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Climate Dynamics of Atmospheric Collapse on Ancient Mars

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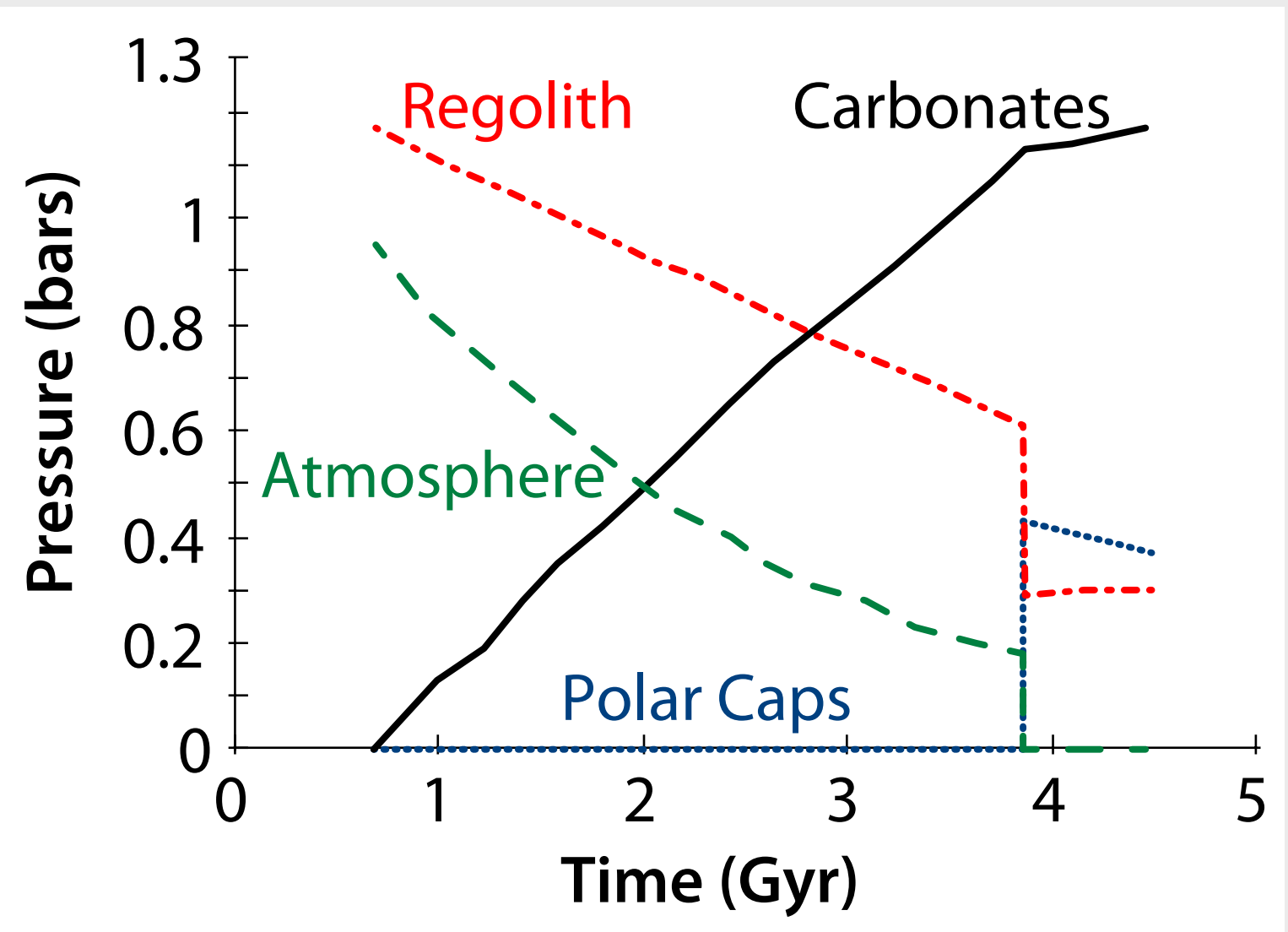
The Twenty Second Summary

Using the MarsWRF GCM, we found that the meridional transport of heat is weaker than previously assumed by energy balance and radiative-convective modeling. For a large range of global mean surface pressure and obliquity, the Martian atmosphere is unstable and collapses on to the polar regions. The range of obliquities for which the atmosphere collapses is greater during early Mars due to the fainter young sun.

Introduction

Global energy balance models of the Martian atmosphere have predicted that early in the Martian history, for a range of initial total CO_2 inventories, the atmospheric CO_2 may unstable relative to surface condensation (Leighton and Murray [1966] and Haberle et al., [1994], among others). This is commonly referred to as atmospheric collapse. A collapsed state may limit the amount of time available for physical and chemical weathering.

> ***atmospheric collapse***
> the presence of at least one permanent CO_2 ice polar cap, and vapor pressure balance between the atmosphere and that polar cap.

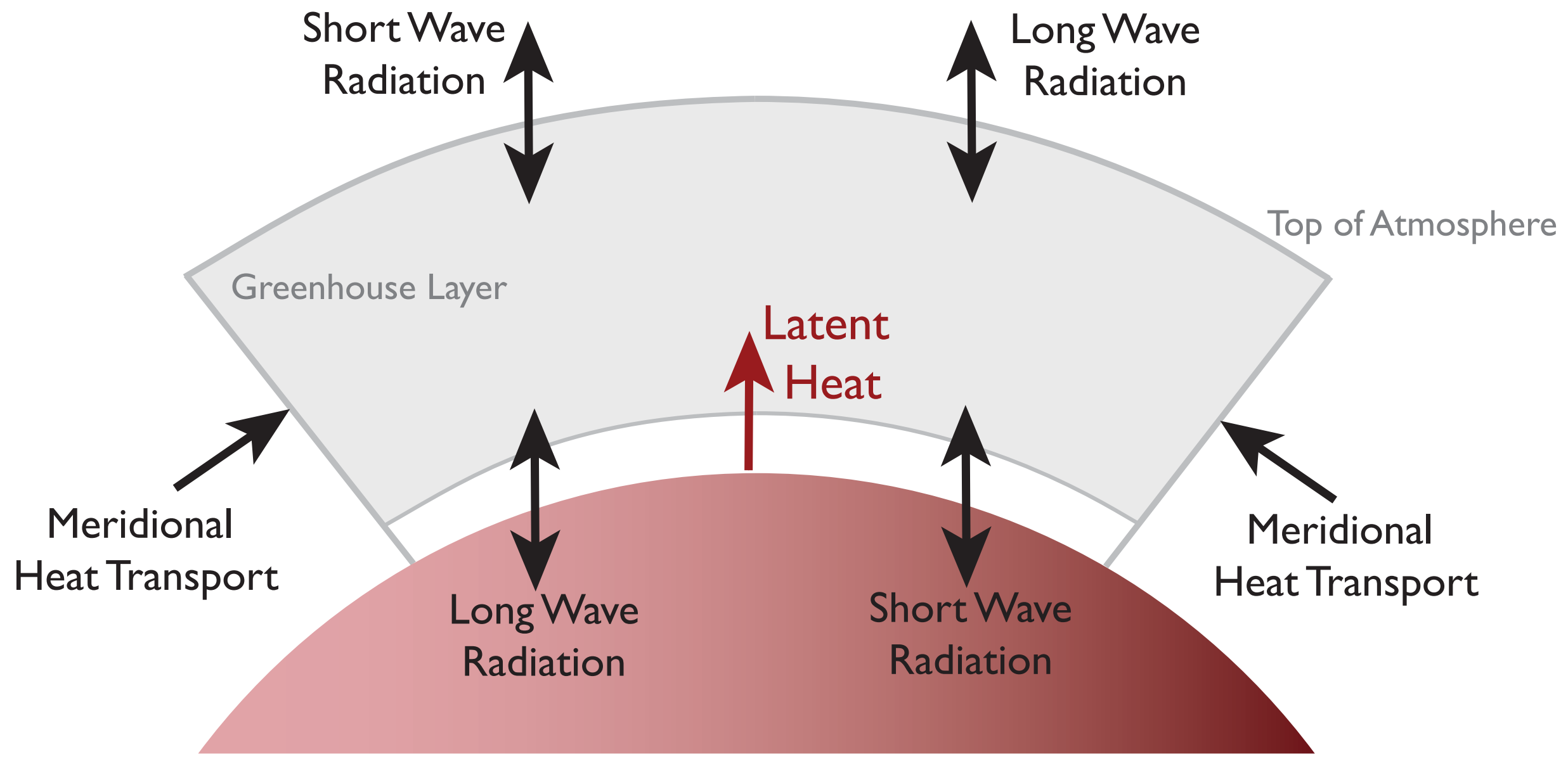


Haberle et al. [1994] used an energy balance model to track the evolution of the Martian CO_2 atmosphere. They tracked multiple reservoirs of CO_2 to simulate possible scenarios for the evolution of the Mars atmosphere, and included atmospheric escape as a permanent sink of CO_2.

This figure, recreated from Haberle et al. [1994], shows one of many possible CO_2 evolutions calculated by Haberle et al. [1994]. Note the sudden collapse of the atmosphere at 4 Gyr.

The global energy balance models that predict atmospheric collapse represent the atmospheric heat transport, which controls atmospheric collapse, in terms of a single, globally uniform parameter. This assumption requires reconsideration since at high CO_2 the details of the horizontal transport of atmospheric heat is significant and may be variable with obliquity, surface pressure, and other factors.

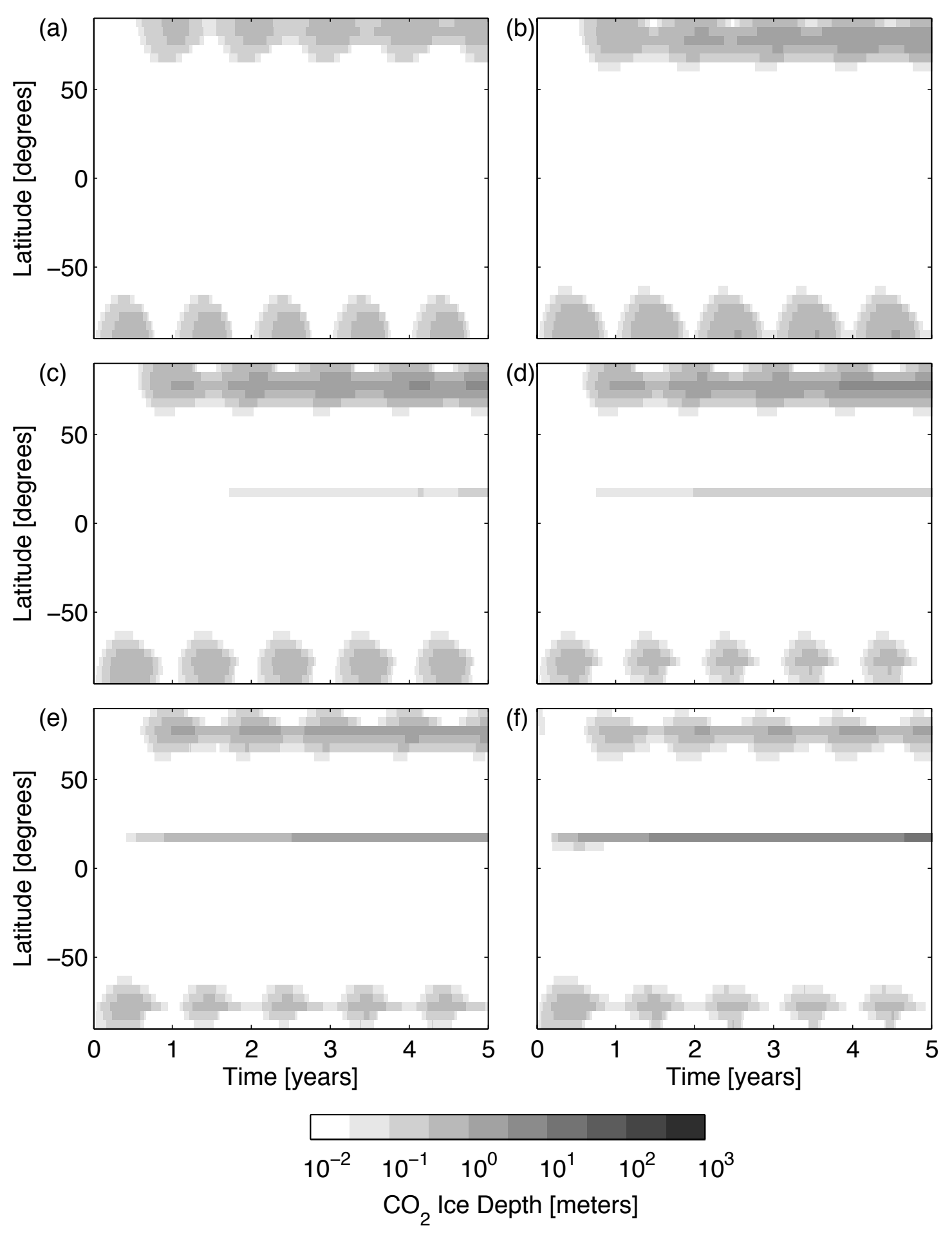
Using a Mars general circulation model (the MarsWRF model [Richardson et al. [2007]), we investigated the details of the three-dimensional, time-varying climate dynamics at the threshold for atmospheric collapse.



Several modeling assumptions/parameters used in this study.

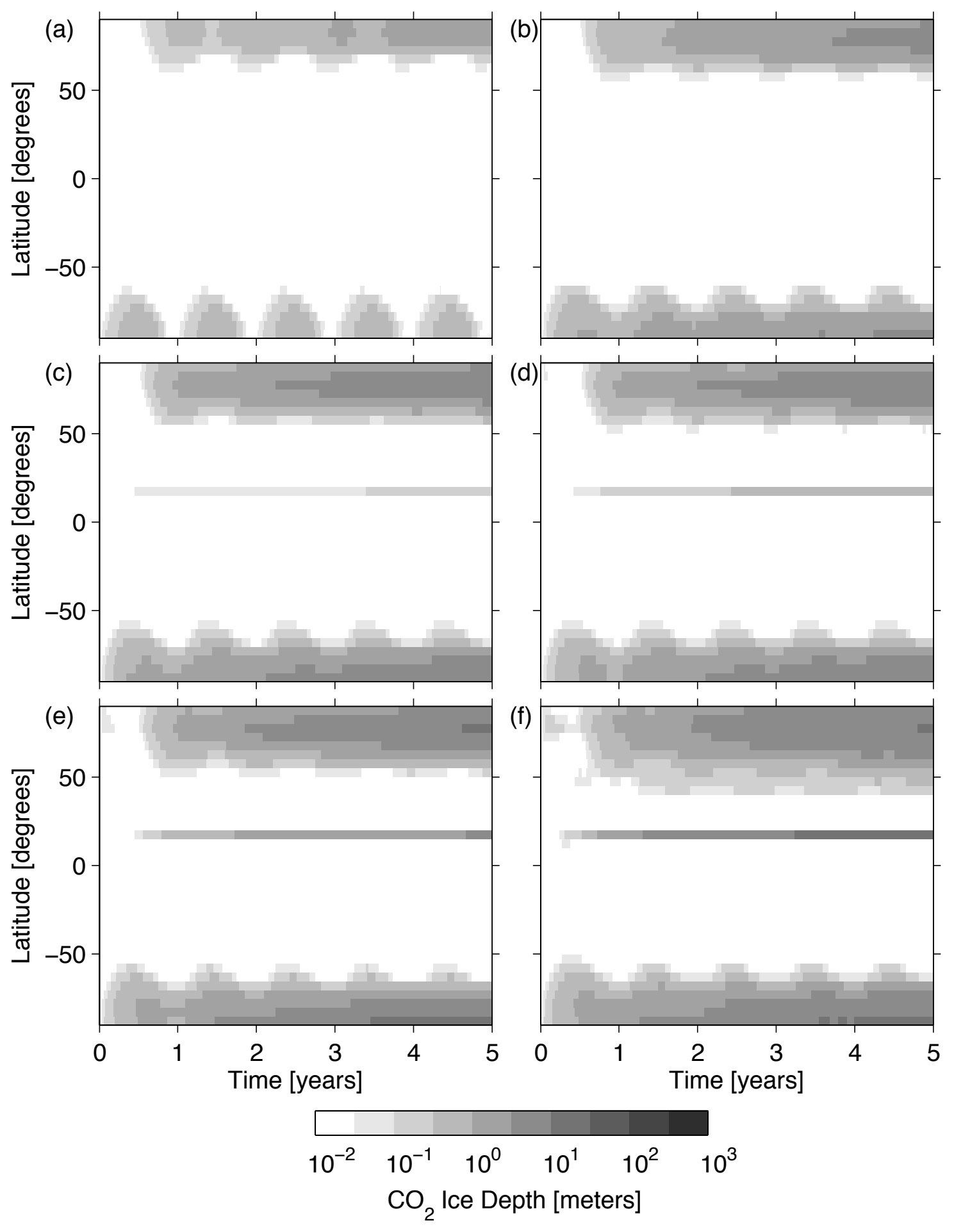
- Simulated a range of obliquities, including zero obliquity.
- Set the eccentricity = 0, which removes seasonality due to orbital eccentricity.
- CO_2 is the only greenhouse gas; there is no atmospheric water vapor.

Results *Examples of how CO_2 ice is deposited during atmospheric collapse.*



The distribution of CO_2 ice for the **15° obliquity simulations and for the current solar luminosity**. Each plot is for a specified initial mean surface pressure: (a) 6 mb, (b) 60 mb, (c) 300 mb, (d) 600 mb, (e) 1200 mb, and (f) 3000 mb.

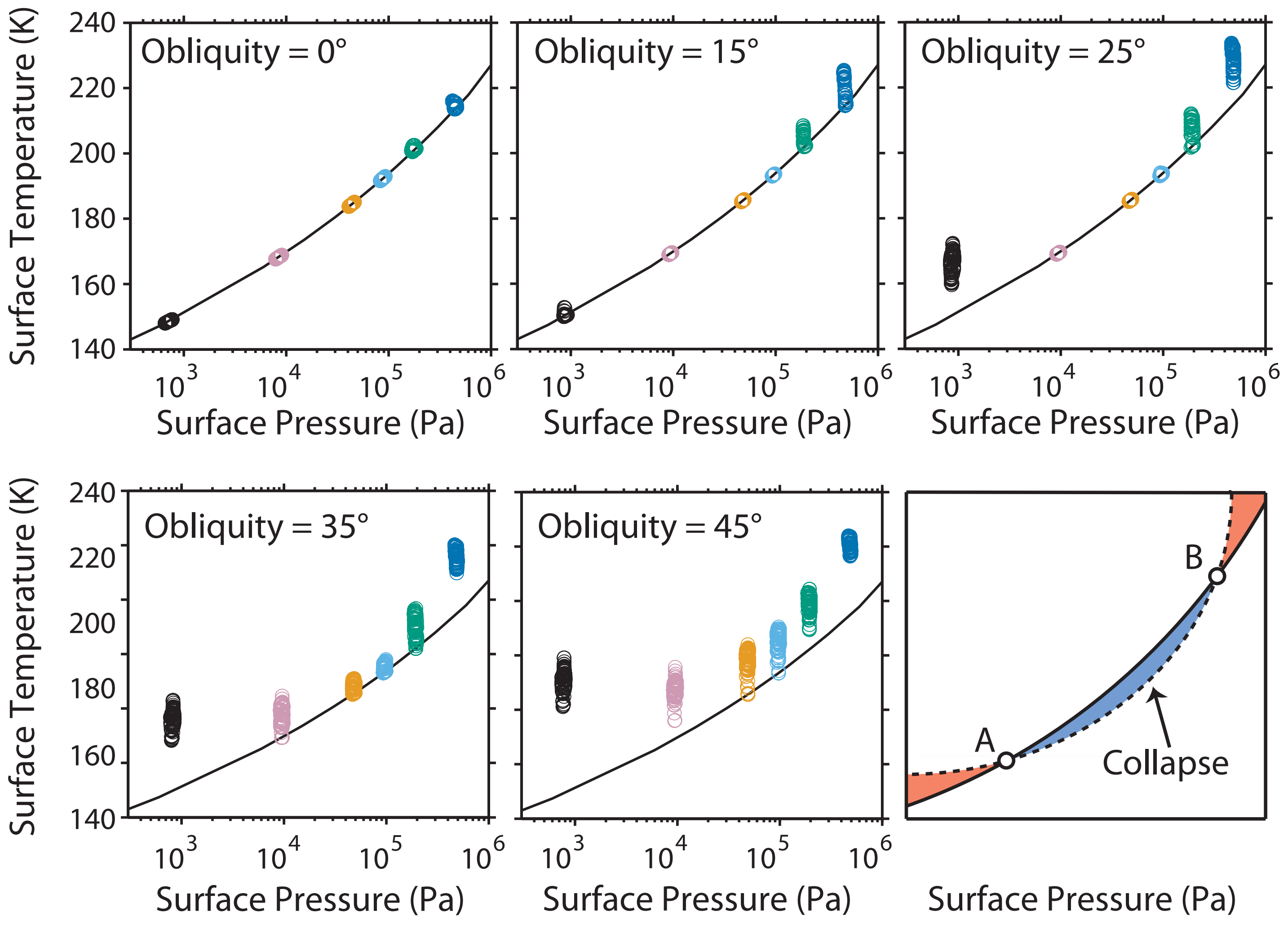
The CO_2 ice distribution reflect both seasonal cycles and topography.



The distribution of CO_2 ice for the **15° obliquity simulations and for faint young sun, i.e. ~75% of current solar luminosity**. Each plot is for a specified initial mean surface pressure: (a) 6 mb, (b) 60 mb, (c) 300 mb, (d) 600 mb, (e) 1200 mb, and (f) 3000 mb.

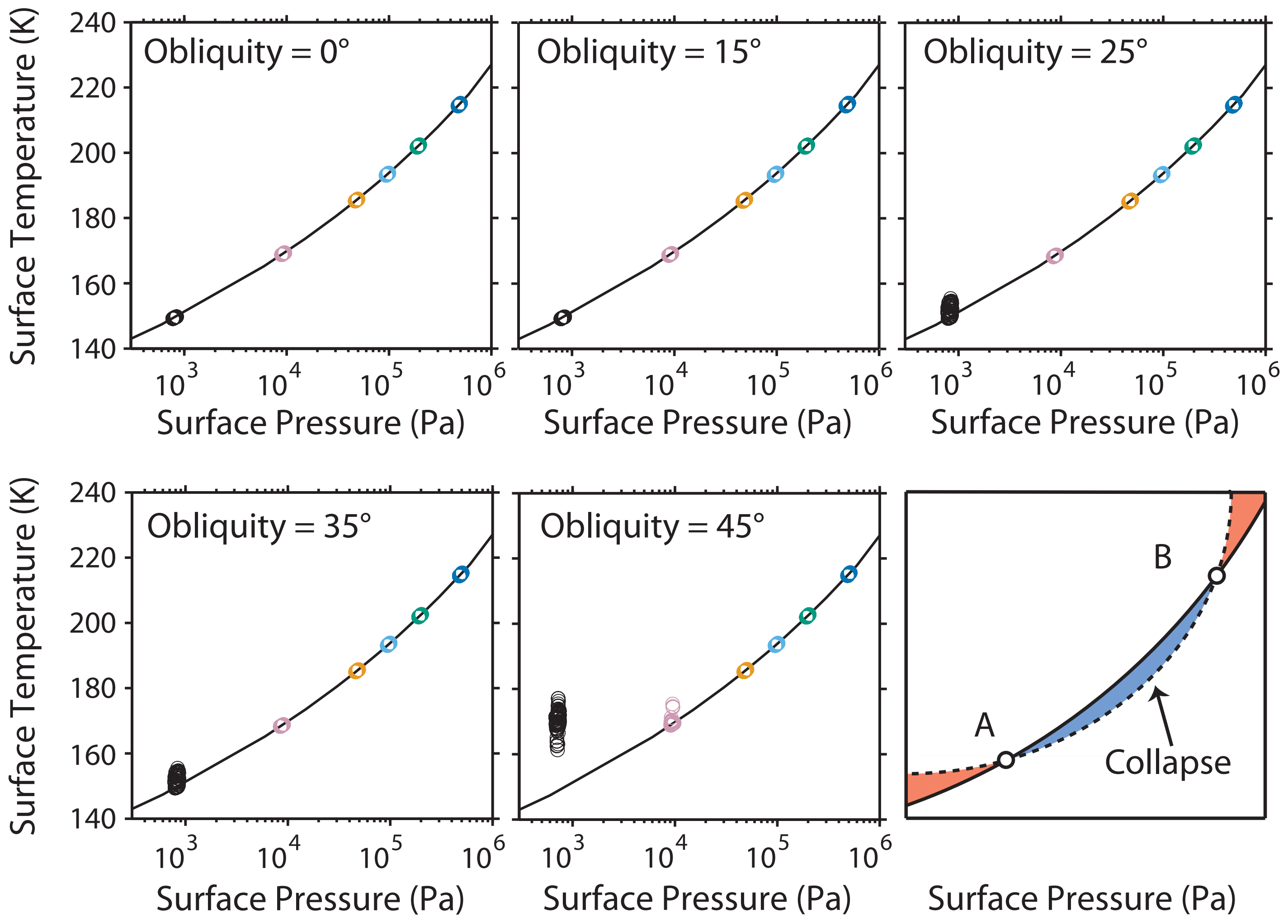
The CO_2 ice distribution reflect both seasonal cycles and topography.

Results *Polar temperatures as a function of obliquity, luminosity, and CO_2 inventory.*



These plots show the mean polar (~85° N) surface temperature as a function of the mean polar surface temperature and planetary obliquity for the **current solar luminosity**. The solid black line is the phase boundary between CO_2 ice and CO_2 vapor -- **above the line, CO_2 exists as vapor, on or below the line CO_2 is ice.**

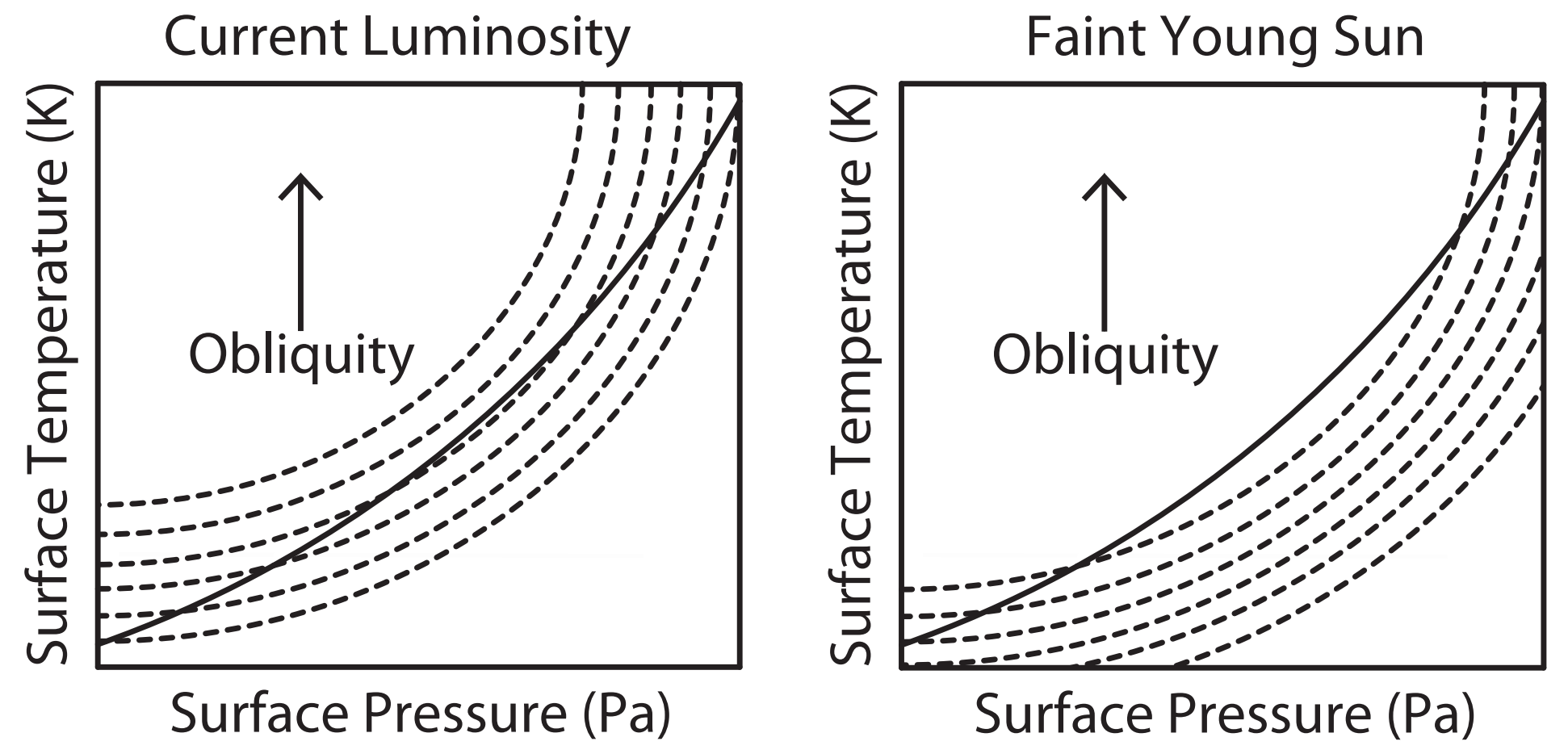
The bottom right plot is a conceptual model of the transition between collapsed and not collapsed climates.



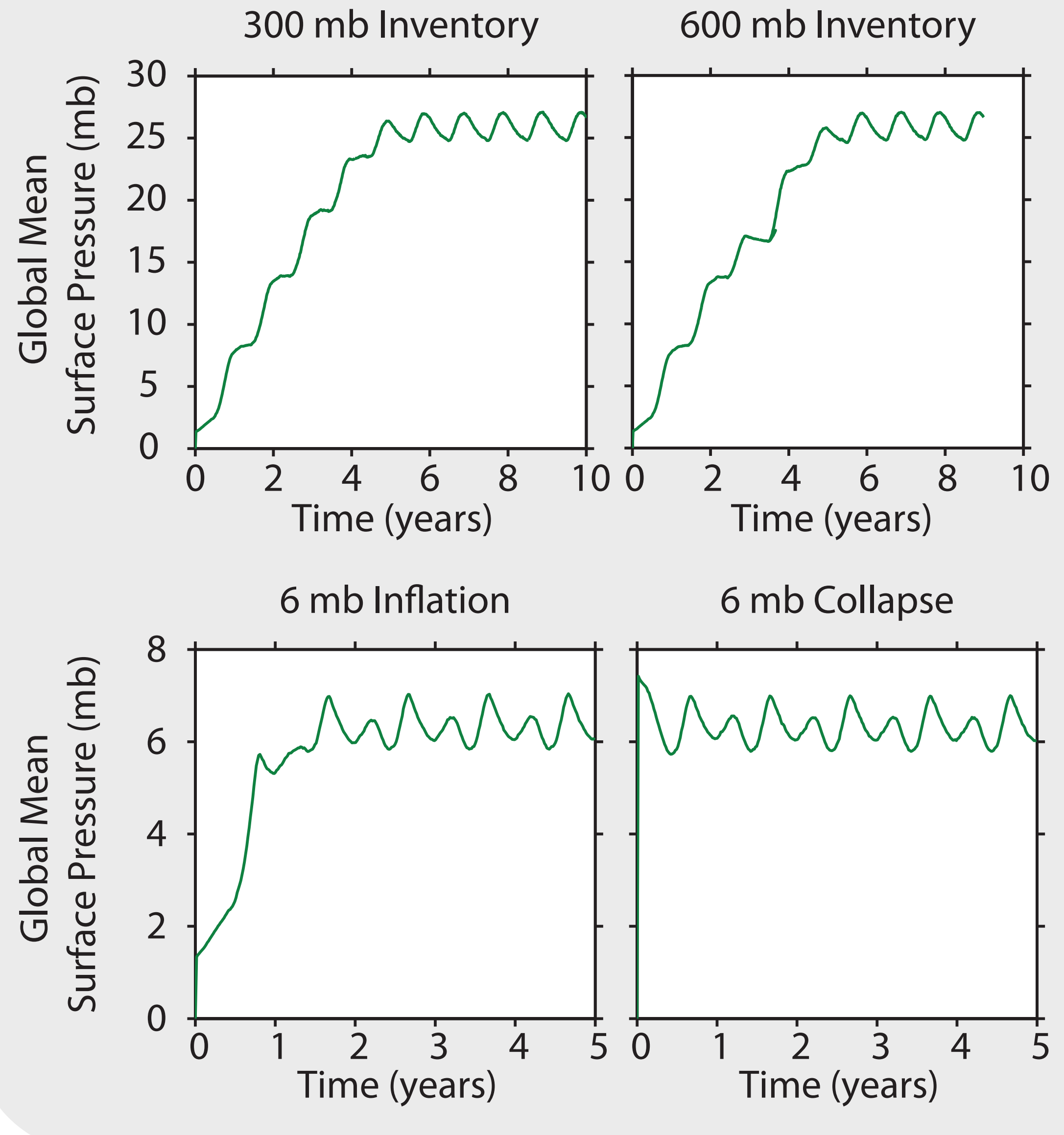
These plots show the mean polar (~85° N) surface temperature as a function of the mean polar surface temperature and planetary obliquity for the **faint young sun, i.e. ~75% of current solar luminosity.**

For the faint young sun, even obliquities as high as 45° provide insufficient energy at the poles to stave off atmospheric collapse, except for the thinnest atmospheres (~6 mb mean surface pressure).

The obliquity affects the polar energy balance by shifting upward the relationship between polar surface temperature and global mean surface pressure. This occurs because at high obliquity the high surface temperatures are spread to higher latitude, which limits the geographic region for which the surface temperatures are less than the CO_2 condensation temperatures.



Results *Okay, the atmosphere collapses. But what happens when the obliquity increases? What about inflation?*



With the collapse simulations, we start with all of the CO_2 in the atmosphere and then allow the climate to evolve. We also looked at the reverse process, what we call 'inflation'. **Inflation simulations begin with the bulk of the CO_2 inventory as ice on the polar caps** and an atmosphere with a global mean surface pressure of 1 mb. The results shown to the left are for the **25° obliquity** case. With these simulations we identified the approximate location of the lower stability point for the assumptions that we have made with our model.

The higher CO_2 inventories inflate to the same global mean surface pressure, approximately 26 mb. Despite the large difference in CO_2 inventories, the equilibrium global mean surface pressure is very similar. The 6 mb simulation, on the other hand, does not inflate to 26 mb due to the limited CO_2 inventory. The 6 mb simulation does, however, inflate to a state nearly identical to the collapse simulation, thus confirming that this is the stable climate for a 6 mb atmosphere at 25° obliquity.

References

Leighton, R. and B. C. Murray. *Science*, 153:136–144, July 1966.
Haberle, R. M., D. Tyler, C. P. McKay, and W. L. Davis. *Icarus*, 109:102–120, May 1994.
Toon, O. B., J. B. Pollack, W. Ward, J. A. Burns, and K. Bilski. *Icarus*, 44(3):552 – 607, 1980.
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