Introduction: Many fluvial features on Mars [1] indicate past active hydrologic cycle. We investigate atmospheric water cycle on an idealized 'land planet,' a planet without oceans on the surface, using a general circulation model. The main target of this study is to clarify the condition under which wet surface can be maintained.

We focus on the effect of change in spin-axis inclination and the average surface. The inclination of the present Mars' spin-axis is close to that of the Earth. However, the Mars' inclination is believed to be changed very much from 0° to 60°[2]. Change of inclination should have profound effect on climate.

Method: We made an idealized land-planet model by removing the oceans, topographies and vegetations from the CCSR/NIES AGCM5.4g, which have been developed for the Earth by the Centre for Climate System Research, University of Tokyo and the National Institute for Environmental Research. We assume 1bar CO2 atmosphere and a circular orbit.

We performed two series of experiments: series A simulates a 'warm' land planet, that is, the surface temperature exceeds the freezing point in summer at least at the subsolar point. On the other hand series B simulates a 'cold' land planet on which the temperature is always below the freezing point everywhere on the planet. In both series, we changed the inclination of the spin axis from 0° to 60°.

In both series, we ignore the surface and underground water transport. We use a bucket model with the saturation depth of 10cm for ground water calculation. The total depth of the bucket is 10m. Ice and snow albedo model are the same with that for the Earth. In both series, the initial condition is a steady state circulation with uniform distribution of ground water.

Results: Atmospheric circulation and hydrologic cycle approach steady state within 10 sidereal years. In the steady state, the annual precipitation corresponds to the annual evaporation everywhere on the surface. Figure 1 shows the some typical patterns of zonal-mean annual precipitation (=the annual evaporation) at the steady state. The inclination clearly affects the hydrological cycle. Though inclination has strong influence on the overall planetary climate, its effect is different for series A and B.

In series A, the precipitation pattern is clearly different between the cases with smaller inclinations (<30°) and larger inclinations (>30°). In the following, we call the former as an 'upright regime' and the latter as an 'oblique regime'. In the upright regime, low latitude areas are dried because of atmospheric water transport to high latitude area. Eventually, ground water is lost and no precipitation occurs in the low latitude areas. Precipitation occurs only in mid- to high-latitude areas. On the other hand, in the oblique regime, the low latitude areas have precipitation in spring and fall. In addition, the summer surface temperature is much higher than that of the upright cases for the same atmospheric mass and annual insolation.

In series B, the planet is entirely covered by snow or ice, namely, it is a 'snow ball' planet. In the following we call this as a 'frozen regime'. The surface temperature is extremely low owing to strong ice albedo feedback. Essentially no horizontal transport of water occurs irrespective of the spin-axis inclination. Both the precipitation and evaporation are just locally balanced and have maximum at the subsolar point. Its magnitude is about one-thousands of the results of series A.

Thus, we found three different regimes: 1. Frozen regime for wet and cold cases, 2a. Upright regime for wet, warm and small inclination cases, and 2b. Oblique regime for wet, warm and large inclination cases.

Determining factors of three climate regimes: The difference between the upright and oblique regimes comes from the relative magnitude of the Hadley-cell width and the Tropic latitude (=inclination). The width of the Hadley cell is always about 30°. If the width of the Hadley cell is larger than the Tropic latitude, the subsolar point is always in the Hadley cell. Hence, low latitude areas are always warmer than mid- to high-latitude areas and water is transported from low to high latitude areas. Thus, low latitude areas are dried. This is the upright regime. On the other hand, if the width of the Hadley cell is smaller than the Tropic latitude, the subsolar point is located outside the Hadley cell in summer. Hence, water is
transported from high-latitude subsolar point to the Hadley region in summer. Thus, in the low latitude area is kept in wet condition. This is the oblique regime.

On the other hand, in the frozen regime, water circulation is just locally balanced and insensitive to the inclination. This is a result of extremely low surface temperatures. At low temperature the atmosphere contains very small amount of water because of low saturation vapor pressure, and the atmospheric motion does not transport water. Extremely low temperature is caused by the occurrence of a snow ball planet, which seems an inevitable consequence of wet and cold case, because the surface snow/ice is supplied by freezing of water vapor evaporated from the solar-heated surface. Thus, even if we artificially remove the snow/ice from the surface, the surface is soon covered by snow, as far as the surface is kept wet.

Both the width of the Hadley cell and occurrence of snowball planet are insensitive to the atmospheric composition and mass. Therefore, occurrence of these three regimes should be general features irrespective of detail of the paleo-atmosphere of Mars.

**Discussion and Implication:** Inclination of the spin axis and the average temperature of the planet affect the precipitation distribution. In particular, transport of water to the low latitude area occurs only in the oblique regime.

**Cold and wet Mars.** If the paleo-Mars was wet and cold, it should be in the frozen regime and the hydrologic cycle should be locally closed. Small networks may be formed, if it is supported by very local circulation probably controlled by local topography. Also, ground ice may melt by geothermal heating and flow. However, this situation does not seem adequate for sustaining flow in large valley networks.

**Warm and wet Mars.** If the paleo-Mars was wet and warm, global scale hydrologic cycle supports precipitation at mid- to high-latitude. If the inclination of the spin axis was small, it should be in the upright regime, and the low latitude areas should be dry out without precipitation. Under such situation, formation of valley networks at low latitude areas is unlikely. Large scale low latitude valley networks can be formed only when the paleo-Mars was in the oblique regime. It should be noted that the summer surface temperature for the oblique regimes is much higher than that of the upright regimes.

Our results suggest that the high obliquity period is a good candidate for the era of fluvial feature formation. Obviously, it does not mean all the fluvial features are formed during high obliquity period.

One major assumption that may affect the results is simplification of topography and exclusion of oceans[3]. Ocean obviously affects the hydrologic cycle. For example, present precipitation at the equatorial region of the Earth is sustained by low latitude oceans. If an ocean exists on northern plain of Mars, it may induce a Monsoon-like circulation. Thus, in the future study, we have to investigate the effects of oceans and topographies.