EVOLUTION OF THE CLIMATE SYSTEM OF MARS: EFFECTS OF OBLIQUITY CHANGE. T. Nakamura and E. Tajika, 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).

Introduction: Greenhouse effect of CO_2 may have been the most important factor for the Martian surface environment throughout the history of Mars. Polar ice caps and surface regolith are considered to be large CO_2 reservoirs to exchange CO_2 with the atmosphere on the Mars (atmosphere-ice caps-regolith (AIR) system). In this respect, Mars has an essentially different climate system from that of the Earth.

It is well known that abrupt climate changes ("climate jump") can occur due to changes in the solar radiation [1] and/or in the atmospheric CO_2 pressure [2] during the Earth's history. In the case of Mars, stability and evolution of the Martian climate system has been also discussed for a long time [e.g., 3, 4]. For example, it is suggested that the climate jump due to decrease in the total amount of CO_2 in the AIR system must have occurred during the Martian history [4].

However, all the previous studies are under the condition of annual mean solar radiation. In reality, its seasonal variation may have significant effects on the energy balance in the Martian climate system. It is, therefore, necessary to evaluate effects of the seasonal change of the solar incident flux due to the inclined rotation axis. It is known that obliquity of Mars (inclination of the Martian rotation axis) could have changed between 0° and 60° [e.g., 5]. Obliquity variation could have profound effects on 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 variations in the obliquity.

Model: We introduce a one-dimensional energy balance climate model (EBM) with seasonal changes of solar incident flux developed by James and North [6]. The EBM is represented mathematically as follows:

$$C\frac{\partial T}{\partial t} = D\nabla^2 T + QS(\phi,t)\left[1 - a(\phi,\phi_s)\right] - I(\phi,t) + LM(\phi) \qquad (1)$$

where C is the heat capacity of the ground and the atmosphere, D is a thermal diffusion coefficient, Q is the solar constant at the orbit of Mars, ϕ is latitude (ϕ_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, I is the outgoing infrared radiation, L is the latent heat of CO_2 per unit mass, and M is mass of CO_2 which sublimate or condensate.

We assume the total amount of CO_2 contained in the AIR system as follows:

$$P_{total} = P_{air} + P_{ice} + P_{rego} \qquad (2)$$

where P_{air} is the atmospheric pressure, P_{ice} is the amount of CO_2 as ice caps, and P_{rego} is the amount of CO_2 adsorbed in the regolith. We can obtain solutions for the AIR system by solving the energy balance and the CO_2 budget among these reservoirs.

Results and discussion: Formation of the polar ice caps depends both on the initial conditions and the amount of CO_2 in the AIR system. Solutions of the EBM can be classified into four cases: (i) a solution which has residual ice caps in summer (residual-cap solution), (ii) a solution which does not have residual ice caps, but has seasonal ice caps during the winter (seasonal-cap solution), (iii) a solution which has no ice caps throughout the year (no-ice-cap solution), and (iv) a solution which has a residual cap on one pole and a seasonal ice cap on another pole.

If the Martian climate was warm and wet in the past because of the strong greenhouse effect of CO_2, the amount of atmospheric CO_2 (then, the total amount of CO_2 in the system) should have been larger than that at present. When we consider the long-timescale evolution ($10^8 \sim 10^9$ years) of the Martian climate system, the total amount of CO_2 within the AIR system should have changed [7, 8, 9]. In such a case, the Martian climate could have been changed from (iii) the no-ice-cap solution to (i) the residual-cap solution abruptly and drastically during its history. This is a "climate jump" due to decrease in the CO_2 in the AIR system which is qualitatively the same as that suggested by Nakamura and Tajika [4].

On the other hand, it is known that obliquity of Mars could have changed continually between 0° and 60° on short time-scale ($10^5 \sim 10^6$ years) [e.g., 5]. Our numerical results show that obliquity changes have profound effects on the climate system of Mars. The most remarkable effect is that a residual ice cap cannot exist under the condition of larger obliquity (> ~ 45° under the present solar constant). In order to understand the reason for this, we study the energy balance at the pole. The yearly total amount of the outgoing flux from residual ice caps to space is determined as a function of the atmospheric pressure (Figure 1). The solid line represents the yearly total budget of the outgoing infrared radiation from a residual ice cap. There is an upper limit for the yearly total amount of the outgoing radiation at a certain pressure. If the going radiation at a certain pressure. If the yearly total amount of solar radiation onto the residual ice cap is larger than the maximum value, the solar flux cannot balance with the outgoing flux. This means that, in such a case, the residual ice cap cannot exist. The solar radiation supplied on the pole increases with obliquity (see dashed lines in Figure 1). Therefore, a residual ice cap cannot exist if the obliquity is large enough for the yearly total solar radiation to exceed the upper limit of the yearly total outgoing infrared radiation.

The obliquity change could cause a climate jump in the Martian climate system on short timescale. Figure 2 shows the annual mean atmospheric pressure as a function of the obliquity. The present solar constant and 2.0 bar of the total amount of CO_2 in the system are assumed for a nominal example. There are two branches of the solution. One is a "cold" residual-cap solution branch, and the other is a "warm" no-ice-cap solution branch. It is noted that the residual-cap solution branch disappears in higher obliquity region. On the other hand, the no-ice-cap solution branch does not exist in lower obliquity region. Therefore, climate jumps should occur at the ends of two branches. Assuming the state **I** in Figure 2 as an initial state, for example, when the obliquity increases, the state should change to be the state **II**. If the obliquity continues to increase, a climate jump will occur from the state **II** to **III** to reach the state **IV**. This climate jump results in a drastic increase in the atmospheric CO_2 pressure, thus warming. On the other hand, starting from the state is **IV**, if the obliquity decreases, the state changes from the state **IV** to **I** via a climate jump from the state **V** to **VI**. In this case, the climate jump results in a decrease in the atmospheric pressure, thus cooling. It is, therefore, suggested that the Martian climate could have dramatically changed repeatedly in short-term cycles during the Martian history.

References: [1] North G. R. et al. (1981) *Reviews of geophysics and space physics, 19*, 91–121. [2] Ikeda T. and Tajika E. (1999) *GRL, 26*, 349-352. [3] Haberle. R. M. et al. (1994) *Icarus, 109*, 102-120. [4] Nakamura T. and Tajika E. (2001) *EPS, 53*, 851-859. [5] Laskar J. and Robutel P. (1993) *Nature, 361*, 608-612. [6] James P. B. and North G. R. (1982) *JGR, 87*, 10,271-10,283. [7] Pollack J.B. et al. (1987) *Icarus, 71*, 203-224. [8] Melosh H. J. and Vickery A. M. (1989) *Nature, 338*, 487-489. [9] Luhmann J. G. et al. (1992) *GRL, 19*, 2151-2154.

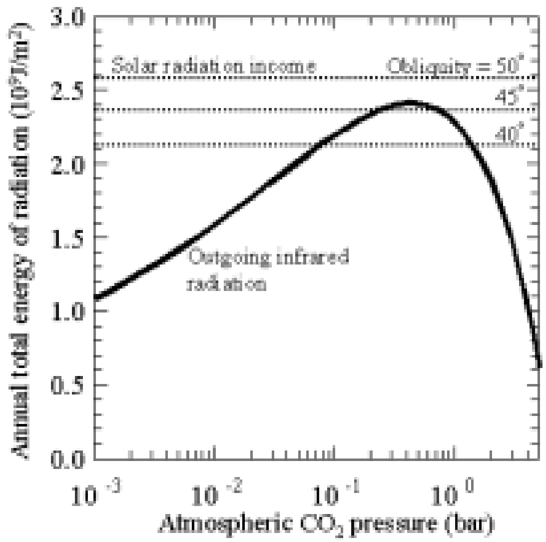

Figure 1. Annual total outgoing infrared radiation emitted from a residual ice cap. Note that there is an upper limit for the outgoing radiation at a certain pressure. The dashed lines indicate the annual total solar radiation income onto the pole under the present solar constant.

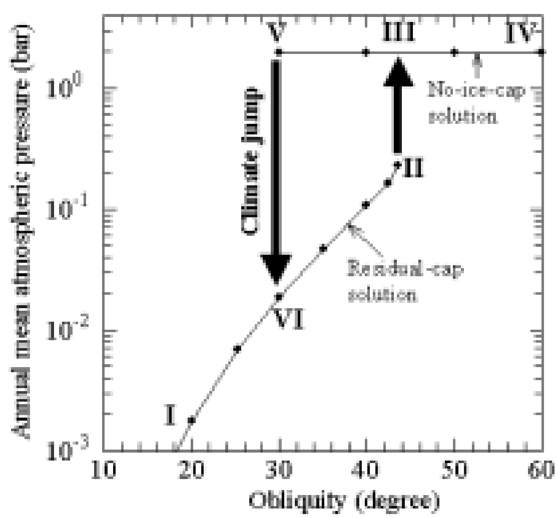

Figure 2. Annual mean atmospheric pressure as a function of the obliquity. It is noted that climate jumps should occur at the ends of branches.