

# Stability and evolution of the climate system of Mars

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(Received December 4, 2000; Revised April 14, 2001; Accepted April 17, 2001)

We construct a one-dimensional energy balance climate model for Mars which incorporates greenhouse effect of CO<sub>2</sub> and latitudinal heat transport so that we can express a latitudinal temperature gradient and change of an areal extent of a polar ice cap. By considering energy balance and CO<sub>2</sub> budget among atmosphere, ice caps, and regolith, we investigate stability and evolution of the climate system of Mars. Under the present condition there are two stable steady state solutions of the system. One corresponds to a partial ice-covered solution (the present state), and the other is a warmer ice-free solution. Although this is also predicted by previous studies, these solutions are qualitatively different from them. When we assume CO<sub>2</sub> as a dominant greenhouse gas for a warm and wet climate on the early Mars, we found that the total amount of CO<sub>2</sub> within the whole system should have been larger than that at present and have decreased by some removal processes. We also found that a climate jump must have occurred during the evolution from the early warm climate to the present state, and ice caps on the early Mars might have extended to the mid-latitude. The atmospheric pressure may have decreased further after the climate jump.

## 1. Introduction

Ever since Mariner 9 and Vikings found many valleys and basins on the surface of Mars, Martian paleoenvironment under which these topographies were created has been discussed. Valley networks and traces of possible paleoshorelines on the Martian surface are regarded as possible evidence of existence of liquid water during the early history of Mars (e.g., Goldspiel and Squyres, 1991; Baker *et al.*, 1992; Head *et al.*, 1999). The low elevation of the northern hemisphere and its flatness might also imply that the northern hemisphere was once covered with a vast ocean (Smith *et al.*, 1998). These features suggest that the ancient Mars might have warm and wet environment. Because solar luminosity was lower in the past than at present (Sagan and Mullen, 1972), it is likely that strong greenhouse effect due to some greenhouse gas species should have worked at that time to make warm environment on the ancient Mars. It was generally believed that the Martian atmosphere was reducing early in its history. However, it has been shown that reducing gases (such as CH<sub>4</sub> and NH<sub>3</sub>) are photochemically unstable (Kuhn and Atreya, 1979). It is now believed that CO<sub>2</sub> was the dominant greenhouse gas in the early atmosphere of Mars, although other possibilities such as greenhouse effect of CH<sub>4</sub> and/or NH<sub>3</sub> cannot be excluded entirely (Kasting, 1997; Sagan and Chyba, 1997).

There are several controlling mechanisms for the atmospheric CO<sub>2</sub> pressure on Mars. For instance, if there was liquid water (oceans or ponds) under warm and wet conditions, CO<sub>2</sub> 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 the heavy bombardment period (Melosh and Vickery, 1989). Escape of atmospheric CO<sub>2</sub> by ion sputtering is also suggested to have occurred throughout the history of Mars (Luhmann *et al.*, 1992). On the other hand, volcanic degassing might have supplied CO<sub>2</sub> to the atmosphere (Baker *et al.*, 1991). It is also important to consider the polar ice caps (e.g., Leighton and Murray, 1966) and the surface regolith (Fanale and Cannon, 1974) which might have been large CO<sub>2</sub> reservoirs to exchange CO<sub>2</sub> with the atmosphere.

Gierasch and Toon (1973) assumed the atmosphere and the polar ice caps as dominant CO<sub>2</sub> reservoirs. They studied multiple solutions for a model of the atmosphere-ice cap (AI) system and analyzed stability of the solutions. They used a zero-dimensional energy balance climate model, although they assumed the winter polar region and the low-latitude region and considered heat transport between them due to baroclinic instability. They found that the AI system has two stable solutions: one is the present state and the other is the warmer state with higher CO<sub>2</sub> pressure.

On the other hand, McKay *et al.* (1991) assumed the atmosphere and the regolith as dominant CO<sub>2</sub> reservoirs, and studied multiple solutions for the atmosphere-regolith (AR) system and stability of solutions. They combined a one-dimensional radiative-convective model proposed by Pollack *et al.* (1987) with a model for CO<sub>2</sub> exchange between the regolith and the atmosphere proposed by Toon *et al.* (1980). They argued that the AR system may have two stable states, depending on sensitivity of CO<sub>2</sub> adsorption by the regolith to the surface temperature. One of them is the present state, and the other is the warmer state with higher CO<sub>2</sub> pressure.

These two studies, however, may have some problems. Gierasch and Toon (1973) did not consider the greenhouse

effect of CO<sub>2</sub> and adsorption of CO<sub>2</sub> by the regolith, and assumed the polar cap to be an infinite CO<sub>2</sub> reservoir with no areal extent. On the other hand, McKay *et al.* (1991) did not consider roles of CO<sub>2</sub>-ice caps as a CO<sub>2</sub> reservoir which may regulate the atmospheric CO<sub>2</sub> pressure and as a reflector of incident solar flux, especially in the distant past.

Haberle *et al.* (1994) modified the energy balance model of Gierasch and Toon (1973) to study the evolution of CO<sub>2</sub> on Mars from the end of the heavy bombardment period to the present by considering chemical weathering, regolith uptake, polar cap formation, and atmospheric escape by sputtering. They argued that the polar caps could have profound effect on behavior of the system: once ice caps were formed, the volume of ice caps increases drastically owing to a feedback effect between surface pressure, greenhouse effect, and heat transport, resulting in a collapse (catastrophic reduction) of the atmosphere. However, they did not discuss multiplicity of the steady state solutions and stability of them, and, because their model is also zero-dimensional, they could not consider areal extent of polar caps which should affect both the energy balance and the condition for ice cap formation.

In this paper, we investigate stability and property of steady state solutions of the Martian climate system. We consider an atmosphere-ice cap-regolith (AIR) system as a climate system of Mars. According to Hoffert *et al.* (1981) and Postawko and Kuhn (1986), atmospheric heat transport controls surface temperature profile, hence areal extent of the CO<sub>2</sub> caps. Therefore, we construct a one-dimensional energy balance climate model combined with greenhouse effect of CO<sub>2</sub> and latitudinal heat transport so that we can express a latitudinal temperature gradient and a change of the areal extent of polar ice caps explicitly. By considering both the energy balance and the CO<sub>2</sub> budget, we examine the steady state and stability of the AIR system. Possible scenarios for the evolution of Martian climate system will be also discussed.

## 2. Model

We introduce a one-dimensional energy balance climate model (1-D EBM) based on North *et al.* (1981). It is, however, noted that the model must be modified in order to describe the climate system of Mars which is quite different from that of the Earth. In this study, we assume annual mean conditions and symmetrical hemispheres in order to compare the previous zero-dimensional annual mean model. The CO<sub>2</sub> ice sheet expands from the pole to a certain latitude (this ice cap edge is called "iceline"), and there is no ice from the iceline to Equator.

The 1-D EBM is an energy balance model that can express latitudinal heat transport. In a steady state, the energy balance at the surface of the  $i$ -th latitude is represented as [Net horizontal heat transport out] <sub>$i$</sub>  + [Outgoing infrared radiation] <sub>$i$</sub>  = [Incident solar radiation absorbed] <sub>$i$</sub> . This may be represented mathematically by the relation

$$-\frac{\partial}{\partial x} \left[ D(1-x^2) \frac{\partial T(x)}{\partial x} \right] + I(x) = \frac{Q}{4} S(x) \{1 - a(x, x_s)\} \quad (1)$$

where  $D$  is a thermal diffusion coefficient,  $x$  is the sine of latitude (that is,  $x = \sin \phi$  where  $\phi$  is the latitude),  $x_s$  cor-

responds to the iceline,  $T(x)$  is the surface temperature in a given latitude band,  $I(x)$  is the outgoing infrared radiation,  $Q$  is the solar constant at the orbit of the planet,  $S(x)$  is the annual mean solar income distribution, and  $a$  is the planetary albedo. In this study, we assume the present solar income distribution as follows (Hoffert *et al.*, 1981).

$$S(x) = 1.235 - 0.693x^2. \quad (2)$$

The boundary conditions for symmetric solutions are given by

$$-D\sqrt{1-x^2} \frac{\partial T(x)}{\partial x} = 0 \text{ for } x = 0, 1. \quad (3)$$

The planetary albedo  $a(x, x_s)$  is expressed as follows.

$$a(x, x_s) = \begin{cases} a_f & \text{for } 0 < x < x_s \\ a_i & \text{for } x_s \leq x < 1. \end{cases} \quad (4)$$

We assumed  $a_f = 0.21$  as the surface albedo of land (Pollack *et al.*, 1987), and  $a_i = 0.65$  as CO<sub>2</sub> ice (Leighton and Murray, 1966).

One of the most important problem to study the stability of CO<sub>2</sub> atmosphere is condensation of CO<sub>2</sub> to form CO<sub>2</sub> clouds (Kasting, 1991). Kasting (1991) argued that condensation of CO<sub>2</sub> should release latent heat and so decreases the lapse rate, resulting in a decrease in the surface temperature in order to maintain energy balance. The CO<sub>2</sub> cloud is a good scatterer for solar radiation, thus it should increase the planetary albedo. Condensation of CO<sub>2</sub> may limit the amount of atmospheric CO<sub>2</sub> when the entire atmosphere is covered with CO<sub>2</sub> cloud.

Recently, Forget and Pierrehumbert (1997) argued that CO<sub>2</sub> ice particle larger than 10  $\mu\text{m}$  can scatter infrared radiation back to the surface. They included this effect in the 1-D radiative-convective model designed for early Mars by Kasting (1991), and showed that greenhouse effect of CO<sub>2</sub> cloud could be quite powerful. Although magnitude of the greenhouse effect of CO<sub>2</sub> cloud should depend on fraction of cloud cover and optical thickness, these properties have not been known. Therefore, the effect of CO<sub>2</sub> clouds on the energy balance may have been still unclear.

In this study, we adopt a traditional expression of outgoing infrared radiation  $I(x)$  which is approximated to a linear function of  $T(x)$  as follows:

$$I(x) = A + BT(x). \quad (5)$$

The coefficients  $A$  and  $B$  depend on the atmospheric CO<sub>2</sub> pressure. We determined these coefficients on the basis of the radiative-convective calculations by Pollack *et al.* (1987) which include greenhouse effects of CO<sub>2</sub> and H<sub>2</sub>O. Although the model of Pollack *et al.* (1987) neglects H<sub>2</sub>O clouds, effects of H<sub>2</sub>O clouds 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<sub>2</sub> clouds. However, we will also discuss the case for CO<sub>2</sub> cloud formation (Kasting, 1991; Forget and Pierrehumbert, 1997) in the later section. We parameterize  $A$  and  $B$  as a function of  $\rho$  ( $= \log P_{\text{air}}$ :  $P_{\text{air}}$  is the surface pressure of CO<sub>2</sub> (in bar)), and change them at  $T_0$  for the most appropriate fitting

as follows:

$$I = \begin{cases} A_1 + B_1 T & \text{for } T > T_0 \\ A_2 + B_2 T & \text{for } T \leq T_0 \end{cases} \quad (6)$$

$$\begin{cases} A = a_1 \rho^4 + a_2 \rho^3 + a_3 \rho^2 + a_4 \rho + a_5 \text{ (W/m}^2\text{)} \\ B = b_1 \rho^4 + b_2 \rho^3 + b_3 \rho^2 + b_4 \rho + b_5 \text{ (W/m}^2\text{K)}. \end{cases} \quad (7)$$

Fitting parameters ( $a_1 \sim a_5$ ,  $b_1 \sim b_5$ , and  $T_0$ ) are shown in Table 1.

According to Gierasch and Toon (1973), we assume that heat is transported meridionally by baroclinic instability. We 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. Then we obtain

$$D = \alpha P_{\text{air}} \quad (8)$$

where  $\alpha$  is a constant which is determined by the present-day condition.

The atmospheric pressure of CO<sub>2</sub> should change owing to changes in the areal extent of ice caps and the amount of CO<sub>2</sub> adsorbed in the regolith. The amount of CO<sub>2</sub> adsorbed in the regolith ( $P_{\text{rego}}$ ) is represented by the equation used in McKay *et al.* (1991). However, we modify their expression to consider latitudinal dimension as follows:

$$P_{\text{rego}} = C \int_0^{x_s} e^{-T(x)/T_d} P_{\text{air}}^\gamma dx \quad (9)$$

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

The amount of CO<sub>2</sub> as polar ice caps ( $P_{\text{ice}}$ ) is estimated from the areal extent of ice caps and assumed CO<sub>2</sub> content in ice caps per unit area. The latitude of iceline is determined from the temperature distribution obtained from the energy balance. The condition for the surface temperature at the iceline is defined here as

$$T(x_s) = T_{\text{sub}}(P_{\text{air}}) \quad (10)$$

where  $T_{\text{sub}}$  represents freezing point of CO<sub>2</sub> as a function of the atmospheric pressure. Although CO<sub>2</sub> ice disappears in summer on the north pole while it remains throughout the year on the south pole on Mars at present (James *et al.*,

Table 1. Fitting parameters for greenhouse model of Pollack *et al.* (1987).

$T_0 = 230.1 \text{ K}$				
$i$	$a_i (A_1)$	$a_i (A_2)$	$b_i (B_1)$	$b_i (B_2)$
1	0.6449	0.1068	-0.003256	-0.00094
2	13.28	2.198	-0.06758	-0.0195
3	99.54	16.48	-0.5069	-0.1464
4	329.9	54.64	-1.68	-0.485
5	-372.7	-61.72	1.898	0.5479

1992; Tanaka and Abe, 1991), we assume symmetry of hemisphere for simplicity. It is noted that the correct amount of this reservoir may have been still unclear. According to the previous studies, the amount of CO<sub>2</sub> in the ice-cap reservoir is estimated to be from several mbars (Fanale *et al.*, 1982) to <254 mbars (more realistically, <a few tens of mbars) (Mellon, 1996). Therefore, the amount of CO<sub>2</sub> in the ice-cap reservoir may be less than a few tens of mbars, or, at least, several mbars. In this study, we assume annually averaged expansion of the CO<sub>2</sub> caps to be as far as 70° for both caps with a thickness of 25 m, then we obtain  $P_{\text{ice}} = 85$  mbar for a nominal current condition. The value we used can be regarded as an upper estimate for the CO<sub>2</sub> ice-cap reservoir.

When we give the total amount of CO<sub>2</sub> contained in the AIR system ( $P_{\text{total}}$ ), that is,

$$P_{\text{total}} = P_{\text{air}} + P_{\text{ice}} + P_{\text{rego}} \quad (11)$$

we can obtain steady state solutions for the system by solving the energy balance and the CO<sub>2</sub> exchange among the reservoirs.

### 3. Results

#### 3.1 Steady state solutions of the 1-D EBM

In this section, we show steady state solutions of the 1-D EBM and discuss some specific features. Figure 1 shows steady state solutions of the 1-D EBM (Eqs. (1)~(8), and (10)) expressed as a curved surface of

$$S_{\text{eff}} \equiv \frac{Q}{Q_0} = f(P_{\text{air}}, \phi_s) \quad (12)$$

where  $S_{\text{eff}}$  is an effective solar constant and  $Q_0$  is the solar constant at the Martian orbit today. Steady state solutions of the AIR system (Eqs. (1)~(11)) exist on this curved surface. Figure 2(a) is a plane of  $\phi_s = 90^\circ$  ( $P_{\text{air}}-S_{\text{eff}}$  plane) of Fig. 1. The region above the curve is the ice-free solutions, and there is no solution below the curve. Figure 2(b) is a projection

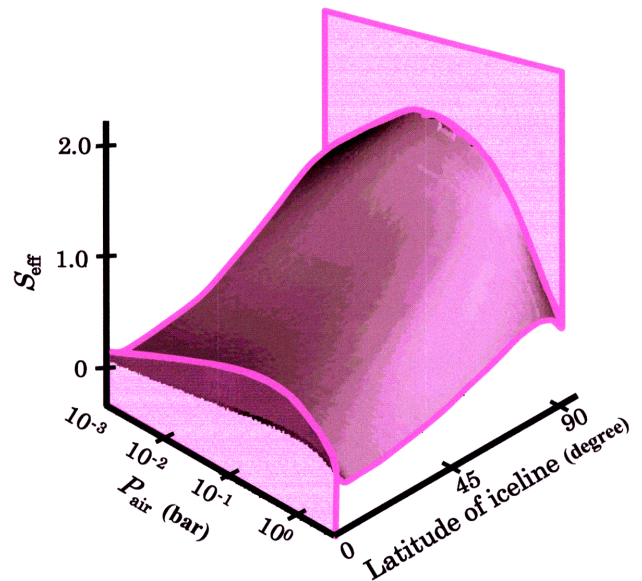


Fig. 1. Steady state solutions of the EBM.

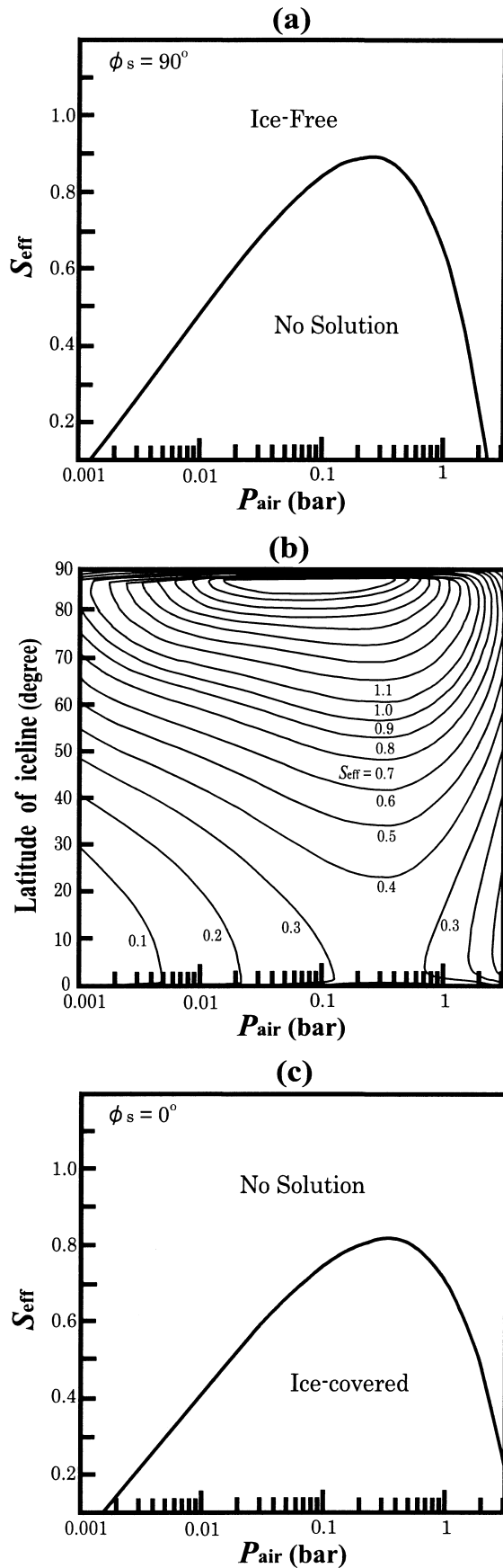


Fig. 2. Cross sections of Fig. 1. (a) A plane of  $\phi_s = 90^\circ$ . The region above the curve is the ice-free solutions. The sign of  $\partial S_{\text{eff}}/\partial P_{\text{air}}$  changes because  $P_{\text{air}}$  affects both the greenhouse effect and the freezing point of  $\text{CO}_2$ . (b) The projection of the solutions onto  $P_{\text{air}}-\phi_s$  plane. (c) A plane of  $\phi_s = 0^\circ$ . The region below the curve is the ice-covered solutions.

of Fig. 1 onto  $P_{\text{air}}-\phi_s$  plane. Figure 2(c) is a plane of  $\phi_s = 0^\circ$  ( $P_{\text{air}}-S_{\text{eff}}$  plane). The region below the curve is the ice-covered solutions, and there is no solution above the curve.

In the climate system of the Earth, there exists ice albedo feedback which is a positive feedback mechanisms derived from albedo difference between land and ice caps (Budyko, 1969). In the Martian climate system, however, additional three feedbacks with respect to  $\text{CO}_2$  ice caps will exist; (1) increase in the atmospheric  $\text{CO}_2$  pressure due to decrease in the ice caps and decrease in the amount of  $\text{CO}_2$  adsorbed in the regolith should result in increase in the greenhouse effect and further decrease in the ice caps (this represents a positive feedback), (2) increase in the atmospheric  $\text{CO}_2$  pressure due to decrease in the ice caps and in the amount of  $\text{CO}_2$  adsorbed in the regolith should result in increase in freezing point of  $\text{CO}_2$ , which prevents the ice caps from reducing (this represents a negative feedback). We name (1) and (2) "greenhouse feedback" and "freezing point feedback", respectively. Another feedback mechanism is (3) a "heat transport feedback". Change in the atmospheric  $\text{CO}_2$  pressure should change efficiency of the latitudinal heat transport. When  $P_{\text{air}}$  increases, the efficiency of the latitudinal heat transport increases. Then, if the net budget of latitudinal heat transport is positive at the iceline (that is, higher latitude region), the polar caps should shrink. This is a positive feedback mechanism. On the other hand, if the net budget of latitudinal heat transport is negative at the iceline (that is, lower latitude region), the polar caps should expand. In this case, it represents a negative feedback mechanism. This negative feedback was not taken into account in the previous models of Gierasch and Toon (1973) and Haberle *et al.* (1994), because the ice cap could not extend to lower latitude region in their models.

It is noted that signs of  $\partial S_{\text{eff}}/\partial \phi_s$ ,  $\partial S_{\text{eff}}/\partial P_{\text{air}}$ , and  $\partial \phi_s/\partial P_{\text{air}}$  change along the solution surface (Fig. 1). The sign of  $\partial S_{\text{eff}}/\partial \phi_s$  changes because of the ice albedo feedback (North *et al.*, 1981). On the other hand, signs of  $\partial S_{\text{eff}}/\partial P_{\text{air}}$  and  $\partial \phi_s/\partial P_{\text{air}}$  are determined by relative strength of two feedback effects: freezing point feedback is stronger than greenhouse feedback where  $\partial S_{\text{eff}}/\partial P_{\text{air}} > 0$  and  $\partial \phi_s/\partial P_{\text{air}} < 0$ . This is because, in that region, the ice cap becomes large owing to the higher freezing point when the atmospheric pressure becomes high. On the other hand, greenhouse feedback is stronger where  $\partial S_{\text{eff}}/\partial P_{\text{air}} < 0$  and  $\partial \phi_s/\partial P_{\text{air}} > 0$ . This is because, in that region, the ice cap becomes small owing to the stronger greenhouse effect when the atmospheric pressure becomes high (see Fig. 2).

### 3.2 Solutions under the current condition

Next, we show the steady state solutions of the 1-D EBM coupled with the AIR system (Eqs. (1)~(11)). Martian surface condition at present is given as boundary condition. Standard values of the parameters are shown in Table 2.

Figures 3 and 4 show the numerical results. In Fig. 3, the solutions are projected on to the  $S_{\text{eff}}-\phi_s$  plane. There exists three steady state solutions under the present solar constant ( $S_{\text{eff}} = 1.0$ ), and we named them from bottom to top, S1, S2, and S3. Globally-ice-covered solutions cannot exist under the present solar constant, because it does not satisfy the balance of the energy budget (see Fig. 2(c)). The solution S1 represents a partial ice-covered solution (ice caps extend to

Table 2. Standard values of model parameters.

Parameter	Value	Reference
$Q^*$	590 W/m <sup>2</sup>	Hoffert <i>et al.</i> (1981)
$\phi_s^*$	70°	James <i>et al.</i> (1992)
$P_{\text{air}}^*$	6 mbar	Pollack <i>et al.</i> (1987)
$P_{\text{ice}}^*$	85 mbar	This study
$P_{\text{rego}}^*$	40 mbar	Zent and Quinn (1995)
$T_d$	35 K	McKay <i>et al.</i> (1991)
$\gamma$	0.275	McKay <i>et al.</i> (1991)
$\alpha$	$5.3 \times 10^{-3}$ m/K·s	This study

\*Present-day values.

some latitude) which corresponds to the present state. Fig. 4 shows the steady state solutions on the  $P_{\text{air}}-\phi_s$  plane. The contours represent the solution for  $S_{\text{eff}}$  to be constant on the curved surface of solutions (Fig. 1). The solid line represents a relation between  $P_{\text{air}}$  and  $\phi_s$  under conditions of  $S_{\text{eff}} = 1.0$  and  $P_{\text{total}} = 131$  mbar, but it does not satisfy the temperature condition for the iceline (Eq. (10)), that is, the solid line satisfies Eqs. (1)~(9) and (11). Thus, intersections of these two curves represent solutions of the EBM coupled with the AIR system. There are three steady state solutions for EBM under the conditions at present (see Fig. 3). Among these, we suggest that the solution S1 is stable and the solution S2 is unstable. This is because the steady state solutions obtained in this study (Fig. 3) is very similar to those obtained in the study for the Earth. According to the discussion on the stability of the climate system of the Earth, when steady state solutions for EBMs are plotted on the solar constant ( $Q$ )—the ice line ( $\phi_s$ ) diagram (like Fig. 3), condition for the positive slope ( $dQ/d\phi_s > 0$ ) of the solution curve is regarded as stable and condition for the negative slope ( $dQ/d\phi_s < 0$ ) is regarded as unstable (e.g., North *et al.*, 1981). This is usually explained intuitively by the relation between change in the solar constant (solar energy input) and direction of areal change of the polar ice cap. When the solution is on the positive slope, the ice cap decreases (increases) as the solar constant increases (decreases). This is physically reasonable. However, when the solution is on the negative slope, the ice cap increases (decreases) while the solar constant increases (decreases). This is physically unreasonable, and, in such a case, the solution is regarded as unstable (North *et al.*, 1981). By analogy with the case for the Earth, we will be able to discuss the stability for the steady state solutions for the climate system of Mars in the same way. Here, “stability” means that, when a small perturbation is given to the solution, the perturbation diminishes for the case of “stable” solution, but it increases for the case of “unstable” solution. In this respect, the above discussion has been proved mathematically for the climate system of the Earth (North *et al.*, 1981). In fact, we can also prove the stability of the steady state solutions for Mars mathematically.

On the other hand, the solution S3 is a stable ice-free (no ice cap) solution which is warmer condition than at present. This is because, when we give a perturbation of the atmospheric pressure to the solution S3, a state of the system will

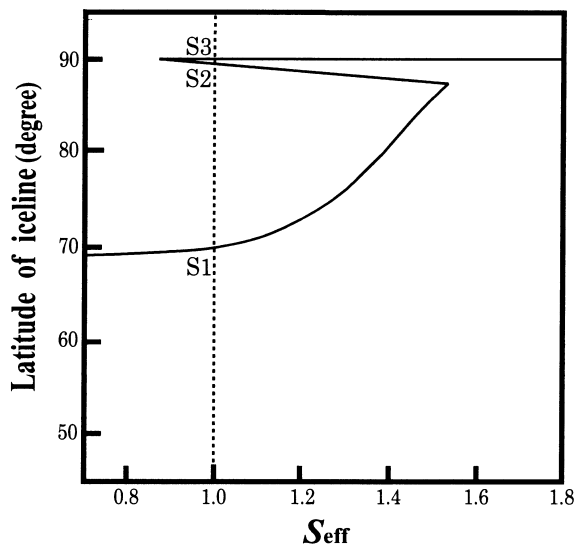


Fig. 3. Steady state solutions of the EBM and the AIR system under the current condition projected onto the  $S_{\text{eff}}-\phi_s$  plane.

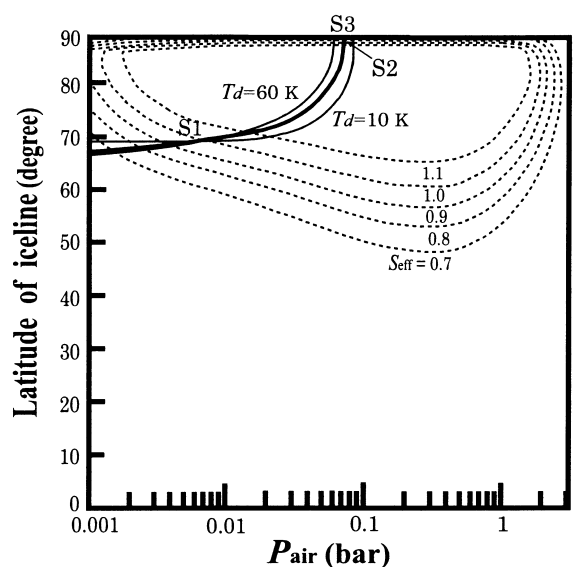


Fig. 4. The projection of the results onto the  $P_{\text{air}}-\phi_s$  plane. Heavy line represents the result for  $S_{\text{eff}} = 1.0$  and  $P_{\text{total}} = 131$  mbar ( $T_d = 35$  K). For comparison, cases for  $T_d = 10$  K and 60 K are represented as thin lines. Intersections of these curves represent the steady state solutions of the 1-D EBM and the AIR system.

go back to the solution S3 because of a negative feedback mechanism owing to gas exchange between the atmosphere and the regolith which depends on the atmospheric pressure. Therefore, there are two stable solutions for the EBM coupled with the AIR system at the present condition.

Stability of the solutions S1, S2, and S3 can also be shown by numerical simulations. Because characteristic time for a response of the regolith should be much longer than that for a response of CO<sub>2</sub> cap stabilization of the atmospheric pressure (Kieffer and Zent, 1992), we deal with the ice caps and the regolith separately. When a small perturbation is given to these steady state solutions, the perturbation decreases with

time for the case of the solution S1 and S3, but it increases with time for the cases of the solution S2. These results are consistent with the above discussion.

## 4. Discussion

### 4.1 Multiple solutions

The AIR system has two stable steady state solutions (the present state and warmer state) under the present solar constant. This multiplicity seems to be consistent with the results of the previous studies (Gierasch and Toon, 1973; McKay *et al.*, 1991). However, the multiple solutions of this study is derived from the one-dimensional model which considers greenhouse effect of CO<sub>2</sub>, adsorption of CO<sub>2</sub> by the regolith, and the change of the ice cap area. Because Gierasch and Toon (1973) did not consider greenhouse effect of CO<sub>2</sub> and the regolith effect, and assumed polar cap as a infinite CO<sub>2</sub> reservoir with no areal extent, their solutions are different qualitatively from those obtained in this study. In fact, McKay *et al.* (1991) showed that the warmer solution of Gierasch and Toon (1973) should disappear when greenhouse effect of CO<sub>2</sub> is considered in the model.

On the other hand, McKay *et al.* (1991) considered greenhouse effect of CO<sub>2</sub> and adsorption of CO<sub>2</sub> by the regolith, but they did not consider effects of CO<sub>2</sub> ice caps. McKay *et al.* (1991) also obtained multiple solutions by using their model although existence of the warmer solution depends strongly on value of the parameter  $T_d$ . They assumed that the amount of CO<sub>2</sub> reserved in the atmosphere and the regolith is constant. However, at the solutions S1 and S3 obtained in this study, the total amount in these two reservoirs is different from each other because of contribution of the ice cap reservoir (although the difference might be small). Therefore, the multiple solutions obtained by McKay *et al.* (1991) are not exactly the same as S1 and S3. Although the amount of ice cap reservoir might be small, this results in an essential difference in the multiplicity of the solutions. McKay *et al.* (1991) argued that whether multiple solutions exist or not depends strongly on the parameter  $T_d$ . Results of this study, however, indicate that multiple solutions exist regardless of the  $T_d$  value for 10 K ~ 60 K (the range McKay *et al.* (1991) examined), as shown in Fig. 4. This is because difference in the amount of CO<sub>2</sub> ice caps results in different  $P_{\text{air}}-T$  relation. Thus, we obtain two pairs of lines (one solid line and one dashed line, see Fig. 5), although McKay *et al.* (1991) considered only one pair of lines. Because each pair has one intersection, there are always two solutions in our model. Our results are also relatively insensitive to the parameter  $\gamma$ . It should be noted that, McKay *et al.* (1991) as well as Gierasch and Toon (1973) studied multiple solutions only at the present time, and it is impossible to consider a condition under which there are larger CO<sub>2</sub> ice caps which might have existed on the early Mars.

Haberle *et al.* (1994) also studied the AIR system. They suggested that more than one kind of scenarios can exist on initial state of Mars, although they did not discuss multiple steady state solutions and stability of the solutions. On the other hand, Haberle *et al.* (1994) argued that a collapse according to a discontinuous jump from a steady state solution to another could occur in the AIR system. In order to deal with this issue in our model, we consider the evolution of the

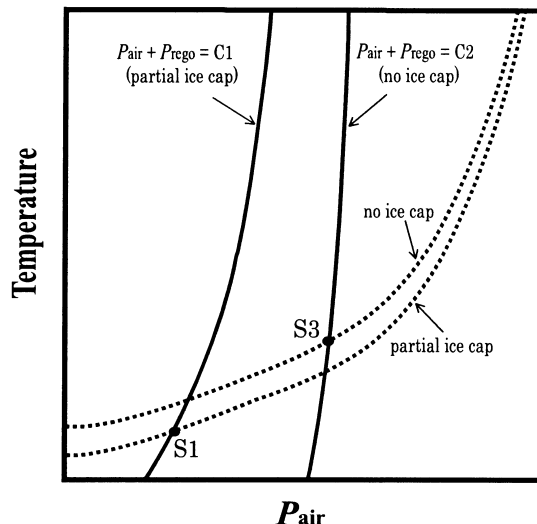


Fig. 5. A schematic illustration of  $P-T$  diagram which appeared in McKay *et al.* (1991). The dashed lines show an average temperature of Mars as a function of  $P_{\text{air}}$  with partial ice cap (the present condition) and with no ice cap. The solid lines represent regolith adsorption curves for  $P_{\text{air}} + P_{\text{rego}} = C_1$  and  $C_2$  ( $C_1 < C_2$ ). Each solid line has one intersection, that is, there are two steady state solutions irrespective of the parameter value.

AIR system.

### 4.2 Evolution of Martian climate

According to stellar evolution models, the solar luminosity has increased since the solar system was formed (e.g., Gough, 1981). Therefore the horizontal axis of Fig. 3 can be regarded as the time axis, and to trace the curve leftward from the present state (S1) should correspond to the Martian climate history tracing back to the past. Because the solar luminosity would have been lower in the past, the surface temperature would have been lower, much more CO<sub>2</sub> would have condensed to expand the ice sheet, and the regolith would have adsorbed more CO<sub>2</sub>. Therefore, in this respect, the atmospheric CO<sub>2</sub> pressure should have been lower in the past. On the other hand, the Martian CO<sub>2</sub> atmosphere might have decreased during the history by some removal processes (e.g., Melosh and Vickery, 1989; Brain and Jakosky, 1998; Luhmann *et al.*, 1992; Pollack *et al.*, 1987). If the Martian climate was warm and wet in the past because of strong greenhouse effect of CO<sub>2</sub>, the amount of atmospheric CO<sub>2</sub> should have been larger than that at present. Then the implication for the amount of CO<sub>2</sub> to have decreased in the past as noted above seems to contradict the past warm climate.

This apparent contradiction results from the assumption for the total amount of CO<sub>2</sub> in the AIR system to have been constant. When we consider the evolution of Martian climate system, the total amount of CO<sub>2</sub> within the system should change. For example, if there existed liquid water, the atmospheric CO<sub>2</sub> would be consumed through silicate weathering followed by precipitation of carbonate minerals (Pollack *et al.*, 1987). It is also suggested that the atmospheric CO<sub>2</sub> has escaped owing to impact erosion of the atmosphere by cometary impacts during the heavy bombardment period (Melosh and Vickery, 1989) and sputtering of reentering O<sup>+</sup> pickup ions over the history of Mars (Luhmann

*et al.*, 1992).

In order to consider the evolution of Martian climate system, we assume the following two extreme scenarios for the removal of CO<sub>2</sub> from the AIR system.

**Case I:** A large amount of CO<sub>2</sub> was removed from the system in a very short period early in the Martian history, and CO<sub>2</sub> did not decrease after that event.

**Case II:** The amount of total CO<sub>2</sub> in the system has decreased gradually during the history of Mars after the end of the heavy bombardment period.

In both cases, we assume that the early Martian climate was warm and wet because of greenhouse effect of CO<sub>2</sub>, and consider how the Martian climate evolves to the present condition. The hystereses of the steady state solution are shown in Fig. 6. For example, when  $S_{\text{eff}} = 0.7$  and  $P_{\text{total}} = 4$  bars, there is one stable steady state solution "A". This is the ice-free solution but liquid water can exist only in the equatorial region (the atmospheric CO<sub>2</sub> pressure is about 3.5 bars). Then, as some amount of CO<sub>2</sub> was removed from the AIR system due to impact erosion and/or weathering followed by carbonate precipitation, the total amount of CO<sub>2</sub> would decrease. In this case, the time scale for decrease in CO<sub>2</sub> would be much shorter than that for increase in the solar luminosity. The solution A would move along the curve leftward with time, and finally reach another solution A' where  $P_{\text{total}} = 1.35$  bars. If the total amount of CO<sub>2</sub> decreases furthermore, the Martian climate state should jump to the partial ice-covered solution "B". This climate jump results in a drastic decrease in the atmospheric pressure and an expansion of the ice caps to the mid-latitude. Both the ice albedo and the

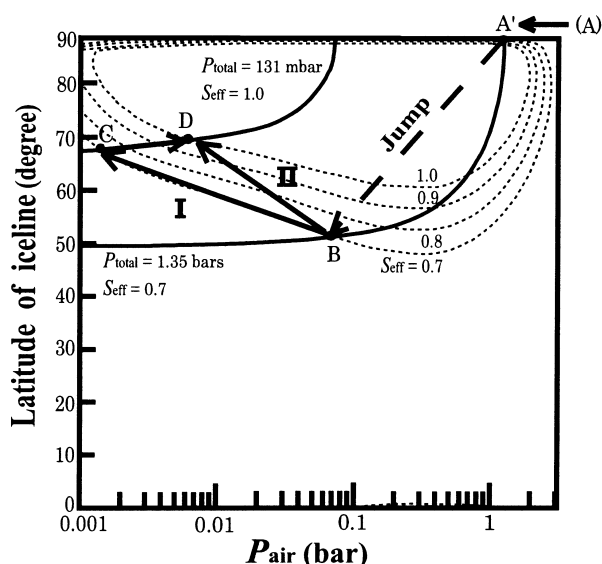


Fig. 6. The climate jump and the following two extreme scenarios for the evolution of the Martian surface environment. Case I: a large amount of CO<sub>2</sub> was removed from the system in a very short period early in the Martian history (A → A' → B → C), and then, the total CO<sub>2</sub> has been constant (C → D). Case II: after the end of the heavy bombardment period (A → A' → B), the amount of total CO<sub>2</sub> in the system has decreased gradually during the history of Mars (B → D). In both cases, climate jump (A' → B) should occur in its earliest history.

greenhouse feedbacks play significant roles in the climate jump: once ice caps were formed, the atmospheric pressure, so the greenhouse effect and the heat transport should decrease, but ice cap formation should increase the planetary albedo. Therefore, formation of the ice caps resulted in further cooling of the polar region. This climate jump is essentially the same as a "collapse" proposed by Haberle *et al.* (1994). However, behaviors of the atmospheric CO<sub>2</sub> pressure through and after the event are different: at the end of the climate jump (solution B),  $P_{\text{air}}$  is higher than that at present in this model, although it is lower than that at present at the end of the collapse in the model of Haberle *et al.* (1994). This is because the model of Haberle *et al.* (1994) cannot express a change of the areal extent of polar ice caps although condition for the freezing point is quite different between at the pole and at the actual iceline. In this respect, our solution is different from that of Haberle *et al.* (1994). The steady state solution B is too cold for liquid water to exist. Thus, effective decrease in the total CO<sub>2</sub> by precipitation of carbonate minerals cannot occur hereafter.

In the Case I, the amount of the CO<sub>2</sub> atmosphere could have decreased during short period compared with the timescale of solar luminosity change (B → C). Then, the solution may have approached the present state with an increase in the solar luminosity (C → D). It is noted that in Fig. 6 the atmospheric pressure at the point B (60 mbars) is much higher than that at the point C (~1.5 mbars). This means not only that the greenhouse effect at the point B is stronger than that at the point C, but also that the freezing point at the point B is much higher than that at point C. In this case (evolution from the point B to the point C in Fig. 6), the effect of decrease in the freezing point exceeds the effect of decrease in the greenhouse effect. As a result, considering the pressure-temperature conditions at the ice line, the ice line retreats to the higher latitude while the CO<sub>2</sub> level (that is, the global surface temperature) is lower at the point C than at the point B, even when the solar luminosity is constant. This is one of the most interesting results in this study. On the other hand, in the Case II, the amount of CO<sub>2</sub> decreased on a timescale comparable to the solar luminosity change (B → D).

As mentioned above, Haberle *et al.* (1994) did not refer to either the B → C path or the B → D path, because  $P_{\text{air}}$  must increase after the collapse in a scenario derived from their model. In both cases, if past Martian climate was warm and wet owing to the greenhouse effect of CO<sub>2</sub>, the climate jump must have occurred during the evolution to the present state, and CO<sub>2</sub> ice caps on the early Mars could have extended to the mid-latitude. It is noted that, even if the atmospheric CO<sub>2</sub> pressure decreases from the ice-free state, CO<sub>2</sub> ice caps cannot be formed directly from that state when  $S_{\text{eff}}$  is larger than 0.88 (see Fig. 2(a)). Therefore, if it were the case, the climate jump must have occurred before 1.6 Gyr ( $S_{\text{eff}} = 0.88$ ) (Gough, 1981). It might be consistent with the suggestion for the existence of the Austral ice sheet which might have extended to the mid-latitude of the southern hemisphere on Mars during the Hesperian age (Baker *et al.*, 1991).

It is noted that there must have been a supply of CO<sub>2</sub> via volcanism, so the total amount of CO<sub>2</sub> may not have decreased throughout the Martian history. Haberle *et al.* (1994)

argued that there is no solution of which the total amount of CO<sub>2</sub> have decreased throughout the Martian history to reach the present condition. On the other hand, using the same model with Haberle *et al.* (1994), Gulick *et al.* (1997) suggested that pulses of CO<sub>2</sub> injected into the atmosphere more recently than 4 Gyr can place the atmosphere into a stable, higher pressure, warmer state. At any rate, accurate evaluation of processes which control the amount of CO<sub>2</sub> in the AIR system should be required.

In this study, formation of H<sub>2</sub>O ice caps is not considered. H<sub>2</sub>O ice caps might have affected the evolution of Mars from warm and wet condition to cold condition. However, H<sub>2</sub>O ice caps must have formed before the formation of CO<sub>2</sub> ice caps. Thus, behaviors of CO<sub>2</sub> ice caps can be discussed, at least qualitatively, even if we do not consider formation of H<sub>2</sub>O ice caps. However, if H<sub>2</sub>O ice caps exists, the temperature in the polar region is lower than that with no H<sub>2</sub>O ice caps owing to its high albedo. In such a case, CO<sub>2</sub> ice caps are formed under the higher solar constant than that predicted in this study.

### 4.3 Problem on CO<sub>2</sub> clouds

According to Kasting (1991), when CO<sub>2</sub> condensation is included in the radiative-convective equilibrium model, the result differs remarkably from that of Pollack *et al.* (1987), especially for  $S_{\text{eff}} = 0.7$  or 0.8. The greenhouse effect should be reduced when  $P_{\text{air}}$  is above a few hundreds mbar because of formation of CO<sub>2</sub> clouds, and what is worse, CO<sub>2</sub> condensation limits the amount of atmospheric CO<sub>2</sub>. On the other hand, Forget and Pierrehumbert (1997) showed that CO<sub>2</sub> ice particle larger than 10  $\mu\text{m}$  can scatter infrared radiation back to the surface, thus CO<sub>2</sub> clouds may have powerful greenhouse effect. Because the effect of CO<sub>2</sub> clouds on the energy balance may have been still unclear, the results shown here might be tentative. Therefore, we also consider the cases in which CO<sub>2</sub> cloud formation is included in the model (Fig. 7).

Figure 7(a) shows the solutions for the case which considers effects of CO<sub>2</sub> cloud formation on the energy balance based on the results of Kasting (1991). In this case, an ice-free solution is impossible during the earliest history of Mars. For an initial state, a partial ice-covered solution (when  $P_{\text{total}} \leq 3$  bars) or ice-covered solution (when  $P_{\text{total}} > 3$  bars) is expected. If the initial state was ice-covered, ice at the equatorial region should have disappeared during the evolution as  $S_{\text{eff}}$  increased, and the steady state should have jumped to a partial ice-covered state to reach the present condition.

Figure 7(b) shows the solutions for the case based on the results of Forget and Pierrehumbert (1997) with radii of the CO<sub>2</sub> ice particles are 50  $\mu\text{m}$ , the optical depth is 10, and dry atmosphere (note that they provided the results only above  $P_{\text{air}} = 100$  mbar). As shown in this figure, area of the ice caps at a certain  $P_{\text{air}}$  is smaller due to powerful greenhouse effect of CO<sub>2</sub> clouds. In this case, if the initial state was ice-free, the solution cannot jump until  $P_{\text{air}}$  decrease to, at least, about 100 mbar, although we cannot know where the jump will occur because of absence of original data below 100 mbar.

It is expected that CO<sub>2</sub> cloud formation has been inhibited in regions of atmospheric subsidence (Forget and Pierrehumbert, 1997). Magnitude of the effect of CO<sub>2</sub> clouds should depend on fraction of cloud cover and optical thickness of

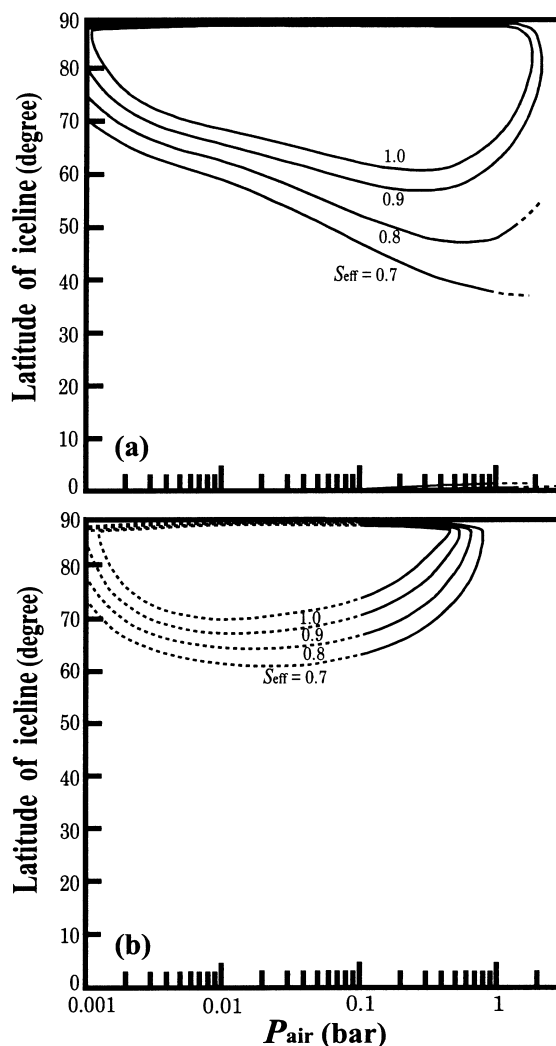


Fig. 7. Steady state solutions of the EBM based on the results of (a) Kasting (1991), and (b) Forget and Pierrehumbert (1997). Dashed curves represent the region where original data is not available.

the CO<sub>2</sub> cloud, but these properties have not been known. In order to solve this problem, it is necessary to introduce a full 3-D climate model, but it is beyond the purpose of this study.

## 5. Summary

In this paper, we have discussed the Martian surface environment. We assumed that CO<sub>2</sub> 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<sub>2</sub> (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<sub>2</sub>.

We examined stability of the steady state solutions of the EBM and the AIR system. The stability is determined from competition among four feedback effects (the ice albedo feedback, the greenhouse feedback, the freezing point feedback, and the heat transport feedback). The ice albedo, the greenhouse, and the heat transport feedbacks are positive feedbacks which make the system unstable, but the freezing



point feedback is negative feedback which makes it stable. When we adopt the present state as a boundary condition and assume the total amount of CO<sub>2</sub> in the AIR system to be constant, there exists two stable steady state solutions under the present solar luminosity. One corresponds to a partial ice-covered solution (the present state), and the other is a warmer ice-free solution. Although this seems to be consistent with the former results by Gierasch and Toon (1973) and McKay *et al.* (1991), our result is different qualitatively from their results.

If the Martian climate was warm and wet owing to the greenhouse effect of CO<sub>2</sub> in the past, the total amount of CO<sub>2</sub> contained in the system must have been much more than that at present. This means that the total amount of CO<sub>2</sub> in the system has been decreased by some removal processes. In this case, we found that the climate jump which is a drastic expansion of ice caps and decrease of the atmosphere must have occurred during the evolutionary path from the warm and wet condition to the present state, and ice caps on the early Mars could have extended to the mid-latitude. The atmospheric pressure may have decreased further after the climate jump.

**Acknowledgments.** The authors are most grateful to Y. Abe and T. Ikeda for helpful discussions and comments on this work. We also thank V. Gulick and an anonymous referee for the helpful reviews.

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