mate models appear to systematically under-predict low frequency variations, and should assess the implications for drought projections that are necessary for the future performances of water resource systems.

Summary.

Changes in climate will result in changes in water resources. Central to these changes will be the ability to estimate the statistical characteristics of the water cycle variables that control the design and reliability of water resource systems. GEWEX has identified as one of its central scientific objectives assessing the consequences of global change on water resources. Our vision is that GEWEX should embrace a scientific agenda that addresses the three issues outlined above that are critical to the design and reliability of water resource systems–specifically, addressing time series non-stationarity in a changing climate; assessing the statistical characteristics of hydrologic extremes (floods and droughts) in climate projections models and their implications for future design; and understanding the apparent under-persistence in water cycle variable time series generated from climate models and the associated implications for the reliability of water resource system. If GEWEX could motivate progress in these areas, it would assume a central role in global change science.

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Collateral Damage from the Death of Stationarity

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In February, 2008, a group of authors writing in *Science* declared that insofar as water management is concerned, stationarity is dead (Milly et al., 2008). What they mean by this claim is that water management decisions can no longer proceed under the assumption that “the idea that natural systems fluctuate within an unchanging envelope of variability.” The authors assert that both scientists and decision makers have long been aware of human disturbances and climate variations and their effects on the water cycle, but have historically considered these effects “to be sufficiently small to allow stationarity-based design.” Such assumptions allowing for stationarity-based design, they argue, are no longer valid. Stationarity is dead.

The authors of the *Science* article assert that the cause of the death of stationarity is human-caused climate change resulting from the emission of greenhouse gases. However, some scholars have argued that treating natural systems as stationary has always been a mistake. Such arguments are frequently found in relation to the water cycle, for instance, in discussion of the often misused notion of the 100-year flood. Stationarity, these scholars might say, has always been dead. But whether or not natural systems are stationary in the absence of greenhouse gas emissions misses the larger point that the assumptions of stationarity that have underpinned water management for many decades are increasingly viewed as flawed. Consequently, there is a need to consider alternatives to stationarity-based policies.

One implication that the authors of *Science* draw from the death of stationarity is that more attention should be paid to modelling and observations of natural processes. They argue that “we need to find ways to identify nonstationary probabilistic models of relevant environmental variables and to use those models to optimize water systems.” In other words, we have to improve our ability to anticipate the future, because relying on the statistics of the past will no longer be a useful guide to what is to come. Of course, more attention to models and observations was often the same recommendation found when stationarity was thought to be alive and well.

Here I suggest a far more consequential implication of the death of stationarity for the role of science in water management decision making than a need for better models and observations. Rather than basing decision-making on a predict (probabilistically of course) then act model, we may have to face up to the fact that skillful prediction of variables of interest to decision makers may simply not be possible. And even if it were possible, we would not be able to identify skill on the same time scales as decisions need to be made. The consequence of this line of argument is that if stationarity is indeed dead, then it has likely taken along with it fanciful notions of foreseeing the future as the basis for optimal actions. Instead, it may be time to rethink how we make decisions in the face of not simply uncertainty, but fundamental and irreducible ignorance. Rather than focus on optimal decisions guided by prediction, we may need instead to focus on robust decisions guided by recognition of the limits of what can be known.

Why Skillful Predictions are Not Possible: The Guaranteed Winner Scam Meets the Hot Hand Fallacy

A skillful prediction is one that improves upon a prediction based on a naive baseline. For weather and climate forecasts the naive baseline that is typically used is climatology. Two simple dynamics associated with the production and interpretation of predictions help to explain why the death of stationary makes the prospects for skillful predictions less likely in the future. By contrast, conventional wisdom holds that nonstationary processes are often more amenable to skillful prediction.

The first involves the consequence of the availability of multitude predictions for most any variable of interest to decision makers. The second dynamic involves a well-known, but nonetheless common, bias in decision making.

The first of these dynamics might be called the "guaranteed winner scam," after the following analogy. Select 65,536 people, and tell them that you have developed a methodology that allows for 100% accurate prediction of the winner of next weekend's big football game. You split the 65,536 people into two equal halves and send one half a guaranteed prediction of victory for one team, and the other half a guaranteed win on the other team. You are guaranteed that your prediction will be viewed to be correct by the 32,768 people who received your correct prediction.

Each week you can proceed in this fashion. By the time 8 weeks have gone by there will be 256 people anxiously waiting for your next week's selection because you have demonstrated remarkable predictive capabilities, having provided them with 8 perfect picks. Presumably they will now be ready to pay a handsome price for the predictions you offer in week 9.

Now instead of predictions of football match winners, think of real-time predictions of natural processes, such as precipitation, floods, or the state of the El Niño Southern Oscillation (ENSO). In such a situation, predictions that build in considerations of nonstationarity will (by definition) differ from predictions based on a stationary climate. With enough of a diversity of predictions and predictive methodologies, there will be a very wide spread of forecasted events for any particular phenomena. And for almost any phenomena of interest, meteorological services, management agencies, scientific literature, as well as pronouncements by individual scientists, will generally provide a wide range of predictions.

Consider for example, Jewson et al. (in press), which presents a suite of 20 different models that lead to predictions for 2007-2012 hurricane landfalls in the United States. The suite of models produce forecasts that span a range from more than eight percent below the 1900-2006 mean to 43 percent above that mean, with 18 values falling in between. Over the 5–year period it is virtually certain that one or more of these models (and there are of course other models and predictions from other sources) will have provided a prediction that will be more accurate than the long-term historical baseline (i.e., will be skillful). And of course, this refers only to the analysis found in a single paper; a broader survey of relevant predictions would arrive at a substantially wider spread.

With such diversity of predictions, the user of these forecasts has no way of knowing whether the skill was the result of true predictive skill or just chance given a very wide range of available predictions. And because the scientific community is constantly introducing new methods of prediction, the "guaranteed winner scam" can go on forever with little hope for certainty. Nonstationarity makes this problem even more intractable, because even if skill could be demonstrated for one set of predictions, nonstationarity could easily mean that such demonstrated skill is not stable and the same methodology may not continue to generate skillful forecasts as relationships evolve and change over time.

Complicating the issue is a second dynamic, the "hot hand fallacy" which was coined by behavioral pschyologists to describe how people misinterpret random sequences, based on how they view the tendency of basketball players to be "streak shooters" or have the "hot hand" (Gilovich et al., 1985). The "hot hand fallacy" holds that the probability in a random process of a "hit" (i.e., a made basket or a successful hurricane landfall forecast) is higher after a "hit" than the baseline probability. (The "gambler's fallacy" is also relevant. It posits that the odds of a miss are higher after a run of "hits.") In other words, people often see patterns in random signals that they then use, incorrectly, to ascribe information about the future.

1972 Melbourne flood – Elizabeth Street. Photo courtesy of the Commonwealth of Australia 2009, Bureau of Meteorology (ABN 92 637 533 532).

The "hot hand fallacy" can manifest itself in several ways with respect to predictions of Earth system processes. First, as argued above, the wide range of available predictions essentially spanning the range of possibilities means that some predictions for the next years will be shown to have been skillful. Even if the skill is the result of the comprehensive randomness of the "guaranteed winner scam" there will be a tendency for people to gravitate to that particular predictive methodology that appears to succeed for future forecasts, much like the person who receives eight consecutive weeks of correct football winners will pay close attention to that issued for week nine. Second, a defining feature of climatology is persistence, suggesting that nature does sometimes really exhibit a "hot hand." However, nonstationarity means that an over-reliance on persistence will eventually lead one astray, even when skill has been shown to exist.

As a result of these dynamics, robust predictive skill can be shown only over a fairly long term, offering real-time predictions and carefully evaluating their performance. For predictions that are issued and evaluated frequently, such as daily weather forecasts, useful determination of skill is possible. But as the time scale of the phenomena stretches to longer timescales, such as seasonal or interannual predictions, the time period necessary to demonstrate skill necessarily is many decades, far beyond the timescale of any decision process. For even longer term forecasts, such as decadal and longer, determination of skill in forecasting simply cannot be done on human timescales. Consequently, judgments of skillful predictive methodologies on shorter time scales must be based on guesswork or other factors beyond empirical information on predictive performance.

Alternatives to Prediction

Fortunately, decision makers have alternatives to prediction. Such alternatives depend no less on science, but they will depend on science beyond predictions generated from sophisticated models. Individuals and organizations commonly take actions without accurate predictions of the future to support them. They manage the uncertainty by making decisions or establishing decision processes that produce satisfactory results in the absence of good predictions. In recent years, a number of researchers have begun to use climate models to provide information that can help evaluate alternative responses to climate change, without necessarily relying on accurate predictions as a key step in the assessment process. The basic concept rests on an exploratory modelling approach in which analysts use multiple runs of one or more simulation models to systematically explore the implications of a wide range of assumptions and to make policy arguments whose validity is unaffected by uncertainties.

As a key step, such analyses use climate models to identify potential vulnerabilities of proposed adaptation strategies. These analyses do not require accurate predictions of future climate change from cutting edge models. Rather they only require a range of plausible representations of future climate that can be used, for instance, to help the water agencies better understand where their vulnerabilities may lie and how they can be addressed. Even without accurate probability distributions over the range of future climate impacts, such information can prove very useful to decision makers.

A robust decision is one that leads to success or avoids failure regardless of circumstances, rendering specific knowledge of the future much less important. Robust strategies perform well compared to the alternatives over a wide range of assumptions about the future. In this sense, robust strategies are "insensitive" to the resolution of the uncertainties.

A focus on robust decision making in recognition of the limited ability to demonstrate predictive skill does not imply that climate model development should cease; further model development can and should inform the plausible ranges used in robust decision-making. However, we must give up fantasies of being about to accurately predict the future, and as importantly, to even know how well we can anticipate the future before it arrives.

By avoiding an approach that places climate prediction at its heart, successful adaptation strategies can be developed in the face of this deep uncertainty. Decision makers should systematically examine the performance of their adaptation strategies over a wide range of plausible futures driven by uncertainty about the future state of climate and many other economic, political and cultural factors. They should choose a strategy that they find sufficiently robust across these alternative futures. Such an approach can identify successful adaptation strategies without accurate and precise predictions of future climate.

The death of stationarity may very well have taken with it notions of our ability to skillfully predict the future. As a consequence, it casts serious doubts on the viability of a predict-and-decide mode of connecting science with decision making. Rather than despair this situation, we should embrace it, as the death of stationarity has been long overdue.

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