The Effect of Obliquity and Surface Condition on the Freezing Condition of A Planet: Implications for Paleo-Mars Climate and Habitable Condition

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Introduction: The condition for the occurrence of a completely frozen state (a "snow-ball" state) is investigated with a general circulation model for both a land planet case (a wet planet without fixed ocean) and an aqua planet (a planet entirely covered by an ocean) with a particular reference to the obliquity.

The condition of the complete freezing is an important indicator for the planetary climate, because it restricts the habitability of the planet. Though the complete freezing does not sterilize the planet, as some types of life may survive on a completely ice-covered planet, it will give restrictions on the types of life. Recent studies suggest a chaotic change of planetary obliquity. Therefore, the effect of obliquity on the complete freezing is an interesting issue on the condition of habitable exoplanets.

Effect of obliquity on the freezing condition is also an important issue for the investigation of the paleo-Mars environment. Fluvial features found on Mars suggest a wet surface and an active hydrological circulation on the paleo-Mars [2]. Mars is believed to have experienced large change in obliquity as much as 60∘ [3]. In addition, paleo-Mars has good chance to fall in a frozen state owing to the faint radiation of the young Sun and the large orbital radius. Thus, dependence of freezing conditions on the obliquity is also an important issue that constrains the paleo-Mars environment.

In previous studies Abe and Numaguchi [1] reported three climate regimes on a land planet depending on the obliquity and the average surface temperature: The "Frozen," "Upright" and "Oblique" regimes. The frozen regime is equivalent to the completely frozen state discussed in this paper. The surface is entirely covered by snow or ice, and very low surface temperature is resulted in owing to a strong albedo feedback of surface ice. Essentially no transport of water occurs in this regime. The upright regime occurs when the obliquity of the planet is smaller than the width of the Hadley cell and the summer temperature exceeds the freezing temperature. The low latitude area is always warmer than the mid and high latitude area. On a land planet, the low latitude area is completely dried. The oblique regime occurs when the obliquity of the planet is larger than the width of the Hadley cell and the summer temperature is above the freezing point. In summer the mid to high latitude area is warmer than the low latitude area in this regime. Large precipitation occurs in low latitude in summer, and there is some precipitation in the mid and high latitude in winter.

Judging from the large difference of the upright and oblique regimes in the precipitation and temperature distribution, the critical level of the solar flux for the freezing should be different between these regimes. Here, we investigated the dependence of the complete freezing condition on the obliquity and the surface condition. We also clarified the position and occurrence condition of the permanent snow/ice cover, which may be important for the interpretation of the geomorphological features on Mars.

Model: We investigated the freezing condition by a general circulation model, CCSR/NIES AGCM5.4g, which have been developed for the Earth's climate modeling by the Centre for Climate System Research, University of Tokyo and the National Institute for Environmental Research. We assumed an Earth-sized planet with 1 bar air atmosphere on a circular orbit. We consider an idealistic planet without topography. On a land planet the surface parameters are fixed to be terrestrial desert (ground albedo 0.3) and a bucket model with the saturation depth of 10 cm is adopted for ground water calculation. The surface and underground water transport is ignored. On an aqua planet the surface is covered by 50m depth slab ocean. Ice and snow albedo models are the same with those for the Earth.

We performed 4 series of experiments with different obliquity: 0°, 23.5°, 45° and 60° for both land and aqua planets. The former two cases are in the upright regime, and the latter two cases are in the oblique regime. Twenty years runs on a land planet and sixty years or more runs on an aqua planet are performed for each solar flux value to obtain the steady hydrological cycle. The step is decreased to 1% near at the critical flux for the transition to the frozen state.

Results: Figure shows the latitudinal distribution of the snow accumulation or ice thickness as the function of the relative solar flux for 23.5° (upright regime) and 60° (oblique regime) cases. White areas in the figure indicate the snow/ice covered surface, and dark areas in the figure indicate no snow/ice cover. This figure shows the snow/ice distribution during the summer of the Northern Hemisphere. Namely, the Southern Hemisphere (shown in the lower half of the each figure) shows the winter condition.

The critical solar flux values for the occurrence of permanent snow/ice and the completely freezing is summarized in Table. The permanent snow/ice cover appears at poles in the upright regime (0° and 23.5° obliquity). However, in the oblique regime (45° and 60° obliquity), the permanent snow/ice cover appears at equatorial region. Once a permanent snow cover appears at equatorial region, only small snow fall occurs in the winter hemisphere. This is because most of water is trapped in the permanent snow, and other regions are dried.

Summary and Implications

1. A land planet shows stronger resistance to the complete freezing than an aqua planet. **2.** Both land and aqua planets in an oblique regime show stronger resistance to the complete freezing than those in an upright regime. However, the dependence on the obliquity is not clear within the upright regime. **3.** On a land planet in an oblique regime, low latitude area is more susceptible to freezing than the mid latitude area. Thus, there is a good chance of low-latitude-only freezing (freezing of low latitude without freezing the entire planet) of a land planet. **4.** On an aqua planet with high obliquity, low latitude freezing occurs at lower solar constant than on a land planet with high obliquity. The range of the solar constant that yields low-latitude-only freezing is much narrower on an aqua planet than that on a land planet. Thus, low-latitude-only freezing is unlikely on an aqua planet.

Implications for the paleo-Mars: 1. In order to keep a wet ground at the low latitude area of paleo-Mars, the planet must be in the oblique regime, or with oceans. Under such conditions, however, the low latitude is relatively easily covered by permanent snow. Thus, it is more difficult to keep unfrozen wet surface on low latitude than to keep Mars from the completely frozen state under the condition of the present obliquity. **2.** If the obliquity changed significantly while Martian water cycle was active and the average temperature was decreasing steadily, there must have been a period while only the low latitude area is covered by permanent snow. It is an interesting question whether we can find such evidence from geological records.

Implication for the Habitability on a Planet: 1. A water rich aqua planet may not be the best place for life, and a land planet with some water may be better than an aqua planet, because an aqua planet easily falls in a completely frozen state. **2.** It is a difficult question whether high obliquity or low obliquity planet is preferable. A high obliquity planet is resistive to the complete freezing, but experiences severe seasonal change. The calmest climate is found on 45° obliquity aqua planet.

References: [1] Abe, Y., and A. Numaguchi 2001: in *Lunar and Planetary Science (CD-ROM),* pp. Abstract #1551, Lunar and Planetary Institute, Houston, 2001; Abe, Y., and A. Numaguchi, 2000. in *Proceedings of the 33nd ISAS Lunar and Planetary Symposium*, pp. 189-192, Institute of Space and Aeronautical Science, Sagamihara.
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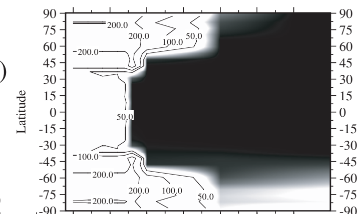
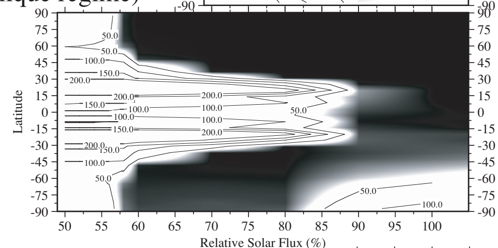
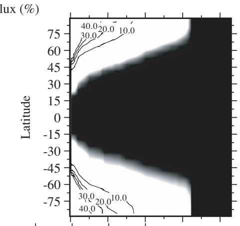
Land Planet
Obliquity 23.5°
(Upright Regime)



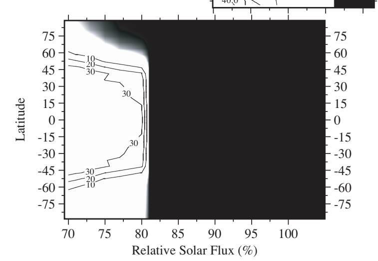
land Planet
Obliquity 60°
(Oblique regime)

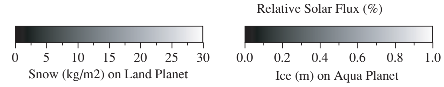


Aqua Planet
Obliquity 23.5°
(Upright Regime)



Aqua Planet
Obliquity 60°
(Oblique regime)





Cases	permanent Snow/Ice	Complete Freezing
Land planet 0° obliquity	>100%	77%
Land planet 23.5° obliquity	90%	77%
Land planet 45° obliquity	90%	67%
land planet 60° obliquity	90%	58%
		90%
Aqua planet 0° obliquity	>100%	90%
Aqua planet 23.5° obliquity	>100%	81%
Aqua planet 45° obliquity	81%	73%
Aqua planet 60° obliquity	80%	

Solar flux relative to that of the present Earth value