

**MULTIPLE SOLUTIONS IN THE MARTIAN CLIMATE SYSTEM UNDER THE SEASONAL CHANGE CONDITION.** T. Nakamura, E. Tajika, and Y. Abe Department of Earth and Planetary Science, The University of Tokyo (7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan; kijun@sys.eps.s.u-tokyo.ac.jp, tajika@eps.s.u-tokyo.ac.jp, and ayutaka@eps.s.u-tokyo.ac.jp).

**Introduction:** Mars has an essentially different climate system from that of the Earth. Although the main components of the atmosphere do not condense on the Earth, the main component of the Martian atmosphere (that is, CO<sub>2</sub>) may condense to form the CO<sub>2</sub> ice caps and/or be adsorbed in the regolith. In the case of the terrestrial climate system, it has been well known that there exist three stable climate states (ice-free, partially ice-covered, and globally ice-covered) under the condition of the present solar incident flux [e.g., 1, 2]. In the case of the Martian climate system, existence of multiple climate states has been discussed for a long time [3, 4]. However, the models of the previous studies were zero-dimensional and did not deal with all the three major CO<sub>2</sub> reservoirs in the Martian surface (the atmosphere, ice caps, and regolith). For example, Gierasch and Toon [3] only considered the atmosphere and the ice caps as CO<sub>2</sub> reservoirs, and McKay et al. [4] considered the atmosphere and the regolith. Nakamura and Tajika [5] developed latitudinally one-dimensional climate model combined with the three CO<sub>2</sub> reservoirs of the atmosphere-ice-regolith (AIR) system on Mars. They showed that other climate state (the ice-free solution) besides the present partially-ice-covered state exists irrespective of parameters' values [5]. These studies, however, used an annual mean models, although both the areal extent of the ice caps and the solar radiation income varies considerably with seasons [e.g., 6]. These changes should result in a considerable change in the energy budget at the Martian surface, and may affect on steady states of the climate system of Mars. In this study, we investigate behaviors of a one-dimensional energy balance climate model under the condition of seasonal change of the solar incident flux, and evaluate effects of seasonal change on the results.

**Model:** We introduce a one-dimensional energy balance climate model (1D-EBM) with seasonal changes of solar incident flux developed by James and North [7]. The 1D-EBM is represented mathematically as follows:

$$C \frac{\partial T}{\partial t} = D \nabla^2 T + QS(f, t) [1 - a(f, f_s)] - I(f, t) + \Theta(T, T_{sub}) L \quad (1)$$

where  $C$  is heat capacity of the ground and the atmosphere,  $D$  is a thermal diffusion coefficient,  $Q$  is the solar constant at the orbit of Mars,  $f$  is latitude ( $f_s$  corresponds to "iceline"),  $S$  is a solar income distribution,  $a$

is the planetary albedo which corresponds to surface albedos of land  $a_f$  and ice caps  $a_i$ , and  $I$  is the outgoing infrared radiation. The last term of the right-hand side of Equation (1) represents an effect of the latent heat for sublimation and condensation of CO<sub>2</sub>, which is required to maintain  $T$  of the freezing point of CO<sub>2</sub> as long as CO<sub>2</sub> ice exists on the ground.

We assume the total amount of CO<sub>2</sub> contained in the AIR system as follows:

$$P_{total} = P_{air} + P_{ice} + P_{regol} \quad (2)$$

where  $P_{air}$  is the atmospheric pressure,  $P_{ice}$  is the amount of CO<sub>2</sub> as ice caps, and  $P_{regol}$  is the amount of CO<sub>2</sub> adsorbed in the regolith. We can obtain solutions for the AIR system by solving the energy balance and the CO<sub>2</sub> budget among these reservoirs.

**Results:** First, we consider the atmosphere-ice (AI) system on Mars, because distribution of CO<sub>2</sub> between the atmosphere and the ice caps is determined only by the energy balance (Equation (1)). In the seasonal change model, the areal extent of the polar ice caps changes with time. Whether the polar ice caps may be formed or not depends on initial and boundary conditions of the system. The polar ice caps remained in summer are called residual ice caps. We can divide the results into three categories: (i) a solution which has residual ice caps in summer (residual-cap solution) which corresponds to the present state, (ii) a solution without residual ice caps, although seasonal ice caps are formed during the winter (no-residual-cap solution), (iii) a solution which has no ice caps throughout the year (no-ice-cap solution).

Figure 1 shows a phase diagram of the AI system. Conditions for three categories are shown in the diagram. The horizontal axis is the total CO<sub>2</sub> in the AI system, and the vertical axis is the effective solar constant. The blue, green, and red areas represent the residual-cap solutions, the no-residual-cap solutions, and the no-ice-cap solutions, respectively. These conditions do not depend on the initial condition. The yellow and violet areas indicate conditions for multiple solutions. In the yellow region, whether the solution has the residual caps or not depends on the initial condition. Similarly, in the violet region, whether the solution is the residual-cap solution or the no-ice-cap solution depends on the initial condition. As shown in Figure 1, under the present solar constant, a solution for no-ice-cap can exist within rather small areas, although the ice-

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free solution always exists under the present solar income in the annual mean model [5]. This is because CO<sub>2</sub> ice caps are easily formed under the low winter solar incident, and once CO<sub>2</sub> ice caps is formed at winter pole, the ice cap does not sublimate easily owing to its high albedo. Therefore, the ice caps are easily formed and remain in summer in the seasonal change model. Because of this, the results for the seasonal change model are rather different from those for the annual mean model.

Next, we consider conditions for multiple solutions in the present Martian system. The multiplicity of solutions under the present solar constant depends on the total amount of CO<sub>2</sub> in the AIR system ( $P_{\text{total}}$ ) at present and efficiency of adsorption of CO<sub>2</sub> by regolith (that is,  $P_{\text{rego}}$  at present). This is because the total CO<sub>2</sub> in the AIR system is determined when  $P_{\text{rego}}$  is given. Therefore, we can determine the conditions of annual mean values of  $P_{\text{ice}}$  and  $P_{\text{rego}}$  at present required for the solutions of no-residual-cap or no-ice-cap in addition to the present climate state (the residual-cap solution) under the present solar constant. Figure 2 shows a diagram which illustrates conditions for multiple solutions under the present solar constant. According to the estimates of  $P_{\text{ice}}$  and  $P_{\text{rego}}$  for the present Mars (illustrated as a rectangle in Figure 2) [8, 9, 10], the no-ice-cap solutions can not exist under the present condition. Figure 2 also shows that even the existence of the warmer (no-residual-cap) solution is uncertain, because estimated ranges for these two parameters are very large. It is, therefore, necessary to evaluate accurate values of  $P_{\text{ice}}$  and  $P_{\text{rego}}$  to conclude multiplicity of the Martian climate.

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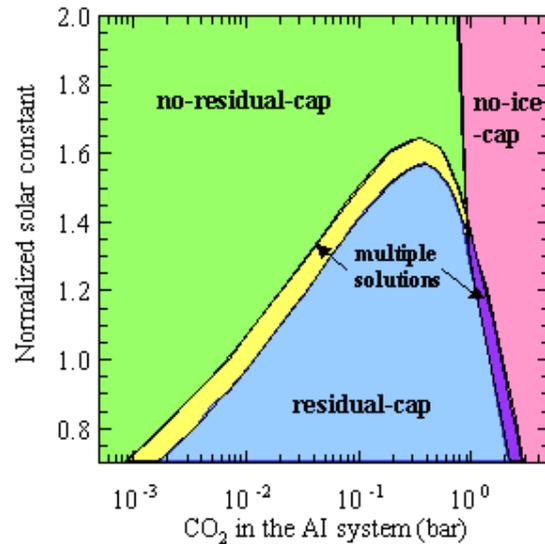


Figure 1. Phase diagram of the AIR system which illustrates conditions for multiple solutions. The horizontal axis is the total amount of CO<sub>2</sub> in the AIR system, and the vertical axis is the effective solar constant.

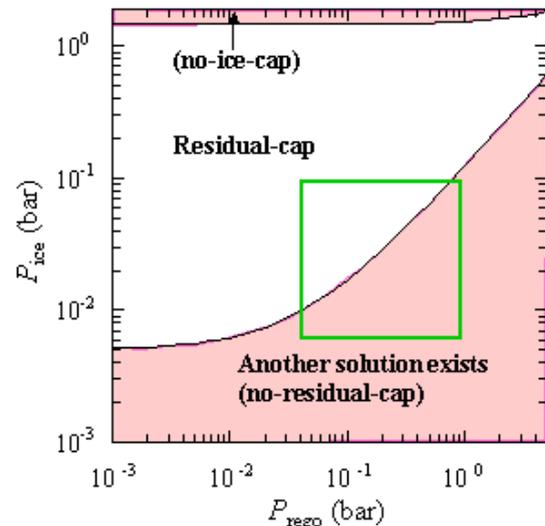


Figure 2. Phase diagram of the AIR system under the present solar constant. The vertical axis is the current  $P_{\text{ice}}$ , and the horizontal axis is the current  $P_{\text{rego}}$ . Multiple solution exists in the hatched region. Estimated ranges of the present size of the two reservoirs ( $P_{\text{ice}}$  and  $P_{\text{rego}}$ ) are also shown as a rectangle.