What are the Modeling Requirements for Seamless Prediction of Weather and Climate from Days to Decades? The Known, the Unknown and the Unknowable.

Report of a Sloan Foundation Workshop (December 1-2, 2007; The Royal Society, U.K.).

Background:

This was the third and the final workshop sponsored by the Alfred P. Sloan Foundation on, "The Known, the Unknown and the Unknowable in Weather and Climate Predictability" through a grant to George Mason University. All the three workshops were organized in collaboration with the Center for Ocean-Land-Atmosphere Studies (COLA). The theme of the first workshop organized by D. Straus, J. Shukla, and B. Kirtman at Savannah, Georgia, Feb. 17-19, 2003 was: "Weather Predictability". A report of this workshop was published as COLA Technical Report No. 175 (2005). The theme of the second workshop, organized by B. Kirtman, J. Shukla, and D. Straus at Montreal, Canada, September 8-10, 2004 was: "Weather Variability in a Changing Climate". A report of this workshop is available from Ben Kirtman and J. Shukla.

The theme of the third workshop organized by J. Shukla and D. Straus at the Royal Society, Dec. 1-2, 2007 was, "What are the Modeling Requirements for Seamless Prediction of Weather and Climate from Days to Decades"? Within the framework of "The Known, the Unknown and the Unknowable" program of the Alfred P. Sloan Foundation, the workshops goals were to examine the known needs for seamless weather and climate prediction, to assess the foreseeable problems whose answers are not known, and to intelligently speculate about unforeseen problems, whose solution may or may not be knowable.

Introduction:

As we prepare to meet the future challenges in the prediction of weather and climate, several lines of thinking have converged on the need for ultra-high resolution global models of the atmosphere, ocean and land. In order to predict high-impact phenomena (such as hurricanes and flood-producing mid-latitude storms) we must resolve not only the phenomena themselves along with the local orography, but also the critical forcing elements (e.g. latent heating due to convective cloud systems) and the associated planetary scale circulations in which the phenomena are embedded. High-resolution modeling is carried out routinely, but only on a regional basis or for short-range prediction. To meaningfully predict the probability of occurrence of extreme phenomena on seasonal and longer time scales, the multi-scale interactions among local, regional and global scales demand the use of global models of equally high resolution for climate simulation and prediction.

Low frequency climate phenomena of importance (such as decadal droughts and intense heat waves) are known to have consistent statistical relationships to soil wetness and SST anomalies. Since the physical forcing mechanism responsible for the critical changes in the planetary scale circulation is not the soil wetness or SST anomalies, but rather the associated shifts in atmospheric latent heating (and especially deep cumulus heating), resolving the systems responsible for this heating *globally* are a necessity for making further progress in climate prediction for *any* region. Our past experience has shown that every advance in the representation of deep cumulus heating has led to widespread improvements in the simulation of climate.

It has been recognized that both initializing and validating such ultra-high resolution models pose formidable challenges, both in the areas of observational data and its assimilation. While much satellite data is available at this resolution, it is not clear whether the vertical resolution of current and future instruments will be high enough for all variables of importance. The need for ocean and land data at these resolutions is also a critical consideration. Beyond the need for data, the development of methodologies for assimilating these data into the climate model components will need significant effort.

The endeavor of simulating and predicting climate with ultra-high resolution fully coupled global models will encounter new frontiers. The current approaches to integrating the basic equations for fluid flow (the dynamical "core") will have to be critically re-evaluated. Has the time come for the use of global unstructured/adaptive grid methods? What are the implications for computer hardware and software architecture? As many processes that are currently parameterized become explicitly resolved (e.g. deep moist convection and cloud systems), the parameterizations for physical processes on yet smaller scales will have to be fundamentally changed (e.g., cloud-radiation interaction, shallow convection, cloud micro-physics and boundary layer turbulence). We do not yet know the problems that will arise. Can we balance the energy and moisture budgets in a realistic manner? If we can explicitly resolve processes and physical scales for which we do not have realistic initial data globally, will the resulting error growth be so rapid as to erase any gains in daily to seasonal predictability? Can we prevent the rapid growth of cloud systems (with very short predictability times) from overwhelming the predictable large-scale circulation?

What are the current trends in computing power and computer architecture? What are possible avenues for collaboration between the scientific community and the computer industry to define the software and hardware requirements for the integration of ultra-high resolution global climate models for multi-decadal and centennial predictions? One of the goals of the workshop was to discuss such issues and to suggest others.

Another important goal of the workshop was to discuss and recommend innovative institutional arrangements will make it possible to undertake development of ultra-high resolution global models and computer architectures for seamless prediction and simulation of global weather and climate systems from days to decades.

Workshop Summary and Recommendations:

1. Progress in climate modeling must be accelerated to meet the multiple requirements of determining strategies for climate mitigation and adaptation, improving the skill of routine operational seasonal-decadal predictions of regional climate variations and maximizing utilization of global in-situ and space observations.

2. The current generation of cyclone-resolving climate models have played a crucial role in improving medium range weather and short-term climate forecasting, and in demonstrating the influence of human activities in changing the Earth's climate and its variability. A concerted and sustained support is required to improve the fidelity of the current physical climate system models for simulating the current climate and improving the accuracy of interactive processes including estimates of climate sensitivity. This can be accomplished by multiple paths: improving parameterizations, increasing resolution and evolving toward Earth-System Models by including complex chemical and biological processes.

3. The workshop participants strongly recommended that climate models for the next IPCC assessment should have spatial resolution of about 10 km in the horizontal (for both atmosphere and ocean), and sufficient vertical resolution to represent well the boundary layer and the tropopause (in the atmosphere), and the mixed layer and the thermocline (in the ocean). It is estimated that about 100 vertical levels in the atmosphere and likewise in the ocean are required.

   The participants recognized the need for comprehensive research effort to establish the credibility of climate change assessments with high resolution models.

4. To accelerate progress towards better understanding of relevant climate processes, our ultimate goal should be to develop a new generation of climate system models which can resolve deep convective cloud systems in the atmosphere, energetic eddies in the oceans and land-atmosphere processes over the continents, and which also have sufficient resolution in vertical for adequate treatment of chemistry and physics in stratosphere and mesosphere. This will require spatial resolutions of about 1-2 km in the atmosphere, 5-10 km in the oceans and 100-500 meters over land, about 100 levels in both atmosphere and oceans.

   It is, however, not realistic to propose km scale models for climate change prediction at least for a decade or so. Our short-term goal should be to utilize 10-km atmosphere and ocean models for climate change projections.

5. Major hurdles in accelerating progress in climate modeling include: 1. Lack of powerful computers and advanced analysis tools dedicated to climate modeling and prediction; 2. Lack of sustained support for a critical mass of scientific and technical staff; 3. Lack of active collaboration among climate scientists, computational scientists, and computer/chip manufacturers.

6. The current trends in computing should make it possible to produce global medium range weather forecasts with models of 1-2 km resolution during the next 10 years. Major enhancements in current computing trends and innovative approaches to model code development are required to make decadal and century scale climate prediction at such resolutions. The workshop participants noted that there are serious signs and research issues to be addressed to make further advances, and recommended that the experimental ultra high resolution (1-2 km) global models should be used to test and improve the parameterizations for high resolution (10 km) global models.

7. The current trends in computing suggest that high-end computing platforms available in 2010-2011 will have 10 petaflops peak capability with 300,000 to 800,000 cores (individual processing elements). Such systems will consume 5-10 MW of electrical power. Current experience suggests that climate model codes will achieve 5-10% of this peak performance, or up to 1 petaflops sustained performance. New algorithms and substantial recoding may be needed to achieve this performance on a very large number of processors. To run global atmospheric models with spatial resolution of 1 km and 100 levels in the vertical will require a sustained capability of 100s of petaflops.

8. The workshop participants recommended that to meet the demands of society in a changing climate, new and imaginative institutional arrangements will be required to accelerate progress in climate modeling and prediction. At the national level, dedicated teams of climate modelers, computational fluid dynamicists, and computer architecture experts should be provided sustained support to build and apply the next generation models. At the regional multi-national level, a cluster of countries with a common interest in regional climate variations should establish dedicated modeling and computing facilities, and foster collaboration among national climate modeling centers. At the international level, a possible way forward will be to establish a dedicated supercomputing facility and a comprehensive collaborative research effort, that is beyond the capability of any single nation. This will help nations make multi-billion and trillion dollar decisions for adaptation and mitigation of climate change.

List of Participants

Sloan Foundation Workshop (*December *1-2, 2007) The Royal Society, U.K.

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The Known, the Unknown and the Unknowable.

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