# ROLE OF $H_2O$ AND $CO_2$ ICES IN MARTIAN CLIMATE CHANGES

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**Introduction:** Several lines of evidence suggest that Mars have experienced climate changes intermittently in its history. Mars might have had a denser atmosphere and warmer climate in the Noachian period [1]. Cyclic and episodic climate changes might have occurred in later epochs after the Noachian [2].

In general, major climate changes suggested for past Mars are attributed to exogenic factors affecting the atmosphere-ice cap system [1, 2]. However, the martian climate system which consists of atmosphere and ice-covered surface likely has inherent variability. One of the most important factor is albedo effects of $H_2O$ and $CO_2$ ices. If liquid $H_2O$ were distributed widely as suggested from the geological evidence [2], it would have frozen as climate cooled. $H_2O$ ices would have raised the surface albedo, which might cause further cooling of climate. On the other hand, the stable atmospheric pressure under low atmospheric pressure may be very sensitive to $CO_2$ ice cap albedo [3]. Therefore, slight decrease in the ice cap albedo would result in complete evaporation of $CO_2$ ice cap [4]. If this climate response to the variation of planetary ice albedo modifies the state of albedo again, then the martian climate may change self-excitedly through this feedback.

The stability of martian climate is studied by investigating the rate of atmospheric CO2 mass exchange due to evaporation and condensation of the ice caps. In particular, we focus on the effects of ice distribution on the climate stability.

**Model:** The model we constructed is a 2-dimensional (horizontal-vertical) energy balance climate model. We assume that energy fluxes due to radiation, atmospheric advection and latent heat of $CO_2$ are balanced in the atmosphere and surface at each latitude,

$$F_H - F_V + F_B - F_T = 0 \quad \text{(Atmosphere)}$$
$$F_S + F_V - F_B - F_L = 0 \quad \text{(Surface)}$$

where $F_S$ is the half-year mean solar flux absorbed by the surface, $F_B$ and $F_T$ are the infrared radiative fluxes at the surface and top of the atmosphere respectively, $F_H$ and $F_V$ are the horizontal and vertical heat fluxes due to the atmospheric advection, and $F_L$ is the latent heat flux due to the evaporation (plus) or condensation (minus) of $CO_2$ at the surface (unit: J $m^{-2}$ $s^{-1}$).

Each term in Eq. (1) and (2) is described as a function of latitude, atmospheric pressure, p, surface atmospheric temperature, $T_a$, and surface temperature, $T_s$. Details of each term and model parameters are described in [5]. By solving these equations for a given p and $F_S$, we find $T_a$, $T_s$, and the value of each term in Eq. (1) and (2) for each latitude. In particular, dividing $F_L$ by the specific latent heat of $CO_2$, we can find the mass fluxes of $CO_2$ evaporation and condensation (unit: kg $m^{-2}$ $s^{-1}$).

**Result:** Integrating the $CO_2$ mass flux over the $CO_2$ ice cap regions, we obtain the annual mean net mass flux, $E_{net}$, from the ice caps to the atmosphere (unit: kg $s^{-1}$, ``the net CO2 evaporation'', hereafter). $E_{net}$ times a martian year is equal to the annual amount of $CO_2$ evaporation. Therefore, the atmospheric pressure is kept constant when $E_{net} = 0$, increases when $E_{net}$ is positive, and decreases when $E_{net}$ is negative.

The solid curve in Fig. 1 shows $E_{net}$ under various atmospheric pressure for the standard model parameter on Mars [5]. The curve in Fig. 1 has the two points where $E_{net} = 0$ (``equilibrium points''). The left-side equilibrium point is stable, and the right-side one is unstable [5]. This implies that two types of climate states can be stable [5]. One corresponds to the case in which the atmospheric pressure is kept at the stable equilibrium point (``the $CO_2$ ice buffer state''), and the other corresponds to the case where $CO_2$ in the ice caps is fully evaporated (``the $CO_2$ ice free state''). Since the $CO_2$ perennial ice cap exists, the present climate state can be recognized as a $CO_2$ ice buffer state. If the climate was warm in the past, a $CO_2$ ice free state would have been realized. Regarding the stability of atmospheric pressure, the results of earlier works [3, 6, 7] are in qualitative agreement with our results.

$E_{net}$ strongly depends on the $H_2O$ ice coverage, for the pressure region higher than $\approx 10^4$ Pa (Fig. 1, dotted curve). This is because, under high atmospheric pressure, $E_{net}$ is almost determined by the pole-ward horizontal atmospheric heat transport, which decreases with cooling of the middle and low latitude region due to the reflection of solar radiation by $H_2O$ ice covers. Accordingly, $E_{net}$ decreases and the unstable equilibrium point shifts to the higher pressure with increasing $H_2O$ ice coverage.

$E_{net}$ is sensitive to $CO_2$ ice cap albedo, $A_{CO2}$, for pressures below $\approx 10^4$ Pa (Fig. 1, dashed curve). This is because, when the pressure is so low that the horizontal atmospheric heat transport is ineffective, $E_{net}$ is determined almost by the solar radiation energy absorbed by the ice cap. Therefore, the position of stable equilibrium point is dependent on $A_{CO2}$. If $A_{CO2}$ is lower than $\approx 0.69$, only the $CO_2$ ice free state is stable, because $E_{net}$ becomes positive at any atmospheric pressure.

**Discussion:** It is likely that Mars had much warmer climate than the present one, with globally distributed liquid $H_2O$ in the Noachian and Hesperian periods [1, 2]. A $CO_2$ ice free state should have been realized at that time, but it would have gradually cooled due to atmospheric escape or chemical weathering [2]. Then, the surface would have been covered with $H_2O$ ice over a wide range of the planet. Once $H_2O$ ice prevailed, $E_{net}$ would decrease (Fig.1, dotted curve). As $E_{net}$ becomes negative, the atmospheric $CO_2$ begins to condense and consequently a $CO_2$ ice buffer state is achieved (``collapse condensation"). The time scale for this collapse condensation can be calculated from $E_{net}(p)$, found to be $\approx 10^3$ yr (Fig.2). Low solar luminosity [8] also has an effect to promote the collapse condensation. Just after the collapse condensation, huge $CO_2$ ice caps would have been formed temporally.

Under the $CO_2$ ice buffer state, the extent of $H_2O$ ice would be gradually diminished to the polar regions. This is because $H_2O$ vapor might have been transported to the colder regions by the atmospheric advection, but hardly returned back to the lower latitudes due to the inhibition of liquid water circulation under cold environment. Once the $H_2O$ ice coverage is reduced, dust particles are easily raised up from exposed regolith to the atmosphere. These dust transported to the polar region might lower the albedo of $CO_2$ ice caps and also cause $E_{net}$ to increase. If the albedo decreased enough for the equilibrium point to disappear, then $CO_2$ ice caps would begin to evaporate and eventually a $CO_2$ ice free state would occur (``runaway evaporation"). The time scale for the runaway evaporation can be calculated to be $\approx 10^3$ yr (Fig. 2, dashed curve).

Once the climate becomes warm again, $H_2O$ ice coverage might increase due to the activation of liquid water circulation. Possible water transport mechanisms include the basal melting of $H_2O$ ice, pole-to-equator ground-water flow [9]. If the $H_2O$ ice coverage increases enough for the net $CO_2$ evaporation to become negative, then $CO_2$ ice buffer state would occur again due to the growth of $CO_2$ ice caps (Fig.3). Warming and cooling event of the martian climate might be repeated through the albedo feedback mechanisms of $H_2O$ and $CO_2$ ices.

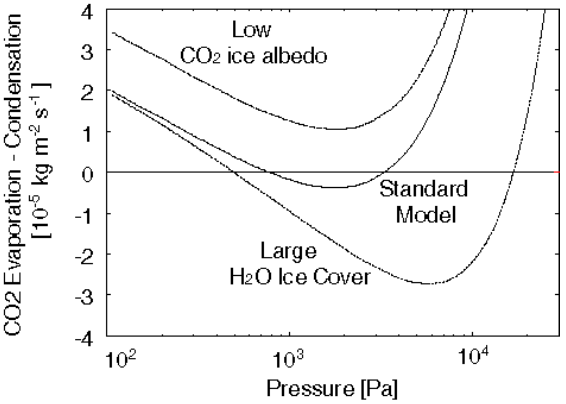

Figure 1: The annual mean net mass flux from the ice caps to the atmosphere under various atmospheric pressure. Solid curve represent the model with standard parameter ($CO_2$ ice cap albedo, $A_{CO2} = 0.70$, and no $H_2O$ ice coverage), dashed curve for lower $CO_2$ ice albedo $A_{CO2} = 0.65$) and dotted curve for larger $H_2O$ ice coverage (the boundary latitude of $H_2O$ ice cover, $\theta_{H2O} = 40$ degree).

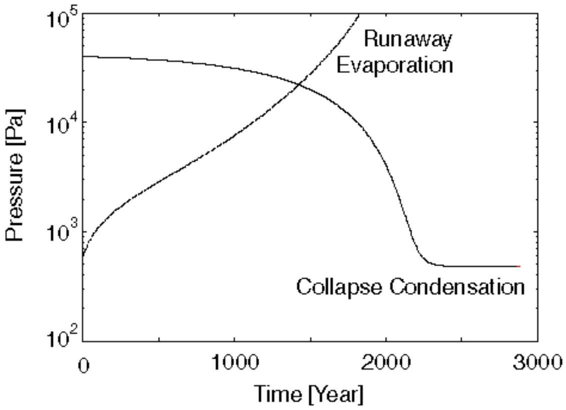

Figure 2: Evolution of the atmospheric pressure due to $CO_2$ collapse condensation (dotted, the boundary latitude of $CO_2$ ice cap, $\theta_{CO2} = 80$ degree and that of $H_2O$ ice cover, $\theta_{H2O} = 0$ degree) and runaway evaporation (dashed, $A_{CO2} = 0.65$, $\theta_{CO2} =$ degree and no $H_2O$ ice coverage).

**References:** [1] Jakosky, B. M. and Phillips, R. J. (2001) *Nature, 412*, 237. [2] Baker, V. R. (2001) *Nature, 412*, 228. [3] Gierasch, P. J. and Toon, O. B. (1973) *J. Atmos. Sci., 30*, 1502. [4] McKay, C. P. *etal* (1991) *Nature, 352*, 489. [5] Yokohata, T. et al. (2001) *submitted to Icarus*. [6] Haberle, R. M. et al. (1994) *Icarus, 109*, 102. [7] Nakamura, T., and E. Tajika (2001) *Earth Planets Space, 53*, 851. [8] Gough, D. O. (1981) *Sol. Phys*., *74*, 21. [9] Clifford, S. M., (1993) *J. Geophys. Res. 98*, 10,973.