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Climate change of Mars-like planets due to obliquity variations: implications for Mars

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[1] The obliquities of the terrestrial planets could have undergone large-amplitude fluctuations. Because the obliquity changes affect the latitudinal distribution of solar radiation, they may have played important roles in the climatic evolution of the planets. We have investigated the effects of obliquity changes on the climate of Mars-like planets with CO_2 atmosphere by using a one-dimensional energy balance climate model. Our numerical results show that the obliquity changes would result in the drastic changes of atmospheric pressure (climate jumps) by runaway sublimation of permanent CO_2 ice. We also found that given a small solar constant and large obliquity, "ring-shaped" regions with permanent CO_2 ice forms at the mid-latitude. *INDEX TERMS:* 0343 Atmospheric Composition and Structure: Planetary atmospheres (5405, 5407, 5409, 5704, 5705, 5707); 1620 Global Change: Climate dynamics (3309); 5407 Planetology: Solid Surface Planets: Atmospheres—evolution; 6225 Planetology: Solar System Objects: Mars. **Citation:** Nakamura, T., and E. Tajika, Climate change of Mars-like planets due to obliquity variations: implications for Mars, *Geophys. Res. Lett.*, *30*(13), 1685, doi:10.1029/2002GL016725, 2003.

1. Introduction

[2] It is known that the obliquity of the terrestrial planets might have changed largely [e.g., *Laskar and Robutel*, 1993]. The effects of obliquity changes on the climate and the stability of an Earth-like hypothetical planet have been examined [*Williams and Kasting*, 1997].

[3] In our solar system, however, there is another type of planet – Mars has a CO_2-dominant atmosphere and does not have oceans. The carbonate-silicate geochemical cycle which occurs on the Earth does not work there. The atmospheric CO_2 may condense to form CO_2 ice (CO_2 ice cap) on the ground. The seasonal condensation/sublimation of CO_2 results in the seasonal variations in pressure, and the permanent CO_2 ice may act as a CO_2 reservoir over more than one Martian year. The regolith is another CO_2 reservoir which exchanges CO_2 with the atmosphere. The atmospheric pressure is determined by the equilibrium of three major CO_2 reservoirs: atmospheric CO_2, ice (solid) CO_2, and CO_2 within the regolith (atmosphere-ice-regolith system, hereafter referred to as AIR system).

[4] The obliquity changes would have played an important role in behaviors of the AIR system of Mars [*Toon et al.*, 1980; *Fanale et al.*, 1982; *Pollack and Toon.*, 1982; *François et al.*, 1990]. In the previous studies, however, the parameter ranges were limited to somewhat restricted conditions.

[5] In this study, we investigate the stability of the climate system of the Mars-like planets against large obliquity changes. The Mars-like planet is defined here as a Mars-sized planet which does not have plate tectonics and oceans but has the AIR system. Investigation into the effects of obliquity changes on the CO_2 atmosphere is important for understanding the climatic behavior and stability of Mars and other possible Mars-like planets or satellites in the extraterrestrial planetary system. For this purpose, we will consider wider ranges of the solar radiation, the obliquity and the amount of exchangeable CO_2 than those previously considered. Evolution and stability of the climate system of Mars will also be discussed.

2. Model

[6] We adopt a time-dependent latitudinally-one-dimensional energy balance climate model with the AIR system based on the model developed for Mars by *Nakamura and Tajika* [2002]. We improved the previous model to treat the energy balance of the ground and the atmosphere separately. The model considers the latitudinal temperature distribution, the areal extent of CO_2 ice, and the meridional heat transport. We also consider seasonal changes of the amount of CO_2 ice and the latent heat through the sublimation and condensation of CO_2. The atmospheric pressure changes owing to changes in the amount of CO_2 ice and CO_2 within the regolith. The CO_2 ice is assumed to form when the surface temperature drops below the freezing point. The amount of CO_2 ice per unit area changes according to condensation and sublimation determined by the energy balance at surface via the latent heat. Thickness of the regolith layer is assumed to be 150 m, which corresponds to a stock of 50 mbars under the present Martian condition [*Zent and Quinn*, 1995]. We can obtain a stable periodic solution as a steady state by solving the energy balance and the CO_2 exchange among the atmosphere, the CO_2 ice, and the regolith. The spatial resolution is 2° in latitude. It is assumed that characteristic time scales for the CO_2 adsorbed within the regolith to reach equilibrium with the atmosphere, are much longer than one Martian year. Finally, in our calculation, we consider the obliquity variations ranging from 0° to 60° based on the estimate by *Laskar and Robutel* [1993] for Mars.

3. Results and Discussion

3.1. General Results

[7] Our numerical results show that behaviors of the Mars-like climate system can be roughly divided into two different types depending on the solar constant: high-solar-radiation type (more than $\sim$450 W/m^2) and low-solar-

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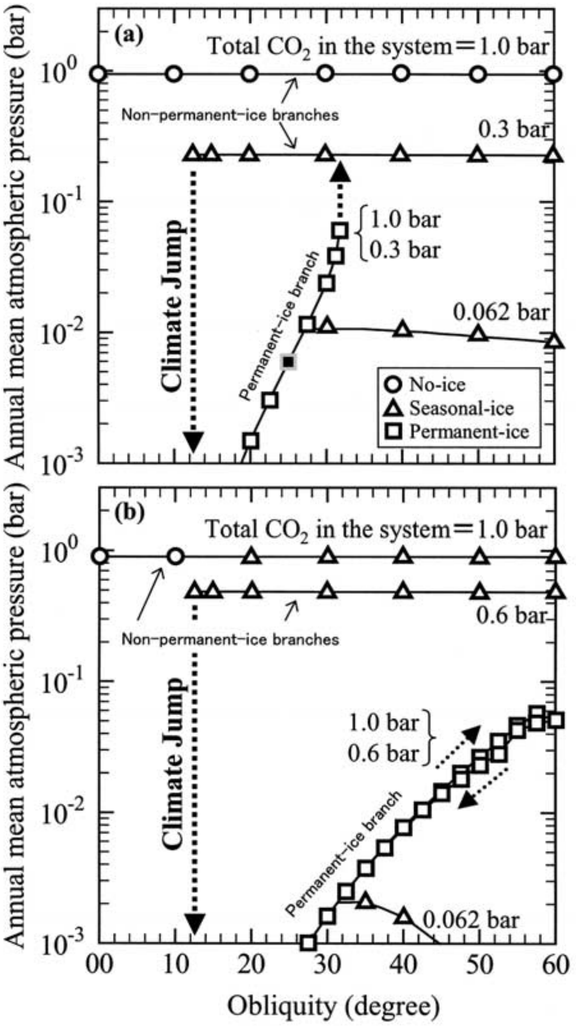

Figure 1. (a) Annual mean atmospheric pressure of the steady state solutions for the high-solar-radiation type (594 W/m^2). Solutions for three cases of the total amount of CO_2 in the system (1.0 bar, 0.3 bar and 0.062 bar) are shown. Arrows indicate directions of the climate jump when the total amount of CO_2 is 0.3 bar. The filled square indicates the present climate state. (b) Annual mean atmospheric pressure for the low-solar-radiation type (416 W/m^2). The dotted arrows indicate a hysteresis of the solutions.

radiation type (less than ~450 W/m^2). Hereafter, we show results for the solar constant of Mars at the present luminosity and orbit (594 W/m^2) as a representative of the high-solar-radiation type, and results for its 70% solar constant (416 W/m^2) which typifies the low-solar-radiation type.

[8] Figure 1 shows the annual mean atmospheric pressure of stable periodic solutions as a function of the obliquity. We found three kinds of solution: (i) a permanent-ice solution (CO_2 ice throughout the year), (ii) a seasonal-ice solution (CO_2 ice exists only in the winter), and (iii) a no-ice solution. The no-ice solution is obtained when the total amount of CO_2 in the AIR system is larger than 0.5 bar. *François et al.* [1990] also found the solutions (i) and (ii), but not (iii) for Mars, because they did not consider the AIR system with such a large amount of total CO_2.

[9] Based on behaviors of the AIR system, it is essential for the solutions to be classified into the following two regimes [*Nakamura and Tajika*, 2002]: (I) "permanent-ice regime" and (II) "non-permanent-ice regime". The permanent-ice solution belongs to the permanent-ice regime, and both the seasonal-ice solution and the no-ice solution belong to the non-permanent-ice regime. The mean atmospheric pressure in the permanent-ice regime does not depend on the total amount of CO_2 in the AIR system, and it increases with the obliquity (Figure 1a). This is because the atmospheric pressure is controlled by the permanent CO_2 ice to maintain the energy balance on the poles (see section 3.2).

[10] On the other hand, in the non-permanent-ice regime, the atmospheric pressure is determined by equilibrium between the atmosphere and the regolith, and depends on the total amount of CO_2 in the AIR system. In this regime, the CO_2 ice is negligible as a CO_2 reservoir. The yearly net budget of CO_2 between the atmosphere and the ice is zero irrespective of the atmospheric pressure. The atmospheric pressure seems to be almost constant irrespective of the obliquity change (Figure 1a). This is because the release or fixation of CO_2 by the regolith is relatively small in such a situation. Even if we assume much thicker regolith layer (e.g., 1000 m), our conclusion is not affected largely.

3.2. Climate Jumps Due to the Obliquity Changes

[11] When the solar constant is large, some solution branches end at certain obliquities (Figure 1a). We can therefore expect that the climate jumps will occur there. For example, the non-permanent-ice branch with 0.3 bar of the total CO_2 does not exist when the obliquity is lower than 12.5°. This is because, when the obliquity is small, the solar radiation income onto the poles becomes too small to sublimate the seasonal CO_2 ice completely in summer. When the obliquity decreases to <12.5°, the climate system will jump from the non-permanent-ice regime into the permanent-ice regime by runaway condensation of CO_2. However, in the case of 1.0 bar of the total CO_2, the non-permanent-ice branch does not disappear in the lower obliquity region because of strong meridional heat transport and greenhouse effect.

[12] On the other hand, if the total amount of CO_2 is large (1.0 bar and 0.3 bar), the permanent-ice branch disappears when the obliquity is higher than 31.75°. Therefore, another climate jump from the permanent-ice regime to the non-permanent-ice regime will occur by runaway sublimation of the permanent CO_2 ice when the obliquity increases to >31.75°. Climate jumps between the two climate regimes and the hystereses of climate change should be the most remarkable features of the behaviors of the AIR system (that is, the Mars-like planets) caused by the obliquity changes.

[13] In order to understand the climate jump from the permanent-ice regime quantitatively, we examine the energy balance at the poles. The annually net latent heat must be zero when the CO_2 budget is in an equilibrium. Figure 2a shows a total outgoing infrared radiation annually emitted from the permanent CO_2 ice as a function of the atmospheric CO_2 pressure (solid curve). The outgoing radiation depends both on the greenhouse effect and the surface CO_2-ice temperature which is in an equilibrium with pressure. When the atmospheric pressure increases, the greenhouse effect, which lowers the outgoing radiation, increases. At the same

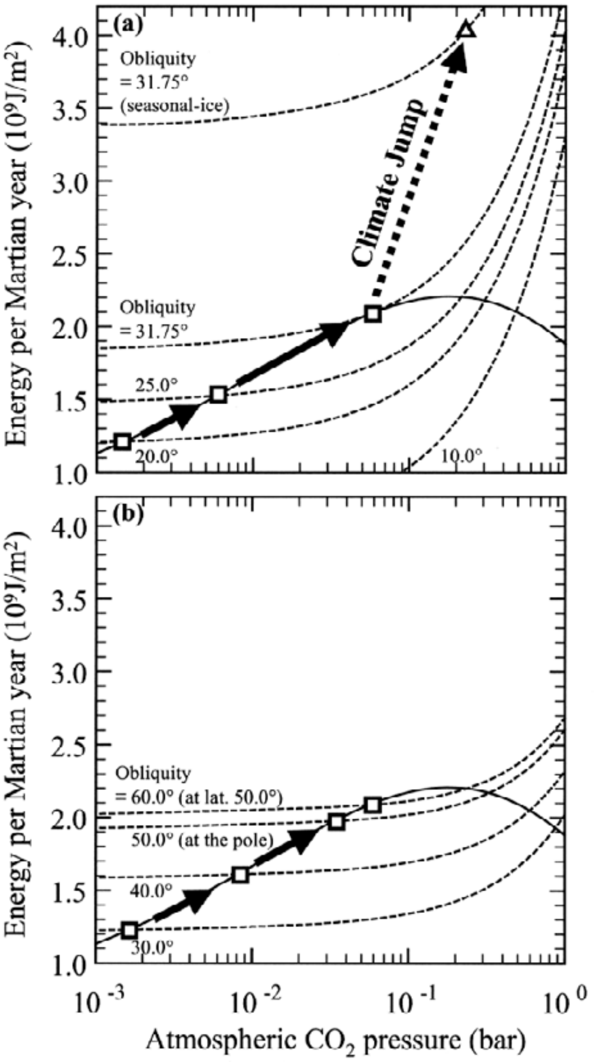

Figure 2. The total outgoing infrared radiation annually emitted from the permanent CO_2 ice at the poles as a function of the atmospheric CO_2 pressure (solid curve). The dashed lines indicate the annually total energy income onto the poles for some obliquity values: (a) the high-solar-radiation type (594 W/m^2), and (b) the low-solar-radiation type (416 W/m^2). The dashed curve for the obliquity of 60° represents the energy income at the latitude of 50°. The squares show the stable permanent-ice solutions corresponding to the squares in Figure 1. The arrows indicate evolutionary path when the obliquity is at an increasing phase.

time, however, the CO_2-ice temperature increases, which raises the outgoing radiation. The solid curve of Figure 2a represents a net effect of these two mechanisms. It should be noted that the increase in the greenhouse effect becomes more effective in the outgoing radiation change, than the increase in the CO_2-ice temperature, under the high atmospheric pressure. On the other hand, each dashed curve represents an annually total energy income due to the solar radiation and the meridional heat transport onto the poles for several obliquity values under the present solar constant for Mars. In this case, as the atmospheric pressure increases, the increasing planetary albedo due to the Rayleigh scattering lowers the solar radiation received. On the other hand, the increasing heat transport tends to raise the energy income. The dashed curve represents a net effect of these two mechanisms. The positive slope of the dashed curve indicates that the effect by the enhanced heat transport is more effective.

[14] Intersections of the solid curve and the dashed curves represent steady state solutions where the energy balance is realized. If the slope of the solid curve at intersections is larger than that of the dashed curves, the solutions are stable against disturbance. The stable solutions are represented as squares in Figure 2a (compare with the solutions represented as squares in Figure 1a). The reason is as follows: when the atmospheric pressure decreases from a stable solution, the outgoing radiation becomes smaller than the energy income onto the poles, and net sublimation of CO_2 from the permanent CO_2 ice should occur. This results in the permanent CO_2 ice to shrink, and the atmospheric pressure increases to the previous level. On the other hand, when the atmospheric pressure increases, net condensation of CO_2 should occur. In this way, the permanent CO_2 ice would control the atmospheric CO_2 pressure.

[15] Arrows shown in Figure 2a indicate an evolutionary path of the climate state with the permanent CO_2 ice, when the obliquity is at an increasing phase. The atmospheric pressure becomes higher as the obliquity increases. This corresponds to the permanent-ice branch in Figure 1a. If the obliquity becomes larger than a certain value (31.75°), the dashed curve (energy income) is always above the solid curve (outgoing radiation). The two curves do not intersect each other, what means runaway sublimation of CO_2 ice. By the sublimation of CO_2, the greenhouse effect should increase, thus resulting in a positive feedback. The climatic state will change from the permanent-ice regime to the non-permanent-ice regime. Because there is an upper limit of the outgoing radiation, the permanent CO_2 ice cannot exist whenever the yearly energy income exceeds the maximum of the outgoing radiation ($\sim 2.2 \times 10^9$ J).

[16] The present Mars may not have a massive CO_2 ice reservoir today. We therefore consider a case for a small amount of exchangeable CO_2 (0.062 bar). This value corresponds to some estimate for the present Mars (for example, 7 mbars of the atmosphere, 5 mbars of the ice, and 50 mbars in the regolith). In this case, the permanent-ice branch cannot reach the critical point (see Figure 1a). Instead, the permanent-ice solution will change continuously into the seasonal-ice solution even if the obliquity is less than 31.75°. *Toon et al.* [1980] and *Fanale et al.* [1982] referred to this type of solution. The disappearance of the permanent-ice solution in this case is due to lack of CO_2 available, and essentially different from the climate jumps for the massive CO_2 case described in this paper.

[17] On the other hand, the amount of exchangeable CO_2 would have decreased during the history of Mars [*Haberle et al.*, 1994; *Nakamura and Tajika*, 2001]. If Mars in the past belonged to the high-solar-radiation type (<3.6 Gyr ago) and had the exchangeable CO_2 of more than a few hundred mbars, the climate of Mars might have been rather unstable due to the repeated climate jumps caused by large obliquity variations.

3.3. Results for the Reduced Solar Radiation

[18] In this section, we discuss the behaviors of low-solar-radiation type. We assume the 70% of the present solar

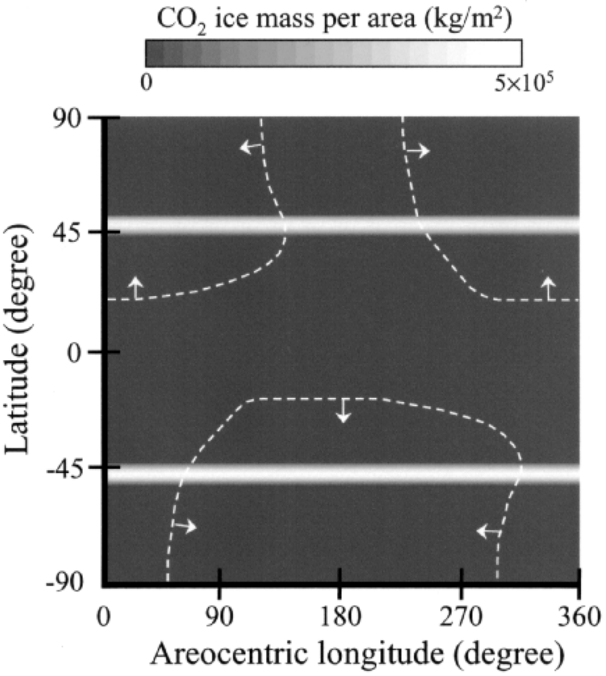

Figure 3. Seasonal distribution of the CO_2 ice under the condition of the 70% solar constant and 60° of the obliquity. White regions represent the permanent CO_2 ice, and gray regions represent an uncovered surface. Dashed lines represent areal extents of the seasonal CO_2 ice. It is noted that the mass per unit area of the permanent ice is much larger than that of the seasonal ice.

constant for Mars (416 W/m^2) as an example of this type (note that the 70% solar constant is equivalent to the very early stage of the Martian history). This may correspond to the Mars-like planets orbiting around a star of lower luminosity or with a longer semi-major axis.

[19] Figure 1b shows the annual mean atmospheric pressure for the low-solar-radiation type. Behaviors of the non-permanent-ice branches are basically the same as those for the high-solar-radiation type (Figure 1a). However, there is a remarkable difference in the permanent-ice branch: it exists even in the higher obliquity region when the total amount of CO_2 is large. Figure 2b shows the energy balance on the permanent CO_2 ice under the 70% solar constant. Because of the low solar radiation, if the obliquity is the same value, the energy income at the poles (dashed curve) becomes lower compared with Figure 2a. Consequently, there is a solution of the energy balance on the permanent CO_2 ice at the poles, even if the obliquity is as high as 50°.

[20] On the other hand, when the obliquity is 60°, the annual-mean solar incident flux is minimum at the mid-latitude [e.g., *Toon et al.*, 1980], although it is minimum at the equator when the obliquity is larger than 70°. Therefore, when the obliquity is 60°, the permanent CO_2 ice forms circularly in the mid-latitude region (Figure 3). This might be because it is the region of the lowest solar radiation and the ice can survive sublimation during the summer. The permanent CO_2 ice in the mid-latitude should be called an "ice ring" rather than an "ice cap". Figure 3 shows a typical solution which has ice rings in both hemispheres (although an ice ring in one hemisphere is also obtained, depending on the initial distribution of CO_2 ice).

[21] Early Mars (4.6–3.6 Gyr ago) may have belonged to this type. If the amount of exchangeable CO_2 was more than a few hundred mbars at that time, the ice ring(s) might have formed at the middle latitude of Mars.

4. Conclusion

[22] We investigated the effects of obliquity variations on the stability of climate of the Mars-like planets. The obliquity variations affect the mean atmospheric pressure of the permanent-ice regime by changing the energy balance on the permanent CO_2. Under the condition of high solar radiation, the permanent-ice regime cannot exist beyond a critical obliquity, resulting in the climate jump. Under the condition of low solar radiation, the climate jump by the disappearance of permanent-ice regime would not occur. Instead, the permanent CO_2 ice forms circularly in the mid-latitude region. In both cases, the climate jump from the non-permanent-ice regime would occur when the total amount of CO_2 is several hundred mbars and the obliquity is small.

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