An Earth-System Prediction Initiative for the 21st Century

Melvyn Shapiro[1], Jagadish Shukla[2], Michel Béland[3], John Church[4], Kevin Trenberth[5], Randall Dole[6], Richard Anthes[7], Brian Hoskins[8], Guy Brasseur[9], Mike Wallace[10], Gordon McBean[11], Antonio Busalacchi[12], Ghassem Asrar[13], David Rogers[14], Gilbert Brunet[15], Leonard Barrie[16], David Parsons[17], David Burridge[18], Tetsuo Nakazawa[19], Martin Miller[20], Philippe Bougeault[21], Zoltan Toth[22], Jerald Meehl[23], Mitch Moncrieff[24], Hervé Le Treut[25], Alberto Troccoli[26], Tim Palmer[27], Jochem Marotzke[28], John Mitchell[29], Adrian Simmons[30], Brian Mills[31], Øystein Hov[32], Haraldur Olafsson[33], Takeshi Enomoto[34], Jim Caughey [35], Louis Uccellini[36] and Arlene Lang[37].

---

[1] Cooperative Institute for Environmental Sciences, University of Colorado, Boulder CO, USA, Geophysical Institute, University of Bergen, Bergen, Norway, National Center for Atmospheric Research (NCAR), Boulder CO, USA; [2]Professor, George Mason University (GMU), and President, Institute of Global Environment and Society (IGES), USA; [3]President, WMO Commission on Atmospheric Sciences (CAS) at Environment Canada's Atmospheric Science and Technology Directorate, Montreal, Canada; [4]Centre for Australian Weather and Climate Research, a partnership between the Bureau of Meteorology and CSIRO, Hobart, SIRO, Australia; [5]Chair, World Climate Research Progamme (WCRP) Observations and Assimilation Panel at the National Center for Atmospheric Research (NCAR), Boulder CO, USA; [6]NOAA Earth System Research Laboratory, Boulder CO, USA; [7]President of the University Corporation for Atmospheric Research, Boulder CO, USA; [7]Head, Dynamical Processes Group, Dept. of Meteorology, Univ. of Reading, UK; [9]Director, Earth and Sun Systems Laboratory and Associate Director of NCAR, Boulder CO, USA; [10]Professor, Dept. of Meteorology, Univ. of Washington, Seattle WA, USA; [11]Professor, Institute for Catastrophic Loss Reduction at University of Western Ontario, London, Ontario, Canada; [12]Chair, WCRP Joint Scientific Committee, Earth System Science Interdisciplinary Center (ESSIC), Univ. of Maryland USA; [13]Director, WCRP, Geneva, Switzerland; [14]President, Health and Climate Foundation, Washington, D.C., USA; [15]Chair, WMO-WWRP Joint Steering Committee and Research Director of Environment, Canada; [16]Director, WMO-WWRP, Geneva; [17]Chief, WMO-WWRP, Geneva; [18]Chair, WMO-THORPEX International Core Steering Committee, Geneva; [19]Chair, Asian Regional Committee for THORPEX, Meteorological Research Institute, Japan Meteorological Agency, Japan; [20]Chair, WMO-CAS/WCRP Working Group on Numerical Experimentation (WGNE) at ECMWF, Reading, UK [21]Head of Research, ECMWF, UK; [21]NOAA/NCEP environmental Modeling Center, USA; [22]NOAA/NCEP Environmental Modeling Center, USA; [23]NCAR, USA; [24]Co-chair, Year Of Tropical convection (YOTC), NCAR, Boulder CO, USA; [25]Directeur du Laboratoire de Météorologie Dynamique, France; [26]; Environmental Systems Science Centre, University of Reading, Reading, UK; [27]Head Probability Forecasting and Diagnostics Division, ECMWF, UK; [28]Director, Max Planck Institute for Meteorology, DE; [29]Met. Office, UK; [30]Chair GCOS/WCRP Atmospheric Observation Panel for Climate and ECMWF; [31]Adaptation and Impacts Research Division, Environment Canada; [32]Director of Research, Norwegian Meteorological Institute, Oslo, Norway; [33]University of Iceland and University of Bergen, Norway, [34]Earth Simulator Center and, Japan Agency for Marine-Earth Science and Technology, Japan; [35]Scientific Officer, THe Observing-system Research and Predictability Experiment (WWRP-THORPEX), Geneva; [36]NOAA/NCEP Environmental Modeling Center, USA; NCAR , [37]Boulder CO, USA.

Capsule: An international multi-disciplinary prediction initiative to accelerate advances in knowledge, use and value of weather, climate and Earth-system information.

1. Introduction

We stand at the threshold of accelerating advances in the prediction of high impact weather and climate and the complex interaction between the physical-biological-chemical *Earth system*[2] and global societies (NRC 2007, 2008). This opportunity stems from notable achievements in monitoring and predicting weather hazards and climate variability and change, and in the use of this information. As examples, forecasts on spatial scales of a few kilometers provide timely and accurate warnings of flooding rainstorms, river flows, tornados, storm surges, hurricane track and landfall and air-quality emergencies. Global 5-day forecasts now have an accuracy comparable to 2-day forecasts of 25 years ago (Fig. 1), with an increasing ability to identify the possibility of extreme weather 7 to 10 days in advance. Seasonal forecasts provide useful information on the development of El Niño/La Niña and their influence on regional weather, such as shifts in the North Pacific storm track. Assessments and projections of global temperature, sea level, ice and precipitation over decades to centuries were critical in establishing the human influence on climate change and provided the scientific underpinning for international action to reduce greenhouse gas and aerosol emissions; Meehl et al. 2007. Risk, impact, adaptation, mitigation and assessment models have become increasingly important in exposing potential vulnerabilities and evaluating the outcomes of different decisions. These accomplishments are among the most significant scientific, technological and societal achievements of the 20th century.

CDC NOAA 5/11/09 3:37 PM
Deleted: -

CDC NOAA 5/11/09 3:37 PM
Deleted: ,

Recognizing the necessity to capitalize on these achievements, delegates from the World Meteorological Organization (WMO), World Climate Research Program (WCRP) and International Geosphere-Biosphere Programme (IGBP) proposed an Earth-system Prediction Initiative at the Group on Earth Observations (GEO) Summit, 2007, Cape Town, South Africa (Shapiro *et al*. 2007). The Initiative would provide the international framework for revolutionary advances in Earth-system prediction and help managers of disaster risks, public health and food security, water supply, energy, and environmental policy minimize the impacts of extreme weather and climate. This global endeavor is as challenging as the International Space Station, Genome Project, and Hubble Telescope, with a high societal benefits-to-cost ratio. It will contribute to international programs for observations, prediction and warning (which program has the warning responsibility? Might be worth mentioning this hazards activity that Goirdon McBean is involved with??, such as the Global Climate Observing System (GCOS), WCRP, World Weather Research Programme (WWRP), and hence to the Global Earth Observation System of

[2] The Earth-system encompasses the atmosphere and its chemical composition, the oceans, land/sea-ice and other cryosphere components; the land-surface, including surface hydrology and wetlands, lakes and human activities. On short-time scales, it includes phenomena that result from the interaction between one or more components, such as ocean waves and storm surges. On longer time scales (e.g., climate), the terrestrial and ocean ecosystems, including the carbon and nitrogen cycles and slowly varying cryosphere components (e.g., the large continental ice sheets and permafrost) are also part of the Earth-system.

Systems (GEOSS). It will build upon the International Council for Science (ICSU), International Ocean Commission (IOC), WMO, World Health Organization (WHO) and GEO, to coordinate the effort across the weather, climate, Earth-system, natural-hazards, and socioeconomic communities.

This article presents the rationale for this Initiative, while the companion papers in this issue (Brunet *et al.* 2009, Moncrieff *et al*. 2009, Shukla *et al.* 2009, and Nobre et al. 2009) introduce key aspects of the Initiative from various research and institutional perspectives.

2. Rationale

Hurricane Katrina, the deadly 2003 European heat wave, the multi-decadal drought south of the Sahel, and the unprecedented wildfires in Australia in 2009 confirm the vulnerability of modern society and the environment to adverse weather and climate. In fact, 75 percent of natural disasters are triggered by extreme weather and climate[3]. To counter this vulnerability with effective mitigation and adaptation requires accurate prediction at global, regional and local scales. Furthermore, today's observation and prediction systems are increasingly applied to address specific needs of environmentally sensitive sectors and resources, including energy, water, human health, transportation, agriculture, fisheries, leisure, ecosystems, biodiversity, and national security. Probabilistic predictions provide quantitative measures of the likelihood of occurrence and severity of different outcomes, including potentially catastrophic extremes. These capabilities yield substantial benefits, because they enable rational decisions that reduce human, economic and environmental losses, and also maximize economic opportunities. The opportunities include selection of optimal trade routes, energy allocation, crop selection, and pollutant emission mitigation strategies. These achievements and opportunities are the culmination of investments by governments, international agencies and other stakeholders in underpinning science and technology and their transition to operational services. These investments greatly expanded our capability to observe the atmosphere, oceans, land and cryosphere, including bio-geochemical properties. High performance computers, global communications, and improvements in numerical methods, have been crucial to advances in predictions and applications. Investments in research have advanced knowledge of atmospheric and oceanic predictability and provided insight into the requirements for addressing the influence of climate variability and change on regional high-impact weather. We foresee the potential to respond more effectively and realize even greater benefit from these and future investments (NRC 2007).

CDC NOAA 5/11/09 3:40 PM
Deleted: ,

CDC NOAA 5/11/09 3:40 PM
Deleted: ,

The societal and environmental vulnerability to regional weather extremes within a changing climate, and projections that these extremes will increase in coming decades (Meehl *et al.* 2007; CCSP, 2008) increases the urgency for advancing mitigation and adaptation capabilities. It is also imperative that we address the uncertainty of climate-

[3] (http://www.unisdr.org/eng/media-room/facts-sheets/2008-disasters-in-numbers-ISDR-CRED.pdf)

change predictions and scenarios. We must better inform climate-change mitigation policies, in particular, carbon sequestration and its interaction with other biogeochemical cycles like reactive nitrogen. This requires introduction and more accurate representation of key processes, such as the Earth/ocean methane release and glacial and sea-ice melting.

There exists a parallel urgency in addressing adaptation. While mitigation is a global problem, adaptation is a local or regional issue. Present suites of climate models are largely incapable of providing this level of detailed information. There is a corresponding need to advance predictive skill and diversify forecast applications on hourly-to-seasonal time scales. Accelerated progress will optimize policy and risk management decisions valued at billions of dollars. The potential to accelerate further advances depends critically on cooperation across many nations, international organizations and scientific disciplines.

To address these fundamental challenges, it is essential to move beyond individual disciplinary boundaries toward a more comprehensive Earth-system approach, with predictive capability that considers connections among different system components and across time scales. The connectivity between climate, weather, land-surface properties, biochemical processes, human health and ecosystems is exemplified by the regional-to-global impact of Saharan sand and dust storms; Fig. 2. These storms, and those of the other great deserts, e.g., the Gobi of China, are a major source of tropospheric aerosols that represent a significant component in the atmospheric regional-to-global radiative balance, thereby affecting climate e.g., Kaufman, *et al.* 2002; Li, *et al.* 2004. Variations in seasonal to sub-seasonal climate circulations, such as the negative phase of the North Atlantic Oscillation (NAO), deflect the North Atlantic storm track southward into the Mediterranean and North Africa, where individual cyclones become catalysts for massive sand and dust events, such in Fig. 2. Cyclone interactions with mountains of North Africa contribute to localized enhancements of the desert winds through mountain waves over the Atlas and Haggar ranges, and enhanced surface wind around the smaller Tibesti and Ajir mountains; Todd, *et al,* 2005. In addition, the large amplitude diurnal temperature cycle over the Sahara modulates the depth of the planetary boundary layer and hence the diurnal concentration of sand and dust; Schepanski, *et al*. 2007. When transported westward over the Atlantic, Saharan dust may affect development of tropical cyclones (Evan *et al* 2006) and replenish nutrients in the soils of the Amazon, which is critical to the sustainability of the rain forest. Northward transport is a major source of aerosols to Europe impacting visibility, health and local weather, e.g., temperature and precipitation. Saharan dust provides nutrients to ocean biota, whose concentrations modulate the opacity of the upper ocean and its radiative characteristics and the oceanic uptake of carbon dioxide, providing another feedback to the climate system. Saharan aerosols are under investigation as major contributors to central African meningitis epidemics that can affect 250,000 people each year.

In short, this is not simply a weather problem or climate problem, or an atmosphere, ocean, land surface, chemistry or biology problem – it is all of these and more. Comprehensive understanding of such events and their consequences requires consideration of the interactions among the different Earth system components, including the interactions with and implications for humankind.

The possibility of "climate surprises", i.e., unexpected rapid climate changes outside of current climate models projections, presents another important example of the necessity for developing a comprehensive Earth system approach. Rapid climate change is a major scientific challenge and a central concern for decision makers, with potentially enormous implications for society and the environment. Possible triggers for rapid changes include relatively fast processes in the Earth system, such as changes in biology through enhanced methane release associated with melting permafrost; changes in sea ice extent, with minimum Arctic sea ice extent having declined approximately 30 percent within the last 29 years; and changes in hydrological processes, NRC, 2002; CCSP, 2008. Rapid changes typically involve feedbacks among different components of the Earth system, necessitating more comprehensive and integrative approaches to address this challenge. Reducing the likelihood of future climate surprises requires improved observations and monitoring of Earth system components and their interactions, advances in understanding the causes for rapid changes, and substantial improvements in modeling, including incorporation of processes not present in current generation climate models; CCSP 2008. Because of the rapid nature of component interactions, joint studies of weather, climate and earth-system phenomena are very informative as to possible responses and feedbacks among the different system components, as in the case of Saharan dust storms.

3. A holistic approach

Earth-system sciences, and mitigation and adaptation strategies require a suite of diagnostic and prediction models integrated over all spatial and temporal scales (Dole 2008; Palmer *et al*., 2008; Brunet *et al,* 2009; Hurrell *et al*. 2009; Meehl *et al.* 2009). This holistic approach is ***spatially and temporally continuous***, spanning highly-localized cloud systems to global circulations, from minutes to millennia; linking mesoscale weather life cycles and climate variability and change. It is ***integrated across the disciplines*** of physics, mathematics, chemistry, social and decision sciences, and their Earth-system elements. It requires ***coordination and support*** across academic institutions, government research and service agencies, private enterprise providers, hazard risk-reduction and adaptation agencies, NGOs, and humanitarian organizations. It ***bridges political boundaries*** from municipalities to nations to the world. Within this framework, socioeconomic and environmental requirements play a leading role in the design and implementation of a new generation of science-based global to regional early warning and planning systems.

In order for weather, climate and Earth-system information to have timely and beneficial impacts, it must have the following elements: ***content*** with accuracy and precision in space and time, and relevance of product information to the users, including a quantified estimate of its accuracy, and probability of occurrence of particular events; ***distribution*** of products on spatial and temporal scales sufficient for action; ***communication*** with product formats that users can comprehend and interpret; ***integration of information*** into user decision-support systems; ***recognition*** by users that the information has value; and

response to the information. These elements are links along a chain of action. If any link is weak or broken, then the impact and the value of the information will be diminished. Socioeconomic research and its applications can identify ways to strengthen these links and lead to the development of new methods for enhancing the use and value of weather, climate, Earth-system, and socioeconomic information.

4. Core elements

The *Earth-system Prediction Initiative* will provide the basis for more skilful predictions with known confidence through advanced observing capabilities, data assimilation, diagnostic and prediction models of weather, climate and Earth-system processes, their interactions and their past, present and future fluctuations and change, including the ways in which predictions inform and affect decision-making frameworks. The research required to achieve these objectives will focus on:

Climate and weather observations to monitor the properties and evolution of the Earth system in every respect, as well as the changes in forcing of the system. The observations must satisfy the climate principles promoted by GCOS for the design/implementation of observations as an element of GEOSS. They must be anchored with benchmark measurements and strive for accuracy, noting that continuity is a primary requirement for reliable detection of global-to-regional anomalies. This requires stemming the ongoing decline in surface and upper-air global observing networks and the development and implementation of a new generation of *in-situ* and space-based systems to meet the ever increasing observational demands of the prediction and early warning systems of today and in future generations. A comprehensive coordinated observing system is the backbone of this Earth information system; Trenberth 2008.

CDC NOAA 5/11/09 3:54 PM
Deleted: -

Coupled high-resolution global and regional data assimilation and analysis systems that integrate observations of the atmosphere, ocean, land and ice from space-based, aircraft, and ground-based observing platforms across the full suite of Earth system modeling components. The Global Monitoring for Environmental and Security (GMES) initiative (Hollingsworth *et al.* 2008), Fig. 7, exemplifies a step in this direction. This process provides the basis for the analysis and reanalysis (as systems improve and more historical data are recovered) of the long-term observational record that is required for monitoring and assessing past events and change, including their socioeconomic impacts. It provides the basis for the analysis of present conditions for initializing new predictions and for verifying earlier predictions. An important aspect linking all these core elements is the performance of Observing System Simulation Experiments to assess the role and value of new observations an measurement platforms in support of Earth system monitoring and prediction.

Advanced prediction models that capture the complex interaction among the atmosphere, oceans, and other components of the Earth system and the human dimension. These models must have sufficient resolution to faithfully represent the multi-scale processes of the Earth-system appropriate for the spatial scale of the applications (Figs. 4, 5); see Brunet *et al.* 2009 and Shukla *et al.* 2009, this issue. They will have to incorporate increasingly diverse components of the Earth system; for example, the next IPCC assessment will include, for the first time, models with interactive carbon cycles. To address challenges such as the potential for rapid changes in sea level beyond current IPCC projections, future models will have to incorporate dynamical ice sheet components to better assess the potential for accelerated ice loss. In the long run, it is likely that human interactions with the system will be modeled as well. Addressing needs for increased model resolution and complexity will require substantial increases in computing capacity beyond current generation global NWP and/or IPCC models, as discussed in more detail below.

Attribution and diagnostic studies to determine causes of past and current conditions including extreme events, such as severe droughts, heat waves, and cyclone frequency, intensity and tracks. Distinguishing between natural variability and human-forced long-term trends is vital to informing both adaptation and mitigation decisions. Establishing attribution requires good estimates of different process forcing, including ensemble model experiments of sufficient size to determine the most likely cause or causes for features of interest at a specified level of confidence. Attribution studies address the predictability of the system, the odds of the observed anomalies and extremes being realized, and the confidence that can be placed in the predictions. This element includes performance assessment and analysis of detailed numerical simulations of weather, climate and Earth-system processes conducted under the WWRP, WCRP, WGNE, GAW, ICSU, IOC and WMO-sponsored programs.

Modern information systems to provide timely, user-friendly, and issue-targeted production of weather, ocean, climate and Earth-system information crucial in assisting decision-making processes for risk reduction and adapting to weather and climate events, developing mitigation policies and achieving sustainable development. This necessitates engagement of the users of environmental information to assess and incorporate their requirements, see, e.g., ICSU 2008.

Fostering multi-disciplinary collaborations and applications that encourage scientists in natural sciences to interact with colleagues from health, economic, water, agriculture, energy, food, and policy disciplines. Recent examples are the Meningitis Environmental Risk Information Technologies (MERIT) project[4] and the UCAR Africa Initiative[5] on tropical health/climate/weather linkages. Collaborations such as the WCRP and WWRP-THORPEX Year of Tropical Convection (YOTC) are engaging the weather and climate communities to improve the prediction of the multi-scale organization of tropical precipitating cloud systems (Fig. 3), see Brunet, *et al.* 2009 and Moncrieff *et al.* 2009, this issue. The 2007-2008 International Polar Year (IPY)[6] included a multidisciplinary approach to marine biology issues, ocean and atmospheric physics, chemistry, and social sciences. These recent collaborations provide a template for future efforts.

[4] http://www.hc-foundation.org
[5] http://www.africa.ucar.edu/index.html
[6] http://www.ipy.org/

Data and forecast archives to provide an internationally-coordinated Earth information system (see NRC 2003) to store and manage data and enable access to global-to-regional operational and historical analyses and forecasts of weather, air quality, climate, other Earth-system components and socioeconomic impacts, commensurate with the highest resolution achievable, given near-term observational and computational constraints. The archive should facilitate advanced analysis and visualizations of observed and predicted events, including assessment of the effectiveness of mitigation and adaptation actions.

High-performance computing (HPC) is crucial to accelerate advances in prediction models and their socioeconomic applications. These models are links in a chain, involving access to billions of time-dependent observations that fuel data-assimilation systems, which in turn provide the initial conditions to a series of prediction and projection models. The scope ranges from minutes to hours for severe weather events, to decades and centuries for climate change scenarios and ecosystem impacts. Advanced HPC will facilitate high-resolution ensemble prediction systems that include many hundreds of possible predictions and projections. These models will incorporate more realistic processes and a high degree of Earth-system complexity, including two-way interactions between society and predicted responses. This requires dedicated facilities with sustained speeds well beyond that of the most advanced computers of today, but which are achievable within the next 10-20 years, see Shukla *et al.* 2009, this issue. Realizing the full research and operational benefits of HPC will require advanced data processing and visualization methods, user-friendly high-speed and broad-bandwidth communication and common data formats. It will include training of scientists in the use of advanced computer systems and integrated data-distribution systems that facilitate access to most information in near real time. It will also require the development of advanced numerical methods and software systems to enable modelling systems to fully exploit the capacity of future generations of supercomputers.

5. Deliverables

The proposed Earth-system Prediction Initiative will:

- Accelerate advances in forecast skill for daily to inter-annual high-impact weather and climate, including the potential frequency, intensity and tracks for winter storms and tropical cyclones, the onset and cessation of regional heat and cold waves, droughts and floods. It will contribute to mitigation and adaptation strategies required for management of energy, water, food production, health, the economy, emergency response and the support of other environmental and socioeconomic strategic planning. It places a high priority on early-warning systems to reduce vulnerability to famine, water shortage, pestilence and disease in developing nations and promote social and economic development.

- Improve observations, projections, and predictions of multi-decadal, global-to-regional climate and coupled Earth-system change including estimates of the frequency and intensity of extreme regional events and the full range of socioeconomic and environmental outcomes, including assumptions, confidence and uncertainty. This will provide the foundation for science-based adaptation and mitigation strategies and sustainable development of global societies.

- Predict and assess the responses and possible unintended consequences of emerging geo-engineering alternatives (Fig. 6) for controlling climate variability and change, e.g., Keith 2001; Angel 2006; Crutzen 2006; Latham *et al.* 2008; Robock 2008.

- Contribute to the development of emerging national and international climate services.

6. The Way Forward

In order to succeed, the Earth System Prediction Initiative requires:

Interdisciplinary research and applications: this demands *intellectual respect* across the scientific disciplines; *collaboration* between those who excel in their own field; *joint proposal development* guided by multi-agency and multi-national environmental and socioeconomic priorities; *long term commitments* from scientists, supporting agencies and stakeholders. It will benefit from the establishment of nation and international *research centers* with access to sufficient computing capability, scientific and technical resources to develop and implement research objectives on the scale envisioned, including drawing upon the broad expertise in universities, private industry, governments and other research centers; see Shukla *et al.* 2009b, this issue.

Excitement and challenge: The endeavour must not only motivate the scientific community, but communicate the importance and the character of its multi-generational impacts and benefits. Most importantly, it must capture the hearts and inspire the minds of young scientists.

Global and regional engagement: The nature and complexity of the scientific and socioeconomic challenges, and the resources, intellect, technology, and infrastructure requires partnerships for the successful development and implementation of the *Initiative*. In this context, the success of the Global Atmospheric Research Program, GARP (see Döös 2004; Uppala *et al*. 2004) provides a template for the successful outcome of global engagement. GARP was the catalyst for great advances in knowledge, global observations and prediction of the coupled atmosphere-ocean circulations in late 20th century. The ECMWF pooled scientific and management capabilities of the Europe to advance medium-range deterministic and probabilistic forecast skill, and the fundamentals of data assimilation, deterministic and ensemble (probabilistic) weather forecasting to a level of success that would not have been achievable if undertaken by a single nation. The Initiative requires champions to inform governments and other stakeholders of the urgency of supporting the effort, recognizing that such enterprises take years to succeed. In this vein, international organizations and agencies are currently coordinating activities that embrace components of the proposed *Initiative*. These activities include:

- GEO as an international coordination framework across disciplines, and observational, prediction, and information systems, that will advocate for advancing climate, weather, water and Earth-system prediction. GEO aims to implement the GEO 2009-2011 Work Plan, and several tasks relevant to this *Initiative*, e.g. Task CL-09-01: *Environmental Information for Decision-making, Risk Management and Adaptation*[7].

- The World Meteorological Organization, sponsor of the World Weather Research Programme (WWRP), the Global Atmosphere Watch (GAW) air chemistry research programme and co-sponsor of GCOS and the World Climate Research Programme (WCRP) are implementing the concepts outlined in this article. In June 2008, the Executive Council of WMO commissioned a *Task Team On Research Aspects Of An Enhanced Climate, Weather, Water And Environmental Prediction Framework* to prepare a strategy focusing on strengthening prediction research and related scientific assessments in support of enhanced climate, weather, water and environmental services in the next decade for consideration by the National Hydrological and Meteorological Services and their research partners. This report is now available on the WMO web site, as well as a set of recommendations to implement the vision expressed in the document **(Need citation here)**. The WWRP and WCRP joint scientific committees are coordinating these recommendations linking global weather and climate research.

- The engagement of ICSU, through its co-sponsorship of GCOS and WCRP and its academic constituency.

7. The Grand Challenge

The proposed Initiative will require unprecedented international collaboration and good will, making the global scope of the problem inescapable. All nations stand to benefit from its success. As nations, we have collaborated to advance global observing systems, weather forecasting, climate prediction, communication networks, and emergency preparedness and response. We must now extend this collaboration to embrace the full Earth-system and the next frontier of socioeconomic and environmental applications of our science. Our community and its supporting organizations are poised for the discoveries ahead, and the opportunity to make its knowledge available to users and decision makers. This is our grand challenge. Addressing this challenge will provide deliverables that are at the forefront of meeting the needs of global societies and the destiny of our planet.

[7] http://www.earthobservations.org/documents.shtml

8. References

Angel, R., 2006: Feasibility of cooling the earth with a cloud of small spacecraft near the inner La15 Grange-point (l1), *Proc. Natl. Acad. Sci.*, **103**, 17184–17189.

Crutzen, P. J., 2006: Albedo enhancement by stratospheric sulphur injections: A contribution to resolve a policy dilemma? *Climatic Change*, **77**, 211–219.

Brunet, G., M. A. Shapiro, B. Hoskins, M. Moncrieff, R. Dole, G. N. Kiladis, B. Kirtman, A. Lorenc, B. Mills, R. Morss, S. Polavarapu, D. Rogers, 2009: Toward a seamless process for the prediction of weather and climate: the advancement of sub-seasonal to seasonal prediction. *Bull. Amer. Met.,* this issue.

Davis, C., W. Wang, S. S. Chen, Y. Chen, K. Corbosiero, M. Demera, J. Dudia, G. Holland, J. Klemp, J. Michalakes, H. Reeves, R. Rotuno, C. Snyder, and Q. Xiao, 2008: Prediction of land falling hurricanes with the Advanced Hurricane WRF Model. *Mon. Wea. Rev*., **126**, 1990-2005.

Dole, R. M., 2008: Linking weather and climate. *Amer. Met. Soc*., *Meteor. Mono.*, **33,** No. 55, 297-348.

Döös, B. R., 2004: The First GARP Global Experiment – a model of international cooperation. *WMO Bulletin,* **53**, No.3, 199-206.

Evan, A. T., J. Dunion, J. A. Foley, A. K. Heidinger, and C. S. Velden, 2006: New evidence for a relationship between Atlantic tropical cyclone activity and African dust outbreaks, *Geophys. Res. Lett.,* **33***, L19813.*

ICSU, International Council of Science, 2008: A Science plan for Integrated Research on Disaster Risk: Addressing the challenge of natural and human-induced environmental hazards. ISBN 978-0-930357-66-5

Hollingsworth, A., and coauthors, 2008: Toward a monitoring and forecasting system for atmospheric composition: The GEMS Project. *Bull. Amer. Meteor. Soc*., **89,** 1147–1164.

Hurrell, J., G.A. Meehl, D. Bader, T. Delworth, B. Kirtman and B. Wielicki, 2009: Climate system prediction, *Bull. Amer. Met. Soc.,* in review.

Keith, D. W., 2001: Geoengineering. *Nature*, **409**, 420.

Latham, J., and coauthors, 2008: Global temperature stabilization via controlled albedo enhancement of low-level maritime clouds. *Philos. Trans. Roy. Soc. A,* 366(1882), 3969–3987.

Li F., A. M. Vogelmann, and V. Ramanathan, 2004: Saharan dust aerosol radiative forcing measured from space. *J. Climate*, **17**, 2558–2571.

Meehl, G. A., and co-authors, 2007: Global Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. *Cambridge University Press*, Cambridge, United Kingdom and New York, NY, USA, 747-845.

Meehl, G.A., L. Goddard, J. Murphy, R.J. Stouffer, G. Boer, G. Danabasoglu, K. Dixon, M.A. Giorgetta, A. Greene, E. Hawkins, G. Hegerl, D. Karoly, N. Keenlyside, M. Kimoto, B. Kirtman, A. Navarra, R. Pulwarty, D. Smith, D. Stammer, and T. Stockdale, 2009: Decadal prediction: Can it be skillful? *Bull. Amer. Meteorol. Soc*., accepted.

Moncrieff, M., D. Waliser, M.A. Shapiro, 2009: The mesoscale organization of tropical convection and its interaction with the global circulation: the Year of Tropical convection (YOTC). *Bull. Amer. Met. Soc.,* this issue.

Schiermeier, Q, 2009: International Polar Year: In from the cold, 25 February 2009. |Nature 457| 1072-1077, doi:10.1038/4571074a.

Nobre, C., K. Noone, S. Seitzinger, M. Lahsen, J. Ometto, G. Brasseur, M. Stadford-Smith, and K. Hibbard, 2009: The International Geochemical Biological Programme (IGBP) Earth-system perspective, *Bull Amer. Met. Soc*., this issue.

NRC, 2003, Satellite observations of the Earth's environment: Accelerating the transition of research to operations, National Academies Press, Washington D.C., 163pp.

NRC, 2007: Earth science and applications from Space-National Imperatives for the next decade and beyond. National Academies Press, Washington, D.C., 428 pp.

NRC, 2008: Earth Observations from Space-The first 50 years of scientific achievements. National Academies Press, Washington, D.C., 129 pp.

Palmer, T. N., F. J. Doblas-Reyes, A. Weisheimer, and M. J. Rodwell, 2008: Toward seamless prediction: Calibration of climate change projections using seasonal forecasts. *Bull. Amer. Meteor. Soc.*, **89**, 459–470.

Robock, A., 2008: 20 reasons why geoengineering may be a bad idea. *Bull. Atomic Scientists*, **64**, 2, 14-18.

Schepanski, K., I. Tegen, B. Laurent, B. Heinold, and A. Macke, 2007, A new Saharan dust source activation frequency map derived from MSG-SEVIRI IR-channels, *Geophys. Res. Lett.*, 34, L18803.

Shapiro, M. A., and coauthors, 2007: The socio-economic and environmental benefits of a revolution in weather, climate and Earth-system analysis and prediction. *The Full Picture*, Group on Earth Observations, Tudor Rose, pp 137-139.

Shukla J, R. Hagedorn, B. Hoskins, J. Kinter, J. Marotzke, M. Miller, T. Palmer, J. Slingo, 2009a: Revolution in Climate Prediction is Both Necessary and Possible: A Declaration at the World Modelling Summit for Climate Prediction. *Bull. Amer. Meteor. Soc.*, **90**, 16-19.

Shukla, J., T.N. Palmer, R. Hagedorn, B. Hoskins, J. Kinter, J. Marotzke, M. Miller, J. Slingo, 2009b: Climate Prediction from Weeks to Decades in the 21st Century: Towards a New Generation of World Climate Research and Computing Facilities. *Bull. Amer. Meteor. Soc.,* this issue.

Simmons, A.J. and A. Hollingsworth, 2002: Some aspects of the improvement in skill of numerical weather prediction. *Quart. J. Roy. Meteor. Soc.,* **128**, 647-677.

Trenberth, K. E., 2008: Observational needs for climate prediction and adaptation. *WMO Bulletin*, **57** (1) 17-21.

Todd, M.C., R. Washington, S. Raghavan, G. Lizcano, and P. Knippertz, 2008: Regional Model Simulations of the Bodélé Low-Level Jet of Northern Chad during the Bodélé Dust Experiment (BoDEx 2005). J. Climate, **21**, 995–1012.

U.S. Committee for the Global Atmospheric Research Program, Division of Physical Sciences, National Research Council, 1969: *National Academy of Sciences*, Washington, D. C., 79pp.

Uppala, S., A. J. Simmons and P. Källberg, 2004: Global numerical weather prediction – an outcome of FGGE and a quantum leap for meteorology. *WMO Bulletin,* **53**, No. 3, 207-212.

Yoshioka, M., N.M. Mahowald, A.J. Conley, W.D. Collins, D.W. Fillmore, C.S. Zender, and D.B. Coleman, 2007: Impact of Desert Dust Radiative Forcing on Sahel Precipitation: Relative Importance of Dust Compared to Sea Surface Temperature Variations, Vegetation Changes, and Greenhouse Gas Warming. *J. Climate*, **20**, 1445–1467.

Appendix 1: Acronyms

CAS: Commission for Atmospheric Science
CIRES: Co-operative Institute for Research in Environmental Science
CliC: Climate and the Cryosphere project of WCRP
CLIVAR, Climate Variability and Predictability project of WCRP
COPES: Coordinated Observation and Prediction of the Earth System
ECMWF: European Centre for Medium-range Weather Forecasts
GAW: Global Atmospheric Watch
GCOS: Global Climate Observing System
GEO: Group on Earth Observations
GEOSS: Global Earth Observation System of Systems
GEWEX: Global Energy and Water cycle Experiment project of the WCRP
GMES: Global Monitoring for Environment and Security
HPC: High Performance Computing
ICSU: International Council for Science
IGBP: International Geosphere-Biosphere Programme
ILEAPS: Integrated Land Ecosystem-Atmosphere Processes Study
IOC: International Organizing Committee
IPCC: Intergovernmental Panel on Climate Change
IPY: International Polar Year
JAMSTEC, Japan Agency for Marine-Earth Science and Technology
MERIT: Meningitis Environmental Risk Information Technologies
NCAR: National Center for Atmosphere Research

NCEP: National Centers for Environmental Prediction
NHMS: National Hydrological and Meteorological Service
NOAA, National Oceanographic and Atmospheric Administration
NRC: National Research Council
PROMOTE: PROtocol MOniToring for the GMES Service Element
SOLAS: Surface Ocean-Lower Atmospheric Study
SPARC: Stratospheric Processes And their Role in Climate project of WCRP
THORPEX: THe Observing-system, Research, and Predictability EXperiment
UCAR: University Corporation for Atmospheric Research
WCRP: World Climate Research Programme
WGNE: Working Group on Numerical Experimentation
WHO: World Health Organization
WMO: World Meteorological Organization
WWRP: World Weather Research Programme
WRF: Weather Research and Forecast model
YOTC: Year of Tropical Convection

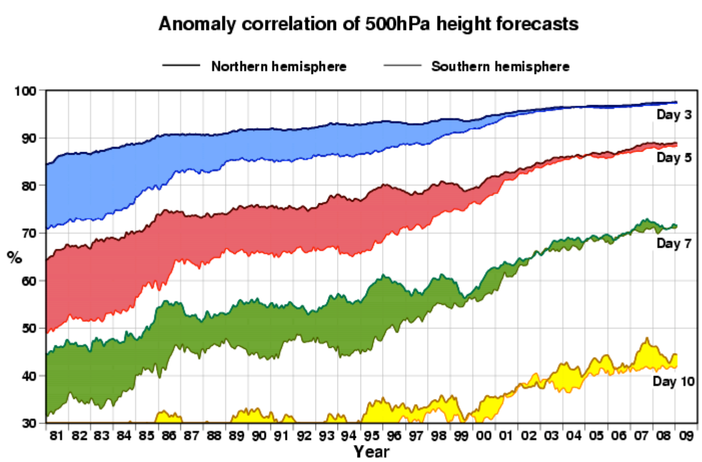

Fig. 1: Evolution of forecast skill for the extratropical northern and southern hemispheres, January 1980 to August 2008. Anomaly-correlation coefficients of 3, 5, 7 and 10-day ECMWF 500-mb height forecasts, plotted as 12-month running means. Shading shows differences in scores between hemispheres at the forecast ranges indicated (updated from Simmons and Hollingsworth 2002).

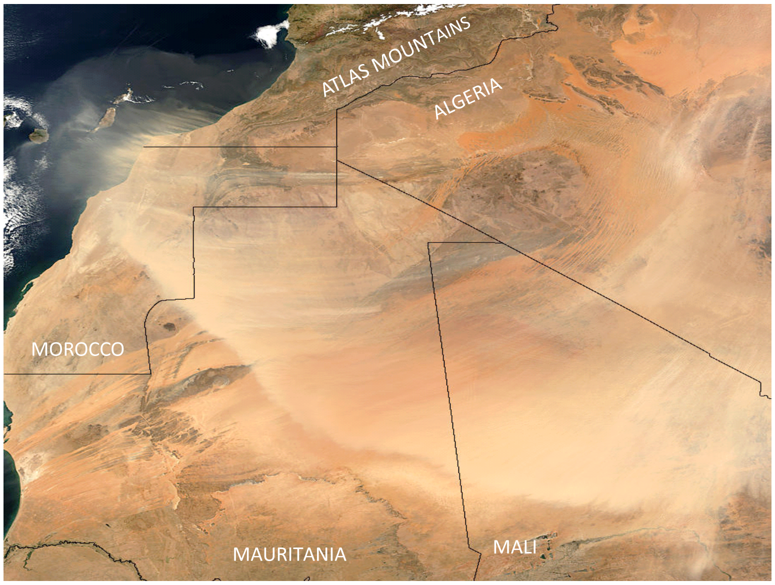

Fig. 2: Fig. 2 MODIS satellite view of an extreme Saharan sand and dust event on 6 March 2004.

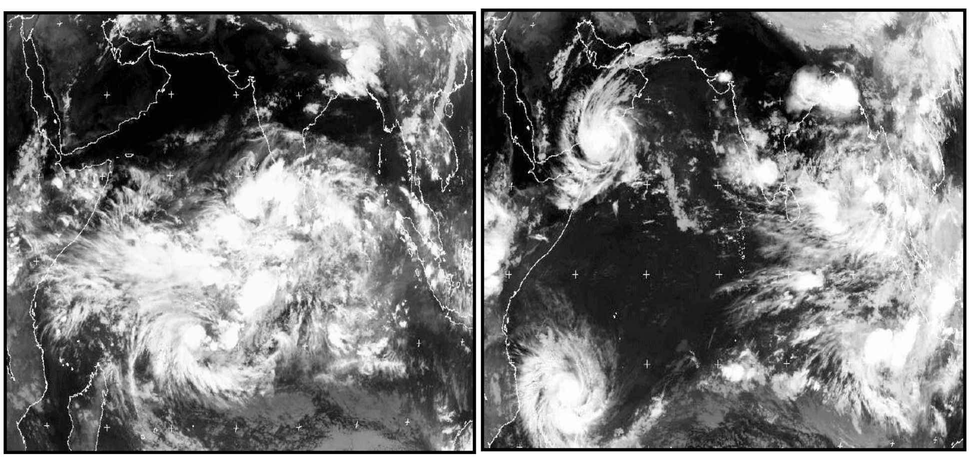

Fig. 3: Multi-scale tropical convective organization associated with a Madden-Julian Oscillation (MJO) over the Indian Ocean on 2 May 2002 *(left panel*). By 9 May 2002 (*right panel*), the MJO propagated eastwards over Indonesia and spawned twin tropical cyclones in its wake, leading to flooding rains and hurricane-force winds over northern Madagascar, and heavy precipitation over Yemen. The twin tropical cyclones illustrate

high-impact organised weather events directly associated with large-scale convective organisation and equatorial waves (see, Moncrieff *et al*. 2009, this issue).

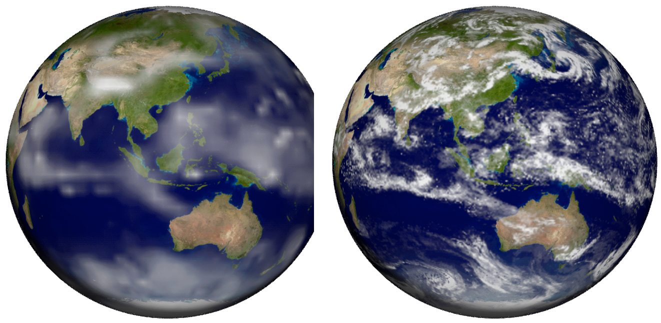

Fig. 4: *Left panel*, global cloud distribution in a 320-km coarse-resolution climate simulation experiment. *Right panel*, same, but for a 20-km resolution simulation with the same model, comparable in resolution to the most advanced operational weather forecast models of today (Moncrieff *et al*. 2009). The proposed *Initiative* will provide high-resolution climate models that capture the properties of regional high-impact weather events, such as tropical cyclones; heat waves; sand and dust storms, associated within multi-decadal climate projections of climate variability and change (Courtesy of Shintaro Karahawa, Earth Simulator Center/JAMSTEC).

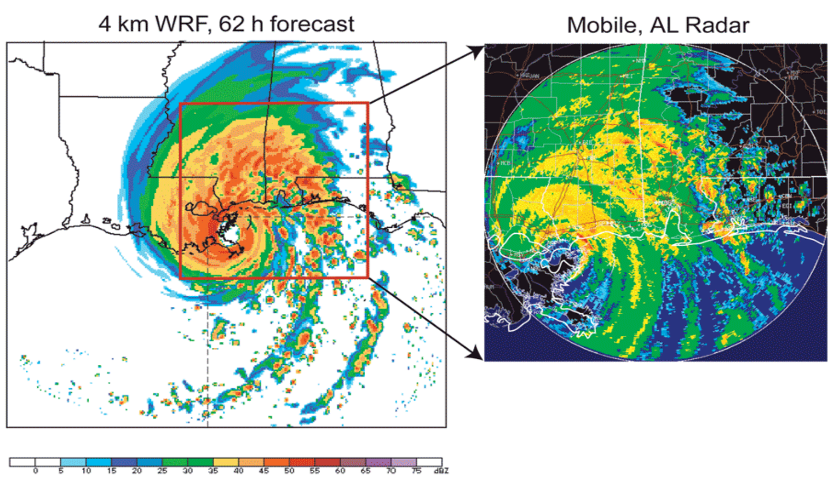

Fig. 5: The capability of high-resolution regional forecast models to predict the intensity of high-impact weather events, such as the 29 August 2005 landfall of hurricane Katrina, over New Orleans, Louisiana, USA, (Davis *et al*. 2008). NCAR/WRF simulation of Hurricane Katrina precipitation radar reflectivity computed 3-days before landfall (left), compared with radar observations of the actual landfall (right). Wthin the next decade, global data-assimilation and deterministic and ensemble medium-range to seasonal prediction systems will advance to such high-resolution capabilities.

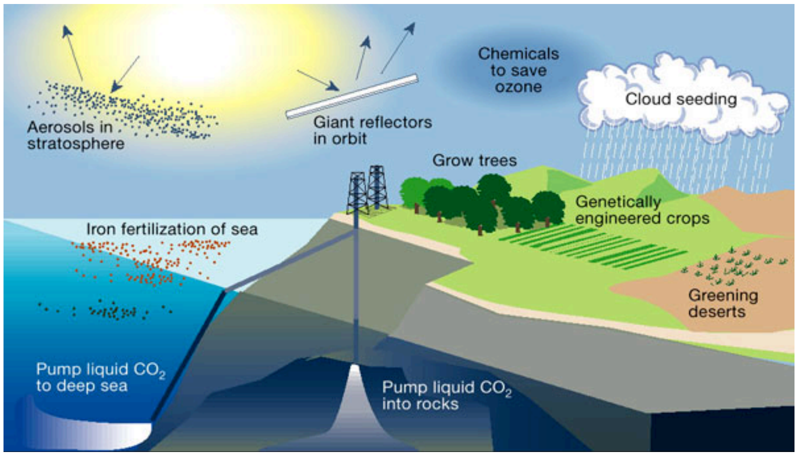

Fig. 6: Schematic representation of various climate-engineering proposals (Keith 2001). It is essential that numerical experimentation with high-resolution weather, climate and complex Earth-system models, with established fidelity and skill, provide scientifically-based assessments of the global-to-regional impact of such engineering hypotheses prior to their design and implementation.

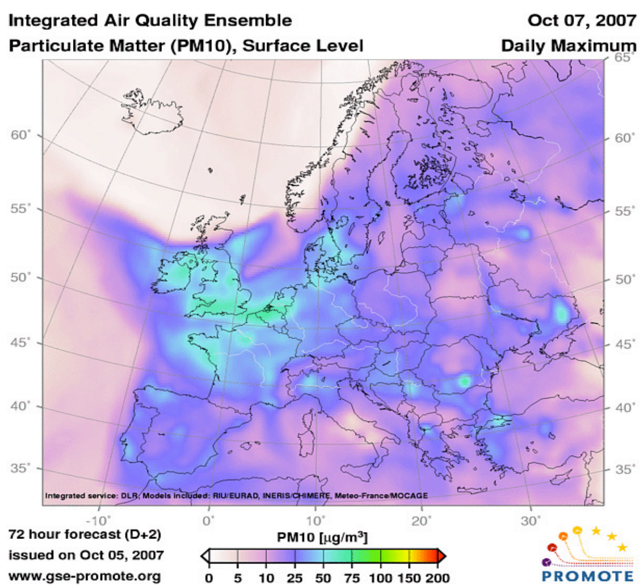

Fig. 7: Air pollutant forecast for Europe prepared by the German Aerospace Research Establishment-German Remote Sensing Data Center (DLR-DFD) as part of the GMES Service Element PROMOTE funded by the European Space Agency. It shows the 72-h ensemble forecast for surface-level particulate matter (PM10) for 7 October, 2007.