RESPONSE OF RESIDUAL CO_2 ICE CAP TO CLIMATE CHANGES ON MARS. K. Takayama, T. Yokohata, M. Odaka and K. Kuramoto, *Division of Earth and Planetary Sciences, Graduate School of Science, Hokkaido University, Sapporo, 060-0810, Japan (kaorun@ep.sci.hokudai.ac.jp).*

Introduction: Partitioning of CO_2 on Mars plays an important role in controlling the state of martian climate. On Mars, CO_2 is exchangeable among the atmosphere, polar-caps and regolith. The existence of plural reservoirs may allow multiple climate states even when the boundary conditions are fixed. For example, when the total amount of CO_2 is given, the climate could be either warm or cold dependent on whether CO_2 exists mainly in the atmosphere or in the ice caps or regolith. Abundant geological evidence including the outflow-channels and polar deposits strongly suggests that the martian climate has been changing through its history. Such climate changes would be realized by the variation of CO_2 partitioning, which may be triggered by changes of boundary conditions such as the solar flux, obliquity and total CO_2 mass on Mars.

In the past studies, residual CO_2 ice cap has been treated as a reservoir with infinite capacity [1, 2, 3] or constant thickness [4] without considering the formation processes. This has inhibited the quantitative treatment of the CO_2 partitioning and the application to topographical study. In this study, we construct a new climate model which can calculate the ice cap topography consistently. We apply this model to the partitioning of CO_2 on Mars, and discuss the past climate change and evolution of polar topography.

Model: CO_2 is assumed to be partitioned among the atmosphere, ice caps and regolith, which is dependent on the latitudinal surface temperature profile. The atmospheric bottom temperature T_a and the surface temperature T_s are calculated as a function of latitude ϕ and the atmospheric pressure p using a 2D energy balance model [3]. Here, we give an annual mean solar flux for each latitude and obtain equilibrium thermal profile. The surface albedo is taken to be 0.7 over CO_2 ice cap areas and 0.215 over the other areas.

The CO_2 mass in each reservoir is given as follows:

$$M^{\mathrm{atm}} = \frac{4\pi R^2 p}{g}$$

$$M^{\mathrm{cap}} = 2\rho^{\mathrm{ice}}_{CO_2} \int_{\phi_l}^{\frac{\pi}{2}} d\phi 2\pi R^2 \cos\phi H(\phi)$$

$$M^{\mathrm{reg}} = 2\int_{0}^{\frac{\pi}{2}} d\phi \rho^{\mathrm{reg}}_{CO_2}(\phi) 2\pi R^2 \cos\phi Z \rho^{\mathrm{reg}}_{\mathrm{soil}}$$

where M^{atm}, M^{cap} and M^{reg} are the CO_2 masses in the atmosphere, ice cap and regolith, respectively, R is the radius of Mars, g is the gravity, H is the height of ice cap, ϕ_l represents the latitude of ice cap edge, $\rho^{\mathrm{ice}}_{CO_2}$ and $\rho^{\mathrm{reg}}_{\mathrm{soil}}$ are the densities of CO_2 ice (1.6×10^3 kg/m^3) and regolith (1.5×10^3 kg/m^3), Z is the depth of regolith which adsorbs CO_2 (assumed to be 1000 m, [5]), and $\rho^{\mathrm{reg}}_{CO_2}$ is the adsorbed CO_2 mass per unit mass of soil.

The shape of ice cap is calculated by solving the equation of mass conservation. Change of ice cap height on each latitude is given by the balance between ice flow and the CO_2 condensation flux which is calculated from the thermal structure of CO_2 atmosphere as follows:

$$\frac{\partial H}{\partial t} = -\frac{\partial F_{\mathrm{ice}}}{\partial x} + \frac{F_L}{\rho^{\mathrm{ice}}_{CO_2} L}$$

$$F_{\mathrm{ice}} = -\frac{2(\rho^{\mathrm{ice}}_{CO_2} g)^n A}{n+2}\left|\frac{\partial H}{\partial x}\right|^{n-1}\frac{\partial H}{\partial x}H^{n+2}$$

$$A = A_d \exp\left(-\frac{Q}{R_G T}\right)$$

where F_{ice} is the flux of ice flow, x is the distance from pole, L is the specific latent heat of CO_2 condensation, n and A_d are the coefficients depending on the properties of ice, Q is the activation energy of ice creep and R_G is the gas constant. We adopt n = 2, A_d = 9.55 $\times10^{-3}$ s^{-1}(MPa)$^{-n}$ and Q = 15,000 J mol^{-1} [6].

CO_2 ice condenses on the region where condensation latent heat flux F_L is positive and sublimates where F_L is negative. As the height of ice cap increases, the atmospheric pressure and condensation temperature decrease, resulting in decrease of CO_2 condensation flux. The condensation ceases at the level where latent heat drops zero. The ice cap is assumed to reach an equilibrium state when there is no time variation of its height.

CO_2 mass adsorbed by regolith $\rho^{\mathrm{reg}}_{CO_2}$ is given by an empirical function of the temperature and pressure [5]. Regolith adsorbs more CO_2 under lower temperature and higher pressure. Here, the actual adsorption surface area is given to be 5 [7].

Result and Discussion: First, let us examine the responses of ice cap extent for various atmospheric pressures. Figure 1

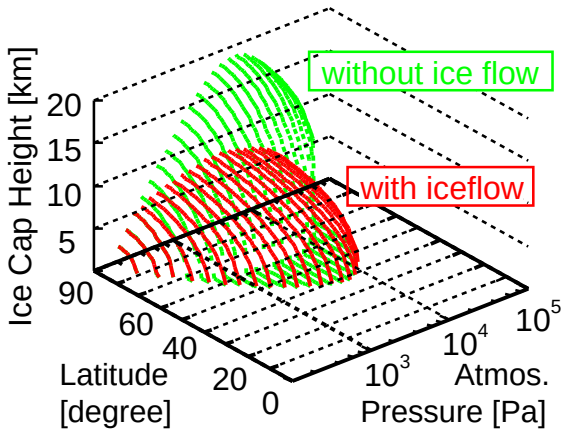

Figure 1: Topography of ice cap as a function of atmospheric pressure. Dark curves show results calculated by considering ice flow and light curves show results neglecting ice flow.

shows the ice cap topography as a function of atmospheric pressure, which is calculated assuming 0.85 times of the present value for the solar radiation and 25.19° for the obliquity. The CO_2 ice caps extend to lowest latitude when the atmospheric pressure is about to $\sim 10^4$ Pa (corresponding to the atmospheric mass of $\sim 10^{17}$ kg). This is because the CO_2 condensation temperature increases with pressure and then the condensation of CO_2 ice occurs more easily, but further increase in atmospheric pressure decreases ice cap extent since the greenhouse effect and the meridional heat transport warm up the high latitudes. When the atmospheric pressure is higher than $\sim 10^5$ Pa, ice caps entirely evaporate. When the CO_2 ice caps form, their height increases with latitude. The lower the latitude of ice cap extent, the larger the ice cap height at poles. The hight of ice cap at poles is about a half of that for the case neglecting ice flow.

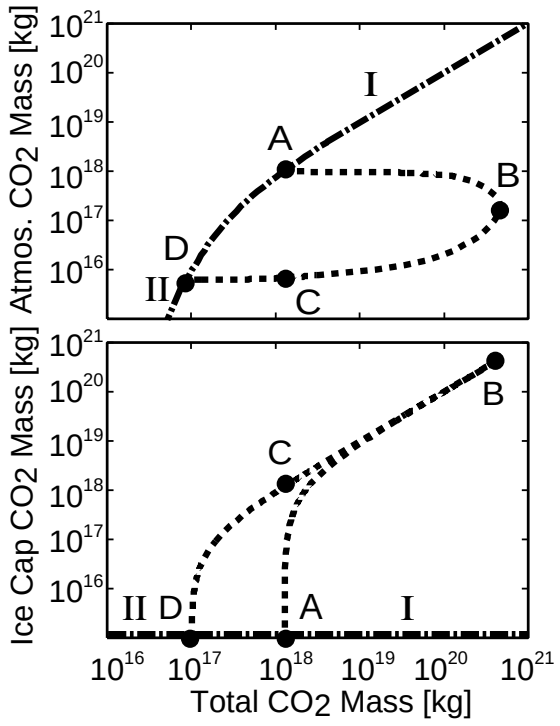

Figure 2: Atmospheric (upper) and ice cap (lower) CO_2 masses as a function of total CO_2 mass. Dotted curves indicate the solutions where ice caps exist under each atmospheric pressure. Dash-dotted curves indicate the solutions without ice caps. The equilibrium states exist only on the curves. Points denoted by the same indices on both figures correspond to the same equilibrium state.

Figure 2 shows the masses of the atmospheric CO_2 and ice cap CO_2 as a function of total CO_2 on Mars under energy balance states. The dotted curves indicate the solutions where ice caps exist. On the other hand, the dash-dotted curves indicate the solutions without ice caps. The regolith CO_2 mass is kept within 10^{17}–10^{18} kg when the total CO_2 mass is larger than 10^{18} kg. The increase of solar radiation, obliquity or thermal diffusive coefficient decreases the total CO_2 masses at crossing point A and at maximum ice cap point C.

When the total CO_2 mass is large enough, most of CO_2 is partitioned into the atmosphere. When the total CO_2 mass decreases, the atmospheric pressure and surface temperature also decrease along the path I. When the system reaches the point A, the growth of ice caps becomes possible due to the condensation of atmospheric CO_2. We call this point the ice cap initiation point. When ice cap begins to form, it grows to the maximum extent C due to the effect of ice albedo feedback and ice flow. The seasonal change of solar radiation and albedo effect of H_2O ice sheet may also trigger the CO_2 ice cap formation [3].

The mass and topography of initial ice cap which formed in the past Mars are estimated by the difference of atmospheric pressure between A and C. In this calculation, the ice cap mass at C is 10^{18} kg with the iceline latitude of 80° and polar height of 1.5 Km. This extent is similar to that of the observed polar deposits. Once ice caps are formed, the climate is kept cold with low atmospheric pressure. As the total CO_2 mass further decreases, the ice cap mass decreases and disappears at D. On the other hand, atmospheric pressure is kept nearly constant before reaching the point D, and then starts to decrease again along to the path II.

References: [1] Gierasch, P. J., and O. B. Toon. 1973. *J. Atmos. Sci.*, 30, 1502–1508.

[2] Haberle, R. M. *et al*. 1994. *Icarus*, 109, 102–120.

[3] Yokohata, T., M. Odaka, and K. Kuramoto. 2002. *Icarus*, 159, 439–448.

[4] Nakamura, T., and E. Tajika, 2001. *Earth Planets Space*, 53, 851–859.

[5] Toon, O. B. *et al*. 1980. *Icarus*, 44, 552–607.

[6] Nye, J. F. *et al*. 2000. *Icarus*, 44, 449–455.

[7] Kieffer, H. H., and A. P. Zent. 1992. *Mars* (Kiffer, H. H. *et al*., eds.), Univ. of Ariz. Press, Tucson, 1180-1220.