A First-Order Global Model of Late Cenozoic Climatic Change: Orbital Forcing as a "Pacemaker" of the Ice Ages

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The development of a theory of the evolution of the climate of the earth over millions of years can be subdivided into three fundamental, nested, problems:

(I) to establish by equilibrium climate models (e.g., general circulation models) the diagnostic relations, valid at any time, between the fast-response climate variables (i.e., the "weather statistics") and both the prescribed external radiative forcing and the prescribed distribution of the slow response variables (e.g., the ice sheets and shelves, the deep ocean state, and the atmospheric CO_2 concentration),

(II) to construct, by an essentially inductive process, a model of the time-dependent evolution of the slow-response climatic variables over time scales longer than the damping times of these variables but shorter than the time scale of tectonic changes in the boundary conditions (e.g, altered geography and elevation of the continents, slow outgassing and weathering) and ultra-slow astronomical changes such as in the solar radiative output, and

(III) to determine the nature of these ultra-slow processes and their effects on the evolution of the equilibrium state of the climatic system about which the above time-dependent variations occur.

In this discussion we touch upon all three problems in the context of the theory of the Quaternary climate, which will be incomplete unless it is embedded in a more general theory for the fuller Cenozoic that can accommodate the onset of the ice-age fluctuations. We construct a simple mathematical model for the Late Cenozoic climatic changes based on the hypothesis that forced and free variations of the concentration of atmospheric greenhouse gases (notably CO_2), coupled with changes in the deep ocean state and ice mass, under the additional "pacemaking" influence of earth-orbital forcing, are primary determinants of the climatic state over this period. Our goal is to illustrate how a single model governing both very long term variations and higher frequency oscillatory variations in the Pleistocene can be formulated with relatively few adjustable parameters. Although the details of these models are speculative, and other factors neglected here are undoubtedly of importance, it is hoped that the "dynamical systems" formalism described can provide a basis for developing a comprehensive theory and systematically extending and improving it.

The equations for the variations of global ice mass (I), carbon dioxide (μ) and ocean temperature (Θ), as presented by Saltzman and Maasch (1991) for our model system are:

$$\frac{dI}{dt} = \alpha_1 - \alpha_2 \tanh(c\mu) - \alpha_3 I - \alpha_2 k_\theta \theta - \alpha_2 k_R [R(t) - R^*] + W_I \tag{4}$$

$$\frac{d\mu}{dt} = \beta_1 - \beta_2\mu + \beta_3\mu^2 - \beta_4\mu^3 - \beta_5\theta + F_\mu(t) + W_\mu \tag{5}$$

$$\frac{d\theta}{dt} = \gamma_1 - \gamma_2 I - \gamma_3\theta + F_\theta(t) + W_\theta \tag{6}$$

where c, k_Θ, and k_R are constants determined from equilibrium climate model (e.g., GCM) experiments relating summer surface temperature at high latitudes to atmospheric CO_2 content, to deep ocean temperature, and to the departure of incoming solar radiation at high latitudes, R(t), from the present value R^*. α_3 and γ_3 are inverse time constants for the response of glacial ice and deep ocean temperature assumed to be $(10ky)^{-1}$ and $(4\ ky)^{-1}$, respectively. α_1, β_1, and γ_1 are the rates at which global ice mass, CO_2, and mean ocean temperature would tend to increase, respectively, if there were no CO_2 in the atmosphere (μ = O), no ice on the planet (I = O), no random forcing (W = O), mean ocean temperature was at O°C, and R at its present value R^*; these coefficients determine the equilibrium values of I, μ, and Θ for any level of forcing F and are to be evaluated from the observed late Pleistocene state as an initial condition (in a hindcast sense). The remaining six coefficients α_2, β_2, β_3, β_4, β_5, and γ_2 are considered to be the adjustable parameters of our model that can be tuned to account for as much of the observed variability and covariability of I, μ, and Θ as possible.

In Fig 1 we depict in a highly simplified schematic form the interactions implied by our model between the three slow-response variables, I, μ, and Θ, and between these variables and both the fast response climatic variables, e.g., surface temperature τ, and external forcing due to both insolation changes and tectonic variations. A heavy dashed arrow denotes an essentially simultaneous, quasi-static (or equilibrated) response of the sign indicated, while a heavy solid arrow denotes an inertial time lag in the response. Because cryospheric bedrock depression, D, forms the basis of many other models we also include possible interactions of ice load with this variable in this diagram. The influence of the slow-response variables on the sign and magnitude of fast response climate can be estimated by GCM sensitivity studies and many useful results have been obtained; the sign shown on the heavy dashed arrows refers to the influence of the slow variables on one particular fast variable, surface temperature τ. Although it is difficult to calculate the relevant fluxes that determine the slow-response changes, we indicate by the signs on the heavy arrows our assumption regarding the signs of the first order effects.

In the lower part of the figure we depict by the thinner lines the Berner-Lasaga-Garrels (1983)-type model for the equilibrated response of atmospheric CO_2 to fundamental tectonic and weathering processes.

By assuming plausible time constants for the glacial ice mass and global mean ocean temperature, and setting the values of six adjustable parameters (rate constants), a solution for the last 5 My is obtained displaying many of the features observed over this time period including the transition to the near-100 ky major ice age oscillations of the late Pleistocene (see Fig 2). In obtaining this solution it is also assumed that variations in tectonic forcing lead to a reduction of the equilibrium CO_2 concentration (perhaps due to increased weathering of rapidly uplifted mountain ranges over this period). As a consequence of this CO_2 reduction the model dynamical system can become unstable, bifurcating to a free oscillatory ice-age regime that is under the "pacemaker" influence of earth-orbital (Milankovitch) forcing.

We view this model as an illustration of the potential of a "dynamical systems" approach to the formulation of a theory of long term climatic change occurring under the constraints of prescribed radiative and tectonic forcing.

References

Saltzman, B. 1990: Three basic problems of paleoclimatic modeling: a personal perspective and review. Climate Dynamics, 5, 67-78.

Saltzman, B. and K. A. Maasch, 1991: A first-order global model of late Cenozoic climatic change II. A simplification of CO_2 dynamics. Climate Dynamics, 5, 201-210.

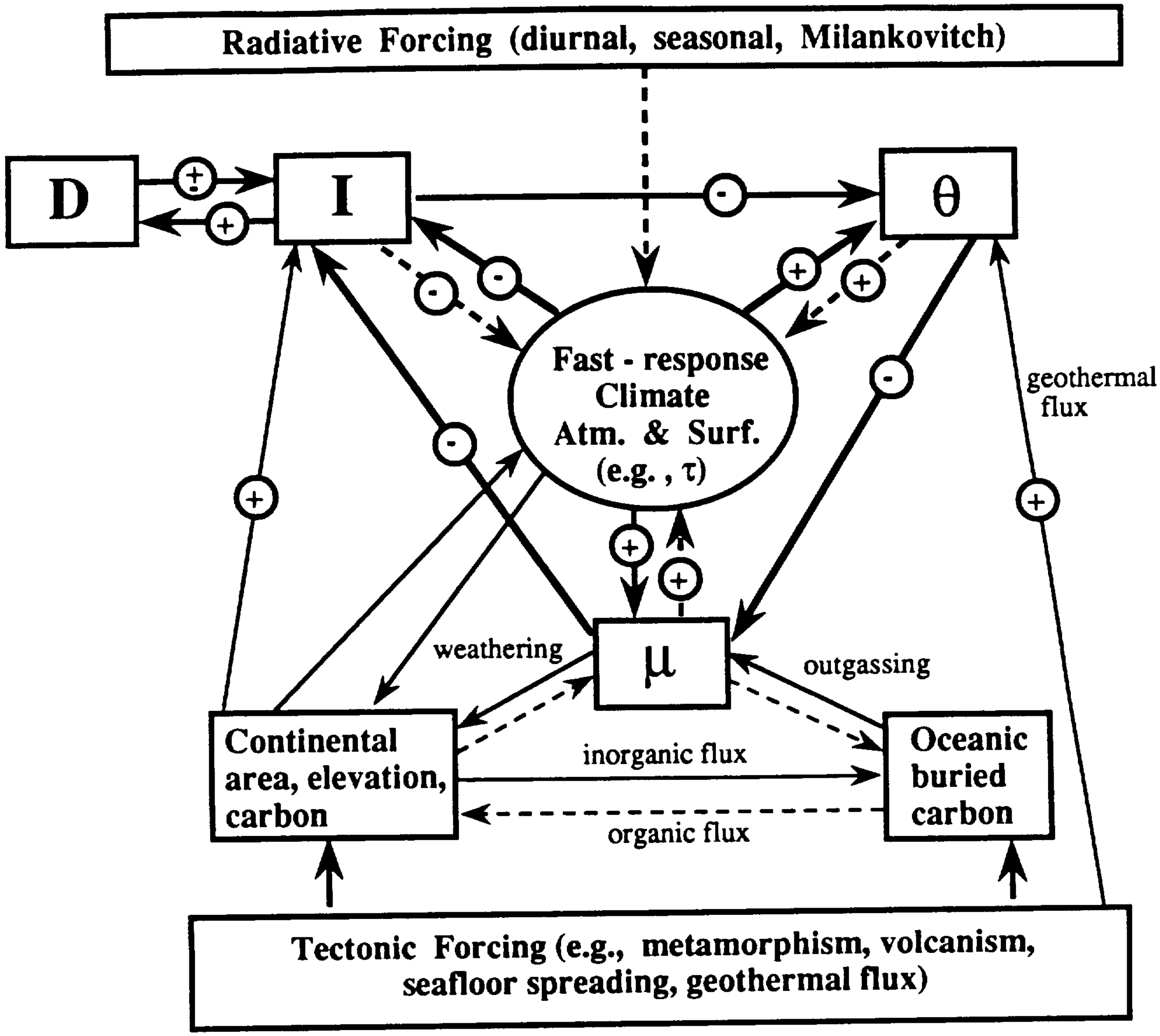

Fig. 1 Schematic diagram showing the interactions implied by the model between the three slow-response variables I, μ, and Θ, the fast-response "climate" variables, such as τ (inner circle), and external forcing due to insolation changes (upper box) and tectonic variations (lower box). The effects of bedrock depression, not included in this model, are represented by D.

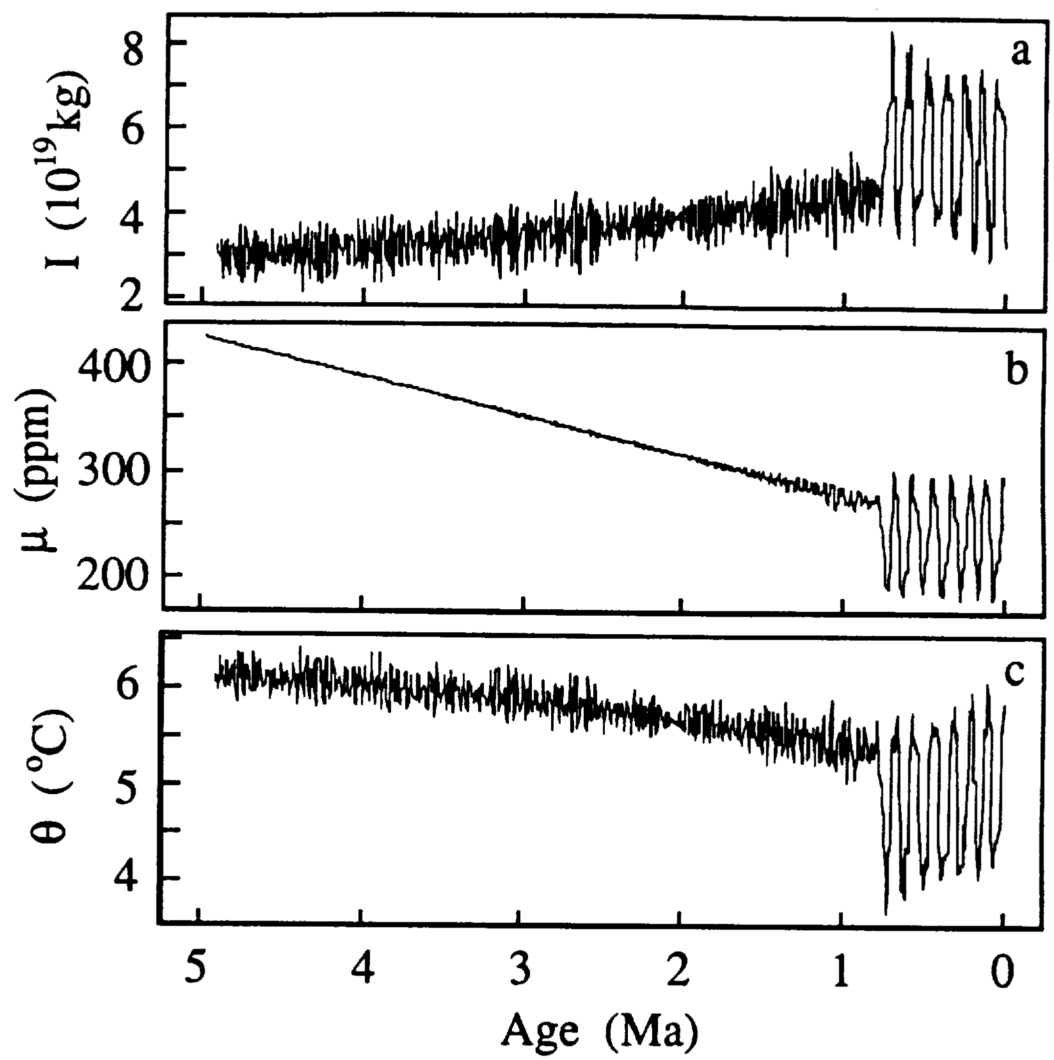

Fig. 2 Orbitally forced solution ($R(t) \neq O$) for the past 5 My, for ice mass (I), atmospheric carbon dioxide (μ), and ocean temperature (Θ), all in dimensional units.