Advancing Science and Societal Benefits of Subseasonal to Seasonal (S2S) Environmental Prediction

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I. Key Challenge – S2S Prediction: Science, Operations & Applications

Demands are growing rapidly in the operational prediction and applications communities for environmental forecasts that fill the gap between medium-range weather (up to 2 weeks) and multi-season (6-12 months) climate forecasts. This intermediate forecast range is referred to as Subseasonal to Seasonal (aka S2S). Skillful S2S predictions provide important and valuable opportunities to inform decision makers, for example, of changes in the risk of extreme events or opportunities for optimizing resource decisions. Impacted decision-making areas include water availability and management, agriculture and food security, energy demand and production, hazard preparation and response, etc. Although many scientific and technological challenges remain to make sub-seasonal forecasts sufficiently reliable, skillful and tailored for users, a great return on investment is to be expected if the science and modeling capabilities associated with S2S prediction can be advanced. These technical advances hinge on maintaining and in some cases enhancing relevant observing resources

> The importance, potential value and challenges associated with S2S prediction are described more completely in a 2010 National Academies of Sciences, Engineering, and Medicine report, sponsored by NOAA, on intraseasonal to interannual climate prediction and predictability (NRC, 2010). A separate Academies' committee is currently finalizing a report, sponsored in part by NASA and ONR, on subseasonal to seasonal forecasting, which will update the 2010 report and recommend a national research agenda (release expected December 2015). The topic was also highlighted in the recent NASA Weather Focus Area Workshop Report (NASA, 2015).

A. Science

The scientific basis for S2S prediction lies in identifying sources of predictability within the coupled Earth system with S2S relevant timescales, and on our ability to understand these processes and phenomena well enough to represent them in a global modeling framework.

Satellite-based observations represent an essential resource for each of these steps. The following is a non-exhaustive list of high level, key science challenges to enable improved S2S predictions:

- Identify and characterize sources of S2S predictability. This includes natural modes of variability (e.g. ENSO, MJO, IOD, QBO), slowly evolving earth system components (e.g. sea ice, soil moisture, snowpack, ocean heat content), and some elements of "external forcing" (e.g. annual cycle, natural or anthropogenic emissions of aerosols).
- Understand and quantify how the above identified sources of predictability individually and collectively influence the development of disruptive and other extreme events (e.g. MJO and ENSO influences on tropical cyclone locations/frequency or mid-latitude blocking events, multi-scale variations of the monsoons).
- Develop accurate models/parameterizations of complex sub-grid scale processes that have significant importance to S2S phenomena and the sorts of predictability sources highlighted above. These include deep convection and mesoscale organization of storm systems, atmospheric boundary layer processes, aerosol-cloud-precipitation interactions, ocean mixed-layer and sea-ice processes, land surface and land-atmospheric interactions involving root zone and surface soil moisture, snow processes and vegetation dynamics.
- Identify the essential elements of coupling across Earth System components that when modeled will fully exploit the available predictability and provide predictive information for applications and societal benefits.

B. Applied Research and Operations

S2S forecasting is at a relatively early stage of development and utilization, bridging a gap between the more mature weather and climate prediction communities. Forecasting the day-to-day weather is primarily an atmospheric initial condition problem, although there can be an influence from ocean and land conditions. Forecasting at the annual and longer range depends strongly on the slowly-evolving components of the earth system such as ocean heat content. Predicting at intermediate, S2S, timescales, poses unique challenges since it involves many processes and multi-scale interactions that operate among the atmosphere, ocean, and land surface. In recent years, there has been significantly more attention given to this intermediate time scale, as sources of predictability have become better understood and modeled and the demand for a seamless suite of forecast products for socio-economic benefits grows (e.g. Barnston et al. 2009; Brunet et al. 2010; Gottschalck et al. 2010; Lin et al. 2010; Vitart et al. 2010; Marshall et al. 2011, 2014, Waliser 2011; Zhang 2013; Scaife et al. 2014; Mo and Lyon 2015).

While a number of operational forecast centers have developed S2S forecast systems, most are experimental – particularly at the subseasonal range – and the national and international community is collectively working to develop and improve these systems as many questions and challenges remain regarding their optimization, potential and use. Such efforts include the North America Multi-Model Ensemble (NMME; Kirtman et al. 2013) and World Climate Research Program (WCRP) – World Weather Research Program (WWRP) joint S2S Prediction Project (Vitart et al. 2012). Both of these projects are based on quasi-operational (e.g. informal requirements or delayed mode) multi-model forecast systems primarily designed for research and experimentation – with both science and applications use in mind. Along with the intrinsic science challenges highlighted above, there are additional challenges that bear directly on the advancement of operational capabilities. Some of these *challenges that dovetail with the need for space-based observations* are:

- Developing optimal strategies for initializing an S2S forecasting system, considering the roles and predictability associated with the atmosphere, ocean, land and cryosphere.
- Developing/improving the initialization of surface variables critical to S2S prediction (e.g. sea ice, snow, soil moisture, ocean mixed-layer).
- Construction of initial conditions that better utilize satellite data in cloudy and precipitating regions where significant challenges remain in data assimilation methodology. Similarly, contending with anthropogenic sources of microwaves that confound and limit use of passive microwave observations (e.g. for soil moisture, freeze-thaw).
- Reduction of model systematic errors in the underlying physical processes and S2S relevant phenomena that affect S2S forecast skill.
- Developing coupled atmosphere-land-ocean data assimilation methodologies.
- Determining optimal verification strategies, including measurements and metrics, for S2S forecasts.
- Translating S2S forecast information into actionable information for societal benefits (e.g. agriculture, water management, energy and food security, public health, hazard preparation and response), as well as developing awareness of S2S forecast products, and sustaining the associated resources that underpin the forecast systems.

C. Applications

The operational S2S forecast systems mentioned above are *typically* composed of coupled land, ocean and atmosphere components, providing, in some cases experimentally, daily ensemble forecasts of a wide variety of physical variables with subdaily temporal resolution (e.g. 6 hours), order 50-100km horizontal resolution and with lead times out to 45 days and in some cases 180 days or more. A number of these quantities can be used directly for decision support (e.g. precipitation, surface temperature and wind, upper level winds, soil moisture and evapotranspiration), and for many applications can be used to subsequently drive other component models used for applications (e.g. air quality, finer scale hydrology, ocean wave modeling/ship routing, lake/coastal hypoxia). As with weather forecasts, the range and depth of the potential impact of useful S2S forecasts is extensive. Examples of use and/or expected use include: 1) agriculture at a local/regional level as well as for food security concerns at national and international levels, 2) water availability and management at local/regional levels as well as for security concerns at national and international levels, 3) hazard preparation and response, including for floods, tropical cyclone and other severe storms, 4) health considerations, including those related to air and water quality, vector-borne diseases, and severe heat and cold conditions, 5) energy production (e.g. wind, hydro) and demand related to anomalous temperature conditions, 6) transportation, including ship routing and guidance for potential Arctic passages, 7) military planning and security concerns related to many of the items above. While the potential of S2S prediction to yield actionable information in these areas is evident, bringing this promise to fruition still requires considerable advances in both research (Section I.A) and operations (Section I.B), both of which depend critically on observations (Section III).

II. Timeliness – Substantial Unexploited Societal Benefits from S2S Predictions

While many end-users have benefited by applying weather and climate forecasts in their decision-making, there remains ample evidence to suggest that such information is underutilized across a wide range of economic sectors (e.g., Pielke and Carbone, 2002; Hansen, 2002; Morss et al., 2008; Rayner et al., 2005; O'Connor et al., 2005; Spillman et al. 2015). This may be explained in part by the presence of 'gaps' in our forecasting capabilities, for example at the sub-seasonal scale of prediction, by a lack of understanding and appreciation of the complex processes and numerous facets involved in decision making, and often major gaps in access to forecasts and knowledge, particularly in developing countries. While assessing the economic value of environmental forecasts is difficult, it is readily evident that a significant portion of our nation's economic security is sensitive to weather/climate and on the availability and accuracy of the associated forecast information (e.g. Dutton, 2002; Morss et al., 2005; 2008; Lazo et al. 2005; 2008; Thiaw and Kumar, 2014). With many of the fundamental prediction components in place (e.g. weather and climate prediction systems and capabilities, and the associated means of information dissemination), coupled with evidence of the significant need for S2S forecast information across a wide array of decision-making areas, S2S prediction represents a key science and societal challenge area ripe for attention and advancement.

III. Space-based Observations – A Cornerstone of S2S Predictions

Space-based observations are critical to sustaining and more fully developing and exploiting S2S predictions for societal benefits. The space observation needs can most simply be categorized into key observation sources for 1) operations, and thus a need for continuity, 2) observations that need to be further developed and expected to be essential for accurate and improved operational S2S forecasting, and 3) observations needed to improve our understanding of S2S processes and phenomena and our forecast models' capabilities and fidelity. *It is worth emphasizing that along with space-based observations, there is significant need for complementary in-situ networks and research campaigns for synergistic use in process research, satellite measurement validation, and the development and validation of the S2S forecast models.* Highlighted below is a non-exhaustive list of a number of the more important space-based observations needed for sustaining and improving S2S prediction.

Operational use/continuity – these measurements, already available and in use, derive from one or more well-established techniques and provide foundational support for S2S forecast systems, including for assimilation, verification and diagnostic evaluation.

- Ocean – SST, surface winds, sea surface height, sea ice cover
- Atmosphere – temperature and humidity profiles, precipitation
- Land Surface – temperature, snow cover

1) **Research need, with potential operational use** – these measurements are still experimental in terms of their measurement approach, use and/or impact on S2S forecast systems. However, given their critical role in S2S processes and sources of predictability, they are expected to be of significant benefit to S2S forecast fidelity.
    - Ocean – sea ice thickness, salinity
    - Atmosphere – boundary layer information, horizontal winds, aerosol characterization

    - Land Surface – soil moisture (surface and root zone), snow water equivalent, evapotranspiration
2) **Research need** – at present, these measurements are deemed important to improve our understanding and modeling of processes that are central to extending the range and accuracy of S2S forecasts.
    - Ocean – mixed-layer depth, surface currents
    - Atmosphere – storm vertical motion, aerosol-cloud-precipitation interactions
    - Land Surface – vegetation dynamics, surface, soil and groundwater interactions

Note that for a number of the measurements above, it is important - for process understanding, model development and/or forecast applications - to have daily and in a number of cases sub-daily sampling for resolving the diurnal cycle, particularly for the atmosphere and ocean/land surface. Requirements on spatial resolution vary, and are tied to a combination of the S2S forecast system resolution (10s km) and the given quantity and its scales of variability (1-100kms).

<u>Critical to the utility of a number of remote sensing systems is the maintenance and/or further development of robust in-situ networks for absolute calibration and error characterization</u>. It is recognized that few if any of the remote sensing observations can be use effectively without adequate, sustained ground validation sites / networks.

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