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Workshop Summary

The 3rd WGNE Workshop on Systematic Errors in Climate and NWP Models
San Francisco, February 12-16, 2007

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INTRODUCTION

The 3rd WGNE Workshop on Systematic Errors in Climate and NWP Models was held in San Francisco, February 12-16, 2007. This document, prepared by several members of the organizing committee, is a synthesis of thematic priorities emerging from the workshop. By necessity, it is limited to topics recurring throughout the week and to systematic errors that appear to deserve dedicated research efforts. Detailed information about these and other model errors discussed at the workshop can be found in the more than 100 workshop presentations available at the following website:
http://www-pcmdi.llnl.gov/wgne2007/presentations

OVERVIEW

Systematic errors in climate and weather prediction models are evident on a wide range of space and time scales. The root causes of these errors are often difficult to address because many complex processes and phenomena, including their feedbacks, interact in the climate system.

Increasingly, our confidence in climate simulations on decadal and longer time scales is dependent on how well they perform on much shorter time scales. Benefiting from the experiences of numerical weather prediction, new diagnostic methods for climate models are proving insightful. Some errors commonly seen in long term climate simulations become evident after relatively short model integrations (of a few days). This suggests that some errors relevant to climate can be studied in a much simpler and cheaper experimental framework than that of a fully coupled ocean-atmosphere general circulation model (OAGCM) that is run for decades to centuries. This approach complements the rigorous testing of model ability to simulate the observed climate record over long periods.

The diurnal cycle of many important quantities (e.g., temperature and precipitation) is poorly simulated in global atmospheric models, thus compromising weather forecasts as well as climate projections. Models that explicitly resolve clouds typically have a more realistic diurnal cycle. Even so, errors in the representation of the longer term atmospheric radiation budget critical to climate simulation may remain. Climate models can only be run at cloud-resolving resolutions for short periods, but careful experimentation at high resolution may benefit parameterization development in ways that could lead to better simulation of the diurnal cycle at climate resolutions.

There are a number of persistent model errors for which we have limited understanding of the underlying processes, and for which there are no clear solutions. Poor simulation of the tropical Pacific has global implications. Model errors affecting intermediate time-scales (e.g., monsoons and the Madden-Julian Oscillation) are often subtle, and the processes responsible for them need not be local. On longer time-scales, the El Niño Southern Oscillation (ENSO) is a dominant mode of climate variability, and there continue to be simulation errors in its spatial structure, frequency, and amplitude. Examples of other coupled atmosphere-ocean modes of variability that require improvement include the Pacific Decadal Oscillation and the Atlantic Multi-Decadal Oscillation. Increasing the use of climate models for seasonal time-scale experimentation may prove to be a practical way to tackle some modeling deficiencies associated with these modes of variability.

Although much is understood about how the climate may change, century-long simulations are still very uncertain because they are critically sensitive to certain processes. How the global cloud field responds to small changes in the Earth’s energy budget is chief among these, with errors in low-level clouds over the sub-tropical oceans being responsible for substantial uncertainty. Another critical area of uncertainty is how and where the upper ocean warms, thereby affecting sea-level due to thermal expansion. Reducing errors associated with these and other climate-critical factors should lead to reduced uncertainty in climate change projections.

Global climate models are being made even more complex with the inclusion of additional processes (e.g., interactive carbon cycle, chemistry, prognostic aerosols, and dynamic vegetation), progressing from today's OAGCMs to full Earth System Models (ESMs). The development of ESMs will benefit from the interaction of different communities, but unless there is a major expansion of human and computational resources, ESMs might be viewed as competitors to further OAGCM development. This situation would be self-defeating, because ESMs will require the elimination of known climate model errors (e.g., accurate precipitation patterns are needed for dynamic vegetation). Ten years ago the climate modeling community was experiencing a comparable challenge, advancing from atmosphere-only to fully coupled atmosphere-ocean models. Initially coupled models suffered from substantial "climate drift" and it took some time to alleviate this problem without the need for un-physical corrections. The stability of ESM solutions likely poses a greater challenge.

Some systematic errors are sensitive to horizontal resolution. Other errors are not, and are presumed to be attributable to deficiencies in the parameterized formulations of non-resolved processes. Nevertheless, recent experimentation suggests that current climate model resolution is significantly too coarse to properly resolve important atmospheric and oceanic phenomena. The coordinated exploration of systematic errors should be conducted at much higher resolution than is typical for current global climate models and hopefully high enough to be operating in a numerically convergent regime for the realistic representation of the most important climate phenomena.

The international community recognizes the importance of reducing systematic errors, and it regularly proposes hypothesis-driven sensitivity experiments to better understand the strengths and weaknesses in model formulations. But the rate at which these ideas are explored are as limited by manpower as they are by computational resources. The number of actual model developers (relative to model product users) is insufficient, and in large part is due to the inability of the field to attract and keep young talent. Hence, improvement of climate models is very difficult, and progress is incremental.

2) Advancing the science with technology

The global modeling community is constantly evaluating new approaches to solve the system of equations that govern the Earth's climate system. Advances in numerical integration techniques are adopted as soon as they have demonstrated their ability to simulate the basic dynamics of the system without introducing systematic errors. The community continues to be on the leading edge of computational science, adapting the implementation of global models to exploit evolving high performance computer architectures.

We are positioned to accelerate progress on long-term climate change projections, but this is paced by improvements in observational data on critical climate processes, manpower to develop and test formulations of physical, chemical, and biogeochemical processes, and the availability of reliable high-performance computing platforms to facilitate the testing of these non-linear systems.

We are not in a position to adequately quantify the role of systematic errors in limiting the veracity of climate model projections. It could be argued that on regional scales systematic errors can severely limit the utility of climate change projections, but it has not been demonstrated that simulated anomalies (with respect to a biased basic state) have no value.

Increased computing resources would undoubtedly accelerate progress in reducing systematic errors in climate models. At the workshop, there were striking examples of how increased atmosphere and ocean horizontal resolution (substantially higher than typical for climate) can improve the simulation of some key climate processes. Continued exploration of model errors should have an increased focus on resolutions that are much higher than is typical for current climate models.

Progress will also be aided by emerging observational technologies for crucial physical processes in the climate system (e.g., clouds, aerosols, surface energy exchanges), which will help to constrain the formulation of these processes in climate models. A balanced investment is required to make more rapid progress on this problem of critical societal importance.

3) Short time-scales (a few hours to a few weeks)

Model errors on these short time-scales have direct implications for numerical weather prediction (NWP). Metrics that gauge forecast performance have demonstrated improvements in both forecast skill and the reduction of errors in tropical cyclone tracks and intensity, as described at this workshop.

The importance of short time-scale errors on the simulation of climate was clearly brought out. There were many examples of climate models being tested in “NWP mode”, whereby these models are realistically initialized and run in a series of short forecasts. The objective of this approach is to evaluate the initial drift from the NWP analyses (and/or from available field data), thereby gaining insights into model parameterization deficiencies. Interestingly, some of the systematic biases commonly seen in long term climate simulations become evident after relatively short (~1day) integrations. This suggests that some difficult errors relevant to climate can be examined in a much simpler and less expensive experimental framework than that of a fully coupled ocean-atmosphere model run for decades to centuries.

Break-out discussions: The diurnal cycle

Accurate simulation of the diurnal cycle is difficult, challenging a model's ability to realistically capture a myriad of local processes. A few examples are noted here: the daily pattern of rain/convection/clouds over land and ocean, land-sea interactions (e.g., sea breezes), propagating convective systems, and the role of the diurnal cycle in monsoons.

In the short term, it was recommended that more effort be devoted to analysis of the diurnal cycles of climate models. This will help us better understand how serious the errors are in existing models and possibly estimate their broader implications. In the longer term, sensitivity studies where the diurnal cycle is forced to be more realistic may help us understand the implications of getting it wrong, although interpretation will likely be difficult. Comprehensive investigation of the diurnal cycle requires a hierarchy of global, regional and cloud-resolving models. Improvement of entire physics packages is clearly required to better handle these highly coupled situations involving a range of scales.

4) Intermediate time-scales (a few weeks to a year)

There are key phenomena on 'intra-seasonal' time-scales that are not fully understood and remain poorly simulated. The Madden-Julian Oscillation (MJO) is a prime example. Resolved and unresolved convectively coupled waves are crucial components of tropical circulation, but are handled poorly. The atmospheric water cycle, especially the partitioning between convective and stratiform precipitation, remains a major source of uncertainty. The heating profile of the atmospheric column is a critical factor for atmospheric modes and tele-connections, but is likely to be incorrect in many models. There is increasing evidence that horizontal and vertical resolution in both the atmosphere and ocean, affects synoptic and intra-seasonal variability, as well as the global mean climate. Also, it is clear that the simulated mean climate must be reasonable in order to realistically capture the many important signatures of intra-seasonal variability. Even at these intermediate time-scales, coupled processes play an important role, but the mechanisms still need to be clarified. Lastly, a particularly troublesome feature is that model errors affecting intermediate time-scales are often subtle, and the processes responsible for them need not be local.

Several recommendations have been made toward reducing errors affecting intermediate time-scales. The considerable benefits of applying NWP techniques to understand climate errors should be further explored in a coupled model context, e.g., via seasonal prediction. Advances in defining MJO metrics and diagnostics have proven invaluable and need to be developed for other phenomena (e.g., tropical waves). Such targeted efforts should aim to be process-based when possible. Methodologies also need to be developed toward exploiting emerging observations. As a prime example, results from CloudSat should help us understand convective/stratiform precipitation as well as vertical profiles of cloud, rain and convective heating.

Break-out discussions: Tropical Biases

In most models, there are persistent errors over the tropical oceans that have collectively become referred to as “tropical biases”. For instance, in the western tropical Pacific many models continue to be plagued by an unrealistic (‘double’ or ‘split’) signature of the Inter-tropical Convergence Zone (ITCZ). The oceanic cold tongue of the eastern Pacific also frequently extends too far west. With colder than observed temperatures there is usually a precipitation deficit in the Indonesian area. Meanwhile, the eastern Pacific south of the equator is too warm, and the annual cycle of SST along the equator is poorly simulated. Other problems plague the Atlantic and Indian Oceans. Some progress in these areas is being made but the tropics are highly dynamically interconnected, with change in one region affecting other regions. Tropical errors also affect the mid-latitudes, thus contributing to errors in the global general circulation. For many climate modelers these pervasive errors are among the most troublesome they face - efforts to understand and alleviate them are too detailed to include in this summary.

Break-out discussions: Intra-seasonal variability and monsoons

Among the outstanding challenges in modeling the MJO is that active-break transitions are not forecast and typically, not represented in GCMs. The root causes have not been identified, but missing physics and lack of basic understanding have limited our ability to simulate these interactions. The broader implications of these errors are that they limit medium-range and seasonal predictability, as well as ENSO forecasting, with the simulation of extreme events and tele-connections being compromised.

Monsoon circulations are sensitive to errors in the mean state. Typical errors include a poor representation of the observed regional rainfall distribution. A better understanding of moisture transports, low-level jets, and land surface interactions (soil moisture, snow, etc.) is needed. Extra-tropical and remote influences can impact monsoons, e.g., atmosphere (stationary waves) and the role of aerosol/dust over the Atlantic. To date, many of the root causes behind errors in simulating the monsoon have not been identified despite their broad implications (e.g., societal and agricultural impacts, compromised teleconnections).

Improved theoretical understanding of the basic physics involved is needed to reduce errors in the simulation of intra-seasonal oscillations and monsoonal systems, as well as better understanding of multi-scale interactions and the role of the oceans and land.

5) Longer time-scales (inter-annual to decadal and longer)

Exploration of how well models simulate various modes of climate variability on longer time-scales is an active area of research. One of the dominant modes of variability, the El Niño Southern Oscillation (ENSO), involves interactions between the atmosphere and ocean. Systematic errors in the simulation of ENSO are of special concern in part because some of the processes responsible for ENSO coupled system interactions on multi-annual time-scales are expected to also be important for climate projections. Other coupled atmosphere-ocean modes of variability are also important (e.g., the Pacific Decadal Oscillation and the Atlantic Multi-decadal Oscillation), cannot be ignored, and are poorly understood and/or modeled.

Century-long simulations are still very uncertain because they are critically sensitive to certain processes. How clouds may "feedback" onto a changing climate is chief among these, and there is increasing recognition of the likely importance of feedbacks associated with changes in low level clouds over the sub-tropical oceans. Another critical area of uncertainty (associated with model errors) is how and where the upper ocean warms, which, due to thermal expansion, will affect sea level. Improved simulation in these areas could reduce the uncertainty in projections of future climate.

Current climate model resolution is too coarse to properly resolve certain atmospheric and ocean processes important to climate. Higher ocean resolution would clearly lead to improved simulation of the Gulf Stream and Antarctic Circumpolar current, eddy heat transports, currents and consequently improved simulation of the sea surface temperature. Among the benefits demonstrated for higher resolution atmospheric models are improved tropical cyclones in NWP, reduced errors in long waves, improved Antarctic Peninsula climate, mid-latitude cyclones, and precipitation extremes. While improved resolution is not a panacea, inadequate resolution is hindering progress in climate modeling. Large dedicated computer resources are required for coupled climate modeling to allow increases of resolution, as well as resources for storage and manipulation of huge amounts of model data.

As they advance, the success of Earth system models (ESMs) will at least in part hinge on realistic simulation of the coupled ocean-atmosphere system.
For example, the vegetation component of ESMs can be extremely sensitive to precipitation in areas where current models have substantial errors. Although exploratory studies with ESMs are certainly warranted, it is essential that ESM development does not inhibit continued efforts to reduce systematic errors in OAGCMs

Break-out discussions: El Niño Southern Oscillation (ENSO)

Coupled model simulations of ENSO have markedly different amplitudes, the structure of the westward extension is often too narrow around the equator, and the frequency of events is too high. The mean state and seasonal errors remain large in many models to the probable detriment of the simulation of ENSO. There is incomplete theoretical understanding of ENSO and detailed observations of events are scarce (e.g., wind stress products vary ~30-40%). Studies suggest that atmosphere models have a dominant role in determining the time-scale of ENSO, with ocean models modulating the amplitude of ENSO. To test ENSO-relevant processes, seasonal-range coupled runs are being explored. These runs provide rich diagnostic possibilities, to see how (and sometimes why) coupled errors develop in the tropics in the context of detailed observations.

Break-out discussions: Metrics for climate models

In the NWP community, standard metrics that gauge the skill of forecasts have been routinely computed for years. There is now increased interest in developing performance metrics for climate models. Establishment of a set of standard metrics could encourage all modeling groups to provide at least a minimal standardized summary of model strengths and weaknesses, which would facilitate monitoring and documenting of changes in model performance. A hierarchy of metrics could be designed to help assess the simulation of a variety of processes and phenomena on a range of time and space scales. Although work on optimizing the utility of metrics is in early stages, it is widely believed that the metrics of most value will almost certainly be application dependent. There have been some initial attempts to construct a single index of model performance, based on a somewhat arbitrary set of metrics. However, the consensus view is that there is little scientific justification for using indices of this kind to make judgments concerning the relative reliability of models for any particular application. Community-based efforts are underway to explore and establish a set of standard metrics relevant for climate models.