

Decadal climate prediction: challenges and opportunities

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Abstract. The scientific understanding of climate change is now sufficiently clear to show that climate change from global warming is already upon us, and the rate of change as projected exceeds anything seen in nature in the past 10,000 years. Uncertainties remain, however, especially regarding how climate will change at regional and local scales where the signal of natural variability is large. Addressing many of these uncertainties will require a movement toward high resolution climate system predictions, with a blurring of the distinction between shorter-term predictions and longer-term climate projections. The key is the realization that climate system predictions, regardless of timescale, will require initialization of coupled general circulation models with best estimates of the current observed state of the atmosphere, oceans, cryosphere, and land surface. Formidable challenges exist: for instance, what is the best method of initialization given imperfect observations and systematic errors in models? What effect does initialization have on climate predictions? What predictions should be attempted, and how would they be verified? Despite such challenges, the unrealized predictability that resides in slowly evolving phenomena, such as ocean current systems, is of paramount importance for society to plan and adapt for the next few decades. Moreover, initialized climate predictions will require stronger collaboration with shared knowledge, infrastructure and technical capabilities among those in the weather and climate prediction communities. The potential benefits include improved understanding and predictions on all time scales

1. Introduction

The Earth's climate is changing, and detection and attribution studies consistently find an anthropogenic signal in the climate record of at least the last half-century. Human activities are rapidly changing the composition of the atmosphere through the burning of fossil fuels and changes in land use, such as those associated with agriculture and deforestation.

Many recent observed changes in climate are broadly consistent with increased radiative heating at the Earth's surface. These include (1) an increase in the globally averaged surface temperature of 0.75°C over the past century, including warming of 0.17°C per decade since 1979; (2) the rapid melting of glaciers in nonpolar regions around the world; (3) dramatic decreases in the areal coverage

and thickness of Arctic sea ice, especially during spring and summer, and of snow cover over northern continents; (4) decreases in the maximum area covered by seasonally frozen ground in the high latitudes of the Northern Hemisphere (NH); (5) a reduction of about two weeks in the annual duration of northern lake and river ice cover; (6) an increase in global ocean surface temperatures of 0.35°C since 1979, with warming evident at all latitudes over each of the ocean basins and to depths of at least 3000 m; (7) an increase in global sea level of 0.18 cm per year since 1961, with a faster rate (0.31 cm per year) since 1993 due to thermal expansion and contributions from melting glaciers and ice caps; (8) increases in the atmospheric moisture content through increased evaporation of surface moisture; and (9) changes in extremes consistent with the warming, such as an increase in the number of heat waves globally, widespread increases in the numbers of warm nights, and rarer occurrences of cold days, cold nights, and days with frost. These many independent observations, and the physical consistency among them, form the basis for the iconic phrase from the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) that the “warming of the climate system is unequivocal.”

The indisputable evidence of global warming and the knowledge that surface temperatures will continue to rise over the next several decades under any plausible emission scenario is now a factor in the planning of many organizations and governments. It does not imply, however, that future changes will be uniform around the globe. Regional and seasonal variations in climate will be notable, especially over periods of a few decades or less. Regional differences in land and ocean temperatures arise, for instance, from natural variability and other factors. Natural variability can result from purely internal atmospheric processes as well as from interactions among the different components of the climate system, such as those between the atmosphere and oceans or the atmosphere and land.

One example is the very strong warming of the central and eastern tropical Pacific Ocean that occurs during El Niño events. These events also produce ocean cooling over portions of the subtropics and the tropical western Pacific. Over the Atlantic, average basin-wide warming is imposed on top of strong, natural variability on multidecadal time scales. The level of natural variability, in contrast, is relatively small over the tropical Indian Ocean, where the surface warming has been steady and large over recent decades.

These differences in regional rates of sea surface temperature (SST) change perturb the atmospheric circulation so that some regions become warmer and wetter, while other regions cool and dry out. For instance, the tendency for the most prominent mode of natural atmospheric circulation variability over the NH, the North Atlantic Oscillation (NAO), to remain in a mostly positive index state over the past several decades has contributed to strong warming and wetter-than-normal conditions over much of northern Europe, while colder and drier conditions have prevailed over much of southern Europe and northern Africa. Hurrell et al. [1] find that these pronounced regional changes in climate associated with the NAO have likely been influenced by changes in the distribution of tropical heating induced by regional changes in tropical SSTs. There are many other examples as well. Atmospheric circulation changes have brought cloudier and wetter conditions in recent decades to the southeastern U.S. [2], while warming has been strong over the West (figure 1). Changes in tropical SSTs are likely a key factor in producing the Dust Bowl era of the 1930s over the central U.S. [3, 4], the devastating droughts over the Sahel and other parts of Africa since the 1980s [5, 6], and the widespread drying over subtropical land regions of the NH in more recent years [7]. Multidecadal variations in tropical and Pacific SSTs have been implicated in decadal changes in temperature and rainfall patterns across the Pacific basin [8], while slow changes in Atlantic SSTs have affected regional climate trends over parts of North America and Europe [9, 10, 11], hemispheric temperature anomalies [11] and hurricane activity in the tropical Atlantic and Caribbean [12, 13, 14].

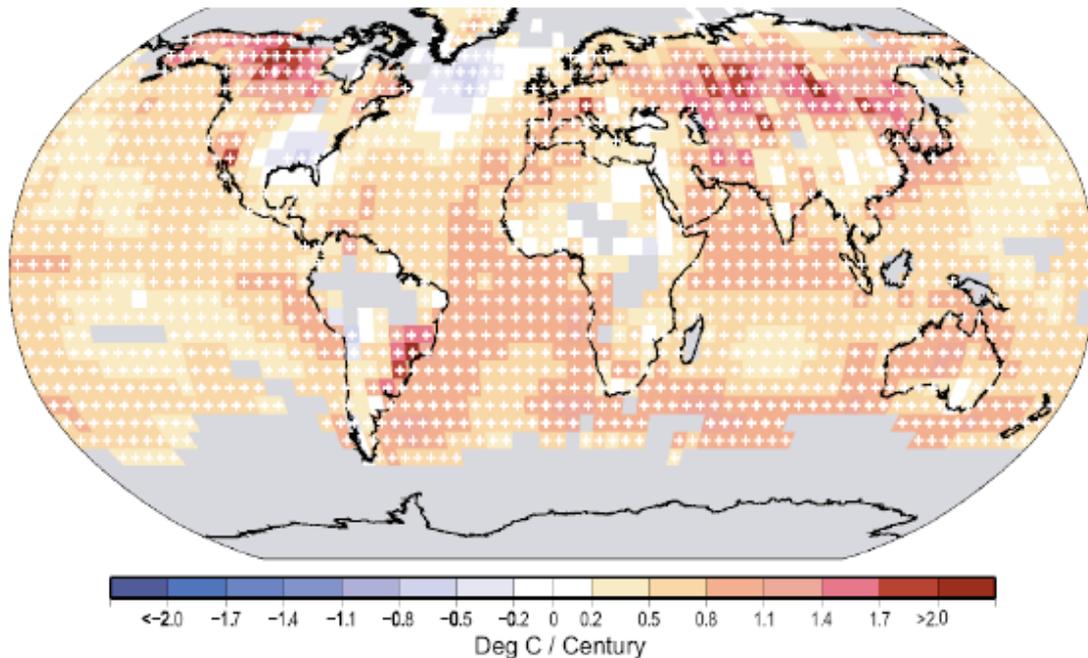


Figure 1. Linear trend of annual temperatures for 1901 to 2005 ($^{\circ}\text{C century}^{-1}$). Areas in grey have insufficient data to produce reliable trends. Trends significant at the 5% level are indicated by white + marks. The figure is taken from Trenberth et al. [2].

Clearly, therefore, at the regional scales on which most planning decisions are made, future warming will not be smooth. Instead, it will be strongly modulated by natural climate variations, and especially those driven by the slowly varying oceans on a time scale of decades. This nonuniformity of change highlights the challenges of regional climate change that has considerable spatial structure and temporal variability. Moreover, it illustrates the need to predict patterns of SSTs around the globe as accurately as possible. Emerging evidence suggests that this might well be possible, at least for a decade or two in advance. Finding ways to account for these variations through initialized climate predictions will provide society with much better information on what kind of climate change to expect.

2. Climate system prediction and the effect of initial conditions

Good and well-documented reasons exist for the historically different approaches that have been taken toward shorter- and longer-term predictions. For weather prediction, detailed analyses of the observed state of the atmosphere are required, but uncertainties in the initial state grow rapidly over several days. Other components of the climate system are typically fixed at observed values. For climate predictions, the initial state of the atmosphere is less critical, and states separated by a day or so can be substituted. However, the initial states of other climate system components, some of which may not be critical to day-to-day weather prediction, become vital.

Therefore, at least two types of predictions may be possible on longer timescales. The first is a prediction of the internal variability of the climate system based on an initialized state of the ocean, atmosphere, land and cryosphere system. Coupled ocean-atmosphere interactions, for instance, are likely important for understanding the temporal evolution of some extratropical regional modes of climate variability, such as the NAO [15]. Within the tropics, variations in SSTs play a dominant role in regional climate, not only through ENSO, but also through other local modes of coupled variability in the Atlantic and Indian Ocean basins [16]. Moreover, land surface processes, such as the role of soil

moisture, as well as changes in both sea ice and land snow cover, are important in establishing the variability of regional climate. Recent research has also indicated that the influence of the stratosphere on the state of the troposphere might also be a significant source of predictability, at least on seasonal timescales.

First attempts at “decadal prediction” with initialized coupled models have shown reduced error growth in globally averaged surface temperature over ten-year periods [17] and improved regional skill relative to predictions made with incomplete knowledge of the ocean state [18]. Decadal-scale predictability in the ocean may arise from fluctuations in gyre and overturning circulations, particularly in the Atlantic. These oceanic fluctuations produce changes in SST that could possibly lead to atmospheric predictability.

In addition to the potential sources of predictability from the initial values of the system, predictability may be derived from changes in radiative forcing. This necessitates the best possible estimates of future emissions of radiatively important pollutants, as well as modeling capabilities to accurately simulate both how these pollutants affect the global energy, carbon and sulfur cycles, and how the climate system subsequently responds to that altered forcing. In this regard, unpredictable volcanic eruptions can be a significant “wild card” to such predictions, although techniques to handle this aspect are under consideration. Despite these difficulties, it is likely that projected changes in radiative forcing are likely an important source of climate predictability, whose importance may grow with the time scale considered.

3. Some challenges

Accurate initial conditions for the global oceans are a major challenge. They could conceivably be provided by existing ocean data assimilation exercises, but salinity reconstructions prior to the ARGO float near-global upper ocean salinity and temperature data remain a significant problem. If model simulations are started prior to the availability of the ocean initial conditions, the model ocean would have to be nudged toward the observed values. How strongly this should be done and what it implies about energy conservation are research issues that are beginning to be explored.

The mass, extent, thickness, and state of sea ice and snow cover are vital at high latitudes. The states of soil moisture and surface vegetation are especially important in understanding and predicting warm season precipitation and temperature anomalies along with other aspects of the land surface. But at this time there is no direct way to provide soil moisture or ground conditions. Any information on systematic changes to the atmosphere (especially its composition and influences from volcanic eruptions) as well as external forcings, such as from changes in the sun, is also needed; otherwise these are specified as fixed at observed values. The potential errors induced by incorrect initial conditions should become less apparent as the simulations evolve but could still be evident through the course of the simulations.

Another significant obstacle is the systematic errors present in current couple climate models, so that the simulated climate is, in some cases, not close to the observed state at any given point in time. All models have systematic errors, some of which are common across the models. There are active research efforts that examine how to initialize the coupled modes of the coupled models given that they do not agree with those of nature. The basic idea is to recognize that the best state estimate for the individual component models may not be the best initial condition for coupled forecasts. Much of the research focuses on how to identify the slow manifold described by the observed estimates and the coupled model and how a mapping between them can be derived.

4. Concluding remarks

Currently, several decadal prediction activities are under way, although all are still in their infancy. The efforts typically fall into one of the following categories: using coupled models for days to decadal prediction or using numerical weather prediction models for seasonal to decadal prediction. Other approaches also are emerging such as the concept of beginning integrations with higher resolution to satisfy weather forecast requirements, then cascading down to lower-resolution versions

of the model with consistent physical parameterization schemes. All of these approaches have various scientific issues, as well as advantages and disadvantages, but they all attempt to remove the distinction between weather and climate.

At the heart of this new perspective of a continuum of prediction problems is the realization that all climate system predictions, regardless of timescale, may require initialization of coupled general circulation models with best estimates of the current observed state of the atmosphere, oceans, cryosphere, and land surface. Even though the prediction problem itself is seamless, the best practical approach to it may be described as unified: models aimed at different timescales and phenomena may have large commonality but place emphasis on different aspects of the system. The potential benefits of this commonality, however, are significant and include improved predictions on all timescales and stronger collaboration and shared knowledge, infrastructure and technical capabilities among those in the weather and climate prediction communities.

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