decisions, there is often a mismatch between the scientific data available and the information needed. The issues and concerns confronting both the public and decision-makers are complex, and addressing them requires a holistic and solution-based approach. There is a need for "symbiotic" relationships between providers and users of climate information to ensure that "actionable" (timely, accessible and easy-to-understand) climate information is developed and used effectively. Jargon-free and understandable explanations are needed to explain uncertainties and ensure the best and most appropriate use of the science-based information by decision-makers.

OSC participants also emphasized the need for training and developing the next generation of scientists and decision-makers who would be able to pursue and promote the use of actionable climate information. They stated that, for WCRP to be successful, it must make capacity development a major focus and an integral part of every activity that WCRP sponsors. This report highlights some early statistics on the greater engagement of students and early-career scientists in WCRP activities during the past two years.

The general consensus among OSC participants was that the WCRP and its affiliate network of international scientists and projects must continue to provide the scientific foundation for understanding and predicting the Earth's climate system, but they must also play a major role in providing the resulting knowledge and information in ways that yield practical solutions to the complex and interrelated challenges required to ensure a sustainable Earth for future generations. The scientific grand challenges identified in the last section of this report capture the spirit of "actionable" climate research that WCRP will be facilitating.

WCRP and its leaders stand ready to support the research community in pursuing the challenges and opportunities identified during the Conference and to provide climate science in service to society in the ensuing decades. We do hope you enjoy reading this accomplishment report and will provide us with your feedback on how best WCRP can continue to facilitate international climate/Earth system research in service to society.

Ghassem R. Asrar,
Director

Antonio J. Busalacchi,
Chair

1. Programme overview

1.1 Science in support of societal needs

Over the past 30 years, WCRP (www.wcrp-climate.org) has greatly contributed to humankind's ability to understand and predict climate through the international coordination of climate research, modelling and prediction. Today, there is an unprecedented demand in many socio-economic sectors for relevant climate information. WCRP is taking the lead in helping the global climate research community create a scientific foundation for meeting this demand.

WCRP provides the international forum to align the efforts of thousands of climate scientists worldwide towards determining climate predictability and human impact on climate. The focus is on producing the best possible climate-observing networks, models and data analysis and making these tools and resulting climate information products available for the service of global society.

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The WCRP Strategic Framework defines the ultimate objective of WCRP as facilitating the analysis and prediction of the Earth's climate system variability and change for use in an increasing range of practical applications of direct relevance, benefit and value to society. To meet its objectives, WCRP has identified several high-priority areas of scientific investigation that would lead to deliverables of direct benefits to practitioners and decision-makers:

- Anthropogenic climate change – detection, attribution and prediction of the impact of human activities on climate. These activities represent a major contribution of WCRP to the United Nations Framework Convention on Climate Change (UNFCCC) and IPCC assessments. They enable the development of mitigation, adaptation and climate risk-management strategies;

- Atmospheric chemistry and climate – a coordinated effort to better understand and represent in models how atmospheric composition affects, and is affected by, climate change – and how they both interact with atmospheric pollution;

- Sea-level rise – a multi-disciplinary study involving oceanographers, glaciologists and hydrologists, aimed at reducing uncertainties in the estimates of all factors contributing to sea-level variability and change and assessing risks of accelerated sea-level rise due to change in the major ice sheets;

- Climate extremes – a research, modelling and attribution initiative to study the phenomena that make society so vulnerable to changes resulting from the enhanced magnitude, frequency and severity of extreme climate conditions, such as droughts, floods and heatwaves, in a warmer world;

- Seasonal climate predictions – based on new observations and improved models. These collective efforts of major prediction centres aim to improve the skill of predictions for months to seasons ahead, offering significant benefits to many sectors of the global economy;

- Decadal climate predictability – research to assess the factors leading to the predictability of climate on decadal timescales, which are critical for investment in planning, developing and operating major national and global infrastructure;

- Monsoon prediction – building on the multiple regional studies that WCRP supports with its partners around the world. The global aim is to consolidate the knowledge of monsoon systems in order to improve prediction of their onset, breaks and overall intensity and to assess the impacts of a changing climate.

Progress on these topics is discussed in the following section 2.

Under the theme "Climate research in service to society", the WCRP OSC in October 2011 (http://conference2011.wcrp-climate.org/) reported on the tremendous progress in climate science that has been made in recent years. Based on scientific papers, presentations and discussions, the following scientific priorities emerged from the Conference:

- The need for prediction of the Earth system, bridging the physical climate system with biogeochemistry and the socio-economic and humanity sciences, in a programme such as ICSU's Future Earth: Research for Global Sustainability;

- Capitalizing on the opportunity provided by new satellite observations to make a major leap in the understanding of clouds and aerosols and their contributions to climate sensitivity;

- The need for skillful climate information on regional scales for the Global Framework for Climate Services (GFCS);

- The importance of quantifying true uncertainty in climate predictions;

- Defining the challenges and opportunities involved in predicting how the forced

Plenary session at the WCRP Open Science Conference, Denver, USA, 2011

anthropogenic component of climate change will modify the natural modes of climate variability over the coming decades;

- The increasing importance of establishing the predictability of polar climate, with the possible opening-up of the Arctic and the importance of international policy for commercial shipping and the extraction of natural resources;

The powerful combination of observations and models is key to our ability to provide science-based climate information for decision-makers.

- The need to better understand the causes of extreme events and to conduct attribution studies in near-real-time;

- Tackling the challenges to providing improved predictions of future regional sea-level change;

- The need to train and empower the next generation of climate scientists.

1.2 WCRP Core Projects

Understanding and predicting climate variability and change require comprehensive investigation of all major components of the Earth/climate system (atmosphere, oceans, land and cryosphere) and their interactions. WCRP supports these studies through the activities of its four Core Projects:

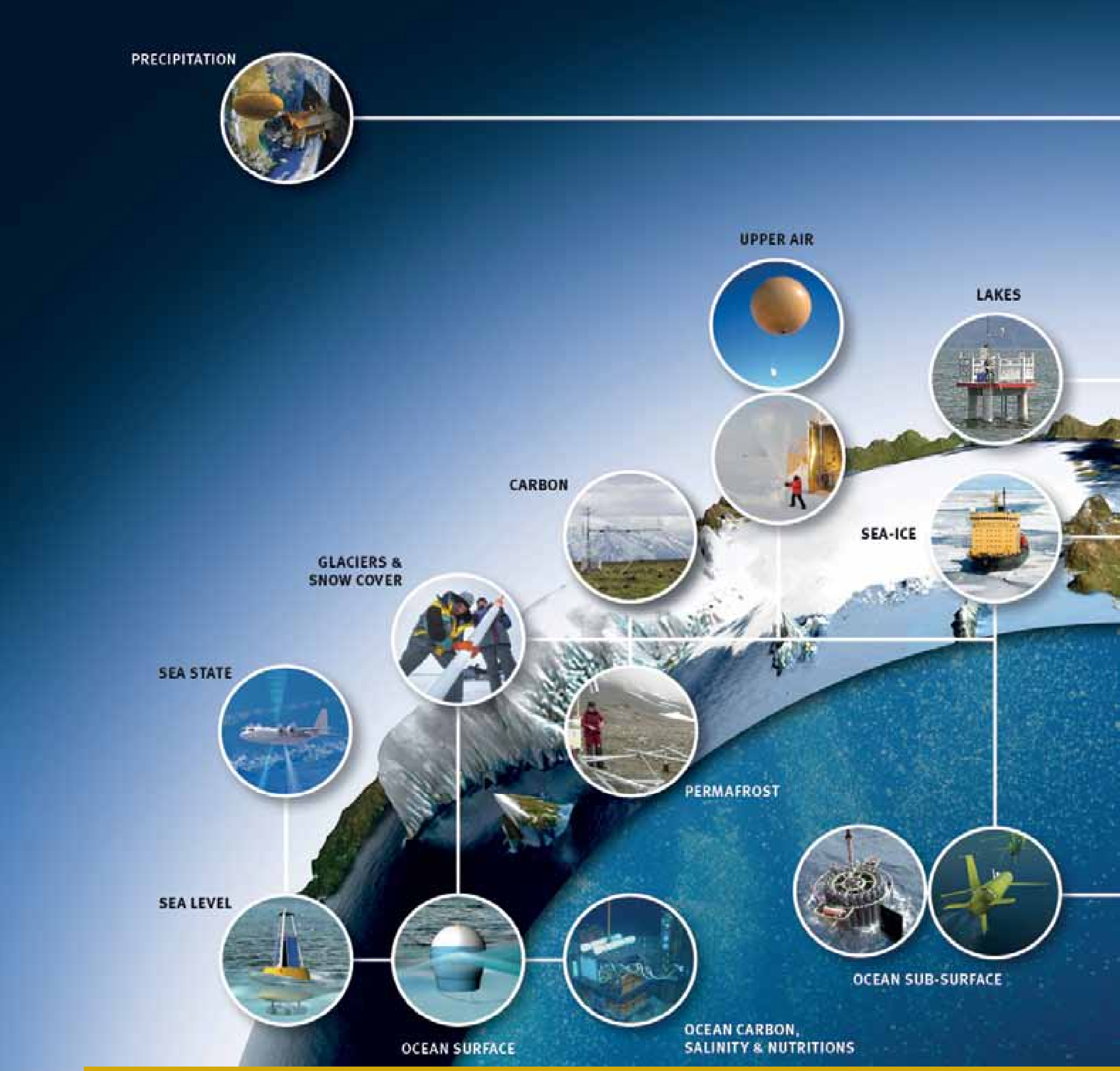
- Climate and Cryosphere (CliC);
- Climate Variability and Predictability (CLIVAR);
- Global Energy and Water Cycle Experiment (GEWEX);
- Stratospheric Processes and their Role in Climate (SPARC).

The international offices of these Core Projects are located in Tromsø (Norway), Southampton (United Kingdom), Silver Spring (USA) and Zurich (Switzerland), respectively. In turn, these project offices have a network of supporting activities/offices in Africa, Asia, South and North America and Europe. They work closely with the Joint Planning Staff (JPS) for WCRP based in Geneva (Switzerland). The work of the Projects is organized through various initiatives and experiments and their respective scientific advisory committees and workshops.

Some examples of past Core Projects and their accomplishments include the Tropical Ocean Global Atmosphere project, which developed the foundations for prediction of El Niño as a foundation for seasonal climate prediction; the World Ocean Circulation Experiment, which provided the first consistent picture of the global ocean circulation; and the Arctic Climate System Study, which demonstrated the potential for intensified climate warming in northern high latitudes.

1.3 Unifying themes in climate research: observations and models

Observations are the foundation for understanding the past and present state of Earth's climate system. Numerical models are fundamental tools for predicting and projecting future climate conditions. The powerful combination of observations and models is key to our ability to provide science-based climate information for decision-makers. WCRP depends on sister programmes such as the Global Climate Observing System (GCOS) and its affiliate networks to obtain, preserve and develop the Earth observing networks. WCRP co-sponsors with GCOS a wide range of projects and activities aiming to achieve these objectives.



Climate observations (courtesy of GCOS)

WCRP observation activities are coordinated by the recently established WCRP Data Advisory Council (WDAC). In addition to promoting the effective use of observations with models and addressing issues related to the coordinated development of data assimilation, reanalysis, Observing System Sensitivity Experiments, and paleoclimate data, WDAC will ensure cooperation with GCOS and other observing programmes on matters such as evaluating and maintaining the Essential Climate Variables (ECVs).

Climate models vary from detailed and complex representation of global and

regional climate or Earth system processes to more idealized climate conditions. They are used in a wide range of research and applications, including process studies, data assimilation and analysis, attribution, historical and paleoclimate simulation, seasonal-to-interannual climate prediction, future climate projections and regional climate simulations. Most climate services and related information used for policy decisions and practical applications are based largely on the output of such models.

WCRP modelling activities are coordinated by the recently established WCRP Modelling

Advisory Council (WMAC). WMAC ensures cooperation with the main WCRP partners and coordination among the WCRP modelling and prediction groups:

- The Working Group on Coupled Modelling (WGCM) organizes coordinated climate model intercomparisons to address compelling science questions for the community; these simulations are also made available for the assessment process of the IPCC;

- The Working Group on Seasonal-to-Interannual Prediction (WGSIP) is developing a programme of numerical experimentation for seasonal-to-interannual variability and predictability, paying special attention to assessing and improving predictions. WGSIP collaborates with WGCM in studies of decadal climate prediction;

- The Working Group on Numerical Experimentation (WGNE), co-sponsored with the WMO Commission for Atmospheric Sciences, focuses largely on the improvement of atmospheric models and cooperates with WGCM and WGSIP on process studies and shared interest in improving atmospheric models.

WCRP plays a major role in supporting the development of new climate information systems to assist in assessing vulnerability, devising coping strategies, determining possible impacts and planning for future changes. A current suite of climate observations and models is resulting in a significant amount of data and information. Research on, and development of, Earth observing systems, models and field experiments comprise an intrinsic part of WCRP activities and contribute to the continuation and expansion of global environmental monitoring.

WCRP Projects also identify and facilitate the gathering, processing and distribution of observations (e.g. of clouds, radiation and precipitation) that are required for understanding key climate processes. These observations may ultimately form the basis for long-term climate records.

1.4 Developing a future network of climate scientists

To accomplish its mission, WCRP engages the international Earth/climate system science community and forges strategic partnerships at national and international levels to ensure a vibrant workforce which will guide the Programme and support its goal and objectives.

WCRP is currently undertaking a wide range of education, training and capacity-development activities and is planning to strengthen these efforts further.

We recognize that WCRP's long-term success depends on the continued engagement of the international science community, especially in developing nations and regions, through strategic partnerships with WCRP sponsors (ICSU, IOC and WMO) and sister organizations such as the Global Change System for Analysis, Research and Training (START), the Asia-Pacific Network for Global Change Research (APN), the International American Institute (IAI) and others.

WCRP is currently undertaking a wide range of education, training and capacity-development activities and plans to strengthen these efforts further by focusing on:

- Facilitating and coordinating climate research, modelling, analysis and prediction to provide the required science-based climate information to decision-makers;

- Assisting the research community and institutions of higher learning in education, training and development of next-generation climate scientists;

- Providing greater opportunities for early-career scientists, especially those from developing regions, to become more active in global, regional and national climate research and applications;

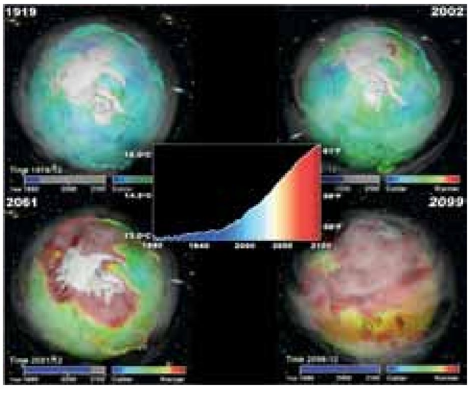
- Empowering the young generation of climate scientists to be more active and gain experience in the analysis and interpretation of climate information to serve the needs of decision-makers and experts who are pursuing climate-adaptation and risk-management planning; and

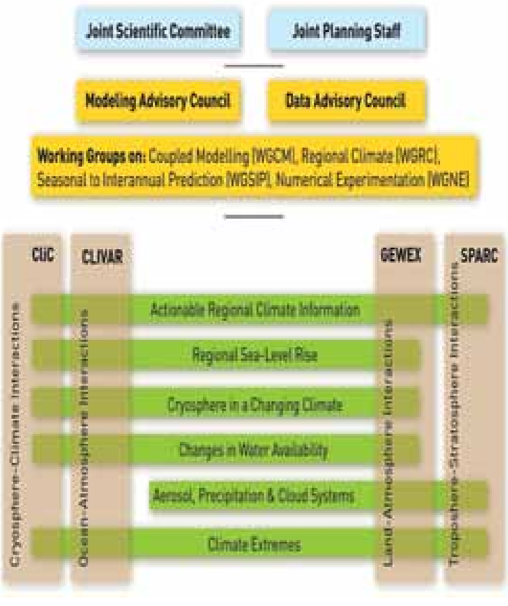
- Establishing an effective dialogue with decision-makers, politicians and those responsible for socio-economic development by finding a common language for sharing the latest knowledge-based information.

	Africa	Americas	Asia	Europe	Oceania
ECS	16	67	38	52	11
Students	9	42	17	35	7
Total	**25**	**109**	**55**	**87**	**18**

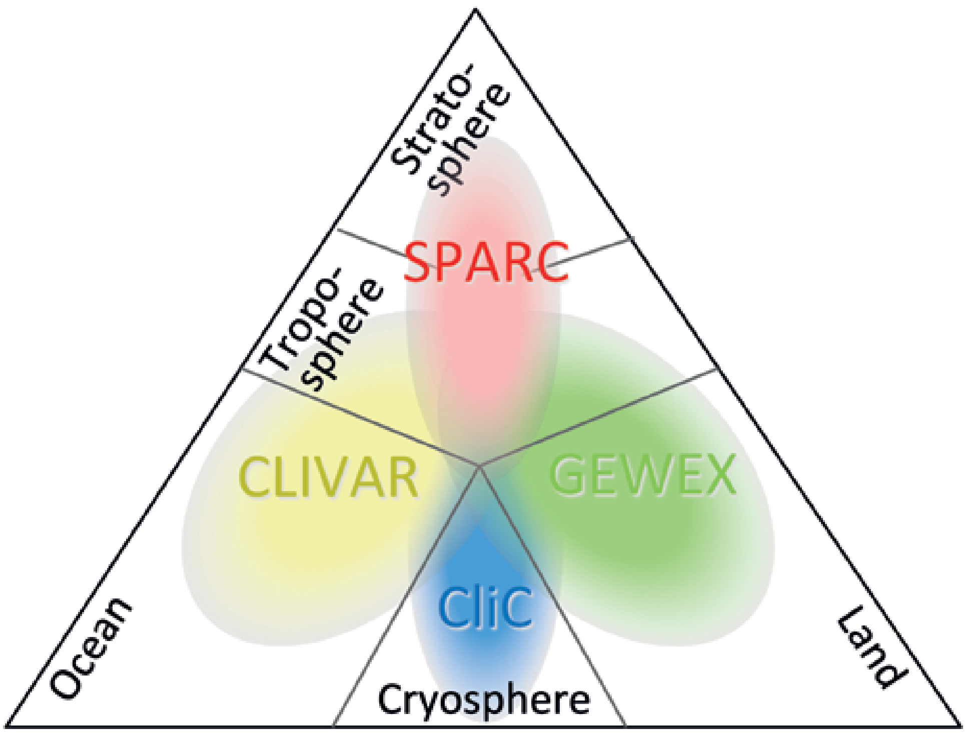
WCRP support for students and early-career scientists (ECS) in 2011-2012

Four maps of the northern hemisphere demonstrate the temperature trend, with average surface temperature for: top left, 1919; top right, 2002; bottom left, 2061; and bottom right, 2099; centre: the global average as a function of time. The computations were based on observed temperature (pre-2000) and a climate model assuming a continued high rate of greenhouse-gas emission (courtesy of Earth System Grid Federation).





Organization of the WCRP



Interdisciplinary research encompassing the Earth's climate system – atmosphere, cryosphere, land and ocean – and their interactions: WCRP, through its four Core Projects (CliC, CLIVAR, GEWEX and SPARC), covers the components of the climate system.

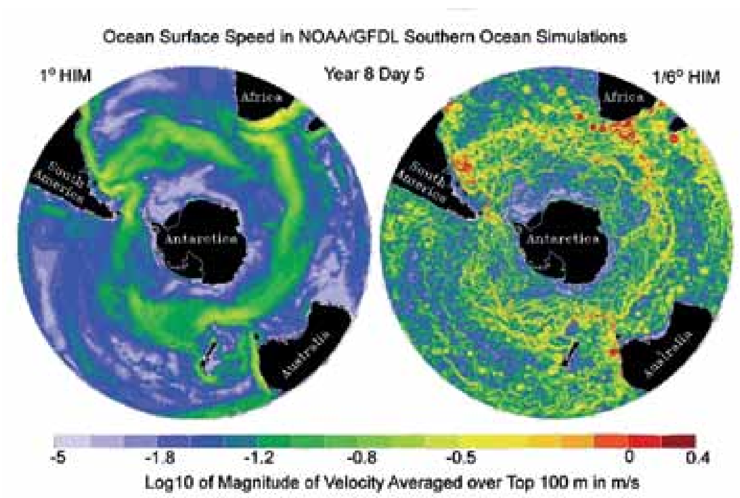
2. Major scientific initiatives and results

2.1 Improving climate projections

More than 20 modelling groups from around the world are currently participating in the WCRP Coupled Model Intercomparison Project (CMIP5) that represents the most ambitious multi-model intercomparison and analysis project ever attempted. WGCM, in consultation with the International Geosphere-Biosphere Programme (IGBP) Analysis Integration and Modelling of the Earth System (AIMES) project and a number of other elements of WCRP and the climate research community, is coordinating the experiments and analysis of results from these model simulations.

The scope of CMIP5 is much broader than that of the previous intercomparison project (CMIP3) and includes four new representative concentration pathways (RCPs) to support developing mitigation scenarios in addition to the long-term concentration-driven Atmosphere-Ocean Global Circulation Model (AOGCM) experiments and emission-driven Earth System Model (ESM) experiments - some of those with partial coupling to explore sensitivity of the carbon-cycle feedback. Many experiments In CMIP5 explore the impact of various natural and human-induced changes on climate. The paleoclimatic experiments assess the ability of models to reproduce past climate conditions to better inform the credibility of the models' future climate projections; and some experiments investigate the role of atmospheric aerosols and chemistry-climate interactions with higher resolution AOGCMs (about 50 km resolution) and even higher resolution (about 25 km) atmosphere-only models.

From a preliminary analysis of the models participating in CMIP5, it emerges that some quantities are better simulated, such as the rate of sea-ice loss in the Arctic, the Atlantic Meridional Overturning

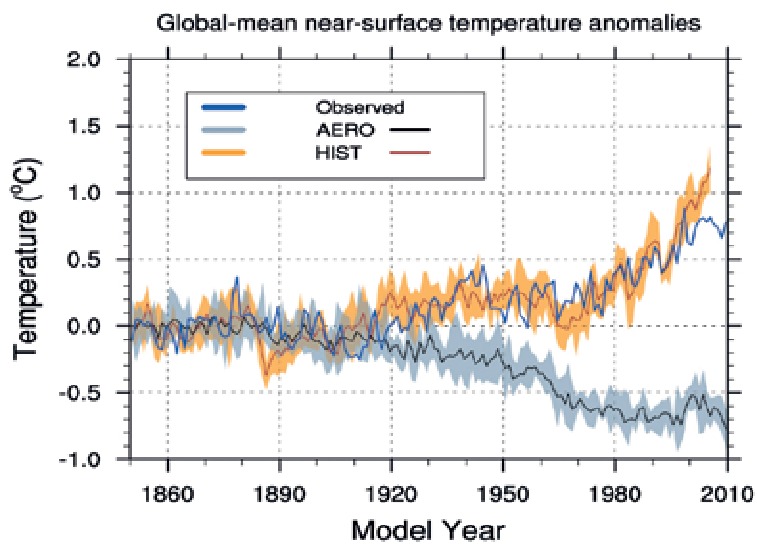


Surface ocean currents in a model of the ocean circulation in the southern hemisphere. High horizontal resolution (1/6°, right) simulates ocean eddies more realistically than low resolution (1° left).

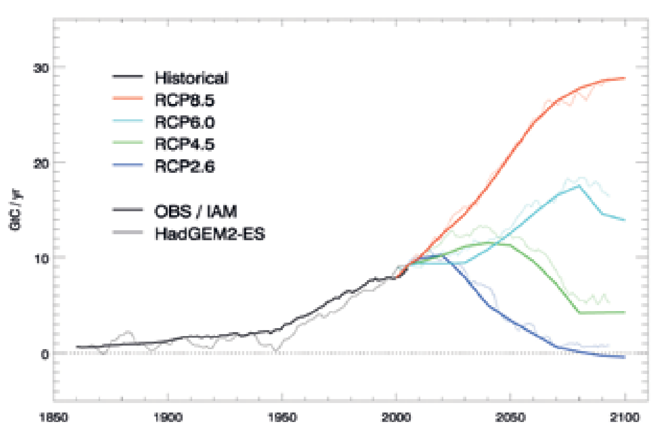
Circulation that controls both short- and long-term climate, and others. CMIP5 also provides many more capabilities and new types of climate-change information, such as carbon-cycle feedback, decadal climate predictions and cloud feedback, to name but a few.

2.2 Attribution and prediction of extreme events

Unusual or extreme weather and climate-related events are of great public concern and interest, yet there are often conflicting messages from scientists about whether



Climate response to aerosol forcings in CMIP5: global mean near-surface temperature anomalies in simulations with all natural and anthropogenic forcings (red line) and with anthropogenic aerosol forcing alone (black line), in one of the CMIP5 models. The shading represents the spread of ensemble members. The observed global mean near-surface temperature anomaly is shown with a blue line (from Boucher et al., 2011).



Carbon dioxide emissions as simulated by a CMIP5 model (HadGEM2-ES) compared with observed emissions for the historical period and those projected for the RCP scenarios (OBS/IAMs) (from Friedlingstein and Jones, 2011)

such events can be linked to climate change. This was one of the themes discussed at the WCRP OSC, where the development of a carefully conducted analysis of observed weather- and climate-related events could serve as a powerful tool for identifying the factors contributing to the occurrence of such events.

New scientific results have shown examples of where there has been an increased risk of extreme weather attributable to human influence on climate. For example, new research has reconciled the results of previous studies by providing scientific explanations concerning the extent to which the 2010 Russian Federation heatwave could be attributed to human-induced climate change. In fact, the same event can be both mostly internally generated in terms of magnitude but also externally driven – through human influence on climate – in terms of probability of occurrence.

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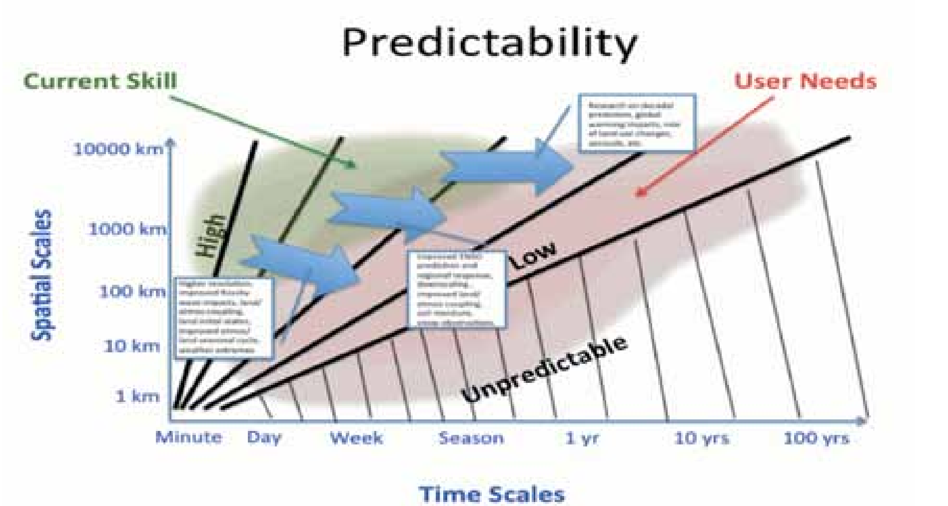
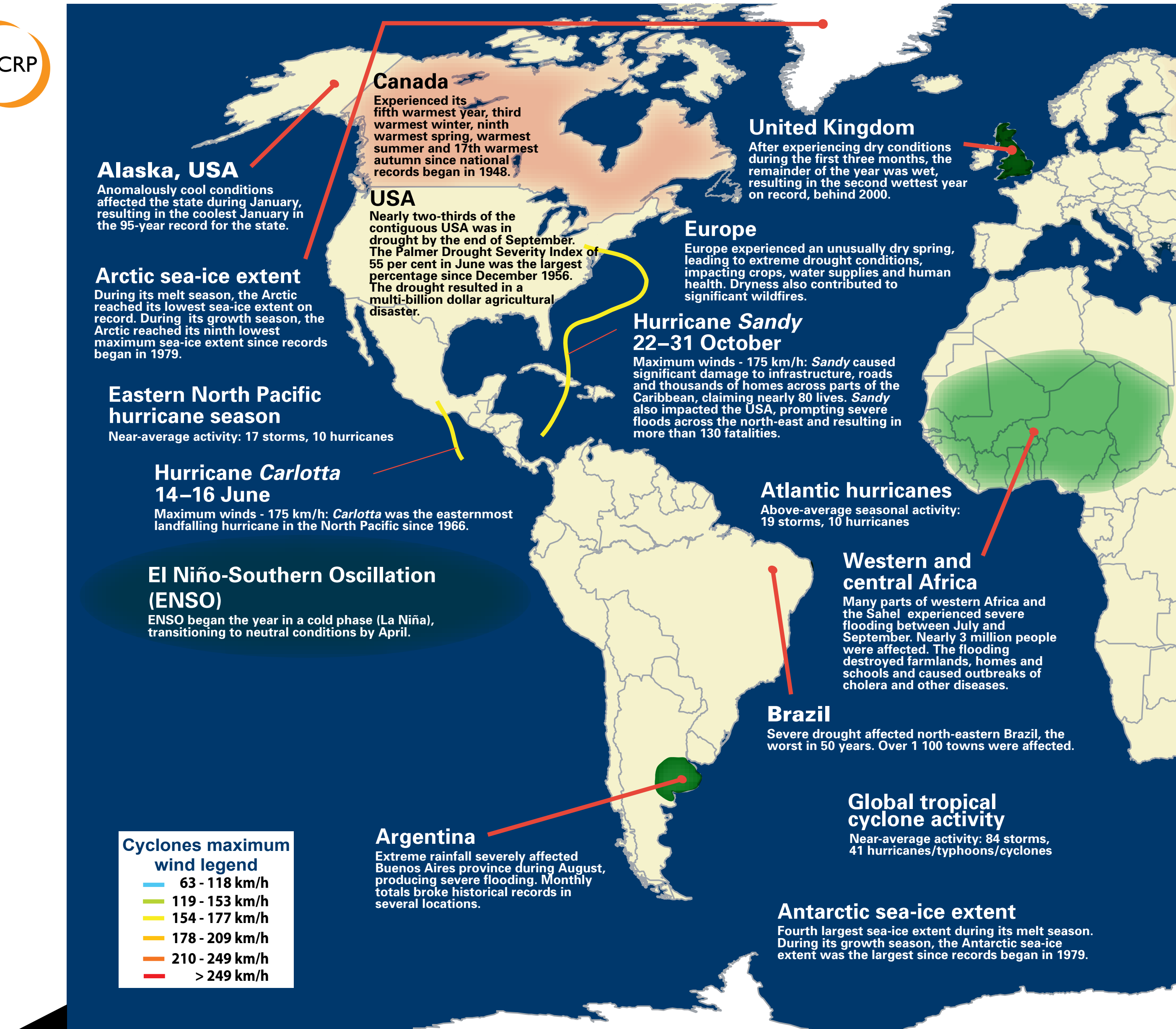
An annual report "Explaining extreme events from a climate perspective" has been published for the first time in the Bulletin of the American Meteorological Society. It contains a collection of papers that examine a number of extreme weather events that occurred in 2011. It is intended that such reports will regularly accompany the annual State of the Climate that is published annually in this journal.

In order to support the development of such assessments, the international Attribution of Climate-related Events (ACE) initiative has been launched to develop the science needed to better respond



Overview of research capabilities and information needs and some of the research directions necessary to improve drought-prediction capabilities: users' needs for drought predictions (pink), current forecast skill (green) and predictability (heavy solid lines). Note the relatively small overlap between the areas of users' needs and skillful forecasts. The hatched area indicates those combinations of space- and timescales that are deemed fundamentally unpredictable. The text indicates areas of research that could lead to improved skill on the space- and timescales indicated by the thick arrows.



Selected significant climate anomalies and events in 2012 (courtesy of NOAA's National Climatic Center)

to the demand for timely, objective and authoritative explanations of extreme events. See http://www.metoffice.gov.uk/research/climate/climate-monitoring/attribution/ace for further details.

One example is the Atlas of Extremes of the Americas, an online atlas of temperature and precipitation extremes, based on the extreme indices provided by observational gridded data and reanalysis products (http://gmao.gsfc.nasa.gov/research/subseasonal/atlas/Extremes.html). This activity is supported by the CLIVAR project and not only helps to improve our understanding of past changes in climate extremes but also provides basic datasets for climate model validation and detection and attribution studies.

Another example is the work of an ad hoc group that completed an overview report

"Drought predictability and prediction in a changing climate: assessing current predictive knowledge and capabilities, user requirements and research priorities" (http://www.clivar.org/organization/extremes/resources/dig). The report examines current prediction capabilities and user needs for drought-related information with the aim of identifying actionable research areas that would benefit from international coordination.

Three major action items resulted from the WCRP workshops on this topic: (a) to develop a drought catalogue; (b) to carry out coordinated analyses of high impact droughts; and (c) to develop a drought early warning system. The workshop participants established three subgroups to implement these recommendations.

These efforts, together with a worldwide survey of user drought information needs and capabilities are now part of the planning for an experimental global drought information system. This initiative is moving forward by building upon extensive worldwide investments in drought monitoring, drought-risk management, drought research and climate-prediction capabilities.

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2.3 Regional sea-level variability and change

Analysis and assessment of sea-level variability and change, especially at the regional level, is a key area of focus for WCRP. A dedicated WCRP Workshop hosted by UNESCO-IOC in Paris in 2010 reviewed the state-of-the-knowledge in sea-level observations, research and modelling in great detail. The outcomes of the Workshop helped to formulate sea-level projections of the IPCC Fifth Assessment Report to be published in 2013. A monograph entitled "Understanding sea-level rise and variability" (edited by J. Church et al.), resulting from a previous WCRP-sponsored workshop, was published in 2009.

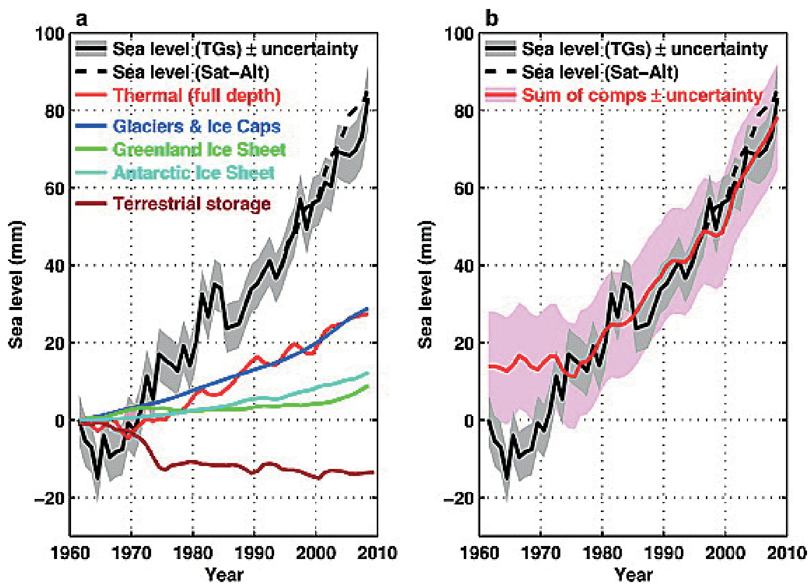
Major progress is being made in improving the observing networks and developing models capable of capturing essential processes that contribute to changes in the cryosphere, such as ice-sheet, sea-ice and glacier dynamics and changes in snow cover and extent. For example, significant efforts are being devoted to measuring and modelling all contributing factors to sea-level variability and change using a variety of techniques and technologies.

To manage the potential risks of sea-level changes and develop adaptive measures, it is imperative to know not only the global mean sea-level value but also its regional and temporal variations.

For the first time, there is a remarkable convergence among independent estimates of rate and magnitude of sea-level change, based on observational records since the 1970s. Another recent observation-based finding is enhanced net mass loss from the major ice sheets: if it continues at recent rates, the contribution of ice sheets to 21st century sea-level rise will be more than from any other contributing factor (e.g. glaciers).

To manage the potential risks of sea-level changes and develop adaptive measures, it is imperative to know not only the global mean sea-level value but also its regional and temporal variations. WCRP is supporting research on understanding the underlying physical and dynamical processes that contribute to the patterns and magnitude of sea-level variability and change on regional scales. These studies have revealed some patterns of such variability, showing clearly that, while sea level is rising on the global average, it may be rising more in some regions of the world and falling in others, owing to the specifics of ocean dynamics and other geophysical processes.

Regional sea-level rise increases the risk of coastal flooding, which also depends on local tides, storm-surges, precipitation and local hydrological conditions. Predictions of regional sea-level change on decadal to centennial timescales that WCRP is enabling will serve as the core of the future multi-factor coastal zone assessments which will inform climate-adaptation and risk-management strategies. The outcomes of



Observed sea level and the sum of its components (from Church et al., 2011): it is possible to explain quantitatively the observed sea-level rise starting in approximately 1972. The remaining discrepancy for the 1960s is attributed to shortcomings in the available data.

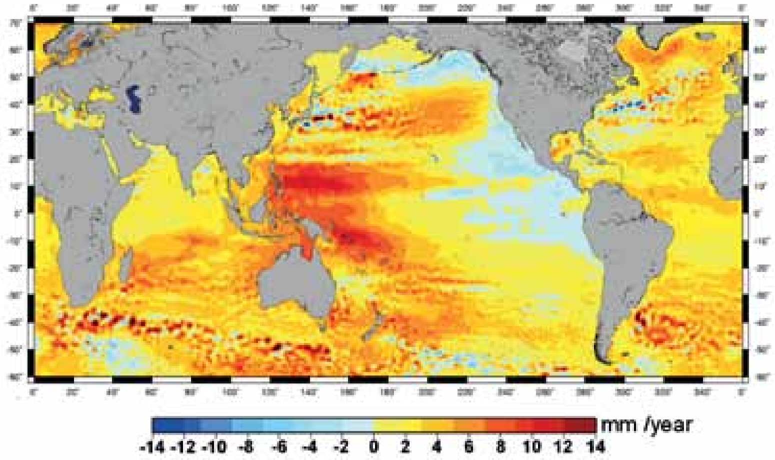
the WCRP sea-level studies will serve as valuable input to future IPCC assessments and will, in turn, help to shape WCRP-coordinated sea-level research for years to come.

2.4 Seasonal-to-interannual climate prediction

A WCRP community-wide assessment on the state of the science for seasonal climate prediction led to a consensus on some best practices for producing, using and assessing seasonal forecasts with the aim of improving seasonal prediction, as well as determining the extent to which seasonal prediction is possible. This assessment pointed to the need for a suite of performance metrics and a common language to be applied systematically for assessing prediction skill. It was agreed that the skill must be evaluated both in terms of forecast quality and forecast value, where quality refers to the technical measurement of forecast performance and value relates to the practical benefits achieved through decisions made according to forecast information, usually in conjunction with other information.

> Progress in seasonal climate prediction depends on improvements in the building blocks of seasonal prediction systems ...

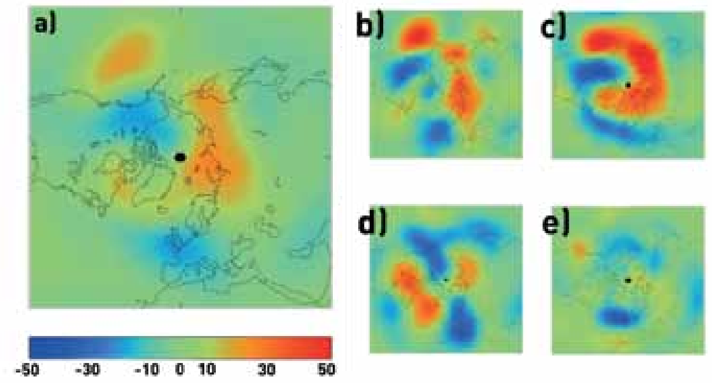
Progress in seasonal climate prediction depends on improvements in the building blocks of seasonal prediction systems: the models, observations and data-assimilation systems, as well as improved forecast verification and a more effective transfer of information to forecast users, increasing forecast value. WCRP is coordinating a multi-model, multi-institutional set of hindcast experiments – the Climate system Historical Forecast Project (CHFP) – for this purpose. CHFP aims to explore the untapped sources of



Spatial patterns of sea level from January 1993 to October 2010 (from Cazenave and Remy, 2011)

predictability on seasonal-to-interannual timescales arising from interactions and memory associated with all the elements of the climate system (atmosphere-ocean-land-ice).

These experiments provide a baseline assessment of current seasonal prediction capabilities using the best available models of the climate system and data for initialization, as well as of IPCC-class climate models in seasonal prediction mode. They provide a framework for assessing current and planned observing systems and a test bed for integrating process studies and field campaigns into model improvements with the ultimate goal of enhancing forecast skills.



Atmospheric pressure difference at 500 hPa for December-January-February (DJF) 2007/2008 when initialized with observed ice versus climatological ice from: (a) multi-model ensemble; individual model simulations from (b) United Kingdom Met Office; (c) Max Plank Institute; (d) Météo-France; and (e) Canadian Centre for Climate Modelling and Analysis. Early results from the CHFP experiment on sea ice suggest that the recent decline in sea ice is contributing to a negative Arctic Oscillation, which would be predictable in seasonal forecast systems (courtesy of Drew Peterson et al.).

2.5 Decadal climate predictability experiments

Near-term climate predictions (also known as decadal climate predictions) were included in CMIP5 in an attempt to satisfy a growing demand for climate information for several years to a few decades ahead. It is well established that, based on knowledge of the initial conditions, important aspects of regional climate are predictable up to a year ahead.

Predictability on this timescale is primarily, though not solely, associated with El Niño-Southern Oscillation (ENSO), and is currently addressed by seasonal forecasting. Skillful interannual-to-decadal climate predictions have been achieved by using changes in boundary conditions such as atmospheric composition and solar irradiance.

The type of information that can be obtained from the decadal experiments have been explored within the framework of the ENSEMBLES project, funded by the European Union, by using two types of climate forecasts: a multi-model (mostly with full initialization) and a perturbed-parameter ensemble with explicit initialization.

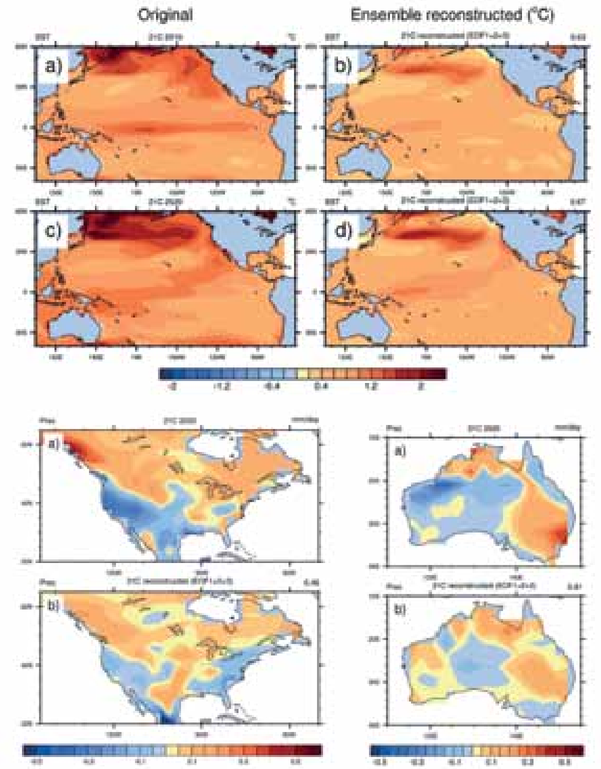
Both approaches have forecast skill over large regions – especially over the tropical oceans and North Atlantic – but also over large continental areas. Most of the prediction skill on temperature is due to external forcing, while improvements in prediction skill due to initialization appear mostly over the North Atlantic and the subtropical Pacific. Atlantic Multi-decadal Variability, associated with the Atlantic Meridional Overturning Circulation (AMOC), presents multi-year predictability which improves in both the multi-model averages and the ensemble averages from single models. For any prediction system, a critical question is to understand how far ahead the mean climate state is predictable on the regional scale with some useful level of skill.

The relative importance of the initial conditions in climate prediction is expected to decrease for longer forecast time, becoming negligible after several decades. After some 15 years, however, skill increases due to the changes in external forcing, mainly associated with increasing greenhouse gases. For example, there is predictability in the Pacific Ocean, where a major decadal-scale feature resembles a slow component of El Niño, often referred to as the Interdecadal Pacific Oscillation (IPO). IPO shows predictability up to nine years ahead in so-called "perfect" model simulations, where multiple initialized ensemble members attempt to predict the evolution in time of one of the other model ensemble members.

For any prediction system, a critical question is to understand how far ahead the mean climate state is predictable on the regional scale with some useful level of skill.

There is also growing evidence that variability in the stratosphere has a significant impact on surface climate. During boreal winter, it is likely that models with a well-resolved stratosphere will have an improved representation of blocking and cold air outbreaks over Europe, owing to the simulation of realistic stratospheric sudden warming events in the stratosphere-resolving models. In addition, stratospheric changes induced by anthropogenic climate change may contribute substantially to changes in storm tracks, sea-level pressure and precipitation.

Recent advances in the knowledge of how stratospheric representation operates in



21st century prediction of sea-surface temperature (SST) in the Pacific region and consequent impacts on North American and Australian precipitation in a perfect-model exercise to demonstrate possible predictability of those features with an initialized AOGCM. The top four panels show simulation of SST anomalies for the reference 19-year periods centred on (a) 2010 and (c) 2020). The regression patterns for the first three empirical orthogonal functions are summed to construct the predicted SST anomaly patterns for the 19-year periods centred on (b) 2010 and (d) 2020). The bottom four panels show an application of the Pacific SST perfect-model predictions to North American and Australian precipitation: (a) reference simulations; and (b) predictions (from Meehl et al., 2010).

climate models (see SPARC Chemistry-Climate Model Validation, CCMVal-2, http://www.sparc-climate.org/activities/ccm-validation/) have led to a number of climate modelling groups undertaking CMIP5 experiments with models that include a well-resolved stratosphere, the so-called "high-top models".

High-top models currently refer to coupled AOGCMs or their extension to ESMs, whose atmospheric model extends above the stratopause. Consequently, the label "low-top" is now applied to any AOGCM/ESM whose atmospheric model component does not reach the stratopause.

About 10 modelling groups are carrying out analyses of the CMIP5 simulations with high-top models and comparing these with low-top model simulations. Low-top models may provide reasonable results for the modelled mean climate but the low top reduces the modelled stratospheric variability and therefore its downward influence. Several hindcast model-based datasets are now available in the CHFP database that include the role of the stratosphere.

2.6 Atmospheric chemistry and climate connection

With focus on stratospheric ozone, the impact of climate change on atmospheric chemistry and, conversely, the impact of changes in atmospheric chemistry and composition on climate have been highlighted in the recent WMO/United Nations Environment Programme (UNEP) report Scientific Assessment of Ozone Depletion: 2010. Major contributions to this assessment derive from SPARC's activity in chemistry-climate model validation (http://www.sparc-climate.org/activities/ccm-validation/) efforts.

According to the IPCC (2007), methane, ozone and halocarbons are the greenhouse gases that directly follow carbon dioxide in terms of strongest increase in radiative forcing owing to anthropogenic activities since the industrial revolution. Changes in tropospheric composition alter stratospheric composition via changes in the input to the stratosphere and, conversely, changes in the stratosphere affect the troposphere via changes in the input of ozone from the stratosphere and also changes in ultraviolet radiation.

Aerosols are other climate-forcing agents. Effects of anthropogenic aerosols on the climate may offset part of the increased radiative forcing of greenhouse gases due to their cooling effect. Aerosols can perturb atmospheric radiation through a direct effect of scattering and absorption of radiation. The effects of aerosols depend critically on their chemical composition and mixing state.

Aerosols can also have an indirect effect via interaction with clouds (water, ice and cirrus clouds) by acting as cloud condensation nuclei (CCN). Further, clouds can modify aerosols, their optical properties, their size distributions and their ability to act as CCN. The indirect effect, which is a strong function of chemical and physical properties of aerosols, can perturb clouds and the hydrological cycle, two pivotal components of the climate system. Stratospheric aerosols greatly alter the chemistry in that region and lead to such spectacular changes as the Antarctic ozone hole, with major consequences for global climate.

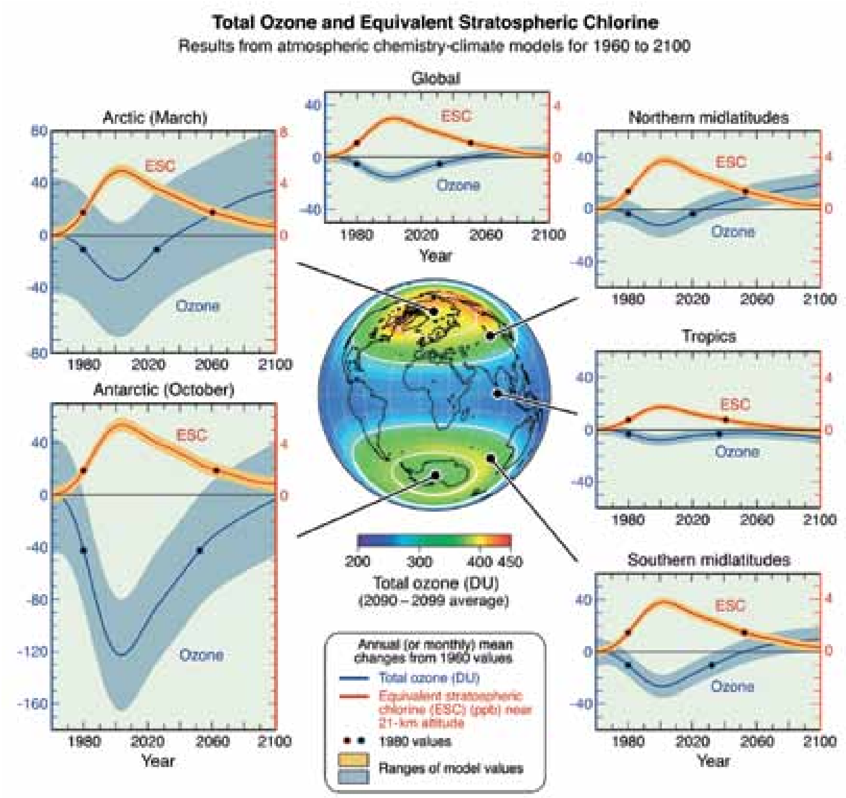
A clear understanding of the processes that connect emissions (sources, precursors) to abundances and the processes that connect the abundances to climate forcings is essential for an accurate prediction of future climate and an assessment of the sensitivity of the climate system and its variations as a result of these processes.

A clear understanding of the processes that connect emissions (sources, precursors) to abundances and the processes that connect the abundances to climate forcings is essential for an accurate prediction of future climate ...

2.7 Monsoon research and prediction

Monsoon rainfall is the life-blood of more than half the world's population, for whom agriculture is the main source of subsistence. WCRP coordinates research worldwide to enhance understanding of monsoonal systems, improve accuracy of their prediction and decipher how climate change may affect them.

The WCRP goal of producing more reliable models and quantifying the uncertainty in their climate-change projections is enabled by international field experiments. For example, observational campaigns, such as the WCRP-sponsored Asian Monsoon Years (AMY, 2007-2012) and the GEWEX/Coordinated Energy and Water Cycle Observations project have archived both in situ and satellite observations



Past and future changes in ozone and ozone-depleting substances (ODSs) are based on chemistry-climate model (CCM) simulations, which allow a consistent, fully coupled treatment of chemistry and climate. Regional and global projections of ozone and ODSs are shown for the period 1960–2010, referenced to 1960 values. Total ozone decreased after 1960 as stratospheric chlorine and bromine concentrations, expressed in equivalent stratospheric chlorine (ESC), steadily increased. ESC values have peaked and are now in a slow decline, reflecting the successful implementation of the Montreal Protocol (1987) and its subsequent amendments. Correspondingly, all the projections show maximum total ozone depletion around year 2000, shortly after which the highest abundances of ESC had been encountered. Thereafter, total ozone increases as ESC slowly declines, except in the tropics. (DU = Dobson units)

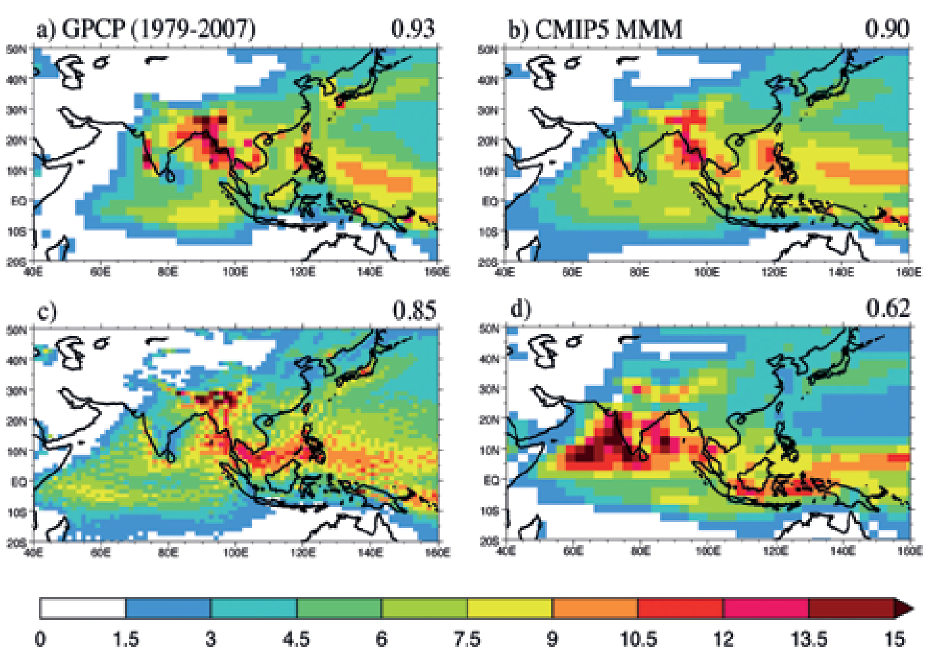
that are used to improve model physics and understand interactions that affect monsoon variability.

Additionally, new observational and modelling campaigns, such as Dynamics of the Madden-Julian Oscillation (DYNAMO) and Year of Tropical Convection (YOTC), seek to improve our understanding and representation of tropical convection in the models, including monsoon active-break cycles, to improve medium-range (10-30 days) and seasonal (~90 days) predictions of monsoons. Other approaches have included observational, numerical and process studies, prediction and predictability experiments, coordinated model evaluation and interaction with the Forum on Regional Climate Monitoring, Assessment and Prediction for Asia. Furthermore, efforts are underway to improve the modelling of aerosols, especially those associated with the Asian Brown Cloud: these are important for simulating the monsoons because they have a significant impact on the radiative heating of the atmosphere and can thus affect the strength of the hydrological cycle.

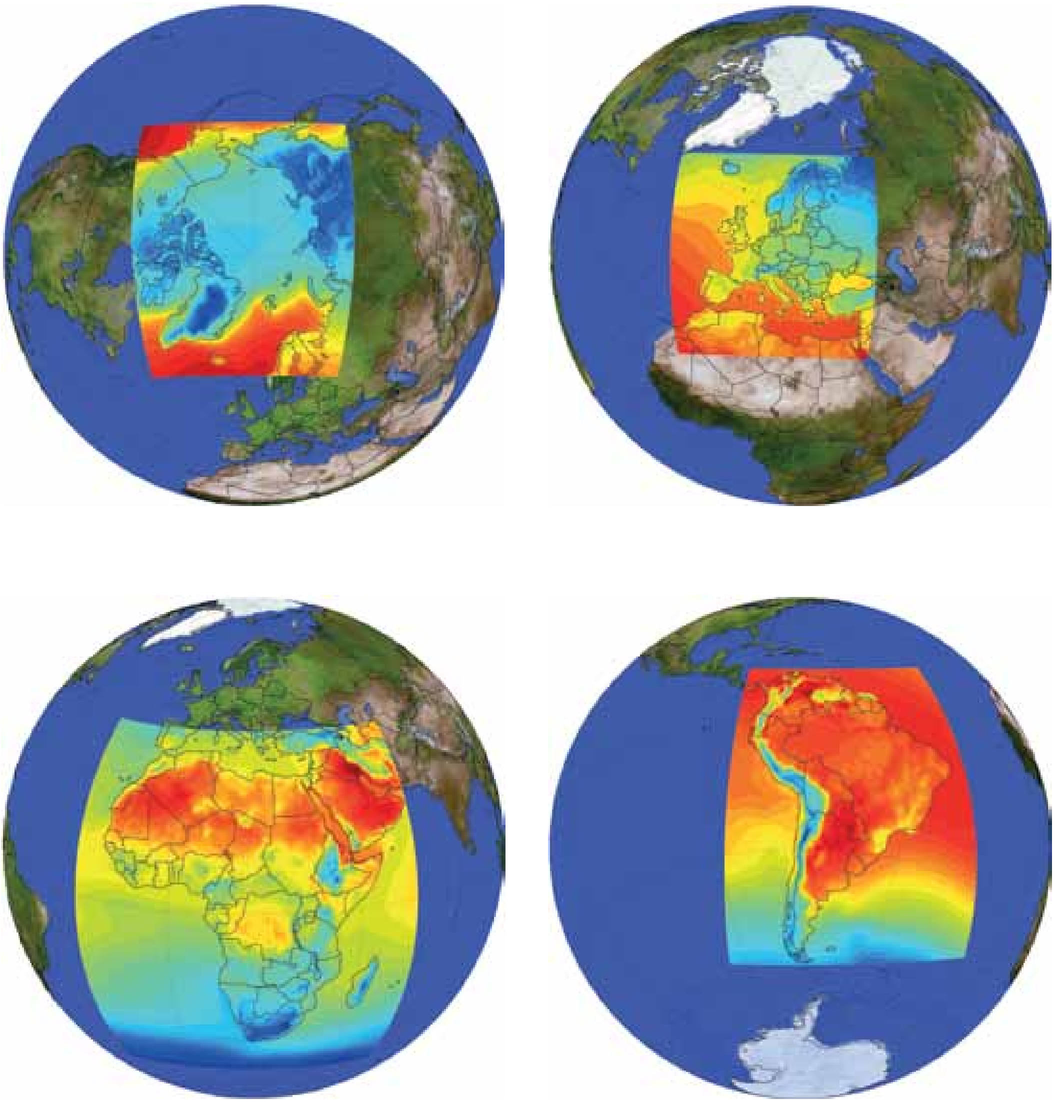
Through the synthesis of modelling and observations, the scientific community is poised to make substantial advances in understanding and ultimately predicting monsoons to manage and mitigate their adverse impacts on life, property, agriculture and water resources in a timely and effective manner.

WCRP coordinates research worldwide to enhance understanding of monsoonal systems, improve accuracy of their prediction and decipher how climate change may affect them.

CLIVAR, for example, sponsored a hindcast experiment to investigate boreal summer monsoons and their intraseasonal variability. Interannual variability of the mean monsoon rainfall is relatively low (~10% of the mean) but seasonal variations of the monsoon have a profound impact on agriculture and freshwater availability in some regions of the world. Monsoon failure (or extreme drought) is often a result of extended intraseasonal monsoon breaks. Monsoon intraseasonal variability is not currently well-simulated or predicted in climate models, especially those used in seasonal climate prediction. Skill assessment of predicting both boreal summer and austral summer intraseasonal monsoon variability is currently underway.



June-September precipitation (mm/day) climatology: (a) observed and (b) simulated from the CMIP5 multi-model mean (MMM); and (c) and (d) two models that show the range of performance. The CMIP5 MMM outperforms all the individual models (courtesy of K. Sperber).



Regional climate information for decision-makers: climate models applied over a limited area can provide information on much smaller scales, supporting regional impact and adaptation assessment and planning, which is vital in many vulnerable areas of the world (courtesy of SMHI).

3. Regional climate studies

The provision of climate information on regional to local scales is an important requirement to support decision-making in response to potential climate change. Such information is needed to assess the impacts of climate variability and change on human and natural systems, enabling the development of suitable adaptation and risk-management strategies at the regional to local level.

3.1 Coordinated Regional Downscaling Experiment

Despite recent advances in the horizontal resolution of most global climate models, there are still limitations in their ability to represent important local forcing features, such as complex topography, land-surface heterogeneity, coastlines and regional water bodies, all of which can modulate the large-scale climate on regional to local scales. Coarse spatial resolution of current models also precludes an accurate description of extreme weather events, which are of fundamental importance in assessing the socio-economic impacts of climate variability and change.

In order to coordinate international regional climate modelling, WCRP established in 2008 the Task Force on Regional Climate Downscaling that began to develop a framework for the Coordinated Regional Climate Downscaling Experiment (CORDEX).

The goal of CORDEX is to foster an international coordinated effort to produce improved regional multi-model, high-resolution climate-change information with documented uncertainties.

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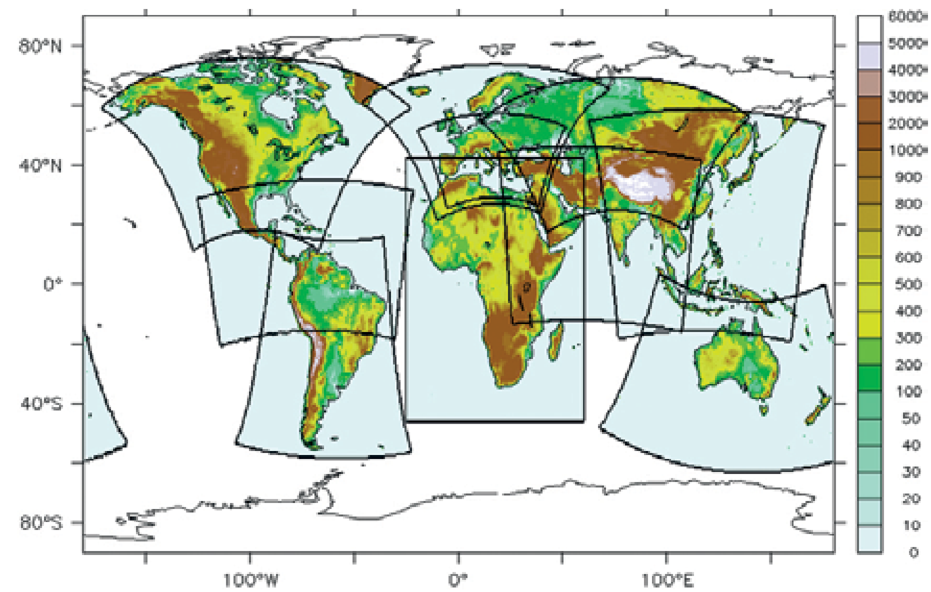
The framework is facilitating the evaluation and, where possible, the improvement of regional climate downscaling techniques for use in many regions worldwide, and to support the vulnerability, impact and adaptation analyses and assessments.

Many CORDEX regions are already self-organizing and are developing matrices of regional climate change projections. In a number of regions, however, one example being Africa, access to reliable regional climate-change information is limited. It is in these regions that the greatest benefits from the collaboration developed through CORDEX are anticipated. The international community therefore decided to target Africa for intensive collaboration and the effort is already producing a significant amount of information on African climate, both to support the IPCC Fifth Assessment Report (IPCC AR5) and to provide useful climate information to decision-makers involved in African climate risk management and adaptation planning.

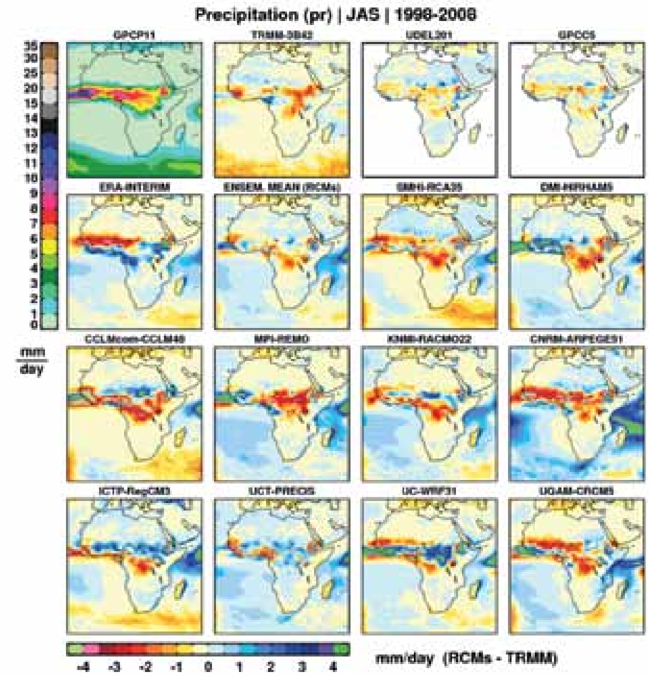
3.2 Hydroclimate projects

African Monsoon Multidisciplinary Analyses (AMMA)

Since its launch in February 2002 in Niamey (Niger), AMMA has focused on improving knowledge and understanding of the West African Monsoon (WAM) system and its variability on daily-to-decadal timescales.



Schematic of the CORDEX regional climate model (RCM) domains (courtesy of C. Jones, Swedish Meteorological and Hydrological Institute (SMHI))



CORDEX multi-model data available for Africa (from top to bottom and left to right): observed mean July-August-September (JAS) precipitation for 1998-2008 and differences compared with observations and the individual RCMs with their ensemble average (from C. Jones et al., 2011)

AMMA is motivated by the societal need for improved prediction of WAM and its impacts on West African nations. In the past decade, AMMA has made substantial progress through strong international cooperation among African, European and US scientists (see AMMA 2nd International Science Plan, http://www.amma-international.org).

WAM has two main modes of variability on the intraseasonal timescale: one of some 15 days and another of some 40 days. These modes can strongly influence precipitation on the regional scale. Their initiation and propagation are partly controlled by atmospheric dynamics, including teleconnections from the Indian monsoon and the Mediterranean region. AMMA has begun monitoring these modes through the active engagement of many African National Meteorological Services. Monitoring of the surface conditions may also contribute in the future to improved intraseasonal prediction.

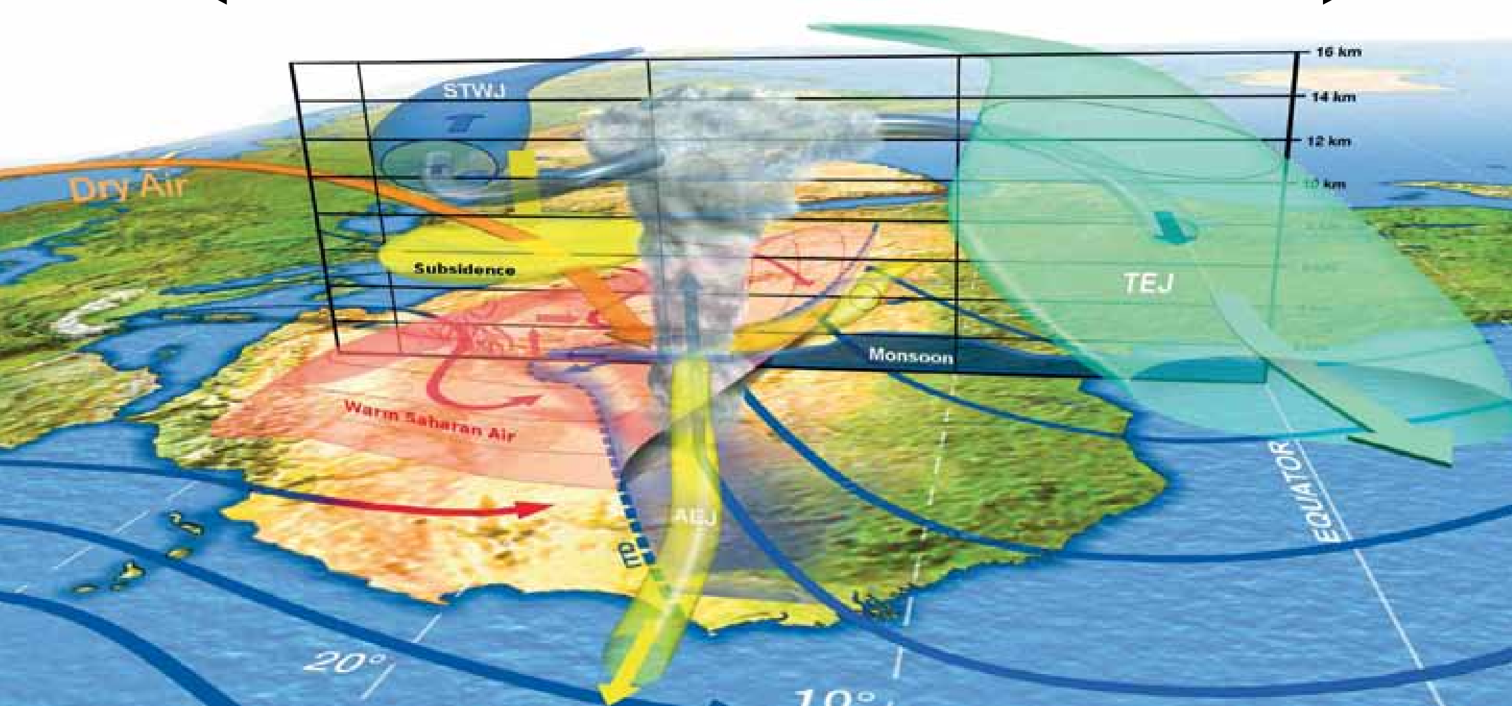
Scientists in the (LPB) region, and in cooperation with international partners, have developed a project to improve skill in predictions of the Basin's hydroclimate that could contribute to improved decision-making in sectors such as water-resource management, agriculture and food production.

The annual cycle of WAM remains a scientific challenge to understand and ultimately predict reliably. AMMA researchers highlighted a rapid poleward shift in peak rainfall between the coastal region and the Sahel at the time of the monsoon onset. The main factor for this shift might be the seasonally varying surface conditions over the ocean and over land. AMMA continues to emphasize and implement observations in the equatorial Atlantic and over the African continent to support research into all aspects of the monsoon system, including its onset.

La Plata Basin (LPB) Project

The La Plata Basin is a significant source of natural capital for the growing populations

Schematic diagram depicting the West African Monsoon System (from Janicot et al., 2011)



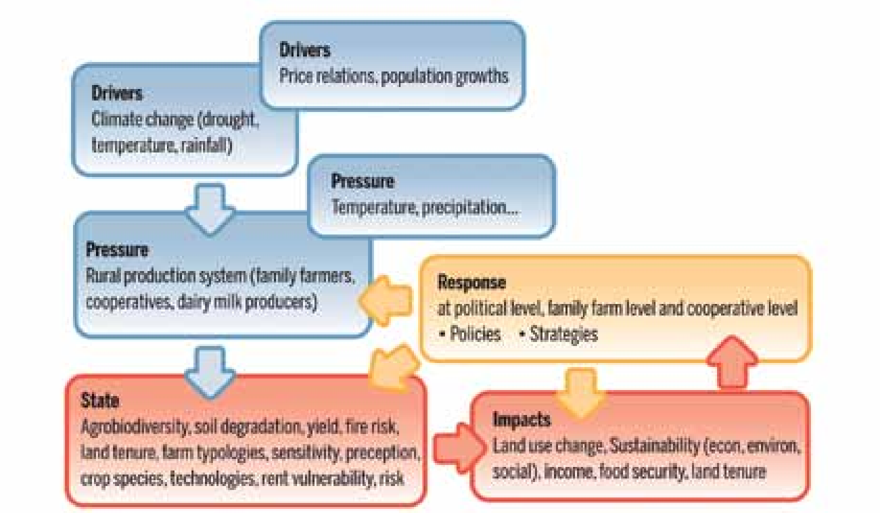
of Argentina, Bolivia (Plurinational State of), Brazil, Paraguay and Uruguay and contributes 70% of the total Gross Domestic Product of these countries. LPB is critical to local economies as an agricultural centre, as a natural waterway for transportation and as a primary producer of hydroelectric energy. Scientists in the region, and in cooperation with international partners, have developed a project to improve skill in predictions of the Basin's hydroclimate that could contribute to improved decision-making in sectors such as water-resource management, agriculture and food production.

Special focus is on developing early warnings of extreme events such as droughts and floods. There is also a need to address the significant environmental degradation that the Basin has experienced in the last decades as a result of land-use alteration, climate change and socio-economic development.

The La Plata Basin Project (http://www.eol.ucar.edu/projects/lpb/) provides a framework for integrating regional studies focused on these topics, leading to improved predictions and assessment of the climate and hydrology system on socio-economic development for the entire basin. The initial phase of LBP involved the production of an ensemble of possible future conditions from which a decision-making process could be derived to support the design of adaptation measures and risk-management strategies. Collaboration with stakeholders is key to understanding the vulnerability of the system of interest, assessing climate-change impacts and suggesting the paths that could be taken in order to reduce the Basin's vulnerability and initiate adaptive measures.

Mediterranean Climate Variability and Predictability (MedCLIVAR)

MedCLIVAR (www.medclivar.eu), launched in 2003, has developed a multidisciplinary approach to studying the evolution of Mediterranean climate, which includes atmospheric, marine and terrestrial components on multiple timescales, ranging from paleoclimatic to future centennial timescales. The scientific



Conceptual framework called Driver, Pressure, State, Impact, Response structure for agriculture studies in the La Plata Basin

themes of the project include past climate variability, connections between the Mediterranean and global climate, the Mediterranean Sea circulation and sea-level changes, feedbacks on the global climate system and the regional responses to greenhouse gases, air pollution and aerosol forcings.

The Mediterranean region is particularly sensitive to variability and changes in the large-scale climate dynamics as it is located in a transitional zone between subtropical temperate and continental climate. Climate change impacts are expected to be particularly strong in terms of mean precipitation reduction, larger-than-global average temperature increase, increased interannual variability of precipitation and temperature, episodic occurrence of temperature extremes, intensity of hydrological cycle extremes (droughts and heavy rainfall events) and increased sea salinity and temperature. The stress arising from these factors, combined with an already stressed system poses many challenges such as uneven distribution of precipitation: scarce and irregular precipitation in many southern areas is further widening the gap between water availability and water demand.

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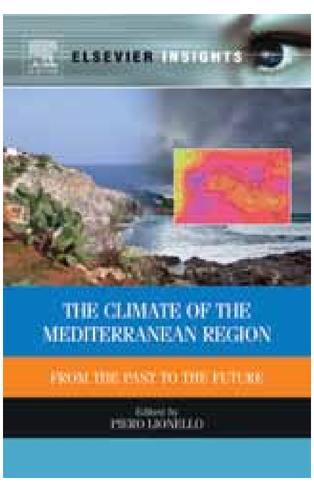


This environmental diversity, together with significant socio-economic pressures that exist between the northern and southern/eastern Mediterranean countries (in the latter, population, urbanization and therefore energy demand are rapidly increasing), will result in the greater vulnerability of the entire region to over-exploitation of water, land and ocean resources in the future. The Mediterranean region must also pay attention to rapidly growing cities and coastal systems that will be affected by sea-level changes.

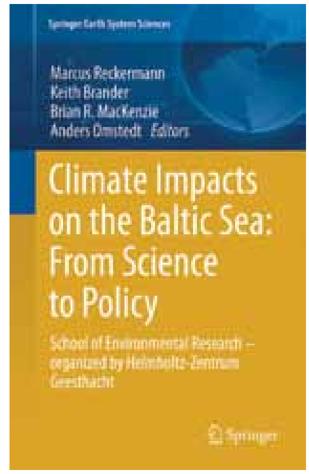
MedCLIVAR organizes scientific and technical workshops, summer schools and co-sponsored scientific meetings at annual conferences, such as the European Geophysical Union, to facilitate greater scientific cooperation among scientists in the region. With the European Science Foundation as main sponsor, MedCLIVAR awarded more than 30 grants to young scientists for training in research and education organizations. MedCLIVAR disseminates the scientific findings and assessments in the form of books and articles in journals and the media. A systematic archive of observations and model data simulations on the Mediterranean climate is presently being established at the World Data Centre for Climate (http://cera-www.dkrz.de/CERA/MedCLIVAR.html) with the aim of sharing all available data for this region among engaged scientists.

Hydrological Cycle in the Mediterranean Experiment (HyMeX)

HyMeX (http://www.hymex.org/) is undertaking process studies and regional climate investigations in coordination with the Mediterranean CORDEX (MED-CORDEX) project. A major focus is the analysis of uncertainties for both dynamical and statistical downscaling techniques by comparing model simulations with observations from the HyMeX sites in France, Israel, Italy and GEWEX high-elevation locations.

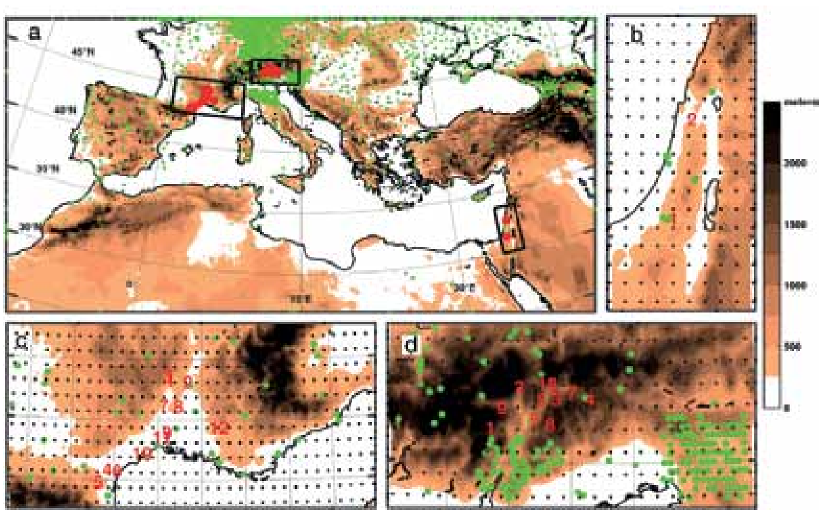
Northern Eurasia Earth Science Partnership Initiative (NEESPI)

NEESPI (http://neespi.org/) is a large-scale, interdisciplinary programme of research, aimed at developing a better understanding of the interactions of the ecosystem, atmosphere and human dynamics in northern Eurasia and how they relate to global climate change.

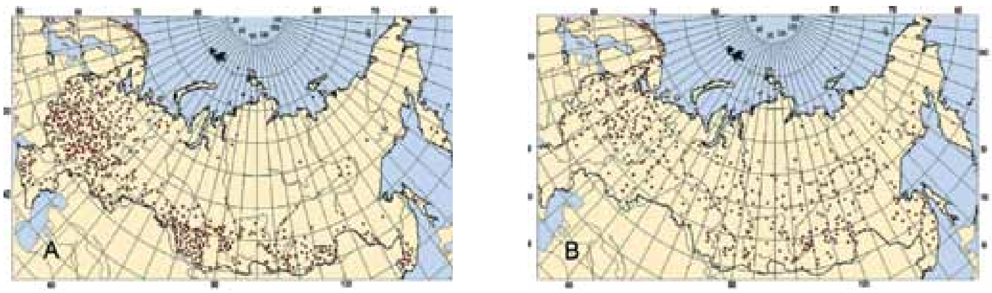


The Baltic Sea Experiment (BALTEX)

BALTEX (http://www.baltex-research.eu/) is an environmental research network to facilitate integrated studies of the Baltic Sea drainage basin. Although the



HyMeX stations (red numbers) used for assessments of uncertainties based on the European Climate Assessment dataset (grid in black dots) and observations from selected sites (green dots). Mediterranean domain used for CORDEX climate simulations (a). Enlarged areas show stations in Israel (b), France (c) and Italy (d) (from P. Drobinski et al., 2011).



NEESPI programme: location of 958 meteorological stations with long-term snow-survey information during the past five decades for surveys in: (A) field (open terrain) (665 stations); and (B) forested (425 stations) environments

initial focus was on the hydrological cycle and the exchange of energy between the atmosphere, the Baltic Sea and the surface of the catchment area, BALTEX now includes study of nutrient fluxes, the carbon cycle and the effects of climate change on the entire system.

Murray Darling Basin (MDB) Study

The Murray Darling Basin study (http://www.mdb-rhp.org.au/) is designed to deliver new scientific and technical insight to enable real-time and interactive analysis of water information and advanced methods for forecasting water availability and floods across Australia. The study focuses on many aspects, including data interoperability, hydrological modelling, water accounting and water-resources assessment.

The contributions from these regional studies and their associated network of scientists have been a major source of scientific understanding that underpin our current understanding of global climate variability and change and its regional manifestations. This knowledge, together with data and information obtained over the past several decades, will be invaluable for assessing the adequacy of downscaled climate information for decision-makers through efforts such as CORDEX in the next decade.

The recently established Working Group on Regional Climate is intended to assist WCRP in bridging the gap between the development of science-based climate information and its use for decision-making in the coming decade, especially through the GFCS.

Observations of planet Earth and especially all climate system components and forcings are increasingly needed for planning and informed decision-making related to climate services (courtesty of the Committee on Earth Observation Satellites (CEOS) and the European Space Agency (ESA)).

4. Analysis of climate system observations

4.1 Reanalysis

Observations are vital for monitoring, understanding and validating weather, air-quality and climate predictions. Retrospective analysis – or reanalysis – of observations is a scientific method for developing a comprehensive record of how weather and climate are changing over time. Observations and a numerical model that simulates one or more aspects of the Earth system are combined objectively to generate a synthesized estimate of the state of the system. A reanalysis typically extends over several decades or longer and covers the entire globe from the Earth's surface to well above the stratosphere.

Reanalysis products are used extensively in climate research and services, including for monitoring and comparing current climate conditions with those of the past, identifying the causes of climate variations and change and developing climate predictions. Information derived from reanalysis is also being used increasingly in commercial and business applications in sectors such as energy, agriculture, water resources and insurance.

Reanalyses have become an integral part of Earth system science research across many disciplines (http://reanalyses.org). While originating in the atmospheric sciences and numerical weather prediction (NWP), the essential methodology has been adopted in the fields of oceanography and terrestrial ecosystems and hydrology, with emerging research in atmospheric composition, the cryosphere and carbon-cycle disciplines. Major challenges lie ahead as the disparate nature of each becomes joined in Earth system analyses.

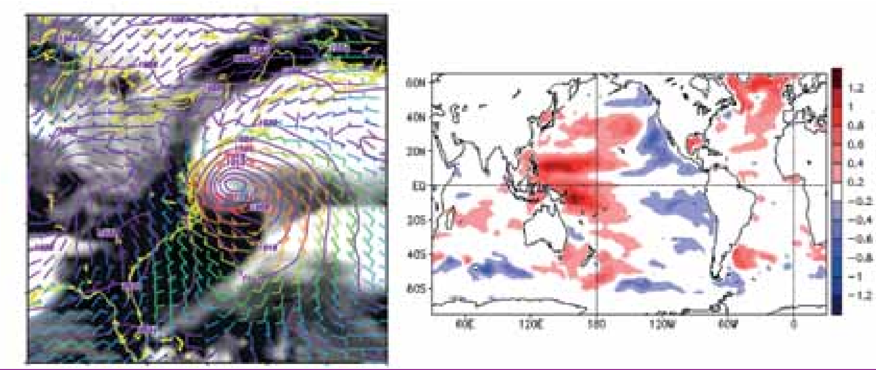
WCRP has facilitated coordination of research and development in this field since its inception by organizing international conferences and panels designed to bring together the developer and user of climate information. For example, the Modern Era Retrospective-analysis for Research and Applications (MERRA), the Climate Forecasting System Reanalysis and the European European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA interim) have been evaluated in depth and many strengths and weaknesses identified.

WCRP has facilitated coordination of research and development in this field since its inception by organizing international conferences and panels designed to bring together the developer and user of climate information.

Preliminary results indicate the potential benefit of coupling the ocean and atmosphere domains for improved forecasts and reanalyses. WCRP will ensure continued international coordination across disciplines and agencies and provide the best available scientific guidance on the latest developments in observations, models, assimilation and analysis fields to the international community.

4.2 Reprocessing

An important and rapidly evolving role in WCRP is the assessment of global datasets produced through international cooperation and coordination. For example, it is often difficult to define a single best climate data source. Datasets are instead most often complementary in nature with varying



Reanalysis products can provide continuous weather and atmospheric and ocean circulation data. Additional parameters not routinely observed, if at all, are derived from the background forecast models. For example: (left) the 1979 President's Day snowstorm depicted from MERRA sea-level pressure, surface winds and cloud fraction; and (right) the linear trend of 300-m ocean-heat content anomalies over the 1993-2009 period (°C/decade) from an ensemble mean of linear trends based on 10 ocean reanalyses (from Xue et al., 2012).

strengths and weaknesses. Essential elements that define the usefulness of a dataset are certainly its accuracy, error characterization, associated documentation, etc. Comprehensive evaluations against reference data and side-by-side comparisons among all available datasets (at different spatial and temporal scales) are, however, prerequisites for informed data choices in user applications.

In addition to error characterization and comparisons among available products, data usefulness depends on factors such as spatial and temporal coverage, data access, length of record and supporting documentation – both project-type documentation and peer-reviewed product description and analysis – and a listing of peer-reviewed research reports that have used the data product.

The WCRP/GEWEX Data and Assessments Panel recently initiated the assessment of all global water and energy datasets, as well as radiative fluxes and forcing terms, including turbulent fluxes and aerosols.

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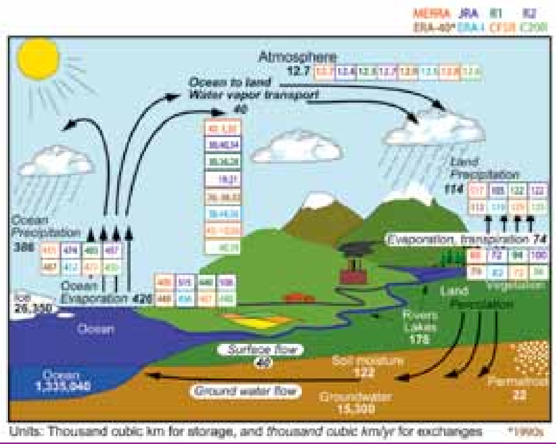
Each of the GEWEX reference products is currently preparing for a reprocessing cycle that will result in common space and time grids, as well as ancillary data and assumptions.

WCRP's view is that these assessments are dynamic activities that may need to be repeated every 5-10 years, depending on the rate at which products are being added or modified within a given discipline. Even if the validation data, procedures and previously assessed data are archived for interim use by new product developers, comprehensive assessments are critical to move the field forward in a systematic way and to enhance greater use of such datasets that require significant investments by national and international organizations.

4.3 Evaluation of space-based global climate datasets

The Global Climate Observing System is an integrated system with two major components: data provided by the satellite



Estimates of the observed hydrological cycle (adapted from Trenberth et al., 2007) to apply to the 2002-2008 period, with units in 1 000 km^3 for storage and 1 000 km^3/yr for exchanges. Superimposed are values from the eight reanalyses for 2002-2008, colour-coded as given at top right. The exception is for ERA-40, which is for the 1990s. For the water vapour transport from ocean to land, the three estimates given for each are: (a) the actual transport estimated from the moisture budget (based on analysed winds and moisture); (b) evaporation minus precipitation from the ocean; and (c) precipitation minus evaporation from the land, which should be identical.

constellation and the global in situ networks in the atmosphere, ocean, on land and in the cryosphere. While satellites can generally provide global coverage, they cannot measure all the variables of interest and they are often not designed to provide data with long-term stability and homogeneity. The in situ networks can be used for calibration and evaluation of satellite data and are vital for the measurement of variables, such as surface and subsurface land and ocean properties, that cannot be measured from satellites.

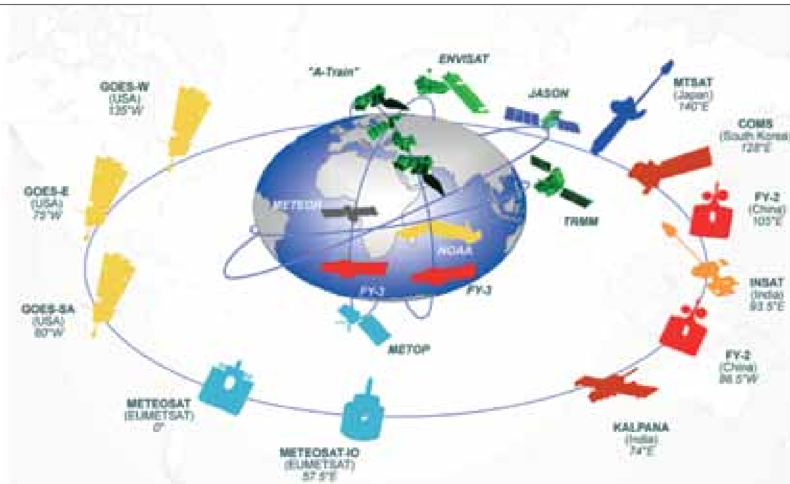
These global systems are supplemented by "supersites", which provide detailed point measurements of several variables in specific climatic zones that are measured with the best available instruments, rigorously calibrated/evaluated against world standards and documented in detail. Observations from these sites can provide anchor points for global climate datasets, as well as yielding information on the processes controlling the budgets of water, energy and chemical species. All three components of the Global Observing System are needed and should be maintained to ensure the required quality and comprehensiveness of global climate datasets.

WCRP, together with GCOS, is encouraging space agencies to give sustained attention to activities that ensure consistency in producing and documenting observational data.

WCRP, together with GCOS, is encouraging space agencies to give sustained attention to activities that ensure consistency in producing and documenting observational data. As calibration methods improve, there is a need to periodically reprocess fundamental climate data records (FCDR) and ECV products that depend on satellite records.

The international efforts on climate processing and reprocessing activities within, inter alia, ESA, the European Organisation for the Exploitation of Meteorological Satellites, the US National

Aeronautics Space Administration (NASA), CEOS and the Coordination Group for Meteorological Satellites, are important



Space-based global observing systems

initiatives for meeting user requirements. All producers of climate datasets are encouraged to carry out self-assessment of the utility and uncertainties of the products.

Independent expert-group assessments of the datasets associated with ECVs, being promoted by WCRP and GCOS, markedly enhance the utility and encourage improvements of individual datasets. WCRP and GCOS are striving to establish an international framework for a consistent approach to the production, evaluation and accessibility of global climate datasets, which will eventually lead to a complete inventory of ECV datasets.

4.4 Surface fluxes action plan

Surface fluxes are of great importance to climate studies because they represent exchanges across the components of the climate system. To characterize these fluxes correctly, conditions on both sides of the interface must be determined. For example, to understand properly the relationship between heat flux and SST, it is necessary to know the characteristics of the mixed layers in the ocean and atmosphere. The spatial and temporal variability of surface fluxes further highlights the need for careful consideration of their measurement and representation in models.

It is also important, from a climate science viewpoint, to consider surface fluxes over land, ice and sea together, as they represent equally important components of the climate system budgets of energy, water and nutrients. Reducing emphasis on any one component precludes its effective use in quantitative assessment of global and regional budgets of these exchanges. Surface flux observations – of both physical and chemical variables over land, ice and ocean – are obtained both directly and indirectly. Datasets are developed from in situ and satellite-based data (or blended datasets from different sources), as well as from model-based simulations. The complexity of determining fluxes has led to many inconsistencies in the datasets available to climate researchers. Many such inconsistencies have been identified through intercomparison studies organized by WCRP. Some scientific issues remain on the basic measurement of fluxes at reference sites or supersites where comprehensive measurements are made.

A number of different networks of supersites have been established around the world. The plethora of instruments and methods used to obtain the same fluxes needs to be assessed. WCRP and GCOS have developed a joint action plan on surface fluxes to be implemented in cooperation with sister international research programmes such as the IGBP.

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Recommended actions include:

- The evaluation of global surface flux datasets from observations and models (for example, development of community guidelines on the evaluation of flux products);
- Developing an international plan to optimize the spatial distribution of reference sites;
- Improving the consistency of measurements and data handling and the promotion of multi-variable sites; and
- Promoting data-sharing across the various communities using similar formats and standards.

4.5 Using observations with models

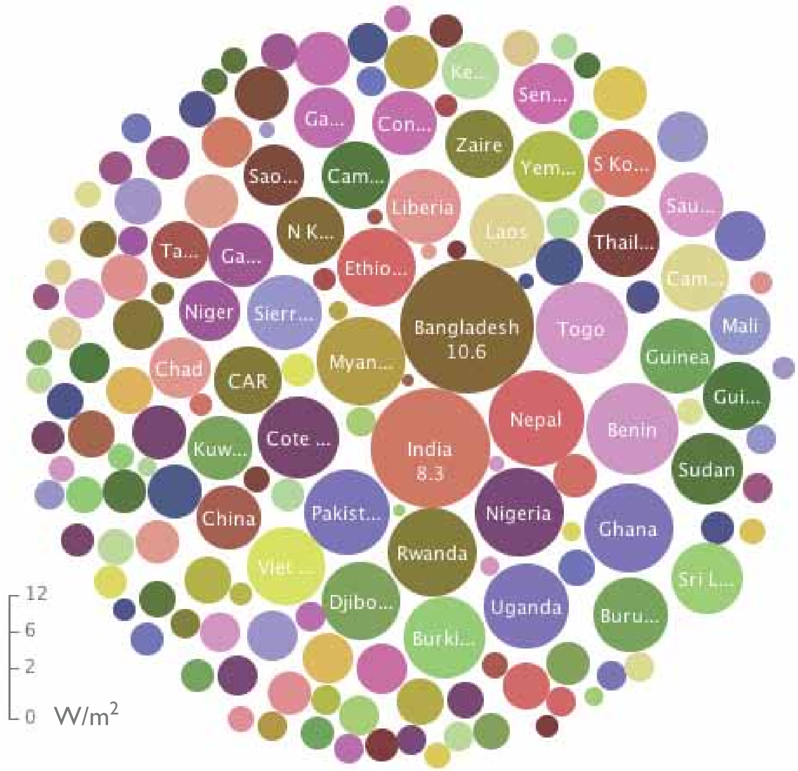
A new WCRP initiative, supported by NASA and the US Department of Energy, will greatly improve intercomparisons of models and observational datasets. Obs4MIPs (http://obs4mips.llnl.gov:8080/wiki) is a pilot effort, which is closely aligned to CMIP5, to improve the connection between data experts and scientists involved in climate model development and evaluation.

The overarching goal is to enable the two expert communities to develop and document some datasets based on space-based observations from the past several decades, consistent with the format and standards of the CMIP5 model output to be made available on the Earth System Grid Federation (ESGF) for use by all researchers around the world.

The Obs4MIPs datasets correspond in time and space to the model simulations developed as a part of the CMIP5 experiments. This technical alignment of observational products with climate model output will greatly facilitate model-data comparisons. Guidelines have also been developed for Obs4MIPs product documentation that is of particular relevance for model evaluation.

Products available via Obs4MIPs are:

- Directly comparable to a model output field defined as part of CMIP5;
- Open to contributions from all data producers that meet Obs4MIPs requirements;
- Well documented, with traceability to track product version changes; and
- Served through ESGF for ease of access by all interested researchers.



A holistic approach to addressing environment, energy and food challenges of the 21st century: for example, proper management of methane and black carbon emissions benefit human health, agriculture and climate (courtesy NASA/Drew Shindell).

5. Contributions of WCRP Core Projects

5.1 Climate and Cryosphere (CliC)

The CliC Project goals are to assess and quantify the impacts that climatic variability and change have on components of the cryosphere, and the consequences of these impacts for the climate system; and to determine the stability of the global cryosphere. In cooperation with its partners, the CliC project developed the Integrated Global Observing Strategy Theme on the Cryosphere that continues to guide the development of cryospheric observations. The Global Cryosphere Watch builds on this legacy.

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Despite steady advances in climate modelling and prediction, the CMIP3 climate models were not able to reproduce, as an ensemble, the observed rate of decline of Arctic sea ice.

A major effort has been made to understand the reasons underlying this significant mismatch between projections and observations. To facilitate the required comparisons, CliC has been supporting the assessment of possible differences between the estimates of Arctic Ocean sea ice obtained using different passive microwave sea-ice algorithms, which are the main source for estimating sea-ice extent and concentration. This effort revealed that the differences in total Arctic sea-ice extent resulting from the use of differing algorithms could be as large as one million square kilometres, thus resulting in the need for a new composite sea-ice extent product.

> One major area of research on the role of cryosphere in climate is the magnitude, timing and form of the permafrost carbon released to the atmosphere in a warmer climate.

These efforts also resulted in improved understanding of the processes governing the evolution of Arctic sea-ice and a deeper insight into model performance. The roles of the static stability of the Arctic boundary layer, the role of numerical resolution in simulating meridional heat transport to the Arctic Ocean and the model climatology in reproducing sea ice and several other factors were examined in detail in this analysis.

Preliminary results from the CMIP5 project show considerably reduced model biases in simulating Arctic Ocean sea ice. Thus, over several recent years, significant progress has been made in both observations and prediction of Arctic Ocean sea-ice cover.

One major area of research on the role of the cryosphere in climate is the magnitude, timing and form of the permafrost carbon that can be released to the atmosphere in a warmer climate. Together with the International Permafrost Association and the Global Carbon Project, CliC initiated a targeted programme of research that aims to assess the amount and form of carbon stored in various permafrost soil types and the vulnerability of these soils to thaw in a warmer climate. Early indications are that, when permafrost-carbon processes are included in climate model scenarios, terrestrial ecosystems north of 60°N are likely to turn from a sink to a source of CO_2 by the end of the 21st century. This preliminary conclusion will be used in future assessments of the carbon cycle and its amplification in the Arctic region. This knowledge will also help improve representation of such complex processes in future climate/ Earth system models.

The importance of adequate representation of forcing factors for cryospheric modules of modern climate and Earth system models cannot be overstated. For example, the balance of snow accumulation and ablation affects the fate of ice sheets and glaciers. Steep terrain is typical for mountainous regions where glaciers are located and for edges of ice sheets. Thus, high spatial resolution is necessary to simulate precipitation for driving ice-sheet and glacier models. Recent years have seen a rapid, focused improvement of models of the polar regions and their ability to simulate polar precipitation, for example under the Ice2Sea project. CliC-affiliated scientists are starting to calibrate regional models for assessment of the future evolution of regional glaciers, for example in Patagonia, South America. Such capabilities are critical in projecting the future state of glaciers and their contribution to freshwater resources, as well as substantiated assessments of sea-level variability and change at the regional level.

5.2 Climate Variability and Predictability (CLIVAR) Project

The focus of CLIVAR is on understanding climate variability, particularly the role of ocean-atmosphere interactions. CLIVAR has identified three major scientific themes or "frontiers" and four "imperatives" to serve as the framework for its activities: Frontier 1 – Anthropogenic climate change: undertake the predictive science that aims to develop the adaptation decisions that must be made in response to human activity;

Frontier 2 – Decadal climate variability, predictability and prediction: identify and understand phenomena that offer some degree of decadal predictability and skillfully predict these climate fluctuations and trends;

Frontier 3 – Intraseasonal and seasonal climate predictability and prediction: identify and understand phenomena that offer some degree of intraseasonal-to-interannual predictability, to skillfully predict these climate fluctuations and trends and to increase interactions of scientists, operational forecasters and decision-makers;

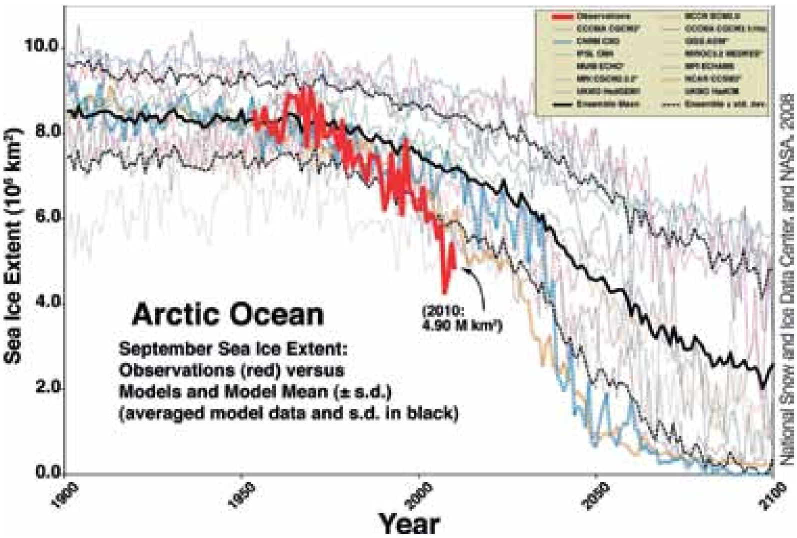
Imperative 1 – Improved atmosphere and ocean component models of Earth system models: reduce the negative impact of biases in model representations of atmospheric and oceanic processes;

Imperative 2 – Data synthesis, analysis, reanalysis and uncertainty: provide credibility to climate projections by understanding the past and present state of the ocean;

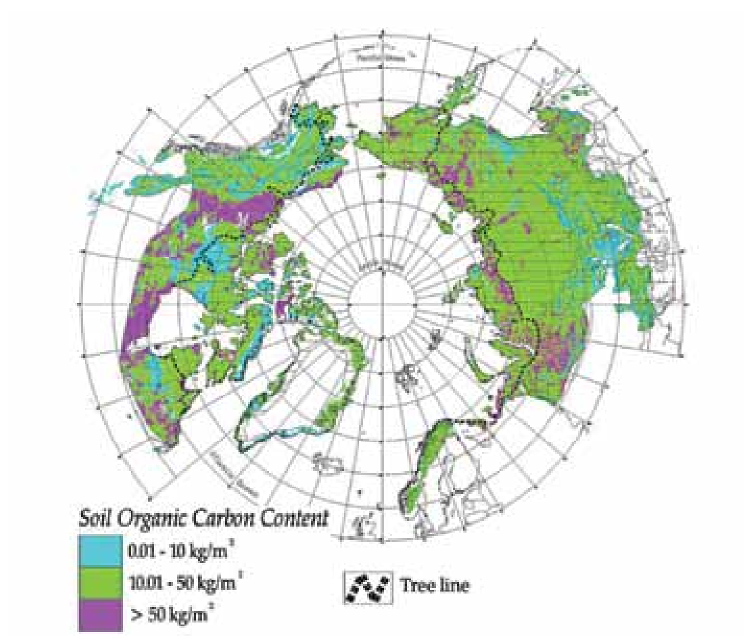
Imperative 3 – Ocean observing system: maintain over many decades a sustained ocean observing system capable of detecting and documenting global climate change;

Imperative 4 – Capacity building.

These scientific frontiers and imperatives are addressed through a network of panels and working groups focused on the various ocean basins (Atlantic, Pacific, Indian and Southern) and monsoon regions (Americas, Asia-Australia and Africa), as well as on modelling, global synthesis and observations. CLIVAR



Arctic sea-ice extent observations (thick red line) and 13 CMIP3 model simulations, together with the multi-model ensemble mean (solid black line) and standard deviation (dotted black line) for September 2007 (adapted from Stroeve et al., 2007)



Distribution of soil organic carbon contents in the northern circumpolar permafrost region (Tarnocai et al., 2009)

co-sponsors an expert team on climate-change detection and indices, as well as a group working on paleoclimate.

CLIVAR is striving to produce and improve global gridded indices of temperature and precipitation extremes. This activity not only helps to improve our understanding of past changes in climate extremes but also provides basic datasets for climate model validation and detection and attribution work.

One example is the Atlas of Extremes over the Americas. This is an online atlas of temperature and precipitation extremes, using CLIVAR-developed indices – both observational gridded data and reanalysis products. CLIVAR is also organizing the computation of indices based on CMIP5 model simulations and will disseminate the resulting data to the wider climate research community. The activity is an important contribution to the IPCC Fifth Assessment Report.

CLIVAR's regional panels have been instrumental in the development and advocacy of observing systems and modelling studies that address critical regions of the world oceans where enhanced observations and understanding are needed to initialize and evaluate climate models and to improve predictions of climate variability and change. Several major ocean field campaigns were coordinated recently to improve our understanding of the role of the world's oceans in climate. These are discussed briefly below.

The CINDY2011/DYNAMO international field campaign took place in and around the central equatorial Indian Ocean from October 2011 to January 2012. The programme collected in situ observations to advance understanding of Madden-Julian Oscillation (MJO) onset and improve MJO prediction and simulation. CLIVAR has also helped to coordinate the development and implementation of monitoring and assessing experimental real-time MJO forecasting from operational forecast centres worldwide. In addition to MJO hindcast skill assessment, the results are contributing to weather and climate models through improved representation of the physical processes.

CLIVAR is active in addressing the large tropical Atlantic biases present in the current generation of seasonal and longer-term prediction systems which lead to large model uncertainties as to the future evolution of the tropical Atlantic climate and limit climate prediction skill. The Tropical Atlantic Climate Experiment is an ongoing multinational observational programme, which aims to advance the understanding of coupled ocean-atmosphere processes and improve climate prediction for the tropical Atlantic region. Climate models suffer from strong SST biases in this region, which could at least be partly related to some local ocean processes.

The CLIVAR-GOOS (Global Ocean Observing System) Panel was instrumental in establishing the Research Moored Array (RAMA) for African-Asian-Australian Monsoon Analysis and Prediction. This array has dramatically changed observations in the Indian Ocean and is contributing to improved understanding of the monsoon climate system, as well

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as model simulation and prediction skill in this region.

The North-western Pacific Ocean Circulation and Climate Experiment aims to observe and explain the structure, variability and dynamics of the ocean circulation in the north-western Pacific region and to clarify its interaction with marginal seas, the Indonesian Throughflow and the subtropical ocean circulation. It will also evaluate the societal impacts of ocean variability in the region and provide a scientific basis for developing a sustained monitoring programme to aid future climate prediction.

The Southern Ocean Observing System activity enhances, coordinates and expands strategic observations of the Southern Ocean, an area that currently suffers from a paucity of observations.

The AMOC project and the associated Rapid Climate Change programme are investigating the role of AMOC in global climate and assessing its variability mechanisms and predictability. The observing network includes trans-basin, overflow and western boundary current observations. Results from several of the in situ programmes established as part of the AMOC monitoring network are now approaching or exceeding a decade in length, making them more valuable than ever. Model studies are increasingly suggesting an identifiable "fingerprint" associated with AMOC variability, manifested in measurable broad-scale fields such as sea level and subsurface temperature patterns. Considerable effort has been directed towards improving the representation of AMOC in climate models with recent successes in reproducing deep-water mass formation and transports.

The Overturning in the Subpolar North Atlantic Project is designed to quantify the large-scale, low-frequency, full water-column net fluxes of mass, heat and freshwater associated with the meridional overturning circulation in the subpolar North Atlantic and will contribute to a sustained AMOC observing system.

CLIVAR has sponsored a series of hindcast experiments to investigate intraseasonal prediction and predictability, with a focus on boreal summer monsoon intraseasonal variability. The monsoon regions of the world, where more than half the global population lives, are especially challenging. Interannual variability of mean monsoon rainfall is relatively low (~10% of the mean), but seasonal variations of the monsoon have a profound impact on agriculture and water availability.

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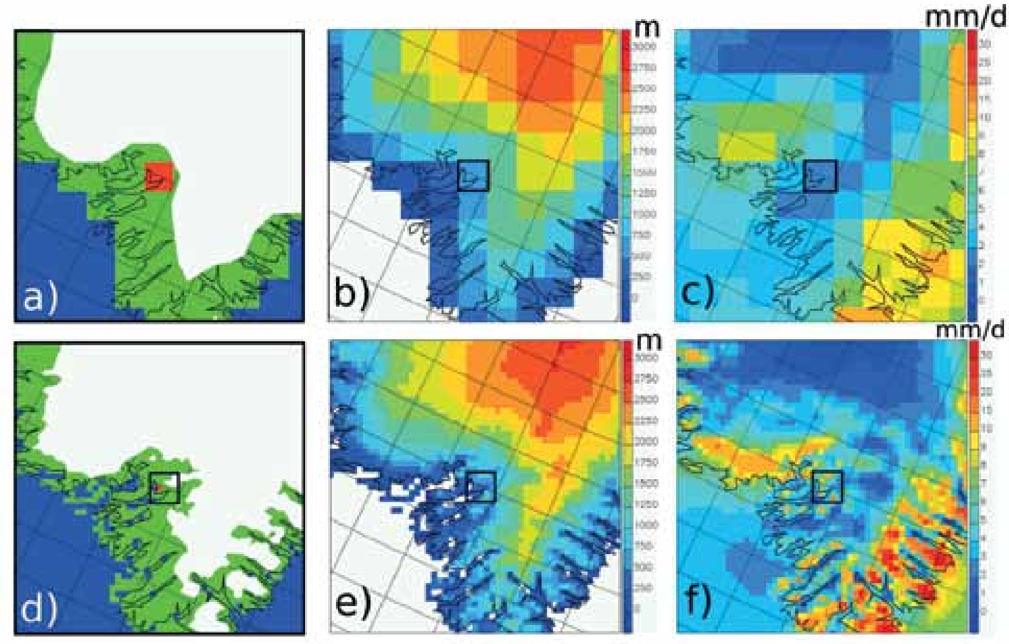
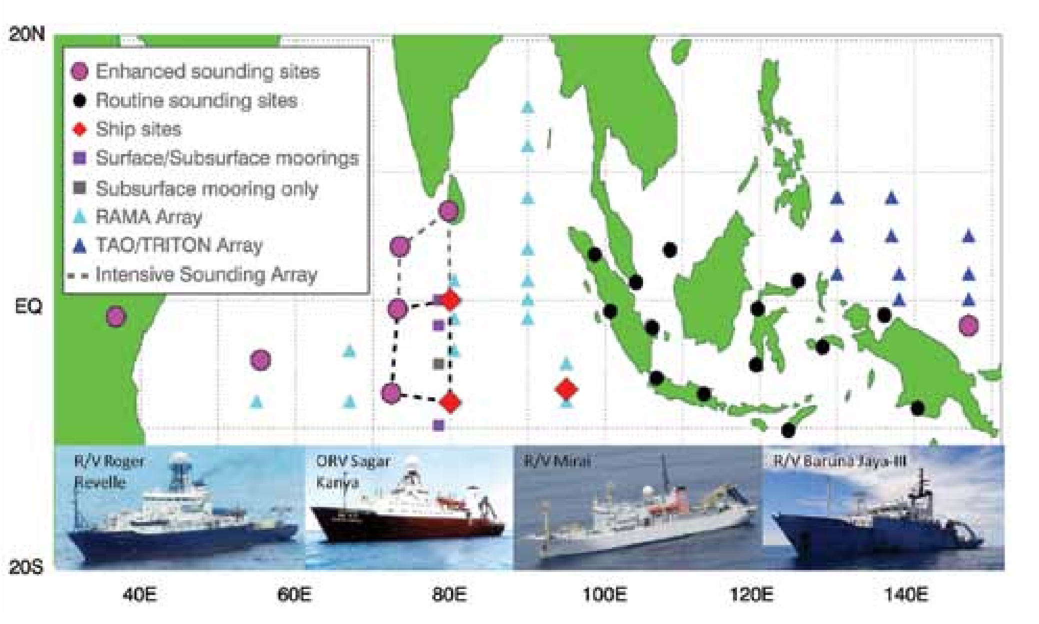
Monsoon failure (or extreme drought) is often a result of extended intraseasonal monsoon breaks. Monsoon intraseasonal variability is not well-simulated or predicted in climate models of the sort used for seasonal prediction. Skill assessment of predicting both boreal summer and austral summer intraseasonal variability is underway. CLIVAR is also coordinating an assessment of the representation of boreal summer intraseasonal variability in CMIP5 versus CMIP3 simulations.

CLIVAR has been promoting several experiments for evaluating, understanding and improving the ocean component in CMIP5 models. Some are aimed at investigating mechanisms for interannual-to-decadal variability and providing initial conditions for decadal predictability studies. The South-west Pacific Ocean Circulation and Climate Experiment



Land-sea mask, topography and winter precipitation in two versions of HIRHAM regional climate models, with resolution of 0.25˚ (~28 km) at 0.05˚ (~5 km) (from Lucas-Picher et al., 2012)

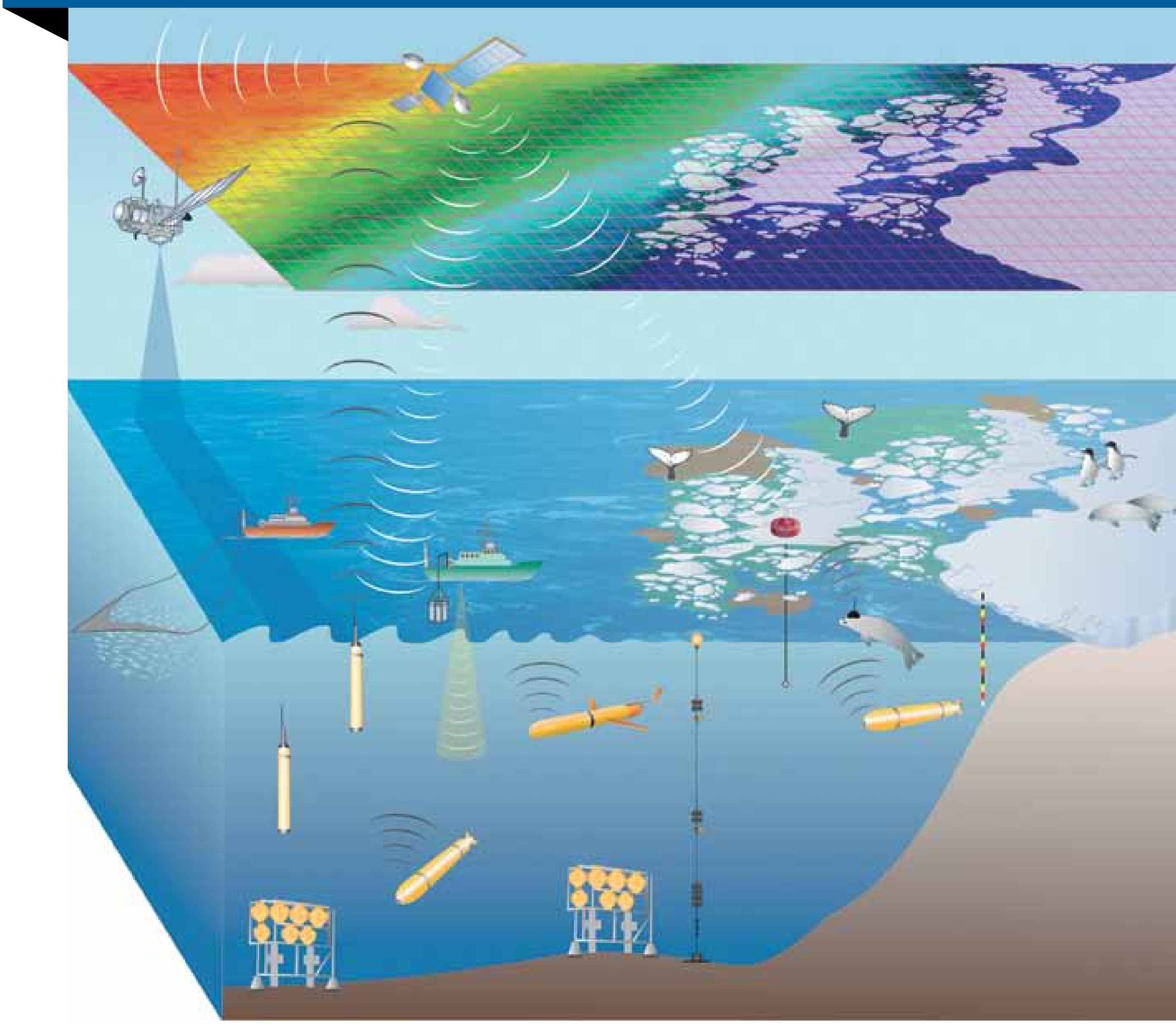


Cindy2011 field campaign

takes a large-scale approach to decadal climate prediction through the better understanding and modelling of the equatorial and South-west Pacific Ocean circulation, alongside a smaller-scale objective targeting coastal and island climate processes and prediction.

A major challenge for climate analysis and prediction is uneven observational coverage in both space and time. Deep-ocean and ice-covered regions are particularly poorly observed and some data are significantly biased. CLIVAR has therefore carried out a number of

Southern Ocean Observing System



ocean synthesis evaluation activities. As the most significant and consistent observed changes in the deep ocean are in the Southern Ocean and adjacent ocean basins, a working group has been formed to write synthesis papers on Southern Ocean Antarctic bottom water and deep ocean changes.

Another outcome has been an activity to facilitate the intercomparison of synthesis products, ending as close to real-time as possible, through identifying different groups to analyse different variables. These would include relevant ocean climate-change metrics, which could then be presented to the wider community. CLIVAR established a Repository for Evaluation of Ocean Simulations (REOS) to provide guidance on how to evaluate ocean model simulation, taking advantage of the regional oceanography expertise represented within CLIVAR's ocean basin activities. The REOS website (http://www.clivar.org/organization/wgomd/reos) provides the climate modelling community with a variety of resources, such as directions to recommended observational datasets, a recommended sets of metrics, literature and scripts.

5.3 Global Energy and Water Cycle Experiment (GEWEX) Project

The overall goal of GEWEX is to observe, analyse, understand and predict the variations of the global energy cycle and hydrological regime and their impact on atmospheric and surface dynamics. GEWEX also seeks to observe and understand regional hydrological processes and water resources and their response to changes in the environment, such as the increase in greenhouse gases and land-use change. To reach this goal, GEWEX scientists seek to:

- Produce consistent research-quality datasets, complete with error descriptions, of the Earth's energy budget and water cycle and their variability on short time- and space-scales (3 h and 25 km) appropriate for process studies during and beyond decades, for use in climate system analysis and model development and validation;
- Enhance the understanding of how energy and water cycle processes function and quantify their contribution to climate feedbacks;
- Improve the predictive capability for key water- and energy- cycle variables and feedbacks through improved parameterizations to better represent hydrometeorological processes, and determine the geographical and seasonal characteristics of their predictability over land areas;
- Undertake joint activities with operational hydrometeorological services, related Earth System Science Partnership (ESSP) projects such as the Global Water System Project, and hydrological research programmes, to demonstrate the value of new GEWEX prediction capabilities, datasets and tools for assessing the consequences of global change.

GEWEX has three major components designed to advance research in atmosphere and atmosphere/land intereactions; regional hydroclimate projects (RHPs); and the production and assessment of global water and energy datasets, and is making substantial progress in all these areas.

The overall goal of GEWEX modelling efforts is to develop and improve the representation of the atmosphere in weather and climate models by improving the model formulation of the energy and water budgets. Investigations are also made to demonstrate predictability of their variability and response to climate forcing.

The principal task of the GEWEX RHPs is to achieve demonstrable skill in predicting changes in water resources and soil moisture as an integral part of the climate system up to seasonal and annual time scales. The network of RHP observing stations provides in situ datasets for different regions, seasons and variables that are used to evaluate remotely sensed products with energy, water and carbon budget components.

GEWEX has three major components designed to advance research in atmosphere and atmosphere/land interactions; regional hydroclimate projects (RHPs); and the production and assessment of global water and energy datasets, and making substantial progress in all these areas.

In turn, RHPs apply in situ and remote-sensing data to studies designed to improve seasonal forecasting, detection and attribution of change and development and analysis of climate projections. RHP datasets, scientific results and tools are provided openly and free of charge to local users and the broader GEWEX community to address matters of concern within their regions. They also contribute to larger-scale studies, for example assessments of global datasets by the GEWEX Data and Assessment Panel's global model intercomparisons, and initiatives such as CORDEX.

GEWEX brings together theoretical and experimental insights into the radiative interactions and climate feedbacks associated with cloud processes to address the fundamental scientific question: how sensitive is the Earth's climate to changes in radiative and other forcings? Answering this question will enable improved prediction of transient natural climate variations, such as El Niño, and provide better understanding of the consequences of natural and human-induced climate changes.

GEWEX coordinates the production of global datasets on clouds, precipitation, aerosols, ocean-sensible and latent heat flux, land-sensible and latent heat flux and surface, as well as top-of-the-atmosphere radiative fluxes. An integrated product, using common assumptions across the suite of GEWEX products listed above, is currently under construction. Recent emphasis has shifted from enabling dataset generation to assessing datasets, which includes the process of transferring scientifically generated data products to operationally produced ones and understanding how these datasets relate to one another.

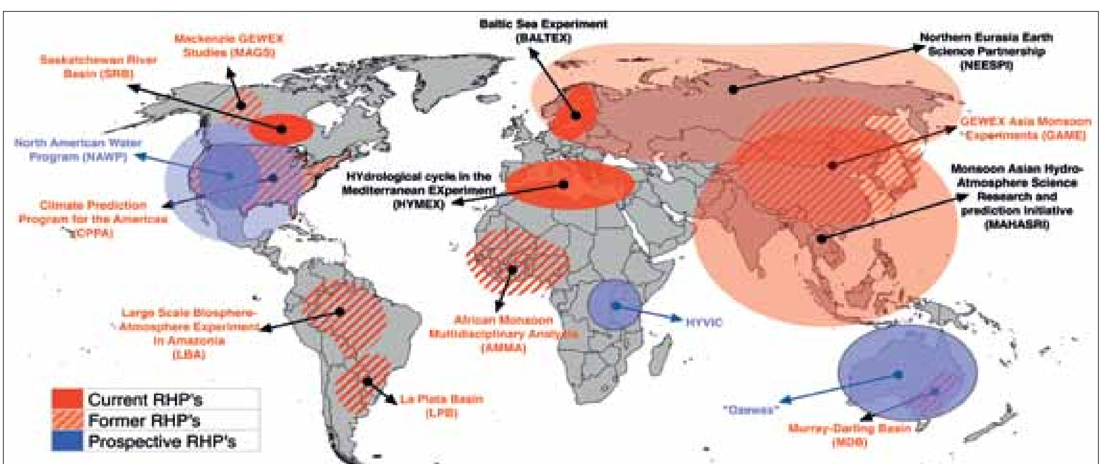
Comprehending what the data (from observations as well as models) represent is crucial but, perhaps even more important, is ensuring that other users of such data do too. Key assessment activities include not only the classical comparisons with in situ observations but also intercomparisons among products and detailed surveys related to the intended uses of products. In addition to recommendations, assessments should strive to save procedures and datasets that allow future product developers to repeat the assessment for their product. The recently released GEWEX Radiative Flux Assessment involved 75 participants representing nearly all the space and weather agencies of the world. A major global assessment of clouds has recently been published and other assessments, including temperature and water-vapour products, are ongoing.

Looking to the future, GEWEX has identified four Grand Science Questions (GSQs) where new observations and computer and model advancements indicate that significant progress can be made. Answers to these GSQs would bring socio-economic benefits, particularly those relating to water availability, food security, energy consumption and human health:

- **How can we better understand and predict precipitation variability and changes?** This involves the exploitation of improved datasets (satellite and in situ) of precipitation, as well as related variables, such as soil moisture, water storage and sea-surface salinity expected in the coming five years. These data will be evaluated and analysed and used to confront models in new ways that will improve simulations of precipitation and lead to improved predictions of the hydrological cycle. These results should all lead to improved understanding and prediction of precipitation variability and related climate services.

- **How do changes in land surface and hydrology influence past and future changes in water availability and security?** There is a need to address terrestrial water-storage changes and to balance the water budget over land through exploitation of new datasets, data assimilation and improved physical understanding and modelling skill on all scales with links to the entire hydrological cycle, including hydrogeological aspects of groundwater recharge. In particular, the use of realistic land-surface complexity with all human-induced effects taken into account is required. The results should enhance the evaluation of the vulnerability of water systems, especially to extremes, which are vital for considerations of water security and can be used to increase resilience through good management and governance.

- **How does a warming world affect climate extremes, especially droughts, floods and heatwaves, and how do land-area processes, in particular, contribute?** A warming world is



GEWEX Regional Hydroclimate Projects

expected to alter the occurrence and magnitude of extremes such as droughts, heavy rainfall and floods, as well as the geographical distribution of rain and snow. Such changes are related to an acceleration of the hydrological cycle and circulation changes.

- **How well are models able to handle extremes and how can we improve their capability?** New improved and updated datasets at high frequency (e.g. hourly) are needed, together with new activities to promote analyses quantifying which changes are consistent with expectations and how we can best contribute to improving their prediction in a future climate. New applications should be developed for improved tracking and warning systems and for assessing changes in risk of drought, floods, river flow, storms, coastal sea-level surges and ocean waves.

- **How can understanding of the effects and uncertainties of water and energy exchanges in the current and changing climate be improved and conveyed?** The goal is to improve consistency between net solar and infra-red radiation and sensible and latent heat fluxes at the surface to reveal processes that, in turn, must be replicated in climate models, on multiple scales. This question relates also to uncertainties introduced by incomplete understanding of cloud-aerosol-precipitation interactions and their feedbacks to the climate system. Upgraded GEWEX datasets, global reanalyses of atmosphere and ocean and improved modelling, together with advanced diagnostics being planned throughout the GEWEX panels, play key roles in advancing this topic. The result is improved tools and products for climate services.

Plans to investigate each of these questions are being assembled by GEWEX researchers in partnership with other WCRP groups and panels, as well as in partnership with other national and international research programmes.

5.4 Stratospheric Processes and their Role in Climate (SPARC) Project

SPARC coordinates international efforts to bring knowledge of the stratosphere for research on climate variability, change and prediction. It includes three large scientific themes as described below.

SPARC research on climate and chemistry interactions has been initially focusing on the changes of the stratospheric ozone, which is of central interest for the WMO/UNEP periodic Scientific Assessments serving the Vienna Convention and its Montreal Protocol. The experience and capacity developed by SPARC in stratospheric ozone research now make it possible to begin the systematic study of other chemical constituencies, water vapour and aerosols, not only in the stratosphere but also in the troposphere, and to embark on the

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Understanding and predicting climate-change signatures in the stratosphere is fundamental for obtaining a more complete and comprehensive picture of climate change. Based on a variety of observations, SPARC scientists develop methods for detecting past changes and variations in stratospheric variables and propose their explanations in terms of natural and anthropogenic effects. These studies serve as the basis for assessing the future evolution of stratospheric variables and assigning some degree of confidence to such predictions.

Research on stratosphere-troposphere coupling helps to identify the dominant mechanisms of their dynamic and radiative interactions. Due to generally longer timescales of stratospheric processes, such research is extremely promising for enabling extended-range tropospheric weather forecasting.

SPARC undertakes process studies, conducts field observations and data studies, develops model experiments and prepares dedicated assessments to address knowledge gaps in its three large-scale project themes. The success of SPARC research on the role of the stratosphere in climate now makes it possible to extend the scope of activities towards a fuller coverage of atmospheric chemistry and tropospheric dynamics.

The peer-reviewed Chemistry Climate Model Validation (CCMVal) Report (SPARC Report No. 5) was the result of a strong community-based research effort and provided key input into the 2010 WMO/UNEP Scientific Assessment of Ozone Depletion. The Report pioneered the systematic use of process-oriented performance metrics to evaluate chemistry-climate models (CCMs). The improved understanding of the strengths and weaknesses of CCMs in the second phase of CCMVal in 2010 helped to obtain considerably more comprehensive and self-consistent multi-model projections of the ODSs than the projections obtained during the first phase of the project.

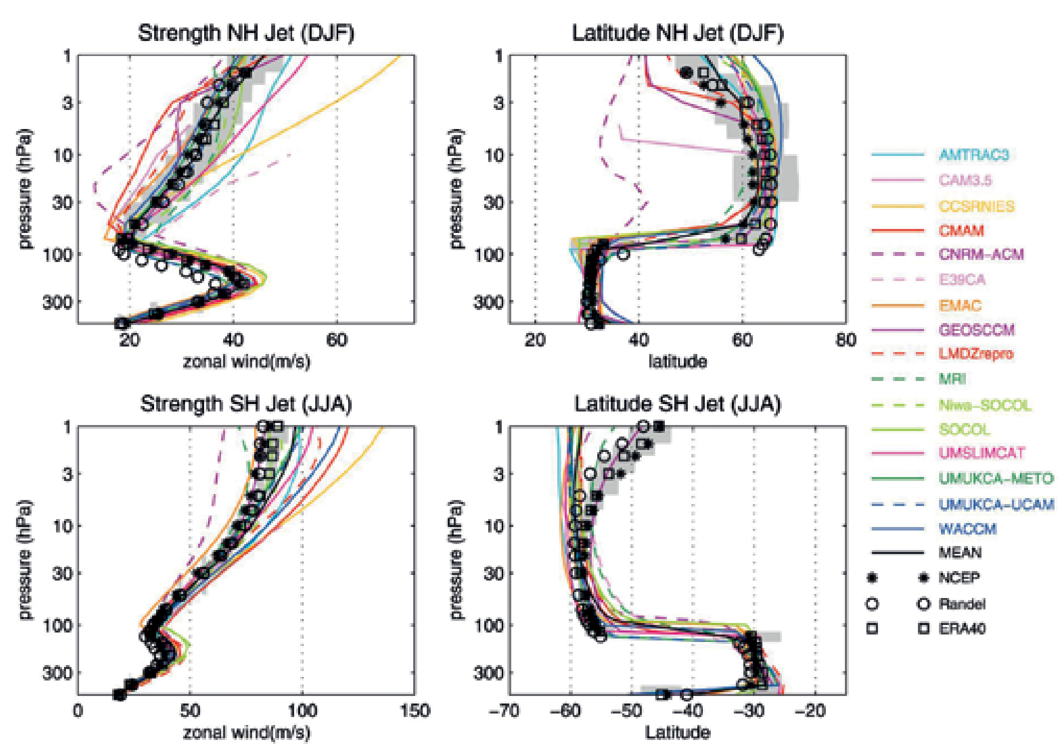
The simulations coordinated through the SPARC CCMVal activity also provide climate-relevant information, since it has now been clearly demonstrated that the ozone hole has been the principal driver of past changes in summertime surface climate in the extra-tropical southern hemisphere.

The recovery of the ozone hole is predicted to largely offset the effects of greenhouse gas increases on future summertime circulation changes. A major new challenge for the SPARC chemistry-climate modelling activity, which is working increasingly closely with the IGBP International Global Atmospheric Chemistry project, will be to develop comprehensive troposphere-stratosphere CCMs, including an interactive ocean, tropospheric chemistry and spectrally resolved solar irradiance effects, together with a fully resolved stratosphere.

SPARC activity on gravity waves culminated in a review paper (Alexander et al., 2010) on gravity-wave effects in stratosphere-resolving climate models, recent observations and analysis methods that reveal global patterns in corresponding momentum fluxes. Using very high-resolution models capable of resolving gravity waves and their circulation effects, it was possible to show that deficiencies in the representation of gravity-wave drag remain a significant source of uncertainty in model dynamics, especially in the southern hemisphere.

By comparing momentum fluxes derived from observations and global models, SPARC is attempting to assess the agreement among the various measures of momentum flux and exploit observations to improve gravity-wave parameterizations in global models or to explicitly resolve them in simulations. Early results are showing some strengths and weaknesses of current parameterizations that can lead directly to model improvements. Ongoing work is generating new information on gravity-wave variability that may stimulate the development of new parameterizations. The future focus will be on sources of gravity waves and the processes/parameters that control their circulation effects.

The direct effect of the observed variation in solar ultraviolet radiation affecting stratospheric ozone has the most significant impact and is already included in most climate models, although significant uncertainties in the magnitude and spectral dependence of these variations remain. The effective change in solar radiative forcing between the Maunder Minimum and present is estimated as ~0.24 W m^{-2} and is much smaller than the forcing due to anthropogenic changes, but



Simulated zonally and ensemble-averaged climatology of zonal wind speed and latitude of the jet maxima: (top) for the northern hemisphere (NH), December to February (DJF); and (bottom) for the southern hemisphere (SH), June to August (JJA) compared with the ERA-40 and US National Centers for Environmental Prediction reanalysis and the Randel et al. [2004] climatology. The grey shading indicates a 95% confidence interval for the 20-year mean ERA-40 climatology based on a t-distribution (from Butchard et al., 2011).

	O_3	H_2O	CH_4	N_2O	CCl_3F	CCl_2F_2	CO	HF	SF_6	NO	NO_2	NO_x	HNO_3	HNO_4	N_2O_5	$ClONO_2$	NO_y	HCl	ClO	HOCl	BrO	OH	HO_2	CH_2O	CH_3CN	aerosol
ACE-FTS	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X						X		
Aura-MLS	X	X		X			X						X					X	X	X		X	X			
GOMOS	X										X															X
HALOE	X	X	X					X		X	X	X						X								
HIRDLS	X				X	X					X		X													
LIMS	X	X									X		X													
MAESTRO	X																									
MIPAS	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X		X	X				X		
OSIRIS	X										X	X_d					X_m				X					X
POAM II	X										X															X
POAM III	X	X									X															X
SAGE I	X																									
SAGE II	X	X									X															X
SAGE III	X	X									X															X
SCIAMACHY	X	X									X	X_d									X					X
SMILES	X												X					X	X	X	X		X		X	
Odin/SMR	X	X		X			X			X			X				X_m		X				X_{ld}			
TES	X_t						X_t																			
UARS-MLS	X	X											X						X							

The SPARC Data Initiative targets 25 different long-lived and short-lived trace-gas species (CH_4, N_2O, HNO_3, N_2O_5, NO_x, HCl, ClO, OClO, HOCl, HF, BrO, SF_6, CO, ...), aerosol, ozone and water vapour.

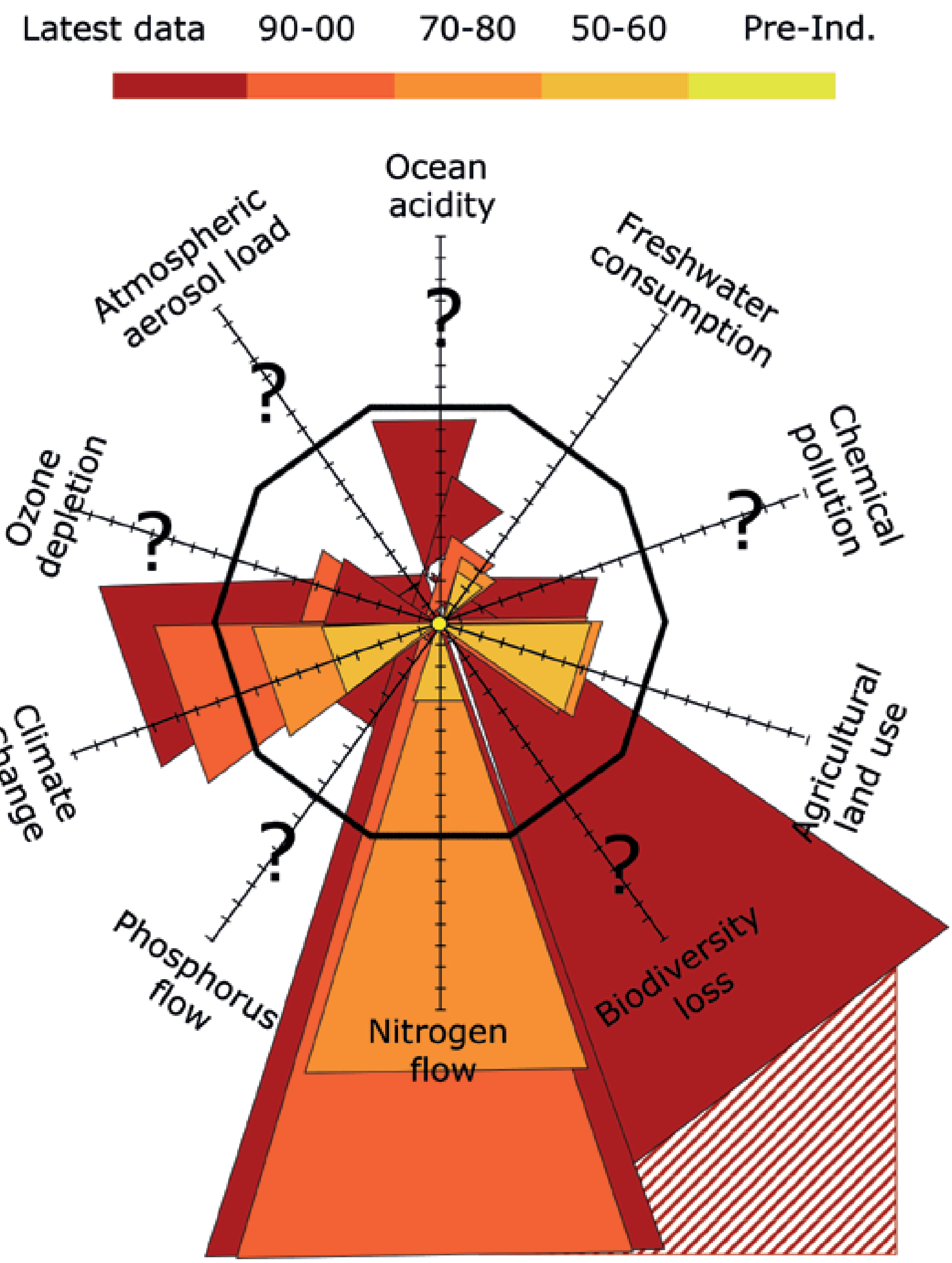
solar forcing can exert a larger impact on decadal timescales.

The SPARC Data Initiative activity, which started in 2009, is reviewing datasets of vertically resolved chemical trace gas and aerosol observations from the upper troposphere to the lower mesosphere obtained from different satellite instruments. The improved knowledge of current and recent instruments, measurement and retrieval techniques and validation activities has resulted in a step change in our understanding of the quality of the available data products and has prompted the development of improved data products. This will facilitate the use of such data in different applications, including the generation of corresponding FCDRs, empirical studies of stratospheric climate change and variability and model-measurement comparisons. SPARC Data Initiative products are already contributing to the SPARC ozone-profile and water-vapour trend analyses. The Initiative will also provide guidance and feedback to space agencies with respect to required improvements in future observations.

SPARC is facilitating discussions on geoengineering options as a means of mitigating the adverse impacts of climate warming. For example, several modelling groups within the SPARC CCMVal community are currently engaged in the SPARC Geoengineering Model Inter-comparison Project studying the applicability and robustness of chemistry-climate models for addressing policy-relevant questions around geoengineering options and their potential risks.

SPARC is facilitating discussions on geoengineering options as a means of mitigating the adverse impacts of climate warming.

These risks (depending on the specific geoengineering technique) might include: regional climate change, including a global reduction in precipitation and an associated increase in the likelihood of regional droughts; rapid reversal of the cooling effect when the application is stopped; continued ocean acidification; ozone depletion; effects on plants by changing the partitioning between direct and diffuse light; and unknown impacts on cirrus clouds. Even if the risks are judged to be acceptable, the feasibility of any particular geoengineering method needs to be reviewed and the cost implications quantified prior to any consideration of such options for policy-related discussions.



Earth System Science Partnership: scientific foundation for assessment of planetary conditions and limits. Scientists identify environmental processes that are fundamental for the planet's ability to support human life. They assess the limits - boundaries - for maintaining a habitable Earth (courtesy of the Stockholm Resilience Centre).

6. Climate information for decision-makers

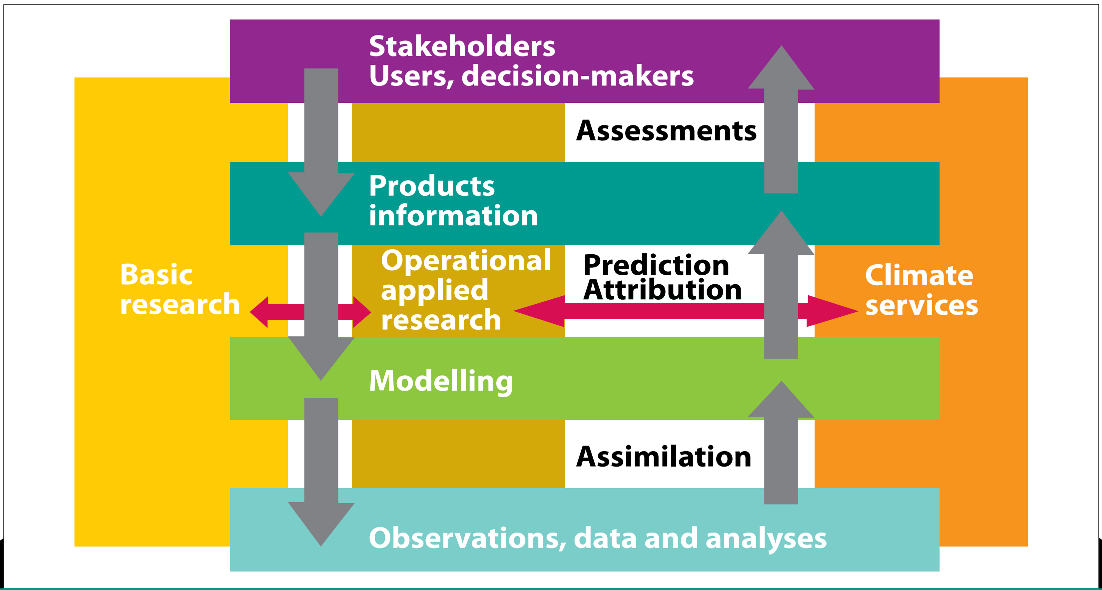
6.1 Contributions to climate assessments

Through its Working Group on Coupled Modelling (WGCM), WCRP coordinates the Coupled Model Intercomparison Project (CMIP). CMIP activities are carried out by 25 modelling centres in 14 countries, and CMIP results are made available openly to researchers and decision-makers for a wide range of purposes, including research, analysis, synthesis and assessments. A major focus for CMIP is to contribute to the IPCC Assessment Reports. For example, Phase 3 of CMIP (CMIP3) provided the basis for several hundred peer-reviewed papers and played a prominent role in the Fourth IPCC Assessment Report (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php).

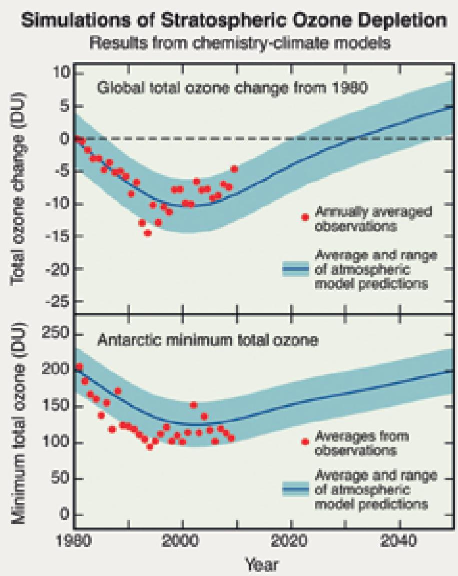
Phase 5 of CMIP (CMIP5) was established by WCRP to provide a community-based infrastructure in support of climate model diagnosis, validation, documentation and data access, thus enabling a diverse community of scientists to analyse climate model output in a systematic fashion. Virtually the entire international climate modelling community has participated in CMIP5 since its inception in 1995. This required greater coordination with the IGBP AIMES project and other partners at the regional and global levels.

6.2 Ozone assessment

Since their inception in the late 1970s, SPARC has been a major contributor to



Conceptual framework for WGCM/WCRP in coordinating climate modelling activities internationally in support of the policy-making process (figure by K. Trenberth, slightly modified by G. Asrar)



Simulations of ozone depletion. Chemistry-climate models of the atmosphere that account for changes in ozone-depleting substances (ODSs) and climate parameters are widely used to assess past ozone changes and project future ozone. Agreement in comparisons of model results with observations increases confidence in the model projections and our understanding of the processes leading to ozone depletion. Observed values of global total ozone (top panel) and minimum total ozone values over Antarctica (bottom panel) decreased beginning in the early 1980s (red points). Ozone is no longer decreasing in either region. The observations lie mostly within the range of projections derived from a group of chemistry-climate models (blue shading). Differences between models and observations can occur due to unusual meteorological conditions, volcanic eruptions, changes in solar activity, or other influences, which are not fully accounted for in the different models. As ODS abundances decrease in the 21st century, chemistry-climate models project global total ozone to increase steadily and exceed 1980 values, and Antarctic minimum ozone to return to 1980 values.

Simulations of stratospheric ozone depletion

the scientific assessments of substances that contribute to the depletion of ozone in the stratosphere. The latest report entitled 2010 WMO/UNEP Scientific Assessment of Ozone Depletion (http://www.wmo.int/pages/prog/arep/gaw/ozone_2010/ozone_asst_report.html) was written and reviewed by some 300 scientists, many of them affiliated with SPARC.

Improved knowledge of stratospheric ozone chemistry and a better understanding of the role of meteorological conditions in its variability provided a richer and more robust set of chemistry-climate model simulations of the potential evolution of the stratospheric ozone layer. An ensemble of ozone projections from the SPARC CCMVal activity shaped the main conclusion of the 2010 Assessment that the recovery of the stratospheric ozone layer to its pre-1980 values is expected in the middle of this century as a result of the successful implementation of the Montreal Protocol and its various amendments.

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Changes in stratospheric ozone have strongly influenced the climate system in the recent past, both globally and regionally, especially over the Antarctic region. In addition to influencing climate, stratospheric ozone is itself influenced, in a multitude of ways, by changes in climate. Only fully interactive chemistry-climate models, in which changes in atmospheric chemical composition, radiation and dynamics are tightly coupled, can realistically simulate expected interactions between changes in climate and changes in stratospheric ozone. Such models require ongoing investment in their development to ensure that they incorporate all mechanisms necessary to simulate chemistry-climate coupling and are suitable for addressing policy-relevant questions within acceptable ranges of uncertainty. Assessing and validating these models also require significant long-term efforts.

To support climate prediction and projection for the Fifth Assessment Report of the IPCC, the Atmospheric Chemistry and Climate Initiative of WCRP/SPARC and IGBP developed an atmospheric ozone database for use by those climate models, contributing to the CMIP5 archive. The ozone database spans the period 1850 to 2100. Using this database, stratospheric ozone changes, greenhouse-gas emissions and natural variability of the Earth's atmosphere can be accounted for simultaneously in future climate projections.

6.3 Cryosphere assessment in the Arctic

In April 2008, the Arctic Council initiated the project Climate Change and the Cryosphere: Snow, Water, Ice and Permafrost in the Arctic (SWIPA) as a follow up to the 2005 Arctic Climate Impact Assessment. The Arctic Monitoring and Assessment Programme coordinated the SWIPA project in cooperation with contributions from WCRP/CliC, the International Arctic Science Committee and the International Arctic Social Sciences Association. This new assessment brings together the latest scientific knowlege about the changing state of each component contributing to the Arctic freshwater budget. It examines how these changes will impact both the Arctic climate and freshwater resources as a whole, as well as people living within the Arctic region and elsewhere.

Information on the future state of the Arctic cryosphere is based on the interpretation of the climate predictions available from the WCRP CMIP3 database. Fifteen key findings presented in the Executive Summary of the Assessment Report pave the way for adaptation measures to climate change in this region, development of communication and outreach and policy actions for mitigating some major contributing factors. CliC-affiliated scientists were principal contributors to the development, review and publication of the SWIPA report.

6.4 Fifth Global Environmental Outlook

WCRP was a contributor to the UNEP Fifth Global Environment Outlook (GEO-5), which was unveiled at the Rio+20 Conference in June 2012. The enormous complexity of the Earth system and its changes on multiple space- and timescales is highlighted in the chapter "Earth system challenges". The conclusions of this chapter state that modern climate science is capable of addressing a significant part of the complex Earth system challenges and producing useful predictions and projections of its future state and climate.

Practically addressing such challenges, however, requires understanding and proper representation of the underlying drivers, including human pressures, such as population growth and economic activity. The proposed "adaptive governance" approach should be underpinned by sustained long-term monitoring and basic and applied research of the Earth system to enable science-based and reliable information for adaptation, mitigation and risk management associated with anticipated environmental changes.

Empowering the future generation of climate scientists to serve the needs of decision-makers in climate-adaptation and risk-management planning.

7. Capacity development

7.1 Supporting climate risk management in the Great Horn of Africa

To assist the developing and Least Developed Countries of the Greater Horn of Africa (GHA) region to undertake and use climate projections appropriately in adaptation planning, WCRP, GCOS, WMO and the Nairobi-based Inter-Governmental Authority on Development (IGAD) Climate Prediction and Applications Centre (ICPAC) joined forces to implement a project to demonstrate key elements of an effective climate-risk management strategy for the region, under the sponsorship of the World Bank.

Reliable and detailed regional climate information is essential for the design of effective strategies for managing risks and adapting to climate variability and change. This depends on the availability of high-quality, long-term observations, the adequacy of climate predictions from numerical models to depict future regional climate conditions, and a thorough understanding and appreciation of the uncertainties and constraints associated with the use of both data and regional and global models. Finally, there must be a two-way interaction or dialogue between the information providers and the users in government and the public and private sectors.

Reliable and detailed regional climate information is essential for the design of effective strategies for managing risks and adapting to climate variability and change.

Three workshops were therefore organized, whose overall objectives were to:

- Help ensure that attention is given by participating countries to observation and data needs;
- Demonstrate the use and value of regional models;
- Provide advice on model limitations;
- Improve capabilities across the GHA for using data records and model projections for adaptation planning.

Information providers and users interacted through the application of climate information for agriculture/food security and water-resources management. The project greatly benefited from the participation of volunteers from the United Kingdom Met Office (UKMO) and the United Nations Development Programme's Africa Adaptation Programme.

7.2 CORDEX Africa and Asia

CORDEX, in partnership with START and regional organizations, development banks and non-governmental organizations, is developing regional research capacity for, among others, Asia, Africa and Latin America. CORDEX presents an unprecedented opportunity to advance knowledge of regional climate responses to global climate change and for these insights to benefit ongoing climate-adaptation and risk-assessment research, policy planning and development investments in these regions.

For example, a consortium of organizations, consisting of WCRP, the University of Cape Town's Climate Systems Analysis Group, START, the International Centre for Theoretical Physics, the SMHI and the Climate and Development Knowledge

Network, initiated an analysis and training programme to provide an initial assessment of CORDEX output for Africa that is regionally focused and prioritized to the continent's information needs.

The training programme focuses on skill development in working with climate model results, analysis of CORDEX datasets and compilation and writing-up of the results for broad dissemination to users. Participants in the training programme are grouped into teams according to the subregions they represent and their respective areas of expertise. This approach, initially focused on Africa, is now being replicated for South Asia and other regions worldwide.

7.3 Training activities

WCRP strives to create opportunities and forge alliances with the international scientific and technical unions, professional societies and other scientific and technical organizations towards achieving their education, training and capacity development objectives. For example, together with the Abdus Salam International Centre for Theoretical Physics (Trieste, Italy) and UKMO, WCRP supported numerous workshops to train scientists in developing downscaled climate-change scenarios and identifying data requirements for climate impacts, vulnerabilities and risk assessments.

WCRP experts from WGSIP and the Variability of the American Monsoon System (VAMOS) Panel introduced global models and, among other topics, probabilistic approaches for seasonal predictions, regionalization and verification of seasonal climate predictions.

The 38 participants from 13 countries who attended the Training Workshop on the Use of Seasonal Predictions for Applications in Latin America explored the use of seasonal forecasts tailored to users' needs in different socio-economic sectors. This training took place in Buenos Aires, Argentina, in August 2010 and was co-sponsored by the IAI, the International Research Institute for Climate and Society, the University Corporation for Atmospheric Research, WCRP and UNESCO.

WCRP experts from WGSIP and the Variability of the American Monsoon System (VAMOS) Panel introduced global models and, among other topics, probabilistic approaches for seasonal predictions, regionalization and verification of seasonal climate predictions. In addition, several experts from different socio-economic sectors shared their experience and research results regarding challenges in the use of seasonal predictions tailored to user needs in agriculture, health, water resources and disaster risk management in Latin America (http://iaibr3.iai.int/twiki/bin/view/TIClimatePredictions2010)

Thirty-five early-career scientists from 20 countries were invited to attend a three-day workshop in connection with the WCRP OSC (19-22 October 2011). The Workshop was organized by the Early Career Scientist Assembly and the Advanced Study Program of the National Center for Atmospheric Research (NCAR) and was co-sponsored by WCRP. The goal of the Workshop was to examine a range of regional climate challenges in developing countries. Topics included regional climate modelling, climate impacts, water resources and air quality.

The Workshop fostered new ideas and collaboration between early-career scientists from around the world. Discussions

Some participants in the Global Facility for Disaster Reduction and Recovery regional modelling workshop at ICPAC (Nairobi, Kenya), comparing model simulations with observations to prepare analysis of impacts of climate conditions on agriculture and water resources

underscored the importance of establishing partnerships with scientists located in typically underrepresented countries to understand and account for the local political, economic and cultural factors on which climate change is superimposed. Such end-to-end communication would also help to ensure that research addresses the particular needs of the communities that are its focus.

Strategic partnerships are essential for effectively advancing climate research and ensuring a legacy of sustained achievements.

8. Partnerships are key to success

8.1 Earth System Science Partnership

WCRP has a rich history of forging strategic partnerships to accomplish its scientific and technical goals/objectives. The Earth System Science Partnership (http://www.essp.org/) was established to facilitate study of the Earth's environment as an integrated system in order to understand how and why it is changing and to explore the implications of these changes for global and regional sustainability. Joint projects were established to investigate impacts of global environmental changes on water, food security, health and carbon, as well as an integrated regional study of the monsoonal system.

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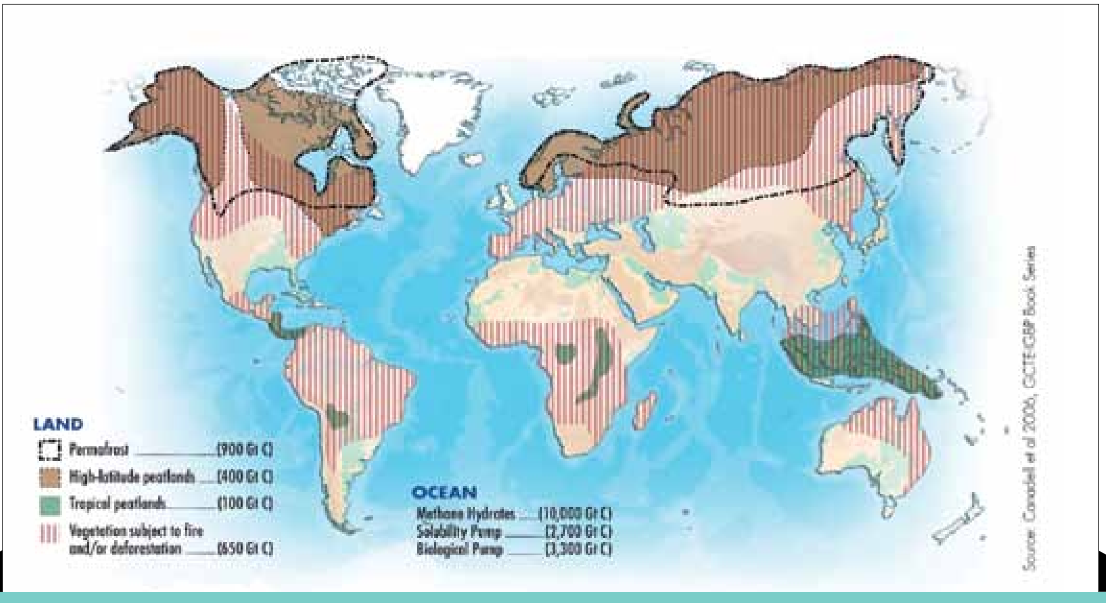
The scope of research envisioned by ESSP required expertise of the network of researchers affiliated with the four international global environmental change research programmes – IGBP, the International Human Dimensions Programme on Global Environmental Change (IHDP), WCRP and the international biodiversity programme DIVERSITAS. A series of focused projects and activities developed from this partnership, with major focus on the role of carbon and water in the Earth system and the impact of the environment on health and ecosystems.

For example, the Global Carbon Project (http://www.globalcarbonproject.org/)



Carbon pools vulnerability (courtesy of ESSP Global Carbon Project) conducts comprehensive and global research on the carbon cycle and its interactions with the human, biophysical and climate system, facilitates the coordination of national and regional carbon programmes and activities and leads a number of global syntheses and assessments to support international conventions and national agendas. The focus of the Global Water Project is on understanding the major modifications of the water cycle that are partly caused by increasing emissions of human-driven greenhouse gases and, thus, are expected to become larger during the 21st century.

A changing water cycle has impacts on carbon stocks and fluxes (e.g. soil and ecosystem respiration and production) and disturbance regimes (e.g. fire frequency and intensity). Global climate models predict, on centennial timescales, an increase of global precipitation, water stress in some regions, interannual variability and extreme events (e.g. droughts and floods).

Agriculture is a contributor to climate change, being directly responsible for some 12-14% of greenhouse-gas emissions, and is affected by climate variability and change. Farmers around the world are already facing an uncertain future as a result of rising temperatures, changing patterns of rainfall and the shifting distribution of pests and diseases. The Climate Change, Agriculture and Food Security project (CCAFS, http://ccafs.cgiar.org/) – another ESSP project – seeks to promote a food-secure world through the provision of science-based information to support sustainable agriculture and enhance livelihoods. In its first year of operation, CCAFS provided scientific evidence and tools to empower farmers, policy-makers, researchers and civil society to manage the agricultural and food system successfully in a changing climate.

Planet Under Pressure (http://www.planetunderpressure2012.net/) was a conference conceived, organized and conducted by ESSP in London, United Kingdom, in March 2012. It brought together, for the first time, more than 3 000 participants from the entire ESSP network, together with experts and stakeholders in the field of adaptation, development and risk management, to take stock of the current state of knowledge and the challenges ahead in development and application of science-based information for decision-makers.

The major outcomes of the Conference were presented as recommendations at the Sustainable Development Rio+20 Summit in Rio de Janeiro, Brazil, June 2012, including:

- Going beyond GDP by taking into account the value of natural capital when measuring progress;
- A new framework for developing a set of goals for global sustainability for all nations;
- The launch of a new international research programme entitled Future Earth: Research for Global Sustainability;
- Establishing regular global sustainability analyses and assessments.

8.2 Global Framework for Climate Services

The Third World Climate Conference (WCC-3) was convened from 31 August to 4 September 2009 in Geneva, Switzerland. It resulted in the establishment of the Global Framework for Climate Services (GFCS) to strengthen production, availability, delivery and application of science-based climate prediction and services. The GFCS is envisioned as having five major components (pillars):

- Observations;
- Research, modelling and prediction;
- Climate information system;
- Users' interface; and
- Capacity development as an all-encompassing component.

The feasibility of building the GFCS relies on the solid foundation of climate observations, research, modelling and prediction that has been built over the past few decades.

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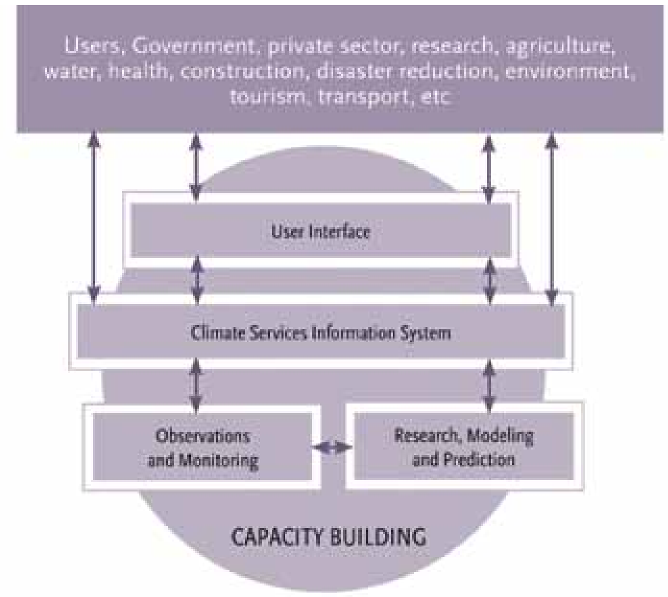
GFCS implementation will also require, however, additional targeted and user-focused climate research to satisfy the rapidly increasing needs for science-based climate information by a growing number of socio-economic sectors in all regions of the world. WCRP-affiliated scientists were actively engaged in developing the GFCS concept and they are expected to coordinate and contribute to the implementation of its research, modelling and prediction pillar.

Climate services are currently at the stage where NWP was about two decades ago. Many nations are in the early stages of formulating plans for climate service development. To address the complex and different set of requirements for climate services, WCRP began a dialogue with users to help identify the corresponding research priorities. A joint session of the WCRP Joint Scientific Committee (JSC) and the WMO Technical Commission for Climatology (Antalya, Turkey, 18 February 2010) reviewed observational and modelling research needs for improving seasonal-to-interannual predictions and enhancing the use of climate



A schematic of the components of the Global Framework for Climate Services with capacity-building occurring within and between all other components

information in impact, adaptation and vulnerability studies. To support the successful implementation of the GFCS, participants agreed to collaborate closely on the following issues of direct relevance to climate adaptation and risk management:

- Strengthening and mainstreaming research observations to serve as prototypes for future climate observing systems;
- Developing climate-prediction systems with lead times from seasons to centuries;
- Developing reliable high-resolution products for climate adaptation and risk management;
- Promoting interdisciplinary research to develop sector applications, tools and tailored information;
- Facilitating the flow of user requirements to the research community and climate service producers through user feedback;
- Supporting Regional Climate Centres, National Climate Services and the Climate Outlook Forums mechanism, as well as consensus assessments, such as the WMO Annual State of the Global Climate; and
- Improving the availability of highly skilled expertise to undertake climate research, operational prediction and communication, particularly in developing countries.

Based on the outcomes of this dialogue, WCRP developed an implementation plan for the research, modelling and prediction pillar of GFCS. In order to ensure timely and effective delivery of climate information to meet user needs, WCRP will lead significant experimental and theoretical work aimed at improving dataset and forecast quality, extending the forecast lead time and/or range for subseasonal-to-seasonal climate predictions, improving climate models and developing techniques for observations and data assimilation.

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For the GFCS to be successful, climate scientists must establish strategic partnerships with practitioners and users of climate information. Leading professional organizations in food and agriculture, water-resource management, disaster risk and human health must work together and with the WMO technical commissions to assess user requirements in their areas of expertise, availability of supporting research, data and information products and the current or future ability of climate science to satisfy the identified requirements.

The overall goal should be to transform the existing set of independent research and development activities into a coherent integrated process of developing the multitude of highly focused and useful products which will be in great demand for decision-makers and will have a market value for the private sector.

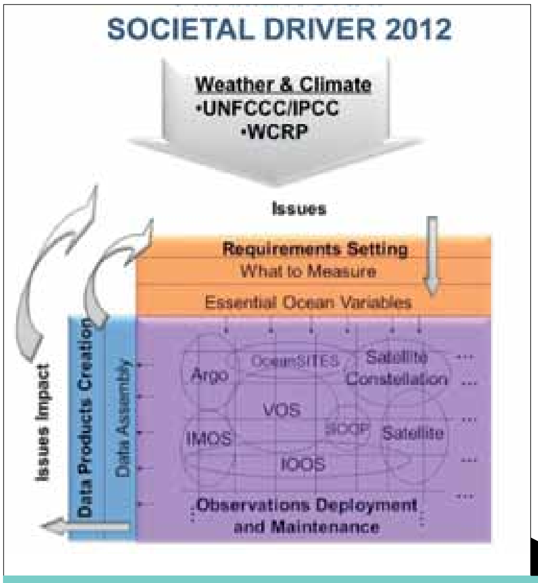
One major WCRP contribution to the GFCS is the provision of science-based climate information at the regional level. Climate anomalies tend to manifest themselves on the regional scale and most climate-related decisions are taken at regional, national and local level. To underpin regional climate service development, WCRP established a Working Group on Regional Climate and decided to focus its work on developing and providing the most important regional climate information. Specific requirements for regional climate products will be determined in coordination with WMO regional associations and other partners in areas of mutual interest.

One element of this activity is the provision of climate information services to least-developed and developing countries to support enhancement of their national climate-change adaptive capacity and introduce efficient climate risk-management strategies for a wide range of space- and timescales. The regional capacity-development activities described earlier will be an integral part of this effort supporting the implementation of the GFCS.

8.3 Oceans and societal needs

WCRP has been at the forefront of progress in satellite and in situ observing of the global oceans, development of ocean models and their coupling with the atmosphere and in developing useful scientific information for assessments of the state of the oceans. These efforts have been instrumental in building today's ocean observing systems that are key to our ability to understanding how oceans behave in the current climate and how they may affect and be affected by future climate.

The OceanObs'09 Conference was convened in September 2009, in Venice, Italy, to build a common vision for the provision of routine and sustained global information on the marine environment sufficient to meet society's needs. More than 600 participants from 36 nations came together under the sponsorship of UNESCO-IOC and a wide range of sponsors, including WCRP. The sponsors of, and participants in, OceanObs'09 pledged to work together towards an integrated ocean observing system. A limited-lifetime post-Conference working group was established to work in broad consultation with the international community to recommend a framework for moving global sustained ocean observations forward in the next decade with a major focus on integrating feasible new biogeochemical, ecosystem and physical observations, while sustaining present observations and considering how best to take advantage of existing structures.



Benefits of IFSOO: alignment of the requirement-setting processes, observing elements and data and information systems will increase societal benefits of the ocean observing system.

This resulted in the Integrated Framework for Sustained Ocean Observations (IFSOO). IFSOO and its coordination processes should be organized around essential ocean variables (EOVs) rather than by a specific observing system, platform, programme or region. The new EOVs will be carried out according to their readiness levels, allowing timely implementation of components that are already mature, while encouraging innovation and coordinated efforts to improve readiness of missing components and building overall capacity to implement them.

It is envisioned that IFSOO will: (a) improve communications and data-sharing across the community, resulting in faster and better-coordinated information to support both research and societal needs; (b) contribute to capacity-building and enhancement of ocean observations in developing countries; (c) increase confidence and support among sponsoring and funding entities; and (d) foster innovation and scientific discovery.

8.4 Weather, climate and environmental prediction – seamless approach

The scope and diversity of science-based information required for decision-makers calls for a "seamless" approach to research, modelling and prediction. This concept requires greater cooperation and coordination between the traditional disciplines of weather, climate, water, chemistry, physics, biology, etc. and a continuum in space and time that covers regions to globe and hours to decades and longer. The benefits to be accrued from such an approach derive from greater scientific progress in complex underlying processes to overcome some existing uncertainties in our knowledge, in order to improve the quality and availability of current services and to enable new ones. Such capabilities are instrumental for successful implementation of GFCS, Future Earth and IFSOO.

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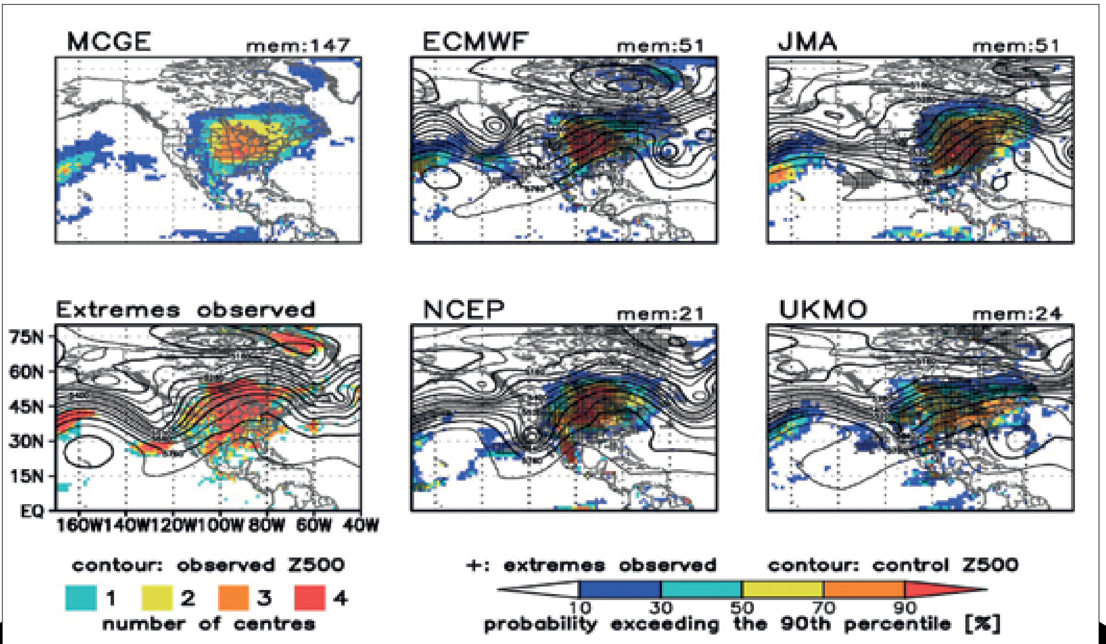
WCRP modelling groups are embracing the seamless approach and establishing joint activities in this context. For example, WGNE and WGCM plan to run climate models in weather-forecast mode (Transpose-AMIP, http://www.transpose-amip.info/) to enable detailed evaluation of the processes involved through a comparison of the model outputs with observations for particular meteorological events. In addition, understanding the development of biases as they grow from a well-initialized state can provide significant insights for future improvement of the model.

The centres which run both climate and NWP models in a unified system frequently find that model errors are common across timescales and that analysis and evaluation of NWP simulations for particular meteorological events can yield significant insight into the cause of such errors. Analysis in regions where extra observations are deployed can be particularly useful as the period over which the hindcasts are to be run has been chosen to tie in with the WCRP YOTC project, and the hindcast periods are aligned with one or more of the intense observing periods for VOCALS (VAMOS Ocean-Cloud-Atmosphere-Land Study), AMY and T-PARC (WMO World Weather Research Programme (WWRP) THORPEX Pacific Asian Regional Campaign).

Comparison with the CMIP5 experiments will enable investigation of whether model differences observed on longer timescales can also be seen on short ones and potentially gain knowledge of the underlying processes. This should allow a more thorough assessment of



Heatwave in North America (March 2012): occurrence probability of extreme warm temperature at 2 m as predicted nine days ahead by four different models compared with the observations (provided by Tetsuo Nakazawa, courtesy of THORPEX)

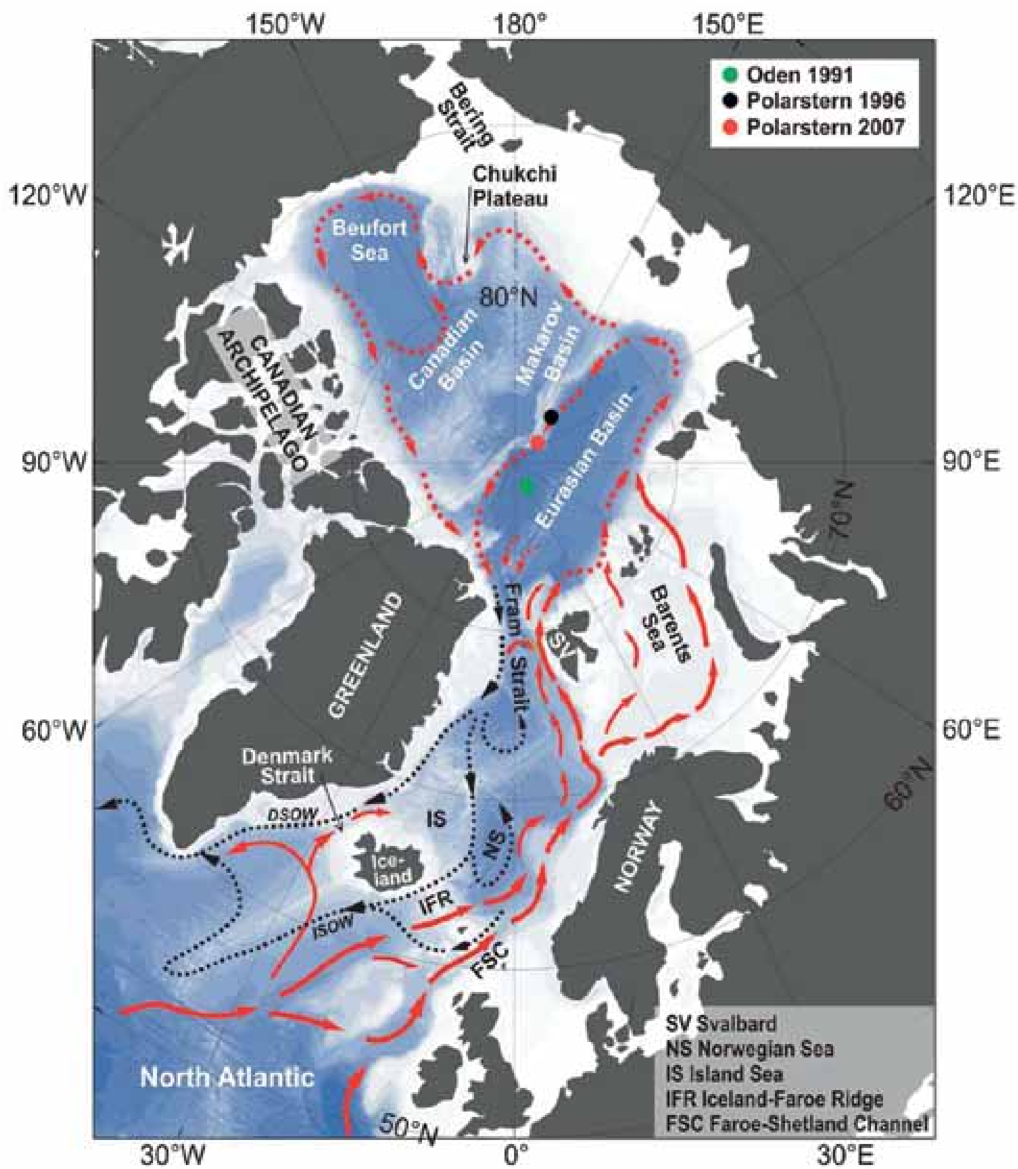
confidence in the controlling processes operating within the CMIP5/AR5 models.

Considerable progress has been made in improving the skill of medium-range weather forecasts and in developing operational seasonal forecasting, especially during the past decade. Forecasting in the intermediate range between the medium range (i.e. weeks to a month) and seasons is difficult as the importance of the initial conditions wanes and the importance of slower boundary conditions such as SST increases but has only a modest influence on the weather and climate, especially away from the tropical regions.

Tropical SSTs play an important role, not only in controlling the weather/climate in the tropics but also in the extra-tropics, through various teleconnections. For example, ENSO is the best-known long-lived source of predictability in the tropics but changes in SST in the Indian Ocean are also significant, though the forecast horizon is likely to be shorter than for ENSO. Predicting changes in equatorial Atlantic SSTs has been less successful.

Another long-lived atmospheric phenomena is MJO, which exerts a strong influence on tropical weather and climate, influencing extra-tropical weather through interactions with phenomena such as the North Atlantic Oscillation and other teleconnections. Considerable progress has been made recently in improving the representation of MJO, leading to improved predictability on the intraseasonal timescale.

The improvement stems primarily from better convective parameterization as compared to increased model resolution. These studies and other WCRP-coordinated



Physical mechanisms proposed for decadal climate predictability in the polar oceans are associated with the production of Denmark Strait overflow water (DSOW), which is a major source of North Atlantic deep-water formation. The North Atlantic inflows come through two entry points, the Faroe-Shetland Channel (FSC) and the Iceland-Faroe Ridge (IFR), and are then modified by surface fluxes while they transit through the Nordic seas. The figure (from Karcher et al., 2011) shows a schematic circulation of the mid-depth Atlantic derived water (red solid line) and dense, deep water (black dashed line). The Arctic Ocean and Barents Sea act as "switchyards" and add decadal-timescale delays to the system. These delays are variable in time and differ for surface and mid-depth waters. The latter results in transient anomalies of the water-density stratification that offer some predictive potential.

research activities suggest that there is a potentially useful predictability on subseasonal timescales, intermediate between weather and seasonal timescales and that it is worthwhile developing a research strategy to explore and exploit this potential.

The main goal of the new joint WCRP and WWRP Subseasonal to Seasonal Prediction project is to coordinate among operational centres the work for improving forecast skill and applications on the subseasonal timescale by bringing together the relevant activities of WCRP, WWRP and other potential partners. The subseasonal-to-seasonal scale is of special interest for societal and economic development and a wide range of decision-making.

Over the last few decades, the polar regions have exhibited some of the most striking changes due to – and also contributing to – climate variability and change. These complex feedback mechanisms in the polar climate system amplify the effects of greenhouse-gas-induced warming (so-called polar amplification): the Arctic is warming at a rate several times faster than the global mean. In contrast, the average Antarctic sea-ice extent is observed to be increasing slightly for reasons that are not completely understood.

The largest observed changes in the Antarctic climate have occurred during the summer season and are primarily attributed to changes in stratospheric ozone concentrations and extent. Models predict that the reversal of this process over the coming decades, as the stratospheric ozone layer recovers, will largely offset the effect of greenhouse-gas-induced warming on summertime southern hemisphere high-latitude regions. It is therefore likely that the observed summertime trends will weaken substantially or could even reverse over the next half-century. This is a major area of research for WCRP and its four Core Projects in the coming decade.

The strong coupling between the polar oceans, sea ice, troposphere and stratosphere calls for an interdisciplinary approach to research on polar climate systems. Moreover, natural climate variability in the polar regions is large and manifests itself in "modes of variability", whose physical nature and causality are not sufficiently well understood. This was the main motivation for WCRP to review the seasonal and multi-decadal predictability of polar climate as an interdisciplinary research topic.

The main goal of the new joint WCRP and the WWRP Subseasonal to Seasonal Prediction initiative is to coordinate among operational centres the work for improving forecast skill and applications on the subseasonal timescale by bringing together the relevant activities of WCRP, WWRP and other potential partners.

A WCRP workshop in Bergen, Norway, in October 2010, brought together a wide range of experts on polar climate variability and predictability, including all physical science disciplines, and covered a wide range of scientific methodologies such as making and analysing observations, developing theories, studying processes and performing prognostic and diagnostic model simulations. It identified polar climate research priorities, evaluated the current state of knowledge for these priorities and identified the observations, modelling and research needs for improving polar climate predictability. Based on these recommendations, WCRP, in partnership with the International Arctic Science Committee, is developing a plan of activities aimed at improving predictive capabilities for the polar regions.

This initiative will result in a set of specific, targeted activities ranging from focused workshops to coordinated modelling and field experiments that will be closely coordinated with a sister Polar Prediction Project of WWRP. The two initiatives comprise a major contribution to the emerging WMO-sponsored Global Integrated Polar Prediction System.

8.5 Future Earth: Research for Global Sustainability

Building on the success of existing ICSU co-sponsored global environmental change programmes (DIVERSITAS, IHDP, IGBP, WCRP and ESSP), Future Earth is a new 10-year international research initiative that will develop the knowledge for responding effectively to the risks and opportunities of global environmental change and for supporting transformation towards global sustainability in the coming decades. The initiative is scientifically sponsored by an alliance of partners, including ICSU, the International Social Science Council, the Belmont Forum of funding agencies, the United Nations University, UNEP and UNESCO, with WMO as observer.

The Future Earth initiative will answer fundamental questions about how and why the global environment is changing; what are likely future changes; what the implications are for the well-being of humans and other species; what choices can be made to enhance resilience, create positive futures and reduce harmful risks and vulnerabilities; and how this knowledge can support policy decisions and sustainable development.

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Future Earth will deliver cutting-edge research in an integrated and collaborative manner, including:

- Monitoring and forecasting changes in the Earth system, embracing climate, carbon, biodiversity and ecosystem services and human activities, building on current high-quality research partnerships and activities;
- Filling knowledge gaps and providing early warnings on the limits and tipping points of Earth's life-carrying capacity and how global environmental change may affect our ability to fulfill human needs for food, water, health, energy, etc.
- Connecting scientific knowledge effectively with policies and practices through, for example, research into the potential impacts of policy, behavioural and technology options;
- Providing major contributions to existing scientific assessments on global change, such as IPCC, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), ICSU, etc., and emerging ones;

- Supporting the assessment of progress made towards achieving goals for sustainable development;
- Fostering innovative approaches to integrate knowledge systems (data, observations, modelling, etc.);
- Supporting the development of new generations of researchers and fostering enthusiasm and skills to work across disciplines to promote a holistic approach towards sustainability.

Future Earth plans to develop a globally distributed network of knowledge nodes in order to be responsive to the needs and priorities of decision-makers at regional and national level, encourage broader participation of users in the global environmental change research agenda and activities and disseminate knowledge for sustainability across the globe.

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New challenges and exciting research require international partnership and coordination that yield "actionable information" for decision-makers.

9. Future plan and priorities

The WCRP science strategy calls for "actionable" climate science to support decision-makers who are confronted with the challenges and opportunities posed by the environment, energy and economic development associated with the impending rapid growth in world population for the rest of this century. To ensure adequacy of such information and its timely access and use, WCRP must engage in an active dialogue with these stakeholders and decision-makers in the design, development and dissemination phases of its research activities.

Such a symbiotic relationship will demonstrate the value of existing and newly developed scientific knowledge to WCRP constituencies and its affiliate network of scientists and projects in a timely and effective manner. It will also provide a feedback loop to researchers for improving existing products and services or developing new ones.

While research will remain the central tenet of WCRP, this new approach to identifying research priorities and implementing them will be a distinct departure from the way WCRP and its affiliate projects have carried out their activities in the past. WCRP and its Core Projects are thus organizing their subsidiary bodies and activities and forging alliances with new organizations so as to accomplish these tasks successfully.

WCRP leadership has identified six scientific grand challenges – based on the outcome of the WCRP OSC – for integrating the research activities coordinated by its four Core Projects to provide the envisioned "actionable" science to decision-makers on timescales ranging from seasons to a century and from global to regional space-scales. By definition, a grand challenge should be highly specific and focused, identifying a specific barrier to progress in a critical area of climate science.

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This focus enables the development of targeted research efforts with the likelihood of significant progress over five to seven years, even if its ultimate success is uncertain. It should thus enable the implementation of effective and measurable performance metrics.

By being transformative, a grand challenge should bring the best minds to the table, on a voluntary basis, building and strengthening communities of innovators that are collaborative, perhaps also extending beyond "in-house expertise". It should capture the public's imagination by teams of leading scientists working to solve pressing challenges and offer compelling solutions and storylines to engage the interest of the media and the public. The WCRP scientific grand challenges are:

- Provision of skillful future climate information on regional scales (e.g. decadal predictability);
- Regional sea-level variability and change;

- Cryosphere response to climate change (including ice sheets, water resources, polar predictability, permafrost and carbon);
- Improved understanding of the interactions of clouds and radiation (including the role of aerosols and precipitation and contributions to climate sensitivity);
- Past and future changes in water availability (with connections to water security and water-resources management);
- The science underpinning the prediction and attribution of extreme events.

WCRP must also focus its efforts on capacity development to ensure that future generations of affiliate researchers and research networks are equipped with the required expertise and capabilities to address these grand challenges. More effective partnership with its sister global environmental research programmes, new climate services providing organizations, development agencies and banks and research funding agencies will ensure timely access to required expertise and resources beyond WCRP's existing and immediate network of partners.

The WCRP strategy and approach to international research coordination in the future should also be responsive to the needs of its primary sponsors and their major initiatives such as the Global Framework for Climate Services, Future Earth and the Integrated Framework for Sustained Ocean Observations. We extend an open invitation to interested organizations and scientists that share this exciting vision of bringing together the best scientific expertise and knowledge from around the world and developing a solution-based approach to addressing contemporary global, regional and local environmental challenges in the service of global society.

We believe that this is the best gift that we can offer to our generation, our children and their children.

Ghassem R. Asrar, Director
Antonio J. Busalacchi, Chair

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Argentina
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Serbia
South Africa
Spain
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Switzerland
Turkey
United Kingdom
United States of America

Acronyms

AABW	Antarctic bottom water
ACE	Attribution of Climate-related Events
AIMES	Analysis Integration and Modelling of the Earth System (IGBP)
AMIP	Atmospheric Model Intercomparison Project (WCRP)
AOGCM	Atmosphere-Ocean Global Circulation Model
AMAP	Arctic Monitoring and Assessment Programme
AMMA	African Monsoon Multidisciplinary Analysis
AMOC	Atlantic Meridional Overturning Circulation
AMY	Asian Monsoon Years
AOGCM	Atmosphere-Ocean Global Circulation Model
APN	Asia-Pacific Network for Global Change Research
AR4	IPCC Fourth Assessment Report
AR5	IPCC Fifth Assessment Report
CACGP	international Commission on Atmospheric Chemistry and Global Pollution
CAS	Commission for Atmospheric Sciences (WMO)
CCAFS	Climate Change, Agriculture and Food Security
CCCma	Canadian Centre for Climate Modelling and Analysis
CCM	chemistry-climate model
CCMVal	Chemistry-Climate Model Validation Project (SPARC)
CCN	cloud condensation nuclei
CEOP	Committee on Earth Observation Satellites
CHFP	Climate system Historical Forecast Project
CINDY2011	Cooperative Indian Ocean Experiment on interseasonal Variability in the Year 2011
CliC	Climate and Cryosphere Project (WCRP)
CLIVAR	Climate Variability and Predictability Project (WCRP)
CMIP	Coupled Model Intercomparison Project (WCRP)
CORDEX	Coordinated Regional Climate Downscaling Experiment
DIVERSITAS	An international programme of biodiversity science (ICSU/IUBS/SCOPE/UNESCO)
DYNAMO	Dynamics of the Madden-Julian Oscillation
ECS	early career scientist
ECV	Essential Climate Variable
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño-Southern Oscillation
EOV	essential ocean variables
ERAinterim	ECMWF interim Re-Analysis
ESA	European Space Agency
ESC	equivalent stratospheric chlorine
ESGF	Earth System Grid Federation
ESM	Earth System Model
ESSP	Earth System Science Partnership

FCDR	Fundamental Climate Data Records
FE	Future Earth: Research for Global Sustainability (ICSU)
GCOS	Global Climate Observing System (WMO/UNESCO-IOC/ICSU)
GDP	Gross Domestic Product
GEWEX	Global Energy and Water Cycle Experiment (WCRP)
GFCS	Global Framework for Climate Services
GHA	Greater Horn of Africa
GHG	greenhouse gas
GPCP	Global Precipitation Climatology Project (WCRP)
GSQs	Grand Science Questions (WCRP/GEWEX)
HE	High Elevation (GEWEX)
HyMeX	Hydrological Cycle in the Mediterranean Experiment
IAI	Inter-American Institute for global change research
IASC	International Arctic Science Committee
ICPAC	Inter-Governmental Authority on Development (IGAD) Climate Prediction and Applications Centre
ICSU	International Council for Science
IFSOO	Integrated Framework for Sustained Ocean Observations (UNESCO)
IGBP	International Geosphere-Biosphere Programme (ICSU)
IHDP	International Human Dimensions Programme on Global Environmental Change
IOC	Intergovernmental Oceanographic Commission (UNESCO)
IPCC	Intergovernmental Panel on Climate Change (WMO/UNEP)
IPO	Interdecadal Pacific Oscillation
IUBS	International Union of Biological Sciences
JMA	Japan Meteorological Agency
JPS	Joint Planning Staff (WCRP)
JSC	Joint Scientific Committee (WCRP)
LPB	La Plata Basin
MCGE	Multi-Center Grand Ensembles
MDB	Murray Darling Basin
MedCLIVAR	Mediterranean Climate Variability and Predictability
MERRA	Modern Era Retrospective-analysis for Research and Applications
MJO	Madden-Julian Oscillation
MMM	Multi-model mean
NASA	National Aeronautics and Space Administration (USA)
NCAR	National Center for Atmospheric Research (USA)
NCEP	National Centers for Environmental Prediction (USA)
NEESPI	Northern Eurasia Earth Science Partnership Initiative
NWP	numerical weather prediction
ODS	ozone-depleting substance
OSC	Open Science Conference (WCRP)
RAMA	Research Moored Array
RCD	regional climate downscaling
RCM	Regional Climate Model
RCP	Representative Concentration Pathway (WCRP)
REOS	Repository for Evaluation of Ocean Simulations (WCRP/CLIVAR)
RHP	Regional Hydroclimate Projects (WCRP/GEWEX)
SCAR	Scientific Committee on Antarctic Research (ICSU)

SCOPE	Scientific Committee on Problems of the Environment
SMHI	Swedish Meteorological and Hydrological Institute
SOLARIS	Solar Influences for SPARC
SPARC	Stratospheric Processes and their Role in Climate (WCRP)
START	Global Change System for Analysis, Research and Training
SST	sea-surface temperature
SWIPA	Snow, Water, Ice and Permafrost in the Arctic
TAO	Tropical Atmosphere Ocean (WCRP)
THORPEX	The Observing System Research and Predictability Experiment (WMO/WWRP)
TRITON	Triangle Trans-Ocean Buoy Network (TAO project)
TRMM	Tropical Rainfall Measuring Mission (NASA)
UCAR	University Corporation for Atmospheric Research (USA)
UKMO	United Kingdom Met Office
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
VAMOS	Variability of the American Monsoon System (WCRP/CLIVAR)
VOCALS	VAMOS Ocean Cloud Atmosphere Land Study
WAM	West African Monsoon
WCRP	World Climate Research Programme (WMO/ICSU/IOC)
WDAC	WCRP Data Advisory Council
WDCC	World Data Centre for Climate
WGCM	Working Group on Coupled Modelling (WCRP)
WGNE	Working Group on Numerical Experimentation (WCRP/CAS)
WGSIP	Working Group on Seasonal to Interannual Prediction (WCRP)
WMAC	WCRP Modelling Advisory Council
WMO	World Meteorological Organization
WWRP	World Weather Research Programme (WMO)
YOTC	Year of Tropical Convection (WCRP/WWRP/THORPEX)