ASSESSING THE ROLE OF CLIMATE IN ENVIRONMENTAL SYSTEMS ANALYSIS AND MODELING

Robert J. Oglesby
Department of Earth and Atmospheric Sciences, Purdue University, USA

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Summary

Climate is an essential part of the Earth system so modeling of the climate system is a key aspect of environmental modeling. Climate models are usually physically-based in that they rely on fundamental physical conservation principles. They also, however, have a large empirical or statistical component in that they contain many elaborate parameterizations of physical processes whose parameter values must be obtained by fitting to observations. Climate is explicitly or implicitly involved in almost every aspect of environmental modeling. Since climate is a statistical representation of the atmosphere and other relevant earth system components in general, the longer the time

scale the more pressing the need to explicitly incorporate climate and possible climatic change.

The role of climate in environmental modeling was demonstrated through use of two case studies. The first case study considered the effects on climate of smoke from biomass burning. This smoke can have a direct radiative effect, and can also make existing clouds thicker. Both effects were considered separately, using a state-of-the-art climate model. Local and regional temperature effects can be as large as 5–6 °C. A second case study was presented of a project aimed at linking together rainfall runoff and climate models. Key ongoing questions in study include:

- Can the rainfall runoff model calibrated in only a limited number of regions (or basins) be applied to the GCM universally over the globe, that is, how sensitive is the model to the parameters of the rainfall runoff model?
- Can we find realistic physical descriptors for the rainfall runoff model based on the surface type such as vegetation, topography, soil texture and surface slope?

These and many other questions will be addressed in the future as increasingly sophisticated climate models are used to help solve complex and difficult environmental problems. (See: Rainfall-runoff model, GCM.)

1. Brief Description of the Climate System and How it is Modeled

1.1. Climate System Basics

The climate system is a complex, multicomponent entity that spans a wide range of time and space scales. Key components normally considered to be part of the complete climate system include the atmosphere, the oceans, the geobiosphere (bare earth as well as vegetation), and the cryosphere (land ice and snow and sea ice). Knowledge of the interactions (i.e. mass and energy fluxes) between these components is critical to understanding the climate system, as are the workings internal to each component. The atmosphere, ocean, and for most purposes the cryosphere are best thought of (and modeled) as systems composed of fluids, so in most respects the climate system as a whole could be considered as a fluid body. Indeed, the environment as a whole can essentially be thought of as a fluid in a turbulent state.The atmosphere generally has fairly short time scales, from less than a day through a few weeks. The upper ocean also has fairly short time scales, from a few days to a few years, but the bulk of the deep ocean has much longer inertial time scales, from tens to hundreds or even a few thousands of years.

Sea ice and land snow cover have relatively short time scales (of a few days to a few years), but massive continental ice sheets can have very long time scales, on the order of tens of thousands of years. Thus, relevant time scales for the various components of the climate system span at least 6 orders of magnitude. Clearly, fully predictive modeling of the entire climate system is a massive job far beyond the capacity of even the most advanced supercomputers presently available (or likely to be available anytime in the foreseeable future). The climate system can be considered a composite system that as a whole is thermodynamically closed (impermeable boundaries to mass but not energy).

The individual subsystems (components) of the overall system are thermodynamically open (transfers of both mass and energy allowed), and cascading (the output of mass and/or energy from one subsystem becomes the input into another subsystem). The state of the climate system can be represented in terms of physical variables that represent additive or extensive properties (volume, internal energy, mass of individual components, angular momentum), or in terms of intensive properties ("fields") that are independent of total mass and that may change in time (temperature, pressures, velocities, etc.).

If, for specific time scales, the internal climate system behaves as if it has forgotten its past, and responds mainly to external boundary conditions then it can be considered almost in a state of equilibrium. (The external boundary conditions which are imposed on the climate model can be true external variables such as solar radiation, or internal variables, such as ice sheets or atmospheric CO_2, whose inertial time-scales are sufficiently long that they can be taken as constant over the time-scale of interest. These can be thought of as the drivers of climate.) This is distinctly different than weather forecasting, which is fundamentally an initial-value problem. It is also what allows us to define climate in terms of ensemble means and variabilities of individual climatic states. If any initial state always leads to the same near-equilibrium climatic state (i.e. same set of statistical properties) then the system is said to be ergodic or transitive. If instead there are two or more different sets of statistical properties, with different initial conditions leading to different states, the system is said to be intransitive. If there are different "subsets" of statistical properties that a transitive system assumes during its evolution from different initial states through long but finite periods of time, the system is said to be almost intransitive. In this case, the climatic state, beginning from any initial condition, will always converge to the same statistics eventually, but will go through finite periods with distinctly different climatic regimes while doing so. This case probably best represents the true climate system.

1.2. Climate Modeling Basics

The following can be used as a definition of a climate model: An hypothesis (usually, but not necessarily in the form of mathematical statements) that describes some process or processes we think are physically important for climate and/or climatic change, with the physical consistency of the model formulation and the agreement with observations serving to "test" the hypothesis (i.e. the model). The major goal of any (physically-based) modeling effort is to serve as a test of our understanding of how some observed or reconstructed phenomena came to be. A secondary, but crucial, goal is to use the model to make a prediction (either a forecast or a "hindcast").

Two distinct types of climate models can be identified:

i Diagnostic, or equilibrium models, with time derivatives either implicitly or explicitly set to zero. These models are most commonly solved for climatic means and variances for a specific past time, or in response to assumed forcings.

ii Prognostic models, where time derivatives are crucial and with the variation with time of particular variables the desired result (i.e. a time series).

Most commonly these models are used to solve for changes in climatic means and variances. Emphasized in this article are equilibrium models, as they are the ones most commonly used for climate research both at present and into the foreseeable future. Climate models span the range from simple Energy Balance Models (EBMs) to more sophisticated Statistical Dynamical Models (SDMs), to the very complex General Circulation Models (GCMs) of the atmosphere and ocean. GCMs are generally regarded as the most powerful tools currently available for the study of climate; the other types of (simpler) models are used today mostly for exploratory studies (if at all).

Two basic characteristics of GCMs include:

(i) they are computationally very demanding, even of the most "advanced" supercomputers;

(ii) they produce output during the run instead of at the end of the run, therefore the output can be massive.

These types of climate models can be considered as deterministic models in that they are based on fundamental conservation principles of physics. However, as is explicit in the name of the mid-range (in terms of complexity) statistical dynamical models; all of these models also contain a strong statistical component because of their dependence on parameterizations of important physical processes. Almost by definition, a *parameterization* is empirically (i.e. statistically) based. A successful environmental model must usually combine an underlying physical base with a stochastic element. A basic issue is striking an appropriate balance between the determinism and the stochasticity in the model development.

1.2.1. The Energy Balance Model (EBM)

The EBM essentially computes the atmospheric temperature at a given vertical level (usually identified as the surface temperature), by balancing incoming radiation, outgoing radiation, and (diffusive) transport of heat. These models are valid on time scales of weeks or longer (so that the diffusion coefficient used for heat transport is averaged over many weather systems).

Advantages to the EBM include:

- they are quick and easy to run;
- they do a very effective job at determining surface temperatures.

Disadvantages to them include:

- they yield no explicit climatic variables besides temperatures;
- they contain no hydrologic cycle or dynamics (atmospheric motions);
- they appear overly sensitive compared to more complex models, that is the response of the climatic variables under consideration to a change in forcing is larger than that simulated by the next two classes of models described below.

1.2.2. The Statistical Dynamical Model (SDM)

The SDM is a genuine climate model that solves directly for climatic means and variances on time scales of a month to a year. These models include a computation of surface temperature similar to that of an EBM, but they also include an explicit computation of dynamics, although synoptic-scale events (timescales of less than a month) must be parameterized in terms of climatic means and variances.

Advantages to the SDM include:

- they are simple and easy to run;
- they explicitly compute most common climatic variables (e.g. hydrologic cycle);
- they are "true" climate models, in that they solve directly for climatic variables on an appropriate time scale.

Disadvantages include:

- these models usually have no longitudinal resolution (they are solved for zonal averages only) due to insufficient theory;
- the needed synoptic-scale parameterizations are usually poorly known.

1.2.3. The General Circulation Model (GCM)

The first, largely unsuccessful, attempt at constructing a GCM was by L.F. Richardson during the 1910s (using all by-hand computations). Richardson's calculations took two weeks, involved a 6-hour simulation, and had a pressure change an order of magnitude too large that propagated in the opposite direction of what it should have. (Basically, Richardson's qualitative concepts were fine but at this time there was little recognition of the problem of stability in numerically-obtained solutions.) The GCM was revived during the 1950s and 1960s as knowledge of atmospheric (and oceanic) circulation increased, as well as general experience with numerical methods. These models did not, however, become a widely used tool until the 1980s, when computers became sufficiently powerful to use the models in a true production mode in the sense that multiple long runs investigating a range of climate-related problems could be made. The basic purpose of the GCM is to move parcels of air (or water if considering the ocean) around on a time-scale of a few minutes. These models solve for daily weather patterns, which then must be aggregated to determine climate statistics, in the same manner as the true "observed" climate are determined from actual observations. Even with today's computers, these are relatively coarse resolution models—from 1–8º in latitude and longitude horizontally, and from 4–18 layers in the vertical. Nonetheless, the GCM is generally considered the most powerful tool currently available for the equilibrium modeling of climate.Regional climate models are essentially GCM-type models that are run at higher resolution, but for a limited domain (e.g. the continental US). They must be forced at the lateral boundaries; this can be done using either analyzed observations or output from a global GCM. The intent of a regional model is not to improve the overall large-scale simulation, but rather to allow more explicit incorporation of such factors as topography and land use, which can have major local impacts on temperatures and precipitation.

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Biographical Sketch

Robert J. Oglesby is currently a Senior Research Scientist in Climate Modeling at the NASA Global Hydrology and Climate Center. Prior to that, he was an Associate Professor of Atmospheric Sciences at Purdue University. Professor Oglesby obtained his undergraduate degree in Physical Geography from the University of California at Davis in 1985. He then obtained his Ph.D. in Geophysical Fluid Dynamics from Yale University in 1990, submitting a dissertation on 'Modeling Polar Glaciation with Equilibrium Climate Models' under supervisor Barry Saltzman. After serving an appointment as a post-doctoral researcher in the Department of Geological Sciences at Brown University, Professor Oglesby assumed his faculty position at Purdue in 1992. Professor Oglesby's research specialty is in large-scale modeling of the Earth Climate System, with a particular emphasis on the roles of agents of climatic change. More recently he has begun incorporating regional models into his work as well as the coupling of climate models to models of other environmental processes. Some of the topics he and his students have covered in their modeling work include the climatic effects of increased carbon dioxide, the smoke from biomass burning, and atmospheric sulfates. They have also worked extensively on using climate models to simulate flood and drought conditions over continental interiors. Another key interest involves using climate models to simulate changes in glaciation over Antarctica, and other regions subject to glaciation that may be sensitive to climate change. Professor Oglesby as authored or co-authored over 40 papers that have been published in scientific journals, as well as almost 100 book chapters and conference proceedings. He has also presented more than 20 invited papers at major scientific meetings and conferences