Ocean and Atmosphere: Predicting Monthly to Seasonal Climate Variability and the Oceanic and Atmospheric Causes and Effects

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Abstract: **One major Earth System Model component is a coupled model that provides a predictive framework and describes the ocean-atmosphere circulations, and the water and energy cycles. Major future predictive capabilities will extend predictions well past the present limits of weather predictability, to include monthly to seasonal predictions of climate variability and the oceanic and atmospheric causes and effects of this variability.**

I. INTRODUCTION

There is currently a major gap in our understanding and predictive capabilities that encompasses time scales that lie just beyond the limits of deterministic weather prediction and just short of one season [1]. These so-called "intra-seasonal" time scales provide a fundamental link between weather and short-term climate and are a dominant factor in modulating weather predictability and limiting predictability on seasonal and longer time scales. Improvements on these time scales are key to fulfilling NASA's long-term vision for improving weather and short term climate prediction, as well as, for achieving NOAA's goal of a "seamless suite" of weather and climate forecast products.

The basic difficulty is that, unlike weather where it is known that memory of the initial conditions is the dominant control on forecast skill, and seasonal and longer averages where boundary forcing (e.g. sea surface temperatures) dominates forecast skill, the basic factors controlling and limiting predictability on intra-seasonal time scales are still poorly understood. This reflects an inadequate understanding of variability on these time scales including such phenomena as the Pacific/North American (PNA) pattern, the Madden-Julian Oscillation (MJO), the North Atlantic Oscillation (NAO), and the Arctic Oscillation (AO). Among the unresolved issues on these time scales are the nature of tropical/extratropical interactions, the impact of sea surface temperature (SST) forcing, the role of land/atmosphere interactions, interactions with weather (especially extreme events) and longer-term climate variability, and the role of the stratosphere.

Beyond about two weeks, individual weather systems are not predictable and it is the statistics of the variability that become relevant. Hence, predicting intra-seasonal variability is fundamentally a probabilistic problem that requires forecasting the evolution of the governing probability density functions (PDFs) in a way that naturally bridges the gap between weather, and seasonal and longer-term predictions. To do this, we must work to identify, quantify and reduce the uncertainties of the prediction problem: these consist of both the uncertainties in the initial state of the Earth System (atmosphere, land and ocean) and the uncertainties in our Earth System models. We must also adequately represent the true uncertainties in the system associated with internal chaos.

Tackling this problem requires a comprehensive, global, coupled modeling and data assimilation framework together with improved observations of the Earth System. In the following we outline some of the key requirements and NASA's role in fulfilling them.

II. MODELING REQUIREMENTS

There are a number of requirements that Earth System Models (ESMs) must satisfy in order to successfully address the gap in our predictive capabilities on intra-seasonal time scales. A key aspect of these requirements is the merging of what have traditionally been separate requirements and development efforts in weather and climate modeling. In the former the need for high resolution and accurate initial atmospheric conditions and improved forecast skill have driven development. In the latter, the parameterization of physical processes, conservation requirements, and the veracity of various climate statistics have driven development. Both sets of priorities play a role in the intra-seasonal problem.

The land surface hydrological state (e.g. soil moisture and snow) is one of the most promising sources of warm season predictability on intra-seasonal time scales. There are, however, substantial uncertainties in the strength of the coupling between the land and atmosphere, and inadequate observations of soil moisture and other land conditions for initializing the models. The latter will be discussed in the next section. The former has profound implications for the level of predictability that may exist as a result of atmosphere/land interactions. Much work is required to identify and model the sources and time scales of land memory and the coupling with the atmosphere. In addition, high resolution land models will be required to properly

model soil moisture variability, run-off, river routing, snow melt and other aspects of land hydrology.

ESMs must provide improved forecasts of tropical SSTs on intra-seasonal time scales. For probabilistic forecasts, it is critical that the models provide not only an estimate of the state of the SST, but also realistic estimates of the uncertainties. This will require improvements to the ocean surface mixed-layer processes and improvements to the simulation of tropical atmospheric variability, particularly the MJO. Such improvements are key to predicting, for example, the timing of the onset and demise of ENSO and other tropical Pacific SST variability. Improvements are also required to provide improved SST prediction in the tropical Indian and Atlantic Oceans: current coupled models do very poorly in both basins. It is yet to be established to what extent this is due to improper atmosphere/ocean coupling in these basins, and to what extent this reflects deficiencies in the atmospheric linkages between the ocean basins. Further work is also required to determine what aspects of SST variability impact atmospheric variability on intra-seasonal time scales (e.g. do we need to resolve daily, weekly, or just monthly time scales?). Issues of coupling tied to the MJO, ocean preconditioning for sequences of weather events, and a substantial diurnal cycle, suggest we must do considerably better than the current baseline products that are supplied as weekly averages.

It is essential that the ESMs properly simulate the basic modes of intra-seasonal atmospheric variability, including their spatial structure, their time scales, and amplitudes. As already mentioned, several key modes contribute to the variability on these time scales including the PNA, the MJO, the NAO and the AO. Improvements in the MJO, for example, will require advances in the simulation and understanding of the role of the planetary boundary layer, convection and clouds, as well as the potential role of ocean-atmosphere interactions. The PNA appears to be in part an internal mode of atmospheric variability, with structures and time scales that depend on the characteristics of the mean Pacific jet, though the phase of the PNA may also be impacted by tropical Pacific SST anomalies. The PNA also influences weather systems and may play a key role in the occurrence of extreme weather events, and major shifts in the position of storm tracks on monthly time scales. Simulating the PNA and its impacts thus requires models that have an unbiased climatology, realistic weather variability, and also produce a realistic response to seasonal and longer-term SST variations such as those associated with ENSO. The NAO and AO are large-scale modes of variability that appear to have substantial impacts on the weather and climate of the northern high latitudes (note that a mode analogous to the AO also exists in the Southern Hemisphere – the so-called Antarctic Oscillation or AAO). The nature of these modes and their predictability are not well understood. There is some indication that the stratosphere plays an important role so that the ESMs must include a well-resolved middle atmosphere.

Tackling the above modeling issues requires new and improved observations, and the modeling infrastructure and simulation capabilities and resources that are necessary to carry out a concerted, coordinated, and focused model development effort. NASA has taken the lead role in funding and organizing the Earth System Modeling Framework (ESMF [2]. The uniform framework and common low level utilities provided by ESMF should greatly facilitate the exchange of ideas and collaboration on model development. NASA has also developed a first generation ESM suitable for seasonal-to-interannual prediction research and experimental forecasting. This development will continue and expand within the ESMF to contribute to the intra-seasonal prediction problem, as well as to the national effort to develop ESMs for long-term climate variability and climate change studies.

III. OBSERVATIONAL AND DATA ASSIMILATION REQUIREMENTS

There are a number of key observational and data assimilation requirements for improving our understanding and prediction capabilities at intra-seasonal time scales. These requirements can be grouped into those necessary for the initialization and verification of model predictions, and those that are critical for ESM development and validation.

For the initialization problem, a key requirement is for much improved observations of the tropics in order to help initialize the state of the MJO and other intra-seasonal tropical variability. This includes observations of the instantaneous large-scale divergent wind field, the moisture field, and the associated forcing fields associated with the development of precipitation and clouds. Global soil moisture, snow and streamflow observations on weekly or shorter time scales will be critical to realizing the potential predictability of the land surface on intra-seasonal time scales. Improved estimates of the state of the SSTs, sea surface salinity and ocean surface mixed layer depth, the atmospheric boundary layer, and the ocean subsurface density fields, will be key to the ability of the models to properly maintain and evolve the longer term ENSO and other SST variability, as well as, to properly simulate any rapid transitions and/or embedded variability that can occur on intra-seasonal time scales. Improved estimates of the 3-dimensional structure and forcing of the stratospheric will be necessary to properly initialize those slow components of the stratospheric circulation that appear to be important for influencing the troposphere on weekly and longer time scales.

The Earth Observing System (EOS) and related NASA observing programs are now beginning to provide us with a host of new and more accurate observations of the ocean, land and atmosphere to help initialize ESMs. Ocean surface topography from TOPEX/Poseidon and Jason and surface wind stress from Seawinds are necessary to forecast changes in ocean state and the evolution of SSTs. Land surface models driven by precipitation from the Tropical Rainfall Measuring Mission (TRMM), and the emerging network of passive microwave observations of precipitation (precursors

to the Global precipitation mission, GPM) will be necessary for land surface initial conditions. Surface radiative forcing from Clouds and Earth's Radiant Energy System (CERES) and Moderate resolution Imaging Spectroradiometer (MODIS) instruments and other radiative flux estimates will also be crucial to this effort. While full tropospheric sounding of winds is a long-term requirement, the Atmospheric InfraRed Sounder (AIRS) will provide needed improvements in vertical temperature structure and inference of balance wind structures via data assimilation.

Data Assimilation is the natural tool for combining the many satellite and in situ observations into global, comprehensive, and consistent data sets necessary for initializing ESMs. It is particularly advantageous to have the same model used in the predictions and in the data assimilation system. As such, the predictions undergo less initial shock and adjustment: this is especially important for the land surface and the ocean where initial adjustments can be large and of sufficiently long duration to severely impact forecast skill on intra-seasonal and longer time scales. Finally, the analysis error estimates provided during the course of the assimilation provide a natural basis for evolving the forecast uncertainties in the coupled atmosphere-land-ocean system. Providing realistic analysis errors is, however, a difficult problem and there are currently no satisfactory methods that account for both initial condition and model-related errors. As data assimilation systems begin to be formulated under ESMF, ensemble techniques that employ multiple models and/or model components should become more feasible, and allow for more accurate estimates of the forecast uncertainties. In fact, an ensemble prediction approach (already carried out successfully for the seasonal problem) will likely be the key method for forecasting the governing PDFs on intra-seasonal time scales. The success of such an approach will depend on our ability to accurately estimate and sample from the initial condition and model error distributions, and on having sufficient computing resources to run large-ensemble ESM forecasts.

Model development is best served by comprehensive observations that can help to validate physical processes, and longer-term data sets that can help to validate the ability of the model to simulate and predict various known low-frequency phenomena such as ENSO the MJO, and the PNA pattern. One of the major challenges to improved predictions is accurate coupling of the hydrologic and energy cycles in models. A chronic problem with ESMs is accurate representation of energy exchange between the atmosphere and the underlying land/ocean/cryosphere complex. Measurements of cloud radiative forcing (CERES, MODIS), precipitation and latent heat release (TRMM, and the Advanced Microwave Scanning Radiometer, AMSR), moisture (AMSR, AIRS) and other quantities are rapidly being integrated into observational estimates of the "fast" component of the water and energy cycle variability of our planet. These data, together with observations from process studies such as the Large-scale Atmosphere Biosphere Experiment (LBA), Cirrus Regional study of Tropical Anvils

and Cirrus Layers (CRYSTAL), and the North American Monsoon Experiment (NAME), offer new opportunities to correct long-standing systemic biases and shortcomings in model parameterizations of microphysical processes, deep convection, shallow boundary layer clouds, evaporation, and related processes.

Consistent long-term (multi-decade) data sets are crucial for evaluating the ability of ESMs to simulate intra-seasonal variability, for understanding the sources of predictability, and for assessing skill levels. Existing "reanalysis" data sets are inadequate for a number of reasons including a poor representation of the tropics (e.g. precipitation and clouds), inconsistent land surface conditions, and various inhomogeneities associated with changes in the observing systems. NASA is currently joining NOAA in an effort to develop a national program for the analysis of the climate system [3] that should help produce the long term, comprehensive and consistent climate data sets necessary for evaluating our ESMs.

IV. CONCLUDING REMARKS

Future improvements in both weather and short-term climate predictions require a concerted effort to tackle the intra-seasonal prediction problem. Improvements at these time scales are critical to our efforts to provide probabilistic forecasts that naturally bridge the gap between weather, and seasonal and longer-term predictions. Our key challenges are to identify, quantify and reduce the key uncertainties of the prediction problem including the uncertainties in the initial state of the Earth System (atmosphere, land and ocean) and the uncertainties in our Earth System models.

NASA (together with other agencies) has taken up this challenge by providing the community with improved observations of the Earth System, the basic infrastructure for accelerating model development (ESMF), the beginnings of an effort to develop long-term consistent analyses through data assimilation, and both internal and external support for research and development geared to improving our weather and climate prediction capabilities.

REFERENCES

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