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An Energy Balance Climate Model With Hydrological Cycle
1. Model Description and Sensitivity to Internal Parameters

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A thermodynamical model designed to illustrate the effect of a hydrological cycle on climate sensitivity is presented. The model contains three climatic variables: two temperatures referring to an idealized atmosphere and ocean, respectively, and atmospheric humidity. The independent variables are time and latitude. Atmosphere and ocean are coupled by radiation and convection at their interface. Some structure of the atmospheric circulation is retained by differentiating between the dynamics of a low latitude zone ($0° - \phi_H$) and that of a high latitude zone ($\phi_H - 90°$), where $\phi_H \approx 30°$ is the intersection of meridional temperature gradient and critical gradient for baroclinic instability. The atmospheric transport is split into an advective and a diffusive part, while the oceanic transport is approximated by pure diffusion. The coefficients associated with horizontal and vertical motion are modelled in terms of temperature gradients. The predicted water vapor gives rise to precipitation and clouds and influences (via cloud cover and greenhouse effect) the radiation balance of the system.The model is integrated for annual mean conditions until an asymptotic equilibrium is reached. The free (internal) parameters of the system are determined by optimization methods so that simulated temperature, heat flux and hydrological cycle are in close agreement with observations. The sensitivity of the model is governed by radiation parameters. Of these, the cloud albedo is the most sensitive quantity. By contrast, the model is relatively little affected by parameters associated with horizontal and vertical transport of heat.

1. INTRODUCTION

The hydrological cycle consisting of evaporation of water, advection of water vapor, its condensation in clouds and precipitation, affects the Earth's climate in a number of ways. For instance, water vapor is the prime atmospheric constituent involved in the greenhouse effect, and is thus responsible for much higher surface temperatures than would otherwise be achieved. Water vapor produces a positive feedback, amplifying, e.g., the greenhouse warming by CO_2 by a factor of the order 2. Evaporation of water from the ocean's surface into the atmosphere is the major heat loss for the ocean, while condensation of water vapor into clouds and precipitation is the major heat source for the atmosphere. At the same time, however, evaporation adds moisture to the atmosphere and thus triggers the greenhouse effect while precipitation removes moisture and thus dampens the greenhouse warming. So the net effect of phase changes of water remains largely unclear.

Moreover, cloud cover affects the radiation balance via cloud albedo and cloud radiative feedback. However, whether shortwave reflection or longwave emission dominates or whether they compensate each other, is strongly dependent on the height of the clouds and their optical properties and is still controversial.

In the present paper, I describe a thermodynamical model, which consists of a simple hydrological cycle and the energy balance of a coupled atmosphere–ocean system. It is designed for studying the role of the hydrological cycle, the relevance of positive and negative feedback mechanisms, the sensitivity to changes in model parameters, the structural stability of the system, and the longtime behavior in the presence of time dependent forcing.

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Combinations of energy balance models with a hydrological cycle are rare. Notable exceptions are the studies of *Roads and Vallis* [1984] and *Bowman* [1985], who coupled heat and moisture by separate equations. However, neither *Roads and Vallis* [1984] nor *Bowman* [1985] incorporate the vapor-temperature feedback, although it is the greenhouse effect which strongly affects the Earth's climate. Also, neither of them presents a multiparameter study of their model's sensitivity, which may be used to identify the most important climate mechanisms.

The present model (abbreviated ZAM, zonally averaged model) is a generalization of *Jentsch's* [1987] globally averaged model (abbreviated GAM). ZAM differs from GAM by its meridional variations. Otherwise, it resembles GAM in many respects. The Earth's climate is treated as a two-domain problem, with a vertically averaged atmosphere over an underlying homogenous ocean. Only annual mean conditions are considered. The existence of land is ignored. Thus, the northern hemisphere is considered identical to the southern hemisphere. Atmosphere and ocean are represented by separate balance equations, coupled by exchange of heat, radiation and moisture at their interface. Supplementary to this, a budget equation for atmospheric water vapor is incorporated. It feeds water vapor and cloudiness into the radiation balance of both atmosphere and surface. A budget equation for ice is not considered. However, for surface temperatures below freezing, the ocean is taken to be covered by ice, which enhances the surface albedo and reduces the transport of heat.

Horizontal heat fluxes in the atmosphere are split into a mean flow contribution (advection) in low latitudes and turbulent flow contribution (diffusion) in middle to high latitudes. The two zones are distinguished by the fact that in low latitudes, the meridional temperature gradient lies below the critical gradient for baroclinic instability, while in higher latitudes, it lies above the critical value [e.g., *Stone*, 1978] . Therefore, the low latitude zone may be identified as the Hadley cell (typically ranging between $-30°$ and $30°$)