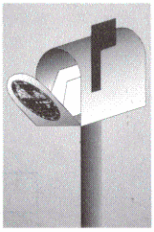
letters to the editor



Climate Prediction as an Initial Value Problem
Comments on AMS Policy Statement on Tornado Forecasting and Warning
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Climate Prediction as an Initial Value Problem

One set of commonly used definitions of weather and climate distinguishes these terms in the context of prediction: weather is considered an initial value problem, while climate is assumed to be a boundary value problem. Another perspective holds that climate and weather prediction are both initial value problems (Palmer 1998). If climate prediction were a boundary value problem, then the simulations of future climate will "forget" the initial values assumed in a model. The assumption that climate prediction is a boundary value problem is used, for example, to justify predicting future climate based on anthropogenic doubling of greenhouse gases. This correspondence proposes that weather prediction is a subset of climate predictions and that both are, therefore, initial value problems in the context of nonlinear geophysical flow. The consequence of climate prediction being an initial value problem is summarized in this correspondence.

The boundaries in the context of climate prediction are the ocean surface and the land surface. If these boundaries are fixed in time, evolve independently of the atmosphere such that their time evolution could be prescribed, or have response times that are much longer than the time period of interest in the climate prediction, than one may conclude that climate prediction is a boundary problem.

Lorenz (1979) proposed the concept of forced and free variations of weather and climate. He refers to forced variations as those caused by external conditions, such as changes in solar irradiance. Volcanic aerosols also cause forced variations. He refers to free variations as those that "are generally assumed to take place independently of any changes in external conditions." Day-to-day weather variations are presented as an example of free variations. He also suggests that "free climatic variations in which the underlying surface plays an essential role may therefore be physically possible."

There have been no model experiments to assess climate prediction in which atmosphere–ocean–land surface processes were included. Existing papers on this subject have been limited to coupled atmosphere–ocean global models (e.g., Cubasch et al. 1994; Larow and Krishnamurti 1998) or atmospheric models alone (e.g., Bengtsson et al. 1996). In Bengtsson et al. (1996), the ocean sea surface temperature is prescribed and vegetation effects, in their words, are "grossly simplified."

However, if the ocean surface and/or land surface changes over the same time period as the atmospheric changes, then the nonlinear feedbacks (i.e., two-way fluxes) between the air, land, and water eliminate an interpretation of the ocean–atmosphere and land–atmosphere interfaces as boundaries. Rather than "boundaries," these interfaces become interactive mediums. The two-way fluxes that occur between the atmosphere and ocean, and between the atmosphere and the land surface, must therefore necessarily be considered as part of the predictive system. On the timescale of what we typically call short-term weather prediction (days), important feedbacks include biophysical (e.g., vegetation controls on the Bowen ratio), snow cover, clouds (e.g., in their effect on the surface energy budget), and precipitation (e.g., that which changes the soil moisture) processes. This timescale is already considered an initial value problem (Sivillo et al. 1997). Seasonal and interannual weather prediction include the following feedbacks: *biogeochemical* (e.g., vegetation growth and senescence), *anthropogenic aerosols* (e.g., through their effect on the long- and shortwave radiative fluxes), *sea ice,* and *ocean sea surface temperature* (e.g., changes in upwelling such as associated with an El Niño) effects. For even longer time periods (of years to decades and longer), the additional feedbacks include *biogeographical processes* (e.g., changes in vegetation spe-

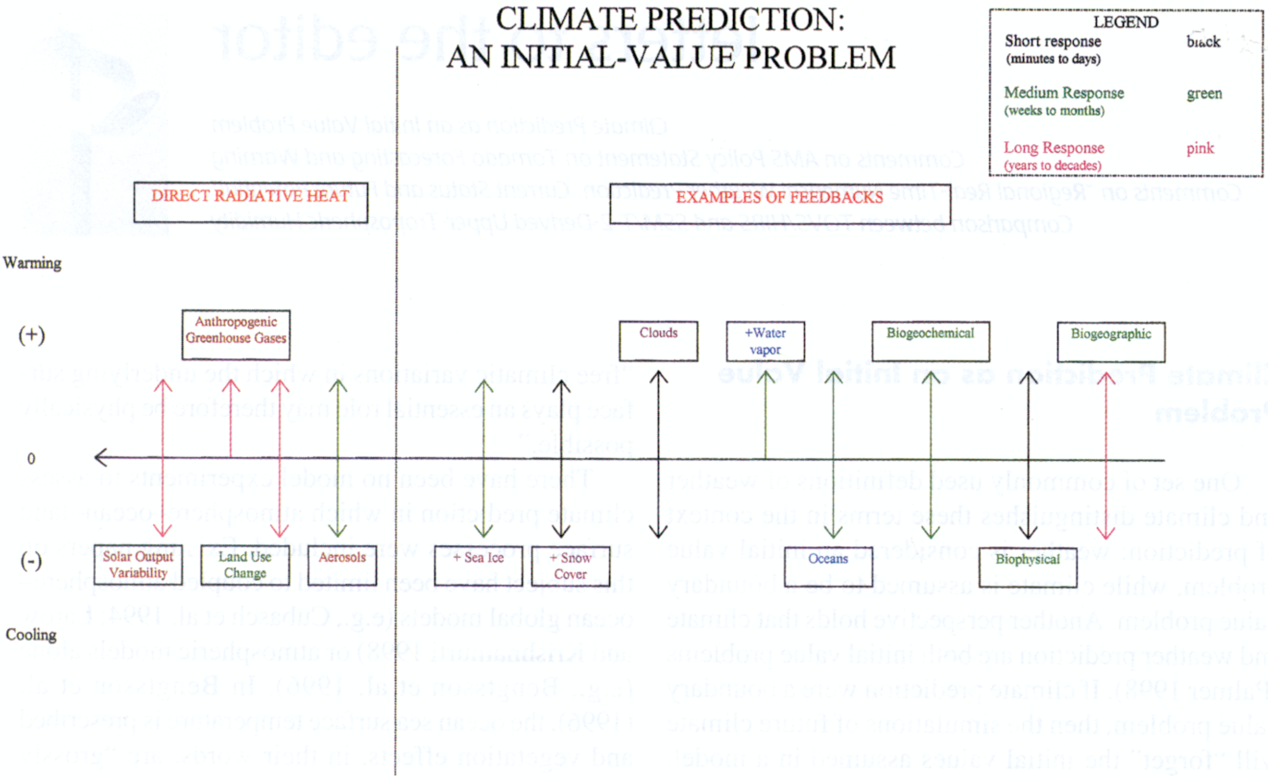

FIG. 1. Schematic illustration of direct effects and feedback influences with respect to climate prediction. The length of the arrows has no meaning here, although the possible sign each effect could have is shown.

cies composition and distribution), *human-caused land use changes*, and *deep ocean circulation effects* on the ocean surface temperature and salinity. In the context of Lorenz's (1979) terminology, each of these feedbacks are free variations.

Figure 1 schematically illustrates direct and feedback effects on global mean temperature, as an example of the complexity of climate prediction. Using Lorenz's terminology, the direct effects could be considered forced variations, while the feedbacks are part of the free variations.

Each of these timescales must be considered initial value problems because the predictions are dependent on the initial value for at least some aspects of the ocean–atmosphere–land surface coupled system. A range of recent work (Claussen 1994, 1998; Claussen et al. 1998; Foley 1994; Texier et al. 1997) has shown that the initial specification of the land surface exerts a strong control on the subsequent atmospheric circulation in global climate prediction models. Cubasch et al. (1994) suggest in a greenhouse gas warming experiment with a coupled ocean–atmosphere model that the time evolution of the modeled global mean warming is "strongly dependent on the initial state of the climate system."

Recent work that we have performed using a regional climate model illustrates how modeled seasonal weather is altered if two-way atmosphere–land surface interactions are included. The land surface model includes both biophysical (short term) and biogeochemical (medium term) interactions with the atmosphere. The biogeochemical model uses the CENTURY model (Parton 1996) in which plants grow in response to temperature and precipitation. Figure 2 illustrates the precipitation response in the atmospheric model when the amount of vegetation is specified (i.e., treating vegetation as an external condition) and when vegetation can grow in response to the atmospheric model input (i.e., treating vegetation as an internal variable). The difference between the model results over just one growing season is clearly evident. In the specified vegetation experiment, the model is simulating a "forced climate," while when vegetation is included in the model, a "free climate system" results. Details of this work are to be reported in Lu (1999).

An important practical conclusion results if climate prediction is an initial value problem. This means that there are necessarily limits on the time into the future that we can predict climate, since the feedbacks between the ocean, atmosphere, and land surface are large and nonlinear. These limits have not been determined, yet climate "predictions" are routinely communicated to policy makers on timescales of decades and centuries. Second, in the context of predicting what the future climate would be in response to an anthropogenic forcing such as carbon dioxide input, there are, as of yet, undefined limits on what aspects of future climate we can forecast even if all the important ocean–atmosphere–land surface feedbacks were included and also accurately represented in the models. This leads to the conclusion that weather prediction is a subset of climate prediction. Societally useful (i.e., reliable, accurate, etc.) climate prediction requires that all of the feedbacks and other physical processes included in weather prediction be represented in the climate prediction model. In addition, longer-term feedback and physical processes must be included. This makes climate prediction a much more difficult problem than weather prediction.

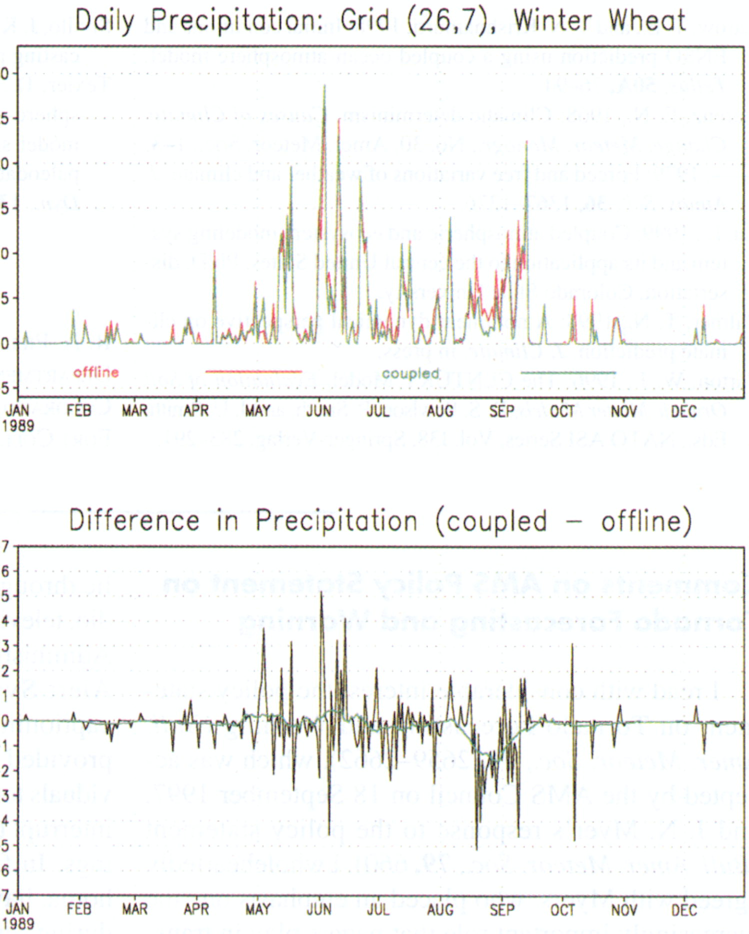

FIG. 2. Example of two model simulations for a location in the central United States where winter wheat is grown. The left axes are in units of millimeters per day. In the off-line experiment, observed temperatures and precipitation are input to a biogeochemical model (CENTURY; Parton 1996). In the coupled experiment, the temperature and precipitation are simulated in the climate version of the Regional Atmospheric Modeling System (RAMS) model and used as inputs to the CENTURY model on a weekly timescale. The difference in precipitation results from the feedbacks between the RAMS and CENTURY model as the amount of leaf area in the CENTURY model responds to the atmospheric input. Details of this study are to be reported in Lu (1999).

The climate system could also be "almost intransitive" using the Lorenz (1968) definitions of transitive and intransitive. This has generally been assumed to be true and is a rationale used to justify doubled-greenhouse gas modeling experiments such as reported in the IPCC (1992, 1996) documents. However, until the hypothesis that the climate system is transitive is rejected (as a result of the variety of significant ocean–atmosphere–land surface feedbacks), model-based forecasts of future climate should be viewed as sensitivity analyses rather than as reliable predictions.

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R. A. Pielke Sr.
Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

Comments on AMS Policy Statement on Tornado Forecasting and Warning

I read with considerable interest the policy statement on Tornado Forecasting and Warning (*Bull. Amer. Meteor. Soc.,* **78,** 2659–2662), which was accepted by the AMS Council on 18 September 1997, and J. N. Myer's response to the policy statement (*Bull. Amer. Meteor. Soc.,* **79,** 660). I wholeheartedly agreed with Myers, who placed an emphasis on "the increasingly important role that pagers play in transmitting severe weather warnings to churches, schools, emergency management agencies, corporations, companies, agencies, and individuals." As a profoundly deaf meteorologist, I have had the opportunity to use an alphanumeric pager because I cannot hear weather information or alerts from a television or radio. During the spring 1998 tornado season in Oklahoma, I found the pager very valuable since it provided the locations and durations of severe thunderstorm and tornado warnings. Without the aid of the pager or the assistance of hearing people, I had no idea of what was going on during the severe weather activity; I was left only guessing. I, therefore, stress the increasingly vital role that pagers play in transmitting severe weather warnings to hearing-impaired (deaf and hard-of-hearing) individuals who otherwise do not receive or "hear with their alert eyes" as much weather information as the hearing do. I recalled reading a letter from deaf residents in Arkansas who were not warned of a tornado passing by their residences at night. There have been some cases where hearing-impaired people were injured because they were not warned of severe weather.

The AMS policy states that "tornado warnings issued by the National Weather Service reach the public through a variety of methods including sirens, radio, television, the National Oceanic and Atmospheric Administration's Weather Radio, and the Emergency Alert System" (2660–2661). I stress that closed captioning of severe weather broadcasts should be provided because they help hearing-impaired individuals to know what forecasters are saying when they interrupt television programming with weather warnings. In fact, the television stations in Tulsa, Oklahoma, have recruited volunteers to go to the stations during severe weather events to type real time closed captioning of live weather warnings. While hearing-impaired and deaf viewers can benefit from closed captioning, the hearing- and visually impaired can receive severe weather warnings by connecting National Oceanic and Atmospheric Administration (NOAA) weather radios with alarm tones to other kinds of attention-getting devices such as strobe lights, pagers, bed-shakers, personal computers, and text printers (see the NOAA Weather Radio Web site at http://www.nws.noaa.gov/nwr).

An estimated 20 million Americans have hearing loss. Without the aid of closed-captioned weather broadcasts, NOAA weather radios, and pagers, the safety of the hearing-impaired population cannot and will not be guaranteed. This is especially true of the elderly, the fastest growing category of deaf and hard-of-hearing individuals.

Vincent T. Wood
National Severe Storm Laboratory
Norman, Oklahoma