Dependency of equilibrium states of gray atmosphere on solar constant: from the runaway greenhouse to the snowball states

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Multiple equilibrium solutions of gray atmosphere are investigated for various values of solar constant. The models used are atmospheric general circulation model (GCM) and one-dimensional energy balance model (EBM). The value of surface albedo is set to 0.5 for the region whose surface temperature is below the freezing point, and 0 for other region. The results of numerical calculation of GCM show that the feature of atmospheric state and number of statistically equilibrium solutions change with increasing solar constant, as follows:

(1) Ice-covered state only.
Number of the equilibrium solutions is one.
(2) Ice-covered state and partially ice-covered state.
Number of the equilibrium solutions is two.
(3) Ice-covered state, partially ice-covered state and the runaway greenhouse state. Number of the equilibrium solutions is two.
(4) Ice-covered state, ice-free state and the runaway greenhouse state.
Number of the equilibrium solutions is two.
(5) Ice-covered state and the runaway greenhouse state.
Number of the equilibrium solution is one.
(6) Runaway greenhouse state only.
There is no equilibrium solution.

The number of the equilibrium solutions and their types are similar to those obtained by EBM with utilizing the radiation scheme which is the same as that of GCM, though critical values of solar constant where the climate regime change occurs differ in each model.

All partially ice-covered states obtained by GCM have the latitude of ice line higher than 22 degree. This result suggests that the large ice cap instability occurs in GCM as in EBM. The unstable equilibrium solutions which are recognized in the solutions of EBM may probably exist in the three-dimensional system. However, those unstable equilibrium solutions cannot be obtained in calculations with GCM, that is, time-dependent problem. The equilibrium solutions in EBM whose ice line is located at the latitude lower than 30 degree is unstable. The partially ice-covered states obtained in GCM, in which the latitude of ice line is around 20 degree, are maintained by condensation heating near the ice line latitude.

GCM calculations with increased values of solar constant show oscillation of the ice line latitude of the solution with a small ice cap. This result suggests that stable periodic solutions and unstable equilibrium solutions exist in this regime. There is a possibility that the occurrence of small ice cap instability defined in EBM corresponds to a Hopf bifurcation in the three-dimensional system.