Simple simulation of ice-atmosphere-ocean-land coupling in climatic models

Stephen H. Schneider, Starley L. Thompson & Isabelle Muszynski
National Center for Atmospheric Research*
PO Box 3000
Boulder, CO 80307, USA

ABSTRACT Global climate models that attempt to incorporate fully the complex interactions between land, air, sea and ice are not only very expensive computationally, but typically approximate certain types of interactions in an asynchronous manner; specifically, computational time steps are of different size for the different submodels within the complete climate model. A method of assessing possible errors in such a computational scheme is proposed that utilizes simplified models of the various climatic subsystems.

INTRODUCTION

The only coupled ice-atmosphere-ocean-land climate models attempted so far have been so-called energy balance models (EBM's), in which the internal dynamics of (at least) the atmospheric and oceanic sub-models were not explicitly treated, and all sub-components were treated at very coarse resolution (see e.g., Oerlemans, 1980; Birchfield et al., 1981; Le Treut & Ghil, 1983; Watts & Hayder, 1983; Pollard, 1984; Saltzman et al., 1984). Such simplifying assumptions are justified, of course, given the great complexity and inordinate computational expense of running more complex, higher resolution general circulation models (GCM's) over geologic
time scales. Indeed, even for the simpler problem of running complex air/sea GCM's over $10^2$-$10^3$ years, the usual procedure is to employ much longer time steps for the oceanic sub-model integration than for the more rapidly varying atmospheric model (e.g., Manabe & Bryan, 1969; Washington et al., 1980). However, such asynchronous coupling schemes needed to conserve computer time can introduce substantial errors in the flux exchanges between air and sea, and thus cause large simulation errors (see e.g., Schneider & Harvey, 1986; Harvey 1986).

Given the relatively slow variations in large ice sheets, even when compared to the deep oceans, economic considerations would strongly suggest that any medium to high resolution, coupled land-air-sea-ice models use asynchronous coupling schemes. It is imperative, therefore, to test the relative validity of such schemes before performing expensive coupling experiments with the medium to high resolution models. One method to make such tests is to use much simpler models of each climatic sub-system (e.g., EBM's of the atmosphere and oceans and a very simple zero or one-dimensional ice sheet model), but to preserve the basic formulation of the coupling parameterizations between sub-models. We will call this procedure Simple Simulation of Complex Models (SSCM). SSCM could investigate, for instance, two problems that would arise in coupling. First, there are going to be sampling errors associated with asynchronous coupling, in which the atmospheric fluxes needed for ice sheet calculations are based on, say, one year of atmospheric simulation, but are then used to perform, say, 100 years of ice sheet simulation. Simple models could help to clarify the magnitude of errors that such asynchronous sampling problems could create. A second problem that the SSCM approach could address is to assess the importance of systematic errors in one sub-model—for example, the effect of a 10% systematic error in snowfall over a large ice sheet—on the overall validity of coupled simulations. Such seemingly small “tuning” errors in one sub-model may be very serious in coupled simulations, and the effect of deliberately imposing a specified error in one simple sub-model could be assessed by a SSCM approach.

As an illustration of the SSCM approach, consider a perfectly plastic northern hemisphere ice sheet resting on a bed that was horizontal before isostatic depression. Relating insolation fluctuations due to the slowly varying orbital configuration of the Earth around the sun to changes in the elevation of the snowline over the ice sheet, Weertman (1976) showed that the ice sheet exhibits cycles of growth and decay of an amplitude and period comparable to known sea level variations during the Quaternary.

We express the latitudinal shift of the snowline, $\Delta Q$, as

$$\Delta Q = \Delta Q_{\text{orb}} + \Delta Q_{\text{fdb}} + \Delta Q_{\text{stoch}}$$

where $\Delta Q_{\text{orb}}$ is the shift due to the orbital insolation variation; $\Delta Q_{\text{fdb}}$ is the shift resulting from the ice-climate feedback (as the ice sheet expands, the mean temperature decreases due to the albedo-temperature feedback); and $\Delta Q_{\text{stoch}}$ is a random perturbation. Our simple, coupled ice sheet-climate model then consists of Weertman’s zero-dimensional ice sheet of half-width $L$ and a ‘climatic’ component $\Delta Q$. Let $\Delta t_G$ be the numerical time step for the ice sheet extrapolation, $\tau_G$ be the integration time for the ice sheet component, and $\tau_c$ be the integration time for the climate component. In a synchronous coupling scheme, $\tau_c = \Delta t_G$ and the climatic forcing is recalculated at every ice sheet numerical timestep. In an asynchronous coupling scheme, $\tau_c \geq \Delta t_G$ (for example, $\Delta t_G = 1$ a, $\tau_c = 10$ a, and $\tau_G = 100$ a). For the first 10 years of the ice sheet integration, the climatic forcing is recalculated at every time step (synchronous part of the asynchronous simulation), while for the succeeding 90 years, an assumption is made about the behavior of the climate, and $\Delta Q$ is calculated from this assumption rather than by running the ‘climate model’. A few of the possible assumptions are to keep $\Delta Q_{\text{fdb}}$ constant at its last or mean value during $\tau_c$, to keep $\Delta Q_{\text{orb}}$ and $\Delta Q_{\text{fdb}}$ constant at a representative value, or to use a Taylor series extrapolation for one or both of these terms (e.g., see Schneider & Harvey, 1986).
In keeping with the SSCM approach of model component simplification and explicit intercomponent coupling, this admittedly simple ice sheet-climate model allows study of the transient response of ice volume to perturbations and to systematic and stochastic errors in the climatic forcing.

The simplest SSCM approach to coupled atmosphere-ocean-ice sheet modelling consists of a "box" model formulation, in which a globally averaged atmosphere and a globally averaged ocean (e.g., Schneider & Thompson, 1981; Harvey & Schneider, 1985) are coupled to a zero heat capacity ice sheet "box." The ice obeys a power law rheology, and the vertically averaged longitudinal velocity \( \bar{W} \) is proportional to a power of the gravitational driving stress \( \tau_b = -\rho_i g H \frac{dh'}{dx} \), where \( \rho_i \) is the density of ice, \( g \) the acceleration due to gravity, \( H \) the total ice thickness and \( \frac{dh'}{dx} \) the slope of the surface elevation. The ice volume is then a function of the form

\[
V = f(t, L_N, L_S, M, h, \text{ice rheology})
\]

where \( t \) is time, \( L_N \) and \( L_S \) are the longitudinal dimensions of the northern and southern halves of the ice sheet, \( M \) represents the mass fluxes through the boundaries of the ice sheet, and \( h \) is the bedrock topography. Conservation of mass provides the relationship between time changes in ice volume and the mass fluxes due to surface accumulation and ablation, bottom melting, and calving:

\[
\int_{L_N}^{L_S} \frac{\partial H}{\partial t} dx + \int_{L_N}^{L_S} \frac{\partial (\bar{W}H)}{\partial x} dx = \int_{L_N}^{L_S} M dx
\]

The ice divide, \( x = x_0 \), is assumed fixed in time, but the ice sheet is not necessarily symmetric about \( x_0 \). In order to couple this zero-dimensional ice sheet with the atmosphere, a radiation budget is calculated at the surface of the hypothetical steady state ice sheet, \( h'(x, V(t)) \), which can be associated with \( V(t) \), the ice sheet volume at time \( t \).

In keeping with the SSCM approach of model component simplification and detailed inter-component coupling, these admittedly simple ice sheet models allow study of the sensitivity of the transient response of ice volume to perturbations and systematic and stochastic errors in the energy fluxes at the ice sheet surface and in the surface accumulation rate.

REFERENCES


