

# Multiple climate states and habitability on Mars: Role of the topographic dichotomy and orbital parameters

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The surface environment of the present Mars is cold and dry owing to thin atmosphere composed of carbon dioxides (CO<sub>2</sub>). However, climate system of Mars is characterized by exchanges of CO<sub>2</sub> among the surface reservoirs such as atmosphere, ice cap, and regolith, against changes in solar irradiance and obliquity. The atmospheric CO<sub>2</sub> forms seasonal ice-cap that condenses on high latitudes in winter and sublimates in summer. Thus, the surface temperature-pressure condition is important in considering the climate change on Mars. The change in the solar irradiance and the orbital parameters can significantly modify the surface physical condition. However, it is not systematically assessed which kind of the climate mode can be achieved in the CO<sub>2</sub> exchange system of Mars under wide ranges of various conditions of orbital parameters. Further, Mars has topographic dichotomy with southern highland and low northern plains. How this topographic dichotomy modifies the climate on Mars has not been assessed qualitatively. Here we used a two-dimensional Martian energy balance model that is a modified version of a meridionally one-dimensional model of Nakamura and Tajika (2003). We introduced a simple scheme that considers the topographic effect on the model. We assessed the possible climate on wider ranges of orbital parameters, solar irradiance, and topographic dichotomy.

First of all, we show that the annual mean surface pressure increases exponentially with increasing obliquity on the permanent ice-cap branch regardless of the existence of topography. The critical obliquity for a transition of climate mode from permanent ice-cap branch to seasonal ice-cap branch increases when there is topographic dichotomy, because permanent ice cap tends to remain on the southern polar region with high surface altitude and ice cap has a resistance to increasing energy flux. Next, we examined the dependence of the variation of the precession angle from the vernal equinox. It showed that there is almost no dependency on precession angle with uniform topography, the critical obliquity for the transition of climate mode changes up to about 5 degrees under the existence of the topographic dichotomy. The transition of climate mode occurs at the smallest obliquity when summer in the southern hemisphere is on aphelion, while the transition occurs at the largest obliquity when summer in the southern hemisphere is on perihelion. This is because the southern hemisphere has a dominant control on the seasonal variation of the surface pressure, hence the warming effect of CO<sub>2</sub> is largely controlled by the southern hemisphere.

Finally, we systematically examined the multiple climate states and habitable condition ( $T > 273$  K) on Mars. We show that the habitable condition on the part of Martian surface can be achieved temporarily by thin CO<sub>2</sub> atmosphere (less than 10 mbar) on high obliquity condition ( $> 45$  deg.), but not on low obliquity condition. With the present obliquity (25.2 deg.), about 0.3 bar of CO<sub>2</sub> atmosphere is necessary to make the part of the surface temporarily habitable. In each case, more than 1 bar of CO<sub>2</sub> is necessary to keep the most of planetary surface habitable.

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