JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. E11, 5094, doi:10.1029/2001JE001561, 2002

Stability of the Martian climate system under the seasonal change condition of solar radiation

Takasumi Nakamura and Eiichi Tajika
Department of Earth and Planetary Science, University of Tokyo, Tokyo, Japan

Received 14 March 2001; revised 5 February 2002; accepted 6 June 2002; published 5 November 2002.

[1] Previous studies on stability of the Martian climate system used essentially zero-dimensional energy balance climate models (EBMs) under the condition of annual mean solar radiation income. However, areal extent of polar ice caps should affect the Martian climate through the energy balance and the CO_2 budget, and results under the seasonal change condition of solar radiation will be different from those under the annual mean condition. We therefore construct a one-dimensional energy balance climate model with CO_2-dependent outgoing radiation, seasonal changes of solar radiation income, changes of areal extent of CO_2 ice caps, and adsorption of CO_2 by regolith. We have investigated behaviors of the Martian climate system and, in particular, examined the effect of the seasonal changes of solar radiation by comparing the results of previous studies under the condition of annual mean solar radiation. One of the major discrepancies between them is the condition for multiple solutions of the Martian climate system. Although the Martian climate system always has multiple solutions under the annual mean condition, under the seasonal change condition, existence of multiple solutions depends on the present amounts of CO_2 in the ice caps and the regolith. *INDEX TERMS:* 0325 Atmospheric Composition and Structure: Evolution of the atmosphere; 1610 Global Change: Atmosphere (0315, 0325); 1620 Global Change: Climate dynamics (3309); 5407 Planetology: Solid Surface Planets: Atmospheres evolution; 5416 Planetology: Solid Surface Planets: Glaciation; *KEYWORDS:* Mars, climate, atmosphere, CO_2, evolution, energy balance model

Citation: Nakamura, T., and E. Tajika, Stability of the Martian climate system under the seasonal change condition of solar radiation, *J. Geophys. Res.*, *107*(E11), 5094, doi:10.1029/2001JE001561, 2002.

1. Introduction

[2] Greenhouse effect of CO_2 could have been the most important factor for the Martian environment throughout the history of Mars, because CO_2 is thought to have been a principal constituent of ancient Martian atmosphere as well as the present atmosphere. There are several controlling mechanisms for the atmospheric CO_2 pressure on Mars during its evolutions. For instance, if there was liquid water under warm and wet conditions, CO_2 must have removed from the atmosphere by chemical weathering of silicate rocks followed by precipitation of carbonate [*Pollack et al.*, 1987; *Baker et al.*, 1991]. Even if the surface temperature was below the freezing point of water, large impacts could have removed a part of the atmosphere during heavy bombardment period [*Melosh and Vickery*, 1989], and escape of atmospheric CO_2 by sputtering is suggested to have occurred throughout the history of Mars [*Luhmann et al.*, 1992]. On the other hand, volcanic degassing might have supplied CO_2 to the atmosphere [*Baker et al.*, 1991].

[3] It is important to consider polar ice caps [e.g., *Leighton and Murray*, 1966] and surface regolith [*Fanale and Cannon*, 1974] as large CO_2 reservoirs to exchange CO_2 with the atmosphere on the present Mars. This means that dominant constituent of the Martian atmosphere (that is, CO_2) may condense to form the CO_2 ice caps and/or be adsorbed in the regolith, although the main components of the atmosphere do not condense on the Earth. In this respect, Mars has an essentially different climate system from that of the Earth. It is well known that there exist three stable climate states of the Earth (ice-free, partially ice-covered, and globally ice-covered) under the condition of the present solar incident flux [*North et al.*, 1981]. In the case of the Martian climate system, existence of multiple climate states also has been discussed for a long time [e.g., *Gierasch and Toon*, 1973; *McKay et al.*, 1991; *Nakamura and Tajika*, 2001]. These arguments relate to a possibility for the current climate to change to another warm climate. On the other hand, *Haberle et al.* [1994] studied evolution and stability of the climate system on Mars. *Haberle et al.* [1994] discussed various processes of evolution of the Martian climate system considering decrease in the amount of CO_2 in the system due to chemical weathering and atmospheric escapes, and they provided parameter study of their model. However, *Haberle et al.* [1994] did not mention multiple solutions under the conditions of the amount of CO_2 in the system and the solar constant. In this study, we will focus mainly on the

0148-0227/02/2001JE001561$09.00

problem of multiple solutions of the Martian climate system.

[4] *Gierasch and Toon* [1973] assumed the atmosphere and the polar ice caps as dominant CO_2 reservoirs on Mars. They studied stability of steady state solutions for an essentially zero-dimensional energy balance climate model (EBM) of the atmosphere-ice cap (AI) system. They found that the AI system has two stable solutions under the present solar incident flux: one is the present state and the other is the warmer state with higher CO_2 pressure. However, they did not consider greenhouse effect of CO_2. When it is considered in the model, such a result cannot be obtained [*McKay et al.*, 1991]. *McKay et al.* [1991] assumed the atmosphere and the regolith as dominant CO_2 reservoirs in their zero-dimensional EBM, and studied stability of steady state solutions for the atmosphere-regolith (AR) system. They argued that the AR system may have two stable states: one of them is the present state, and the other is the warmer state with higher CO_2 pressure. However, in their model, existence of the multiple solutions depends strongly on sensitivity of CO_2 adsorption by regolith to the surface temperature.

[5] On the other hand, *Nakamura and Tajika* [2001] developed latitudinally one-dimensional energy balance climate model combined with the three CO_2 reservoirs, that is, the atmosphere-ice-regolith (AIR) system on Mars (here we call it the annual mean model). They showed that there always exist two stable steady state solutions under the present solar luminosity when the present condition is given as a boundary condition. One of the solutions corresponds to a partial ice-covered solution (the present state; Figure 1b), and the other is a warmer ice-free solution (Figure 1a). Although this seems to be consistent with the former results by *Gierasch and Toon* [1973] and *McKay et al.* [1991], *Nakamura and Tajika* [2001] showed that their results are different qualitatively from the former results. In this model, multiple solutions always exist irrespective of parameter values. This is because existence of the ice-free solution does not depend on the atmospheric CO_2 pressure under the present solar constant (see Figure 1). They suggested that it is essential to consider areal extent of the CO_2 ice caps, because it affects both the energy balance and the CO_2 budget.

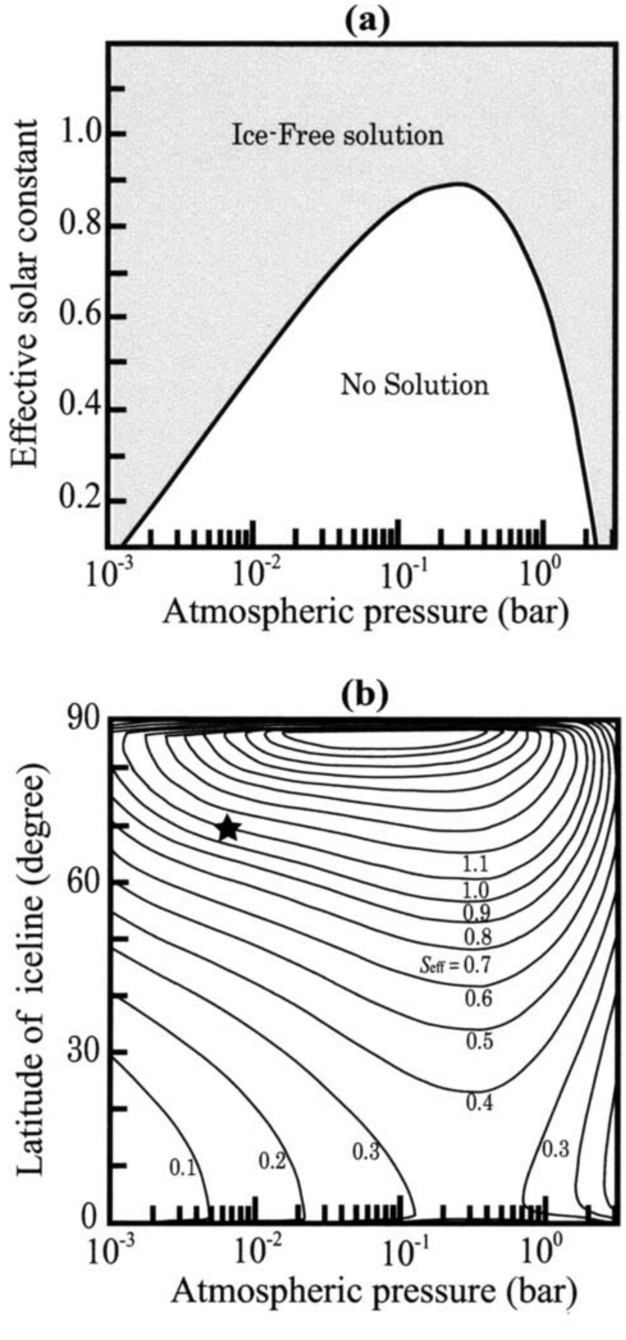

Figure 1. Multiple solutions obtained from the annual mean model (modified from *Nakamura and Tajika* [2001]). (a) Conditions for ice-free solutions. The vertical axis is the effective solar constant (normalized as 1.0 at present), and the horizontal axis is the atmospheric pressure. Ice-free solutions can exist in the shaded region. It is noted that ice-free solutions exist irrespective of the atmospheric pressure at the present solar radiation. (b) Solutions of the annual mean model onto the atmospheric pressure-iceline plane. Contour lines represent the effective solar constant. The present state is indicated as a star.

[6] These three studies used the models under the condition of annual mean solar radiation. However, both the areal extent of the ice caps and the solar radiation income varies considerably with seasons [e.g., *James et al.*, 1992]. These variations may have significant effects on the energy balance in the Martian climate system. As a consequence, the results of the case for the energy balance under the annual mean condition might be quite different from those under the seasonal change condition. However, there is no study which investigates effects of the seasonal change of the solar incident flux on the multiple solutions of 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. 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 (hereafter referred to as the seasonal change model). Objective of this study is to understand the nature and behaviors of the atmosphere-ice cap-regolith system of Mars. We discuss possibility for the current climate to change to another climate based on results of multiplicity of solutions. We will also evaluate effects of seasonal change on the climate system of Mars, and compare the results with those

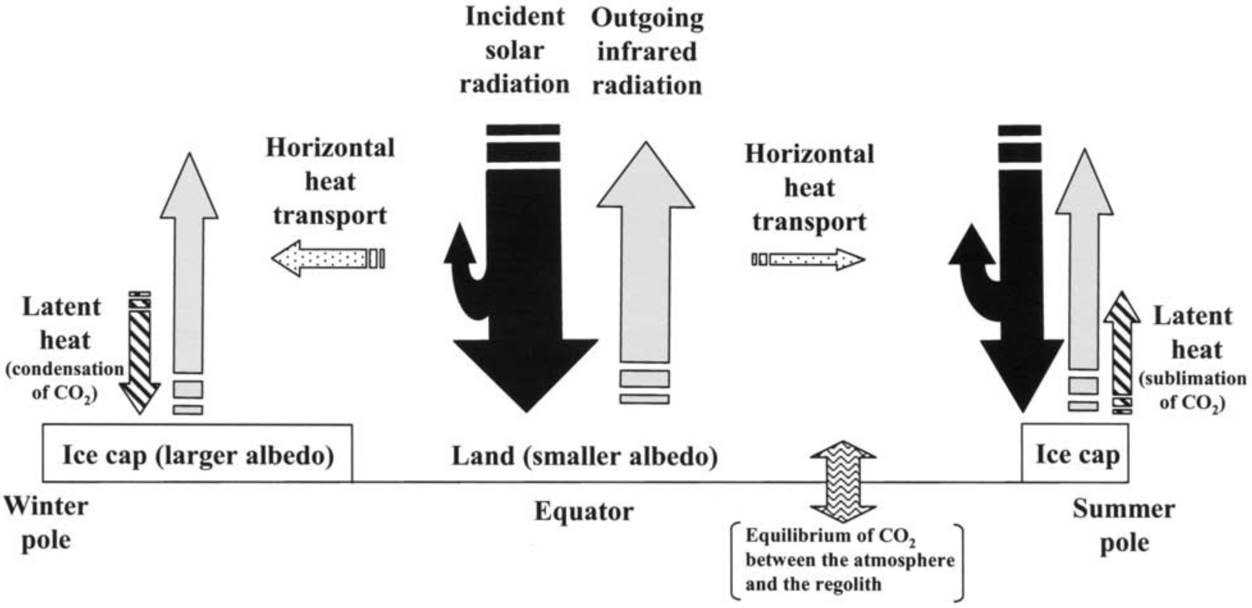

Figure 2. A schematic illustration of the 1D-EBM. Arrows represent the energy fluxes considered in this study.

obtained from the annual mean model of *Nakamura and Tajika* [2001].

2. Model

[7] In order to consider the effects of seasonal change of the solar incident flux on the Martian climate system, a time-dependent one-dimensional energy balance climate model (1D-EBM) for Mars is developed on the basis of *James and North* [1982] and *Nakamura and Tajika* [2001]. Figure 2 shows a schematic illustration of this model. The model is represented mathematically by the relation as follows:

$$c\frac{\partial T}{\partial t} = D\nabla^2 T + QS(1-a) - I + LM(\phi) \qquad (1)$$

where c is heat capacity of the ground combined with the atmosphere, T is the surface temperature in a given latitude band, D is a thermal diffusion coefficient, Q is the solar constant at the orbit of Mars, S is a solar income distribution, a is the planetary albedo, I is the outgoing infrared radiation, L is the latent heat of CO$_2$ per unit mass, M is mass of CO$_2$ which sublimates or condensates per unit time, and ϕ is the latitude (ϕ_s corresponds to the iceline). We assume that heat is transported meridionally by baroclinic instability, and adopt the parameterization of *Stone* [1972] for vertically integrated heat flux which is expressed as a linear function of surface pressure. We also assume that D is independent of latitude.

[8] The CO$_2$ ice caps are assumed to be formed when the temperature $T(\phi)$ becomes below the freezing point $T_{\mathrm{sub}}(P_{\mathrm{air}}(t))$, where P_{air} is the atmospheric pressure. Thermodynamic equilibrium between the atmosphere and the ice caps is assumed to be maintained at all the surface of the ice caps. The thickness of the caps (the amount of CO$_2$ ice in a unit area) changes according to condensation and sublimation of CO$_2$. The amount of CO$_2$ condensation/sublimation is determined to maintain the energy balance at surface via the latent heat.

[9] The boundary conditions for symmetric hemispheres are given by

$$-D\frac{\partial}{\cos\phi\partial\phi}\left(\cos\phi\frac{\partial T}{\partial\phi}\right) = 0 \quad \text{for } \phi = -90^\circ, 90^\circ \qquad (2)$$

The planetary albedo a is expressed as follows.

$$a = a(\phi, \phi_s, P_{\mathrm{air}}) = \begin{cases} a\left(a_f, P_{\mathrm{air}}\right) & \text{for } 0 < |\phi| < |\phi_s| \\ a(a_i, P_{\mathrm{air}}) & \text{for } |\phi_s| \le |\phi| < 90^\circ \end{cases} \qquad (3)$$

The planetary albedo is a function of P_{air} according to *Pollack et al.* [1987], which represents effects of Rayleigh scattering by the atmosphere. We assume $a_f = 0.21$ as the surface albedo of land [*Pollack et al.*, 1987], and $a_i = 0.7$ as CO$_2$ ice in order to satisfy the present condition.

[10] The amount of solar radiation received on the top of the atmosphere depends on time and latitude. That is, the daily total solar radiation on a horizontal surface at the top of the atmosphere of Mars (Q_s) can be represented as a function of latitude ϕ, solar declination δ, and half-day (from sunrise to sunset) length H, as follows [*Aida*, 1982]:

$$Q_s = QS(\phi, t) = \frac{Q}{\pi}(\sin\phi \cdot \sin\delta \cdot H + \cos\phi \cdot \cos\delta \cdot \sin H) \qquad (4)$$

where

$$\sin\delta(t) = \sin\psi \sin(L_s) \qquad (5)$$

$$H = -\cos^{-1}(\tan\phi\tan\delta) \qquad (6)$$

where ψ is obliquity and L_s is the areocentric longitude of the Sun which is measured from the vernal equinox of Mars.

Orbital characteristics of Mars have varied largely throughout the history [*Ward*, 1992]. In this study, however, because we investigate the effects of seasonal change of the solar incident flux on the energy balance model, eccentricity of Mars is assumed to be zero and obliquity is set to the present value (25.2°) for simplicity.

[11] In this study, we determined the outgoing infrared radiation I according to the radiative-convective calculations by *Pollack et al.* [1987] which include greenhouse effects of CO_2 and H_2O. Although the model of *Pollack et al.* [1987] neglects H_2O clouds, its effect should be small when the surface temperature is below 273 K (the condition considered mainly in this study). Their model also neglects effects of the CO_2 clouds. One of the most important problem to study the stability of CO_2 atmosphere is condensation of CO_2 to form CO_2 clouds [*Kasting*, 1991]. *Kasting* [1991] argued that condensation of CO_2 should release latent heat and so decreases the lapse rate, resulting in a decrease in the surface temperature in order to maintain energy balance. Recently, *Forget and Pierrehumbert* [1997] argued that CO_2 ice particle larger than 10 μm can scatter infrared radiation back to the surface, and showed that greenhouse effect of CO_2 cloud could be quite powerful. Although magnitude of the greenhouse effect of CO_2 cloud should depend on fraction of cloud cover and optical thickness, these properties have not been known. Therefore, the effect of CO_2 clouds on the energy balance may have been still unclear. We do not consider the formation of CO_2 clouds in the model for simplicity. However, we will discuss this problem in the later section.

[12] The atmospheric pressure of CO_2 should change owing to changes in the areal extent of ice cap and the amount of CO_2 adsorbed in the regolith. We assume the total amount of CO_2 contained in the AIR system (P_{total}) as follows:

$$P_{\mathrm{total}} = P_{\mathrm{air}} + P_{\mathrm{ice}} + P_{\mathrm{rego}} \tag{7}$$

where P_{air} is the atmospheric pressure, P_{ice} is the amount of CO_2 in the ice caps, and P_{rego} is the amount of CO_2 adsorbed in the regolith. We can obtain steady state solutions for the system by solving the energy balance and the CO_2 exchange among the reservoirs. P_{rego} is represented by the equation used by *Nakamura and Tajika* [2001] as follows:

$$P_{\mathrm{rego}} = C \int_0^{\frac{\pi}{2}} e^{-T(\sin\phi)/T_d} P_{\mathrm{air}}^{\gamma} \cos\phi d\phi \tag{8}$$

where C is a constant normalized by depth of the regolith, and T_d and γ are parameters that determine the response of CO_2 adsorption to surface temperature and pressure, respectively. The values of these parameters are adopted from *McKay et al.* [1991].

3. Results and Discussion

3.1. Partition of CO_2 Between the Atmosphere and the Ice Caps

[13] At the first step, results for the AI system are discussed for simplicity (that is, we assume $C = 0$ in equation (8)). In this case, partition of CO_2 between the atmosphere and the ice caps is determined only by the energy balance. In other words, when the sum of the amount of CO_2 in the atmospheric reservoir (P_{air}) and the ice cap reservoir (P_{ice}) is given ($=P_{\mathrm{a+i}}$), $P_{\mathrm{air}}(t)$ and $P_{\mathrm{ice}}(t)$ can be determined through equations (1)–(4). Under the seasonal change condition, the areal extent of the polar ice caps changes with time. Therefore, the calculations were performed with various initial conditions until variations of temperatures and pressure become periodic.

[14] Formation of the polar ice caps depends both on the initial and the boundary conditions of the system. Here, the polar ice cap which remains in summer is called "residual ice cap", and the polar ice cap which disappears in summer is called "seasonal ice cap". Then, the solutions 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 in one pole and a seasonal ice cap in another pole. These results are illustrated in Figure 3.

[15] Figure 4 shows the atmospheric pressure averaged annually for each case under the condition of the present solar constant. The horizontal axis is the total amount of CO_2 in the AI system. As shown in Figure 4, the solution space can be divided into four regions: (a) seasonal-cap solution, (b) seasonal-cap solution or residual-cap solution (it depends on existence of a residual cap at initial condition), (c) residual-cap solution, and (d) no-ice-cap solution or residual-cap solution (it depends on existence of a residual cap at initial condition). The regions (b) and (d) represent conditions for multiple solutions. In these regions, a solution depends on the initial condition.

[16] According to Figure 4, states of the AI system can be classified into the following two regimes: (I) "residual-cap regime" in which the annual mean atmospheric pressure is constant irrespective of the total amount of CO_2 in the AI system (that is, the solutions (i) and (iv)), and (II) "no-residual-cap regime" in which the atmospheric pressure depends on the amount of CO_2 in the AI system (that is, the solutions (ii) and (iii)). In the case for the residual-cap regime, the atmospheric CO_2 pressure is independent of the total CO_2 in the AI system (Figure 4), although it depends on parameter values (e.g., CO_2 ice albedo). For example, if we use different values of CO_2 ice albedo, the annual mean atmospheric pressure in the residual-cap regime changes (e.g., if we change the CO_2 ice albedo from 0.7 to 0.6, the atmospheric pressure also changes from several mbar to several tens of mbar (~40 mbar)). However, unless we use rather low CO_2 ice albedo (<~0.45), the residual-cap solution exists. As a result, a mathematical structure of solutions such as described in Figure 4 does not change.

[17] Figure 5 shows the annual mean atmospheric pressure for the solution (i) against the effective solar constant S_{eff}. The atmospheric CO_2 pressure is determined as a function of the solar constant, because, in this case, a certain amount of CO_2 is stored in the ice cap throughout the Martian year. When a CO_2 ice cap exists throughout the Martian year (that is, (I) the residual-cap regime), net budget of latent heat accompanied by condensation and sublimation of CO_2 throughout the year depends on the

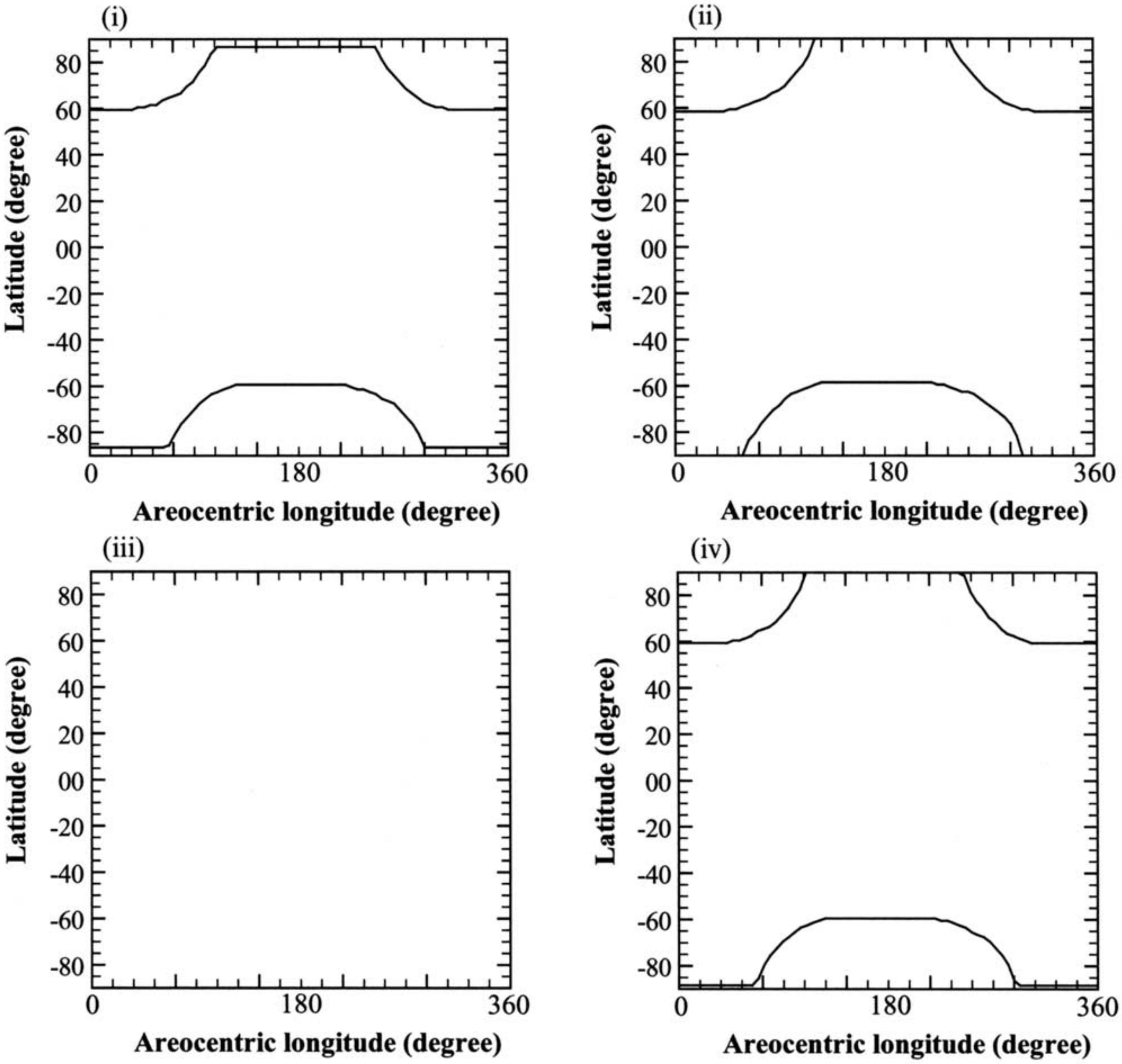

Figure 3. The results of seasonal variations of icelines of CO_2 ice caps. The vertical axis is the latitude and the horizontal axis is the Martian season (areocentric longitude). (i) A solution which has residual ice caps in summer (residual-cap solution). (ii) A solution which does not have residual ice caps, but has seasonal ice caps during winter (seasonal-cap solution). (iii) A solution which has no ice caps throughout the year (no-ice-cap solution). (iv) A solution which has a residual cap in one pole and a seasonal ice cap in another pole.

atmospheric pressure. The net budget is zero under the condition of steady state with the residual ice caps. This is because, in such a case, a freezing point feedback mechanism should work. The freezing point feedback is a mechanism which is a negative feedback due to dependence of the freezing point on the atmospheric pressure [*Nakamura and Tajika*, 2001]. For example, increase in the atmospheric CO_2 pressure due to decrease in the ice caps should increase the freezing point of CO_2, which prevents the ice caps from sublimation. There is another feedback mechanism called greenhouse feedback which is a positive feedback mechanism to prevent condensation of CO_2 with increase in the atmospheric pressure [*Nakamura and Tajika*, 2001]. The solution can be determined if the "negative" freezing point feedback is stronger than the "positive" greenhouse feedback (Figure 6). In this case, the solution is regarded as stable (solid curve in Figure 5). On the other hand, when the greenhouse feedback is stronger than the freezing point feedback, the solution becomes unstable (dashed curve in Figure 5).

[18] For example, if the atmospheric pressure is higher than that of the stable solution, net condensation of CO_2 should be positive. Therefore, the atmospheric pressure will decrease to a certain pressure level (that is, the pressure

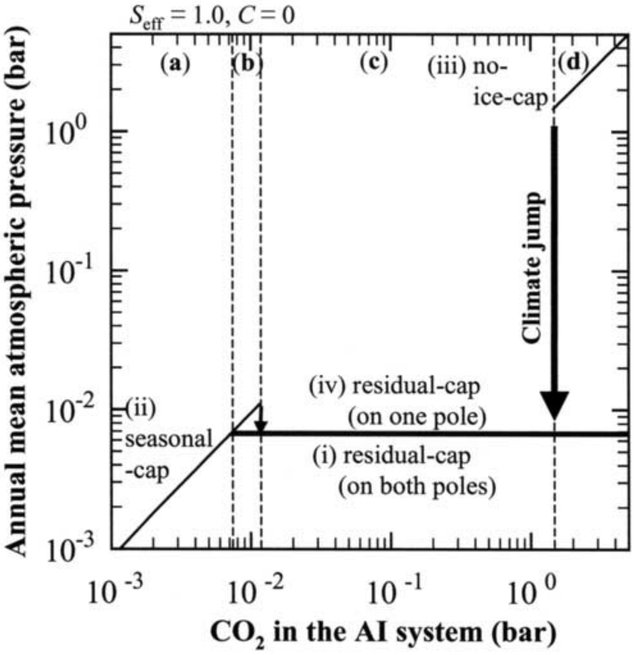

Figure 4. Annual mean atmospheric pressure for each case under the condition of the present solar constant. The horizontal axis is the amount of CO_2 in the AI system. The regions (b) and (d) represent conditions for existence of multiple solutions.

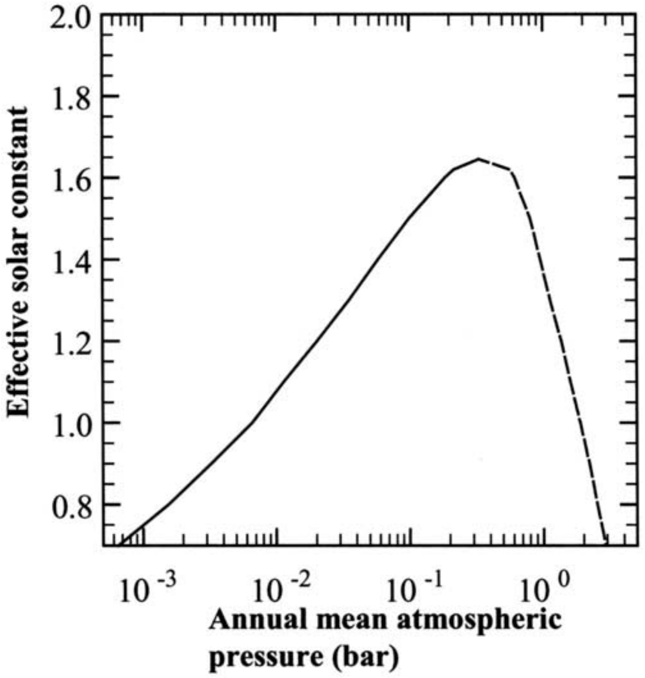

Figure 5. Annual mean atmospheric pressure as a function of the solar constant under the conditions for existence of residual ice caps. The vertical axis is the effective solar constant and the horizontal axis is the atmospheric pressure. Solid curve represents stable solutions and dashed curve represents unstable solutions.

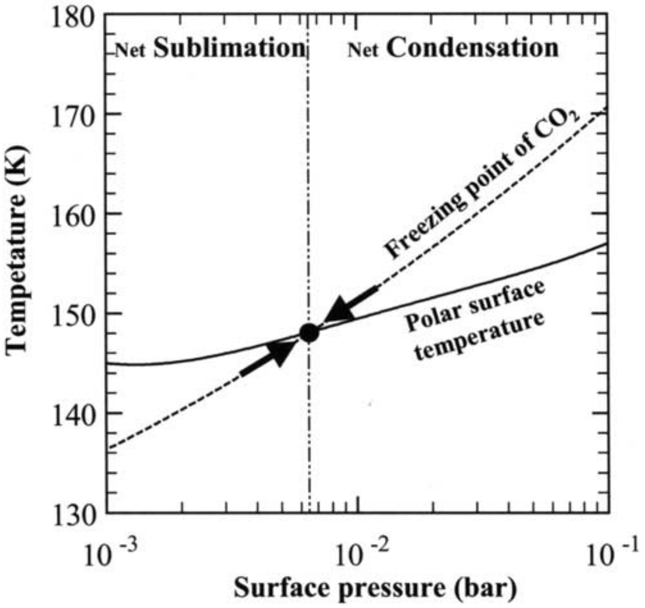

Figure 6. A schematic illustration of a mechanism for stabilization of the atmospheric CO_2 pressure and the surface temperature in the AI system. The solid curve represents surface temperature as a function of the atmospheric pressure, and the dashed curve is the vapor pressure curve of CO_2. The solid circle indicates a stable steady state solution. If atmospheric pressure is higher than that of the solution, the freezing point is higher than the surface temperature. In such a case, condensation of CO_2 should occur to go back to the pressure level of the solution. On the other hand, if atmospheric pressure is lower than that of the solution, sublimation of CO_2 should occur. In this way, the atmospheric CO_2 pressure is stabilized at some pressure level in the case of the residual-cap regime.

level of the solution; see Figure 6). On the other hand, if the atmospheric pressure is lower than that of the solution, net condensation of CO_2 should be negative. Therefore, the atmospheric pressure will increase to the pressure level of the solution. In this way, the atmospheric pressure of the residual-cap solution is determined essentially by balance of the greenhouse effect and the vapor pressure of CO_2 (Figure 6).

[19] In this respect, the case (iv) can be regarded as a kind of the residual-cap regime. Because of these features, the residual-cap regime of the seasonal change model corresponds to the partially ice-covered solution of the annual mean model of *Nakamura and Tajika* [2001]. The case (iv) would be interesting because asymmetry of the two hemispheres results from the symmetric conditions except the initial condition. On the other hand, it is noted that the solution (i) may be difficult to exist in the real world under the current conditions. This is because the solution (iv) will be favored in the current Mars owing to asymmetries in albedo, altitude, orbital eccentricity, and so on. Our model is somewhat idealized in that point, and the solution with two residual caps might be able to exist only in such a symmetric condition. In any case, the solutions (i) and (iv) are very similar to each other qualitatively and quantitatively (Figure 4). In that respect, existence of

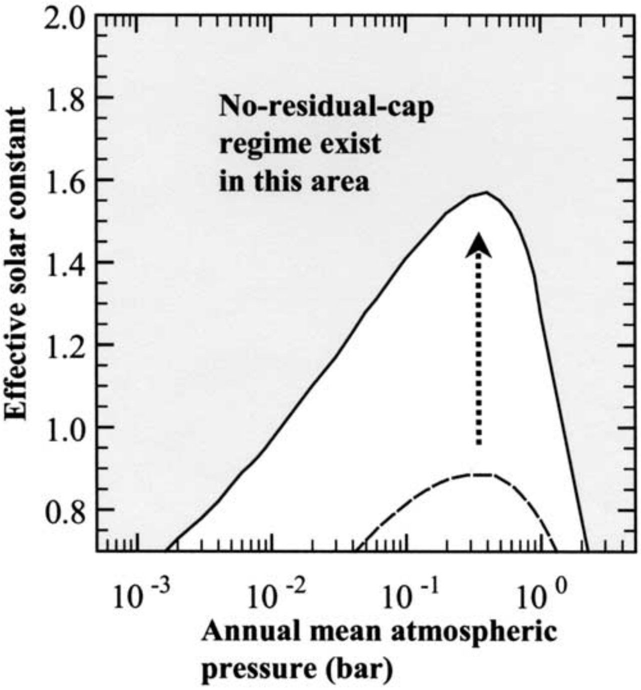

Figure 7. Annual mean atmospheric pressure against the effective solar constant in the case for the no-residual-cap regime. No-residual-cap regime exist in the shaded area. Dashed line represents the boundary of the ice-free solutions obtained from the annual mean model as shown in Figure 1a [*Nakamura and Tajika*, 2001].

residual cap(s) is essential to behaviors of the Martian climate system.

[20] On the other hand, in the case for the no-residual-cap regime, the atmospheric CO_2 pressure depends on the total CO_2 in the AI system (Figure 4). In the case (ii), because the ice cap at a summer pole disappears, CO_2 condensed into the ice cap in winter goes back to the atmosphere within one Martian year. Therefore, the seasonal ice caps do not contribute to a change of the atmospheric pressure over more than one Martian year. Then, the net budget of the latent heat of CO_2 throughout the year is zero irrespective of the atmospheric pressure. In the case (iii), the amount of the atmospheric CO_2 is equal to the total CO_2 in the AI system (because there is no ice cap throughout the year). In this respect, the case (ii) and the case (iii) can be combined into the no-residual-cap regime, which corresponds to the ice-free solution of the annual mean model of *Nakamura and Tajika* [2001].

[21] Figure 7 shows conditions of the annual mean atmospheric pressure against the effective solar constant S_{eff} for the no-residual-cap regime (that is, the cases (ii) and (iii)). Solutions exist in the shaded area. It is noted that the solutions exist both in the lower and in the higher pressure conditions. Under the lower pressure condition, the freezing point is too low for the atmospheric CO_2 to condense to form the residual caps. Under the higher pressure condition, the greenhouse effect is too strong to form seasonal ice caps as well as residual caps. The area above a dashed curve shown in Figure 7 represents the ice-free solution obtained from 1D-EBM under the annual mean condition as shown in Figure 1a [*Nakamura and Tajika*, 2001]. A remarkable difference between the two results is that the no-residual-cap regime is restricted within the higher S_{eff} condition compared with the ice-free region. This means that existence of the no-residual-cap regime is strongly affected by seasonal change of the solar incident flux. This is because CO_2 ice cap is easily formed under the low winter solar incident flux, and once CO_2 ice cap is formed at winter pole, the ice cap does not sublimate easily owing to its high albedo even in summer. Therefore, there is a tendency for the ice cap to remain in summer in the seasonal change model. The higher solar constant is required for sublimation of the ice caps during the summer. Because of this, the results for the seasonal change model are different from those for the annual mean model.

[22] As discussed above, the solution is determined from the solar constant, the total CO_2 in the atmosphere and the ice caps system ($P_{\mathrm{a+i}}$), and the initial condition (the existence of the residual caps). Figure 8 summarizes conditions for each solution. In this figure, the horizontal axis is the total CO_2 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 seasonal-cap solutions, and the no-ice-cap solutions, respectively. The solutions in these regions 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.

3.2. Multiple Solutions of the AIR System

[23] Next, we take the regolith into account as a CO_2 reservoir in the model to study behaviors of the AIR system.

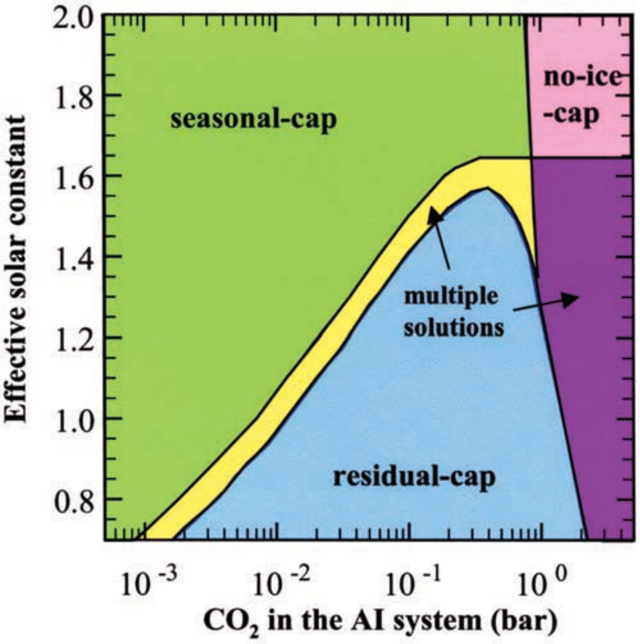

Figure 8. Diagram of the solutions for the AI system. The vertical axis is the effective solar constant and the horizontal axis is the total CO_2 in the AI system.

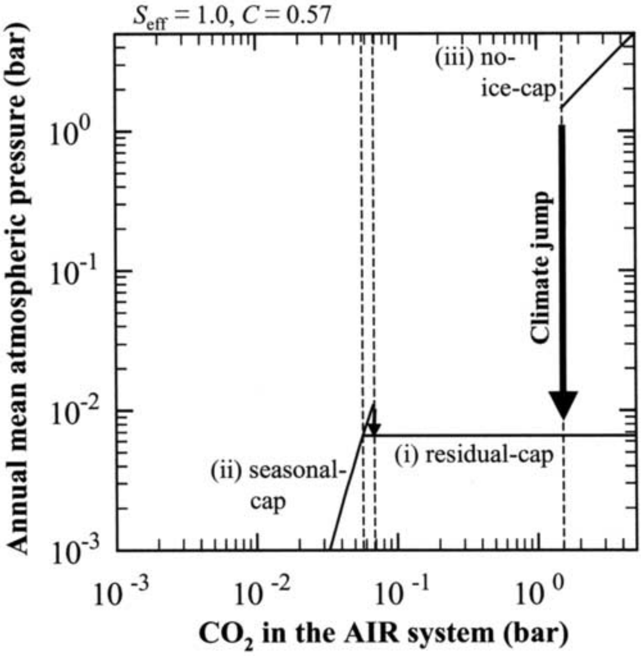

Figure 9. Annual mean atmospheric pressure for each case under the condition of the present solar constant. The horizontal axis is the amount of CO_2 in the AIR system and the vertical axis is the atmospheric pressure. The case for $C = 0.57$ (corresponding to P_{rego} at present is 50 mbar) is shown.

The amount of CO_2 adsorbed in the regolith is represented by equation (8). Here, we use annual mean values of the temperature and the pressure for equation (8). This is because timescale of CO_2 adsorption by regolith will be much longer than the Martian year [*Kieffer and Zent*, 1992]. The distribution of CO_2 among each reservoir is determined from equations (1) and (8), when the total amount of CO_2 in the AIR system (P_{total}) and efficiency of the adsorption of CO_2 by regolith are given. Efficiency of the CO_2 adsorption by regolith depends on a parameter C in equation (8) (the parameter C determines the current amount of CO_2 in the regolith). The efficiency of the adsorption C can be determined from the estimate of the present amount of CO_2 in the regolith.

[24] Solutions for the AIR system are shown in Figures 9 and 10 which correspond to diagrams of AI system as shown in Figures 4 and 8, respectively (note that the horizontal axis represents the total amount of CO_2 in the ''AIR'' system in Figures 9 and 10, although that is the amount of CO_2 in the ''AI'' system in Figures 4 and 8). In Figure 9, the case for $C = 0.57$ is shown. This condition corresponds to the lower estimate of the present P_{rego} ($\sim$50 mbar) [*Zent and Quinn*, 1995]. The behaviors of the solutions are the same as those for $C = 0$ qualitatively, because solutions (i) $\sim$ (iv) are determined by partition of CO_2 between the atmosphere and the ice caps. The solutions move rightward as compared with the solutions for $C = 0$ (Figures 9 and 10) just because the total amount of CO_2 increases owing to the regolith reservoir. In Figure 10, results for the three representative values of C are shown. The case for $C = 0$ corresponds to the results shown in Figure 8 (the AI system), and the cases for $C = 0.57$ (P_{rego} at present is 50 mbar) and $C = 11.4$ (P_{rego} at present is 1 bar) can be regarded as the cases for the lowest estimate of P_{rego} [*Zent and Quinn*, 1995] and the highest estimate of P_{rego} [*Fanale et al.*, 1982], respectively. The regions between two curves for each case represent conditions for the multiple solutions. As the efficiency of the CO_2 adsorption by regolith increases, the solution curves shift rightward, because relative size of the regolith reservoir (so the total amount of CO_2 in the AIR system) becomes large as the efficiency increases. As shown in Figure 10, the regions for the multiple solutions are restricted within specific conditions.

[25] The present Mars has the residual CO_2 ice cap in the south polar region [*Kieffer*, 1979], although the northern CO_2 ice cap disappears during the summer [*Kieffer et al.*, 1976]. The present state of Mars may, therefore, corresponds to the solution (iv), although this might be due to the difference in altitude between the north polar region and the south polar region [*Thomas et al.*, 2000]. As described earlier, this solution is considered to be essentially in the residual-cap regime. According to Figure 10, the conditions for multiple solution are rather restricted, so it seems to be difficult for the present Martian climate system to have another solution (either seasonal-cap or no-ice-cap solutions, that is, no-residual-cap regime) in addition to the present state. However, in the annual mean model, another solution (ice-free solution) always exist in addition to the present state [*Nakamura and Tajika*, 2001]. This may be the most different aspect between the annual mean model and the seasonal change model.

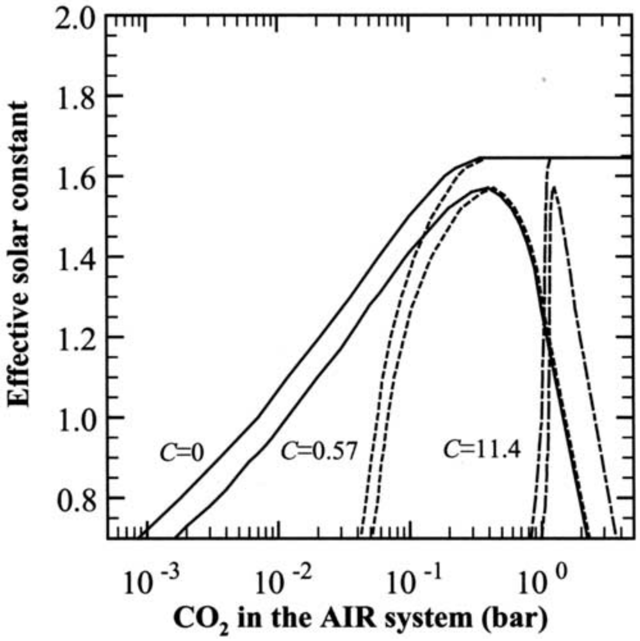

Figure 10. Diagram of the multiple solution for the AIR system. The vertical axis is the effective solar constant and the horizontal axis is the total CO_2 in the AIR system. Results for three representative values of C are shown: (1) $C = 0$, (2) $C = 0.57$ (P_{rego} = 50 mbar at present), and (3) $C = 11.4$ (P_{rego} = 1 bar at present). The region between two lines for each case represents conditions for the multiple solutions.

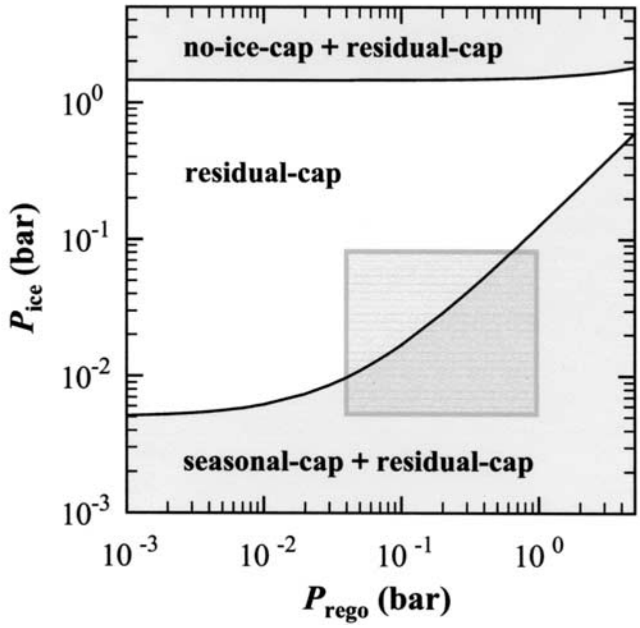

Figure 11. Diagram of the solutions for the AIR system under the present solar radiation and P_{air} conditions. The vertical axis is the current P_{ice} and the horizontal axis is the current P_{rego}. Multiple solutions exist in the shaded regions. Estimated range of the present sizes of two CO_2 reservoirs (P_{ice} and P_{rego}) are shown as a rectangle.

[26] Then, what are the conditions for existence of another (no-residual-cap) state in the present Martian system? Figure 11 shows a diagram which indicates conditions for the Martian climate system to have multiple solutions under the present solar constant. Again, the multiplicity of solutions at the present solar constant depends on the total amount of CO_2 in the present AIR system (P_{total}) and the efficiency of the adsorption of CO_2 by the regolith (that is, the present P_{rego}). Therefore, if present values of P_{ice} and P_{rego} are given as free parameters (P_{air} at present is well known), the conditions for the multiplicity can be determined. In Figure 11, the vertical axis is the current P_{ice} and the horizontal axis is the current P_{rego}. A rectangle in Figure 11 represents estimated ranges of the current P_{ice} and P_{rego} [*Zent and Quinn*, 1995; *Fanale et al.*, 1982; *Mellon*, 1996]. According to Figure 11, no-ice-cap solution may not exist, but there is possibility for existence of seasonal-cap solution under the present solar constant in addition to the present residual-cap solution. Even if we use somewhat different values of model parameters, this conclusion and a mathematical structure of solutions such as described in Figures 11 and 8 do not change. However, because estimates of the present P_{ice} and P_{rego} (illustrated as a rectangle in Figure 11) still have very large uncertainties, the multiplicity of solutions cannot be concluded. In order to resolve this problem, it is necessary to evaluate accurate values of P_{ice} and P_{rego} on Mars at present.

[27] In this section, multiple solutions of 1D-EBM under the seasonal change condition is discussed. The results for the seasonal change model are considerably different from those for the previous annual mean EBM. This difference results from conditions for existence of no-residual-cap regime obtained from the seasonal change model. At the present solar constant, the ice-free solution obtained from the annual mean model always exists regardless of the atmospheric pressure. On the other hand, existence the no-residual-cap regime obtained from the seasonal change model depends on the atmospheric pressure. This is because once CO_2 ice cap is formed at winter pole with very low solar incident flux, the ice cap does not sublimate easily due to its high albedo. Furthermore, no-ice-cap solution should not exist under the present condition in the seasonal change model (Figure 11). This discrepancy results in the considerable differences in the results between the seasonal change model and the annual mean model. This means that it is necessary for the model to take the seasonal variations into account in order to consider possibility of the multiple solutions of the climate system of Mars.

3.3. Problem on CO_2 Clouds

[28] Formation of CO_2 clouds is the most significant problem of our study. The CO_2 clouds will decrease the surface temperature by increasing the planetary albedo and by reducing the tropospheric lapse rate [*Kasting*, 1991], but, on the other hand, it may increase the surface temperature remarkably owing to the greenhouse effect [*Forget and Pierrehumbert*, 1997]. These two are somewhat compensative effects on determining the surface temperature. However, the most important problem may be CO_2 snowfall which will reduce the atmospheric CO_2 level by increasing either the areal extent or thickness of the ice caps.

[29] The problem on CO_2 condensation and CO_2 clouds becomes important, when we consider the climate system with a dense CO_2 atmosphere. When we consider the residual-cap solution or the seasonal-cap solution which exists under the condition of very low pressure of the CO_2 atmosphere (see Figure 4), CO_2 condensation would not be important. In fact, although CO_2 may precipitate during the polar nights on Mars at present, difference in amplitude of seasonal variations in the atmospheric pressure between our result and the observation is less than 0.5 mbar. In this case, the mathematical structure of our solutions does not change. Therefore, effects of CO_2 condensation should be important only for the no-ice-cap solution which exists under the condition of several bars of CO_2 atmosphere.

[30] High latitudinal region during the winter season would be the most favorable for condensation of the atmosphere. If the surface in high latitudinal region is covered with CO_2 ice in winter, the problem is whether the CO_2 ice will sublimate completely or not during the next summer. The amount of CO_2 ice which sublimates during the summer is determined by the incident solar radiation on the CO_2 ice. If the amount of CO_2 ice accumulated during the winter on the surface (by snowfall and/or condensation at the surface) is smaller than this amount, the CO_2 ice will sublimate completely in the next summer. In such a case, variations of the atmospheric pressure will be 10 mbar at the most, assuming that the high latitude region more than 60 degree is covered with CO_2 ice in winter. This is negligible in comparison with the average atmospheric pressure (several bars). Therefore,

the effect of CO_2 condensation on the whole system is trivial in this case.

[31] On the other hand, if the amount of CO_2 ice accumulated on the surface during the winter is larger than the critical value, the CO_2 ice will not sublimate completely and will remain at the surface in summer. This residual cap will trigger runaway condensation and cooling due to the positive (greenhouse and ice-albedo) feedback mechanisms. As a result, the climate state would drop into the residual-cap solution. If it were the case, the no-ice-cap solution at a dense CO_2 atmosphere would be difficult to be realized.

[32] In this analysis, the most important factor is to estimate the amount (and distribution) of CO_2 ice on the surface accumulated during the winter. It is difficult, however, to determine the amount of the CO_2 ice (or snow) taking into account effects of condensation of the atmospheric CO_2 appropriately. It will require more complicated dynamical model with some microphysical processes such as nucleation, condensation, and so on.

4. Summary

[33] In this paper, we have discussed the climatic environment of Mars based both on the energy balance and the CO_2 budgets at the surface of Mars. We assumed that CO_2 has been the dominant constituent of the Martian atmosphere and that the atmosphere, the polar ice caps, and the regolith are major reservoirs of CO_2 (the AIR system). In order to study stability and evolution of the AIR system, we introduced a one-dimensional energy balance climate model (EBM) which considers change of the ice cap area, latitudinal heat transport, and greenhouse effect of CO_2.

[34] We modified the EBM of *Nakamura and Tajika* [2001] to evaluate effects of the seasonal change of the solar incident flux on the results. We compared results for the seasonal change model with those for the annual mean model. The results in the case of seasonal change can be divided into four cases: (i) a solution which has residual ice caps in summer (residual-cap solution), (ii) a solution without residual ice caps, although seasonal ice caps are formed 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 in one pole and a seasonal ice cap in another pole. We can summarize these cases into the two regimes based on a relation between the annual mean atmospheric pressure and the total amount of CO_2 in the system: the cases (i) and (iv) can be regarded as (I) residual-cap regime, and the cases (ii) and (iii) can be combined into (II) no-residual-cap regime.

[35] Discrepancy between the results of two models is condition for multiple solutions of the Martian climate system. In the annual mean model, another solution (ice-free solution) in addition to the present state always exists under the present solar constant. However, in the seasonal change model, no-ice-cap solution does not seem to exist, and existence of the another solution (seasonal-cap solution) depends on the total amount of CO_2 in the AIR system. This is because once CO_2 ice cap is formed at winter pole with very low solar incident flux, the ice cap does not sublimate easily owing to its high albedo. In this case, whether the Martian climate system has another solution under the present solar constant depends on the present amounts of CO_2 in the ice caps and regolith reservoirs.

[36] **Acknowledgments.** The authors are most grateful to Y. Abe for helpful discussions and comments on this work. We also thank anonymous referees for the helpful reviews. This study is supported by JSPS Research Fellowships for Young Scientists.

References

Aida, M., *Atmosphere and Radiation* (in Japanese), pp. 42–45, Tokyo-do, Tokyo, 1982.

Baker, V. R., R. G. Storm, V. C. Gulick, J. S. Kargel, G. Komatsu, and V. S. Kale, Ancient oceans, ice sheets and the hydrological cycle on Mars, *Nature*, *352*, 589–594, 1991.

Fanale, F. P., and W. A. Cannon, Exchange of adsorbed H_2O and CO_2 between the regolith and atmosphere of Mars caused by changes in surface insolation, *J. Geophys. Res.*, *24*, 3397–3402, 1974.

Fanale, F. P., J. R. Salvail, W. B. Banerdt, and R. S. Saunders, Mars: The regolith-atmosphere-cap system and climate change, *Icarus*, *50*, 381–407, 1982.

Forget, F., and R. T. Pierrehumbert, Warming early Mars with carbon dioxide clouds that scatter infrared radiation, *Science*, *278*, 1273–1276, 1997.

Gierasch, P. J., and O. B. Toon, Atmospheric pressure variation and the climate of Mars, *J. Atmos. Sci.*, *30*, 1502–1508, 1973.

Haberle, R. M., D. Tyler, C. P. McKay, and W. L. Davis, A model for the evolution of CO_2 on Mars, *Icarus*, *109*, 102–120, 1994.

James, P. B., and G. R. North, The seasonal CO_2 cycle on Mars: An application of an energy balance climate model, *J. Geophys. Res.*, *87*, 10,271–10,283, 1982.

James, P. B., H. H. Kieffer, and D. A. Paige, The seasonal cycle of carbon dioxide on Mars, in *Mars*, edited by H. H. Kieffer et al., pp. 934–968, Univ. of Ariz. Press, Tucson, 1992.

Kasting, J. F., CO_2 condensation and the climate of early Mars, *Icarus*, *94*, 1–13, 1991.

Kieffer, H. H., Mars south polar spring and summer temperatures: A residual CO_2 frost, *J. Geophys. Res.*, *84*, 8263–8288, 1979.

Kieffer, H. H., and A. P. Zent, Quasi-periodic climate change on Mars, in *Mars*, edited by H. H. Kieffer et al., pp. 1180–1218, Univ. of Ariz. Press, Tucson, 1992.

Kieffer, H. H., S. C. Chase Jr., T. Z. Martin, E. D. Miner, and F. D. Palluconi, Martian north pole summer temperatures: Dirty water ice, *Science*, *194*, 1341–1344, 1976.

Leighton, R. B., and B. C. Murray, Behavior of carbon dioxide and other volatiles on Mars, *Science*, *153*, 136–144, 1966.

Luhmann, J. G., R. E. Johnson, and M. H. G. Zhang, Evolutionary impact of sputtering of the Martian atmosphere by O^+ pickup ions, *Geophys. Res. Lett.*, *19*, 2151–2154, 1992.

McKay, C. P., O. B. Toon, and J. F. Kasting, Making Mars habitable, *Nature*, *352*, 489–496, 1991.

Mellon, M. T., Limits on the CO_2 content of the Martian polar deposits, *Icarus*, *124*, 268–279, 1996.

Melosh, H. J., and A. M. Vickery, Impact erosion of the primordial Martian atmosphere, *Nature*, *338*, 487–489, 1989.

Nakamura, T., and E. Tajika, Stability and evolution of the climate system of Mars, *Earth Planets Space*, *53*, 851–859, 2001.

North, G. R., R. F. Cahalan, and J. A. Coakley Jr., Energy balance climate models, *Rev. Geophys.*, *19*, 91–121, 1981.

Pollack, J. B., J. F. Kasting, S. M. Richardson, and K. Poliakoff, The case for a wet, warm climate on early Mars, *Icarus*, *71*, 203–224, 1987.

Stone, P. H., A simplified radiative-dynamical model for the static stability of rotating atmospheres, *J. Atmos. Sci.*, *29*, 405–418, 1972.

Thomas, P. C., M. C. Malin, K. S. Edgett, M. H. Carr, W. K. Hartmann, A. P. Ingersoll, P. B. James, L. A. Soderblom, J. Veverka, and R. Sullivan, North-south geological differences between the residual polar caps on Mars, *Nature*, *404*, 161–164, 2000.

Ward, W. R., Long-term orbital and spin dynamics of Mars, in *Mars*, edited by H. H. Kieffer et al., pp. 298–320, Univ. of Ariz. Press, Tucson, 1992.

Zent, A. P., and R. C. Quinn, Simultaneous adsorption of CO_2 and H_2O under Mars-like conditions and application to the evolution of the Martian climate, *J. Geophys. Res.*, *100*, 5341–5349, 1995.

T. Nakamura and E. Tajika, Department of Earth and Planetary Science, 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)