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Current Opinion in Environmental Sustainability

Predictability, uncertainty and decision making: a unified perspective to build a bridge from weather to climate

Arun Kumar[1] and Raghu Murtugudde[2]

In this essay, the common thread of limits of predictability and uncertainty that permeate across weather and climate prediction and projections is discussed in the context of developing a strategy for 'seamless' communication and utilization of uncertain information in decision making. In understanding why uncertainty is an unavoidable trait of predictions in the first place, a useful concept is the separation of the Earth System (ES) into internal and external components. This separation allows one to first, recognize that for prediction at all time-scales, the inherent source for limits on predictability is due to the divergence of forecasts from a cloud of initial conditions, and second, thereby recognize that the fundamental source of uncertainty (or unpredictability) is limited by our ability to specify initial conditions for the internal component with perfect accuracy.The unavoidability of uncertainty in predictions, and accepting this fact could be advantageous in the ongoing discussions on how to communicate climate projections and the associated uncertainties by learning from the knowledge base that exists for communicating similar information on weather and seasonal predictions that are generated on a much more frequent basis. Similarly, decision-support systems for developing adaptation and mitigation strategies can use predictions on shorter range as a test-bed to hone their strategies to incorporate predictive uncertainty when dealing with longer-range projections. By practicing the use of decision making tools and the incorporation of uncertain predictions on weather and seasonal time scale, decision makers can improve their level of comfort in accepting uncertainty inherent in longer range predictions and projections on a much less infrequent basis. In this paradigm, evolving strategy for seamless predictions can be blended with a strategy for seamless communication of uncertain information and also with seamless application of decision support systems.

Addresses
[1] Climate Prediction Center, 5830 University Research Court, College Park, MD 20740, United States
[2] ESSIC, University of Maryland, College Park, MD 20742, United States

Corresponding author: Kumar, Arun (arun.kumar@noaa.gov)

Current Opinion in Environmental Sustainability 2013, **5**:327–333

This review comes from a themed issue on **Open issue**

Edited by **Rik Leemans** and **William Solecki**

For a complete overview see the Issue and the Editorial

Received 1 February 2013; Accepted 31 May 2013

Available online 24th June 2013

1877-3435/$ – see front matter, Published by Elsevier B.V.

http://dx.doi.org/10.1016/j.cosust.2013.05.009

Introduction

Climate projection and climate change information, together with associated uncertainty, need to be communicated to the users and incorporated in decision support systems in developing adaptive responses [1••,2,3]. In this context, one needs to recognize that uncertainty is an inherent feature of predictions and projections and that it needs to be better quantified but can never be eliminated. The basic root of uncertainty resides in our inability to specify the initial conditions for the different components of the Earth System (hereafter referred to as ES) — atmosphere, ocean, for example, with perfect accuracy.

Given the long time horizon of climate projection and change, neither do the producers of climate information get to communicate uncertainty to the users very frequently, nor do the users of the information get to incorporate it often in their decision support systems. As a consequence, the methods to communicate and incorporate uncertainty in decision support systems are not put to the test on a routine basis. A possible way to ameliorate this issue is to develop a seamless strategy for communicating and incorporating uncertainty in decision support systems whereby lessons learned from similar practices used in much more frequent weather and seasonal predictions can be translated to climate prediction and projection time scales. The basic underlying paradigm is that decision-makers including laypeople have a better sense of uncertainty in the use of weather predictions because of the frequency of weather forecasts (several times a day and continuous updates online). A similar level of familiarity and ease in the delivery and communication of forecasts must also be established for time-scales beyond weather into extended range (beyond week one) and seasonal time-scales. Decision making under uncertainty can then be better grasped by decision-makers and policy-makers and all sectors of stakeholders for longer time-scales of climate predictions and projections.

Why uncertainty in predictions can never be eliminated?

The weather prediction problem

Evolution of Earth's climate system cannot be predicted perfectly, and involves uncertainties in anticipating its future outcomes. In discerning why uncertainty is an unavoidable trait of predictions, the notion of *internal variations* and *external forcings* is a useful simplification. A decomposition of the ES into internal and external components relies on the notion that the evolution of internal component can largely be considered independent relative to a fixed external component, allowing one to simplify the complex problem of making predictions. We illustrate this concept of the separation of ES into internal and external components for predicting evolution of the atmosphere on 1–2 week time-scale.

Specific to prediction problem on 1–2 week time-scale (often referred to as the weather prediction), the fast evolving atmosphere can be considered as the 'internal' component of the ES, and variations in the other components of the ES — sea surface temperatures (SST), atmospheric composition, natural forcings such as solar constant, and aerosols — can effectively be considered as fixed 'external' facings. One then attempts to predict the weather (the internal component) within the constraints of external forcings as boundary conditions.

Starting from an observed atmospheric state (or the initial condition), the future evolution of atmosphere is made based on solving the equation of motions, and is generally done on computers utilizing weather prediction models. The atmospheric observed state, however, can never be specified with infinite precision, and this limitation ultimately leads to *uncertainty* in the evolution of atmospheric weather patterns over the time-scales of 1–2 weeks [4]. Another source of uncertainty for predictions on is due to errors in the models that are used for weather predictions, for example, inaccuracies in the parameterization of unresolved scales. Uncertainty due to model errors, however, should get smaller as the weather prediction models improve.

In this paradigm of understanding the causes of uncertainty in weather prediction, delineation of the ES into internal and external components is a useful concept both from the point of understanding the source of predictive uncertainty and also for practical aspects of making weather predictions. At the understanding level, this delineation allows us to relate the uncertainty in weather prediction to our limited ability in correctly specifying the initial observed state of the atmosphere. At a practical level, it allows us to treat the external components as a constant forcing without trying to predict their evolution over 1–2 week time scale.

This delineation of the ES into internal and external components also determines the time horizon for making useful weather predictions (which is referred to as limits of predictability). This, in the case of weather prediction, is due to uncertainty in the specification of initial conditions, and inflation of a small cloud of initial errors into a much bigger cloud of future possibilities of forecast states. The time-scale of predictability, or the useful range of weather prediction is limited to the time-scale when 'the cloud of future possibilities' becomes large enough to encompass a wide range of atmospheric states and the prediction problem starts to resemble a process where one is making a random selection from a disparate range of possibilities. This time-scale for useful weather prediction is about a couple of weeks [4]. Over this period of predictability for atmospheric evolution, slowly varying external forcings can safely be assumed as constant, thus simplifying the models that are used in the weather prediction enterprise.

One can also cast the future evolution of the cloud of atmospheric trajectories in a formal framework of concepts of probability — the probability density function (PDF) of the states of the internal component(s) of the ES. In the case of weather prediction, the predictability due to initial conditions is our ability to distinguish the evolving PDF of atmospheric states from the climatological PDF of the atmospheric states, and predictability time-scale is the time-scale until which such a distinction between two PDFs can be made [5,6]. In the context of external forcings, their influence on the PDF is considered to be small. However, difference in PDFs of internal components due to external forcings is a concept that becomes more relevant for predictions and projections on a longer time-scale.

Extending the weather paradigm to seasonal climate prediction

Next, we extend the concept of the separation of ES into internal and external components to seasonal predictions. The historical development of seasonal prediction can be separated into two phases. For seasonal predictions our ability of make useful predictions comes from the influence of slowly evolving boundary conditions in the ES, for example, sea surface temperature. In the first phase of the development of seasonal predictions (now referred to as the two-tiered seasonal prediction system), the future evolution of SST variations was first predicted, and subsequently, predicted SST variations were used as external forcings in atmospheric general circulation models (AGCMs) to discern the influence of SST anomalies on the seasonal evolution of atmospheric variations. In the two-tiered framework of seasonal predictions [7,8], SSTs are still considered as an external forcing with the caveat that over the time-scale of prediction, its evolution is specified, while all other external forcings — atmospheric composition, and so on — are still held constant.

For two-tiered seasonal predictions, the predictability of seasonal mean climate anomalies is due to the influence of SST anomalies on the PDF of the seasonal mean of atmospheric states, and our ability of distinguish the PDF for a particular season from the corresponding climatological PDF [9,10]. The uncertainty in the seasonal prediction (or the spread in possible seasonal mean states), however, is once again due to the divergence of predicted seasonal means evolving from the cloud of atmospheric initial conditions. From the perspective of the source of predictability, seasonal prediction of atmospheric means