ANCIENT MARS AND ATMOSPHERIC COLLAPSE.

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Introduction

One- and two-dimensional global energy balance models of the Martian atmosphere have predicted that early in Martian history, for a range of initial total CO_2 inventories, the CO_2 atmosphere would precipitate and/or deposit until it reached a vapor pressure, or cap-buffered, state (*Haberle et al.*, 1994; *Manning et al.*, 2006). This is commonly referred to as atmospheric collapse. A collapsed state may limit the amount of time available for physical and chemical weathering (*Toon et al.*, 1980). The global energy balance models that predict atmospheric collapse model the atmospheric heat transport, which controls atmosphere collapse, in terms of a single, globally uniform parameter. Proper representation of the atmospheric heat transport is critical when the atmosphere is near a significant transition, such as the threshold for collapse. The threshold for collapse may be controlled by the total CO_2 inventory, the orbital parameters, and the solar insolation. Using the Mars Weather Research and Forecasting (MarsWRF) general circulation model, we investigate the details of the three-dimensional, time varying heat transport at the threshold for atmospheric collapse.

Background

Although the dynamics of CO_2 ice caps had already been extensively examined in terms of seasonal and orbital forcing (e.g. *Leighton and Murray* (1966); *Fanale et al.* (1982); *Ward* (1974), and *Ward et al.* (1974)), the timing of (quasi-)permanent CO_2 cap formation in Mars' history had not been formally addressed before the Mars atmosphere evolution study of *Haberle et al.* (1994). A major finding of *Haberle et al.* (1994) was that surprisingly early in planetary history, and for a range of initial total CO_2 inventories, the atmosphere would be unable to transport enough heat to the poles to stave off year-round CO_2 polar caps. As a consequence of cap formation, the atmosphere would collapse to a vapor pressure, or cap-buffered, state. If Mars were trapped in a collapsed state for extended periods of its planetary history, the amount of time available for physical and chemical weathering would, as a result, be greatly limited. (We define the term "collapsed" or "collapsed atmospheric state" as the presence of at least one permanent CO_2 ice cap, and vapor pressure balance between the atmosphere and that cap.)

The prediction of collapse in the extant global-mean climate models (e.g. *Haberle et al.* (1994) and *Manning et al.* (2006)) involves representation of an inherently three-dimensional, time varying process, heat transport, in terms of a single, globally uniform 'constant'. This constant is unavoidably the weakest link in any low-order (0-D and 1-D) atmospheric evolution model, since the proper representation of heat transport is of critical importance when the atmosphere is near a significant transition, such as the threshold for collapse. A basic theory of atmospheric heat transport as a function of atmospheric mass and planetary spin/orbital parameters is still lacking for atmospheres. The latitudinal dependence of ice cap formation and of the thermal forcing of the surface also suggest the need for a higher-dimensional study (*Haberle et al.*, 1994). Here we report the first application of a sophisticated, three-dimensional global climate model to access the formation of massive early caps. Our first step focuses on the most extreme possible condition for atmospheric collapse, which would occur whenever Mars reaches extremely low to zero obliquity. Then, treating the zero obliquity results as a control, we explore the relationships between atmospheric collapse, obliquity, and heat transport. The results are significant as they are the first to illustrate the thermodynamical (as opposed to chemical or loss-driven) stability/collapse of the Martian paleoclimate with a model capable of prognostically simulating the processes.

MarsWRF GCM

In order to simulate an ancient Martian climate, we used the Mars Weather Research and Forecasting (MarsWRF) GCM, developed by *Richardson et al.* (2007). *Richardson et al.* (2007) created MarsWRF by generalizing and globalizing the NCAR Weather Research and Forecasting model (*Skamarock et al.*, 2005). The model compares well to other leading Martian GCMs [see, e.g., *Richardson et al.* (2007), section 4, and *Johnson et al.* (2008), Figure 1]. Since our focus is on how climate dynamics are affected by CO_2, we do not include dust nor water vapor in our simulations. For radiation calculations, we use a two-stream radiation code that implements a k-distribution radiative transfer scheme. A general description of the k-distribution scheme can be found in *Lacis and Oinas* (1991) and *Fu and Liou* (1992), among other references, while details of the MarsWRF k-distribution implementation are given by *Johnson et al.* (2008).

Simulations are run with a latitude and longitude resolution of $5^\circ \times 5^\circ$ and with 40 vertical levels provided by a terrain-following modified sigma vertical coordinate. The total available CO_2 budget is a model input parameter. When used for the current climate, the model is able to reproduce the surface pressure curves at the Viking Lander sites well. For surface temperature calculations, TES surface albedo and thermal inertia maps are used (*Christensen et al.*, 2001; *Putzig et al.*, 2005) in a multilayer subsurface heat diffusion and surface energy balance model. MOLA topography (*Smith et al.*, 2001) is also used. At locations where surface CO_2 ice is present, the surface albedo is set to 0.6 and the IR emissivity to 0.8. No subsurface (i.e. regolith) storage of CO_2 is considered, making our total CO_2 budget equal to the atmosphere plus cap amounts. Given that the regolith operates on a much slower timescale than the GCM, it is not an important part of the active climate system for our purposes and its role is implicitly accounted for in the total CO_2 inventory.

Simulations

To definitively address whether poleward atmospheric heat transport can, alone, stave-off collapse, the 0° obliquity simulations are the most illuminating. In this situation, solar heating near the poles tends to zero, and condensation cannot be prevented in the absence of transport, regardless of the atmospheric thickness and greenhouse effect. This experiment will form a control for later experiments. Under the constraints of this experiment, we answer the questions: How does the stability of the atmosphere change as a function of atmospheric mass? If the atmospheric heat transport changes significantly with atmospheric mass, then by what changes in the circulation is this accomplished?

By changing the distribution of incident solar radiation, modification of the obliquity can influence the collapse criteria for the atmosphere (*Haberle et al.*, 1994; *Manning et al.*, 2006). For the zero obliquity simulations, the absence of obliquity simplified the system to one in which the only independent variable was initial atmospheric mass. With obliquity added as an independent variable, however, we address the importance of obliquity in the development and maintenance of permanent CO_2 ice caps.

Results

Figure 1 shows some preliminary results from our investigation. Each plot in Figure 1 shows a series of simulations for a given obliquity, ϵ, and for zero eccentricity. In each series of simulations, an individual simulation represents a particular atmospheric thickness at the start of the simulation. For example, in the zero obliquity, $\epsilon = 0^\circ$, plot the solid black line corresponds to a 6 mbar atmosphere. Thus, at the start of the simulation, the model had an atmospheric thickness that corresponded to a mean surface pressure of 6 mbar. The caption for Figure 1 identifies the atmospheric thicknesses associated with each colored line.

As the model evolves in time, some of the atmospheric CO_2 is deposited on the surface as ice. This is represented in the plot by the vertical axis which shows the global fraction of CO_2 ice to the total CO_2 in the simulation. Under atmospheric collapse situations, as seen in the $\epsilon = 0^\circ$ simulations in the upper left plot in Figure 1, this fraction continues to increase in time as the atmospheric CO_2 freezes out. When the time that the polar regions spend in complete darkness out matches the atmospheric heat transport, then collapse occurs. Starting around $\epsilon = 15^\circ$ and higher, however, the polar regions are no longer sufficiently isolated form insolation thus minimizing the amount of heat transport needed to stop collapse. Although only a few of the simulations stop collapsing at $\epsilon = 15^\circ$, by $\epsilon = 25^\circ$ all of the atmospheric thicknesses studied are stable. Note that the seasonal signature of CO_2 is convolved with the collapse curves for the lower obliquities. The zero obliquity simulations show no seasonal variations since we have removed any seasonality by have the obliquity be zero and the eccentricity be zero.

We will present these results and discuss the dynamical controls on the atmospheric collapse process. These results will be integrated into a traditional view of polar heat balance (*Haberle et al.*, 1994; *Manning et al.*, 2006; *Leighton and Murray*, 1966; *Ward*, 1974; *Fanale et al.*, 1982; *Ingersoll*, 1970) and the implications for the evolution of the Martian CO_2 atmosphere will be discussed.

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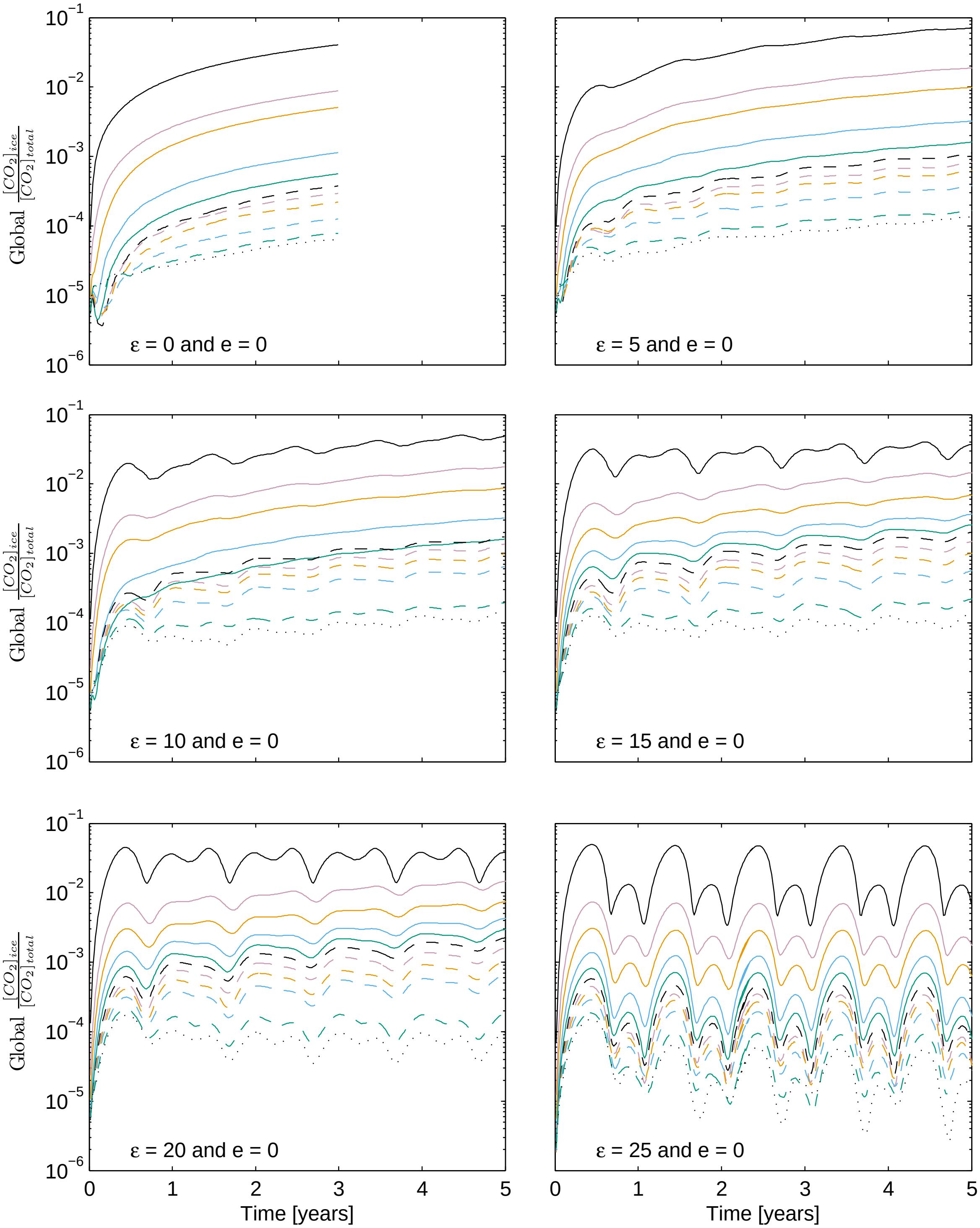

Figure 1: Global accumulation of CO_2 ice for the various pressures and various obliquities, as labeled. For each obliquity, the following initial surface pressures are shown: 6 mbar, as a solid black line; 60 mb as a solid pink line; 150 mbar as a solid orange line; 300 mbar as a solid blue line; 450 mbar as a solid green line; 600 mbar dashed black line; 750 mbar as a dashed pink line; 900 mbar as a dashed orange line; 1.2 bars as a dashed blue line; 2.1 bars as a dashed green line; and, 3 bars as a dotted black line.