A study of the energy balance climate model with CO_2-dependent outgoing radiation: implication for the glaciation during the Cenozoic

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Abstract. We analyze the energy balance climate model with CO_2-dependent outgoing radiation, and obtain the steady-state solution for very wide range of the atmospheric CO_2 partial pressure and the thermal diffusion coefficient. We propose a phase diagram of the climate on the parameter space of the atmospheric CO_2 and the thermal diffusion coefficient for the latitudinal heat transport, which may be useful to understand the climate change through the history of the Earth. It is shown that the formation of polar ice caps can be caused by decrease in the atmospheric CO_2 and the latitudinal heat transport. The different history of glaciation in each hemisphere through the Cenozoic might be the result of difference in the heat transport in each hemisphere. Understanding of the small ice cap instability might be important to interpret the oxygen isotope record at the Eocene-Oligocene boundary.

Introduction

Energy balance climate models (EBMs) have been used widely to study the Earth's climate state [*North et al.*, 1981]. General features of the steady-state solutions of EBMs against the fluctuations caused by the solar insolation have been studied intensively. However, in order to discuss the climate change during the history of the Earth, variations of the atmospheric CO_2 concentration would have probably been much more important than the variation of the solar constant as the climate forcing [e.g., *Berner*, 1997; *Frakes et al.*, 1992].

Several authors have extended EBMs to include the dependency of infrared radiation on the partial pressure of CO_2 [*Caldeira and Kasting*, 1992]. However, there seems to be no previous studies which investigate mathematical structure of the steady-state solutions of such a model intensively, and apply the result to the climate change during the history of the Earth.

In this paper, we analyze the EBM with CO_2-dependent outgoing radiation, and summarize the general feature of the steady-state solutions. Then, we classify the result to construct a phase diagram of the climate on the parameter space of the atmospheric CO_2 partial pressure and the thermal diffusion coefficient for the latitudinal heat transport. Based on this phase diagram, implication for the paleoclimate change, especially for the glaciation during the Cenozoic will be discussed.

Paper number 1998GL900298.
0094-8276/99/1998GL900298$05.00

Energy balance climate model

We use an energy balance climate model based on the Budyko-Sellers-type [*Budyko*, 1969; *Sellers*, 1969] which employs diffusive-type of heat transport and discontinuous albedo at the ice cap edge [*North et al.*, 1981]. The model is represented mathematically by the energy balance equation [*North et al.*, 1981]:

$$-\frac{d}{dx}D(1-x^2)\frac{dT(x)}{dx} + I(\varphi, T) = QS(x)(1-a(T)) \quad (1)$$

where x is the sine of latitude, T is the zonally averaged surface temperature, D is the thermal diffusion coefficient for meridional heat transport, Q is the globally averaged solar incident flux, $a(T)$ is planetary albedo, and $S(x)$ is the normalized mean annual distribution of solar radiation. We consider the outgoing infrared radiation, I, which depends on the atmospheric CO_2 partial pressure (pCO_2), that is, $I = A + BT$. Caldeira and Kasting provided an useful parameterization for this factor by determining the coefficients A and B as a function of pCO_2 obtained by least-square fits of the results of more than 2000 runs of the radiative-convective climate model [*Caldeira and Kasting*, 1992]:

$$\begin{aligned} A &= -326.4 + 9.161\varphi - 3.164\varphi^2 + 0.5468\varphi^3 & (2) \\ B &= 1.953 - 0.04866\varphi + 0.01309\varphi^2 - 0.002577\varphi^3 & (3) \end{aligned}$$

where φ is the natural log of pCO_2 divided by a reference level of 300 p.p.m. Note that this parameterization can be applied to very wide ranges of condition (10^{-4} bar $< pCO_2$ < 2 bar and 194K $< T <$ 303K).

Phase diagram of Earth's climate

We obtain steady-state solutions for the ice edge latitude against pCO_2 (Fig. 1) by solving equation (1) numerically. This result seems to be very similar to the result of that against the solar constant which has been studied so far [*North*, 1984]. The linear stability of the steady-state solutions can be discussed as same as that in the previous studies; the positive slopes of the curve are stable while the negative slopes unstable [*North*, 1975]. Therefore, we can also classify the stable climate states into three branches; the ice-free branch, the glacial branch (the partially ice-covered branch), and the ice-covered branch.

The climate of the Earth is considered to have changed repeatedly between the "Cool Mode" as the time when permanent ice or seasonal ice exists on the polar region and the "Warm Mode" as the time when climate is globally warm with little or no ice [*Frakes et al.*, 1992]. Therefore, in order to study paleoclimate change based on geological evidence, it is important whether ice caps exist on polar regions at

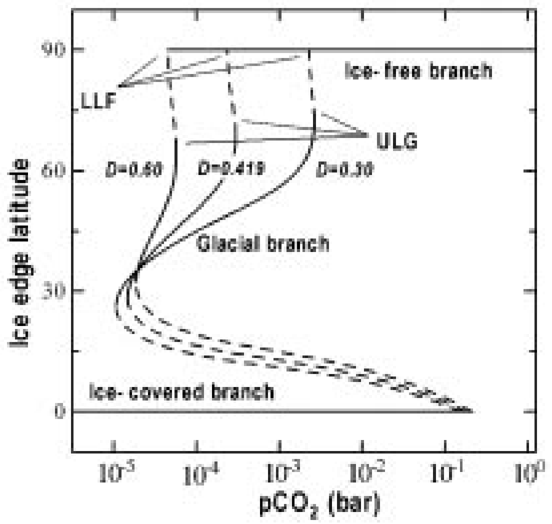

Figure 1. Plots of the steady-state ice edge latitude against the atmospheric CO_2 partial pressure for different thermal diffusion coefficients, D ($Wm^{-2}K^{-1}$). The present-day climatic condition can be obtained under the condition of $pCO_2 = 10^{-3.5}$ bar and $D = 0.419$ $Wm^{-2}K^{-1}$ in this model.

particular ages. In this respect, the upper and lower limits of each branch against pCO_2 should represent important boundaries which correspond to the condition for the existence of polar ice caps. In Fig. 1, the upper and lower limits of each branch are especially important because variations of pCO_2 may cause the transition of climate from one branch to another. For example, as pCO_2 decreases from the state on the ice-free branch, the solution would move along the ice-free branch, and then, fall onto the glacial branch abruptly at the lower limit of the ice-free branch (LLF). On the other hand, as pCO_2 increases from the state on the glacial branch, the solution would move along the glacial branch, and then, jump to the ice-free branch at the upper limit of the glacial branch (ULG).

The latitudinal thermal diffusion coefficient, D, determines the efficiency of the latitudinal heat transport. It could have changed in different conditions of the land-sea distribution and the general circulation of the atmosphere and the ocean. Figure 1 shows that the steady-state solutions (especially the conditions of LLF and ULG) depend largely on the value of D. Therefore, in order to study the formation of ice caps during the Earth's history, we have to consider the variation of D in addition to the variation of pCO_2.

Figure 2 shows variations of the condition for the upper and lower limits of each branch on the D-pCO_2 parameter space. The region between the upper and lower limits of each branch satisfies the condition for the stable steady-state solution of the branch. Therefore, Fig. 2 can be regarded as a "phase diagram" of the Earth's climate. Three branches of the climate in Fig. 1 correspond to three climatic phases in Fig. 2: the ice-free phase (F), the glacial phase (G), and the ice-covered phase(I). It is noted that the Budyko-Sellers-type EBMs have multiple solution for the stable steady-state of the climate system. In other words, a specific condition on the D-pCO_2 parameter space could correspond to more than one climate phase. It is, therefore, noted that each region divided by the solid lines does not show the specific single phase of the climate, but represents the combination of possible climate phases for a specific condition of D and pCO_2 (Fig. 2). It is not only the condition of D and pCO_2 but also the hysterisis of the climate which determines an actual climate at the specific time. For example, in order to change the climate from the Warm Mode (the ice-free phase) to the Cool Mode (the glacial phase or the ice-covered phase), the D-pCO_2 condition should change and cross the lower limit for the ice-free phase (LLF). After crossing the limit, the climate will shift to the glacial phase if it is possible ($D < 0.8Wm^{-2}K^{-1}$), while the climate will shift to the ice-covered phase if the glacial phase is not possible ($D > 0.8Wm^{-2}K^{-1}$).

There seems to be no geological evidence which clearly suggests that the Earth might have been totally ice-covered. Therefore, both the LLF and the ULG would be important for discussing the climate change during the history of the Earth. Because the LLF in the phase diagram always has a negative slope, the transition from the Warm Mode (the ice-free phase) to the Cool Mode (the glacial phase), that is, the formation of the polar ice cap, requires the change of the D-pCO_2 condition from the upper right regime to the lower left in Fig. 2. Therefore, we might consider two extreme cases to cause the glaciation, that is, the glaciation caused by decreasing pCO_2 and that caused by decreasing D.

Recently, variations of paleo-CO_2 level have been estimated by the mathematical models of carbon cycle and the studies of paleosols and fractionation of carbon isotopes by marine phytoplankton [e.g., *Berner*, 1997; *Tajika*, 1998]. On the other hand, the value of D might be obtained by fitting the latitudinal temperature gradient estimated from the EBM to that from the oxygen isotope record. If one can de-

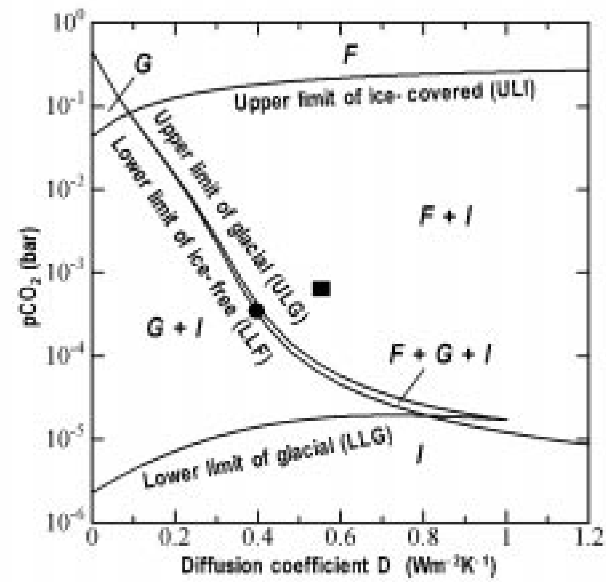

Figure 2. Phase-diagram of the Earth's climate on the D-pCO_2 space. Solid curves represent upper and lower limits of the branches of stable steady-state solutions. Symbols represent the possible stable steady-state climatic phase, that is, the ice-free phase (F), the glacial phase (G), and the ice-covered phase (I). The solid circle and square represent the present and the middle Eocene conditions, respectively (see text).

termine the values of $p\mathrm{CO_2}$ and D at several ages, the phase diagram will provide us better understanding of the climate change in the Earth's history.

Glaciation during the Cenozoic

The long-term evolution of the climate through the Cenozoic is characterized by the global cooling and the formation of the polar ice caps. The formation of large scale ice caps is usually suggested by the increase in δ^{18}O of seawater. During the Cenozoic, the abrupt increases in δ^{18}O of seawater are reported at three ages: the Eocene-Oligocene boundary (38Ma), the Middle Miocene (15Ma), and the Late Pliocene (2.5Ma) [*Miller et al.*, 1987]. In the Eocene, the warm climate might have extended far to the polar region [*Dawson et al.*, 1976], and geological evidence for the existence of polar ice cap has never been found. Therefore, the abrupt increase in δ^{18}O at the Eocene-Oligocene boundary (38Ma) may suggest the first appearance of the polar ice cap in the Cenozoic. According to the recent investigation of the Ocean Drilling Program (ODP), the evidence for the Antarctic ice sheets such as ice-rafted debris (IRD) in the Early Oligocene has been reported, supporting that the Antarctic ice cap was probably formed at 38Ma [*Leg 113 Shipboard Scientific Party*, 1987]. The increase in δ^{18}O at the Middle Miocene (15Ma) might be interpreted as the expansion of the Antarctic ice sheets accompanied by cooling of the deep water [*Miller et al.*, 1987; *Crowley and North*, 1995]. On the other hand, the abrupt increase in δ^{18}O at 2.5Ma suggests the formation of an ice cap on the northern hemisphere, which is supported by the appearance of IRD in the subpolar North Atlantic and the Norwegian Sea, and the till in Iceland and Sierras [*Crowley and North*, 1995].

In Fig. 2, conditions for the Holocene and the middle Eocene are also plotted (the Eocene condition is estimated by the EBM with $p\mathrm{CO_2}$ inferred from the result of the carbon cycle model [*Tajika*, 1998] and the latitudinal temperature distribution reconstructed from δ^{18}O record [*Shackleton and Boersma*, 1981]). As we noted before, we must consider, at least, two different factors (decreasing $p\mathrm{CO_2}$ and decreasing D) for the transition of the climate from the Eocene (the ice-free phase) to present (the glacial phase), although there would be some other factors which might have affected the global cooling and the ice cap growth during this period.

In the early Oligocene, $p\mathrm{CO_2}$ might have been higher than that at present [e.g., *Berner*, 1997; *Tajika*, 1998], and there is no report which suggests a large decrease in $p\mathrm{CO_2}$ at the Eocene-Oligocene boundary. According to the carbon isotope record, either the excursion can not be found or, at least, appears to lag behind the oxygen isotope increase at the boundary [*Zachos et al.*, 1996]. It is, therefore, suggested that the development of the Antarctic ice sheet may not have been caused by the atmospheric $\mathrm{CO_2}$ decrease. The Eocene-Oligocene boundary is considered to be the time for the formation of a continuously deep seaway between the Australia-Tasmania and the East Antarctica [*Kennett*, 1977; *Frakes et al.*, 1992]. As a result, the Antarctica could have been thermally isolated around this time, although the Antarctic Circumpolar Current might have fully established by the opening of the Drake Passage in the middle to late Oligocene [*Kennett*, 1977]. On the other hand, Robert and Chamley suggested that the consequence of collision and tectonics along the continental margin of the Tethys resulted in the restriction of the areas of shallow platforms suitable for the formation and transport of the warm, dense water to the deep ocean associated with heat transport in that period [*Robert and Chamley*, 1992]. It is therefore, suggested that the cause of the formation of the Antarctic ice cap at the Eocene-Oligocene boundary would be a decrease in the efficiency of the latitudinal heat transport. It should be noted that gradual decrease in the latitudinal heat transport would be sufficient for the formation of an ice cap if the diffusion coefficient crosses the LLF line.

On the other hand, by the Late Pliocene, $p\mathrm{CO_2}$ would have decreased to a level similar to that at present [e.g., *Berner*, 1997; *Tajika*, 1998]. In this period, the heat transport of the atmosphere-ocean system might have changed by closing Central American Isthmus. However, the study of the ocean general circulation model indicates that the heat transport toward the North Pole would have been reinforced by closing Central American Isthmus [*Maier-Reimer et al.*, 1990]. Therefore, the formation of the Arctic ice cap in the Late Pliocene may not be caused by decrease in the latitudinal heat transport, but probably caused by decreasing $p\mathrm{CO_2}$.

The global cooling trend during the Cenozoic would have been caused by decrease in the atmospheric $\mathrm{CO_2}$ level. However, the fact that the time of the formation of polar ice cap was different between the northern and the southern hemispheres suggests the different climatic evolution of each hemisphere. It may be difficult to explain for this fact just by the variation of $p\mathrm{CO_2}$. It is noted that the EBM is a simple climate model which has many limitations compared with the General Circulation Models. In particular, the EBM cannot deal with water vapor transport, which should limit the growth of ice sheet. Although the difference in the water vapor transport near the pole and/or in the land-sea distribution in each hemisphere may have played a key role in the different climatic evolution, the difference in the latitudinal heat transport might also have resulted in the different climatic evolution between each hemisphere.

The small ice cap instability would provide a condition for growth of ice cap to a certain finite size [*North*, 1984], but may not constrain its timescales. Therefore, it will be difficult to discriminate between the ice cap growth due to the small ice cap instability and that due to the climate forcing based on the δ^{18}O data. The duration of δ^{18}O change at the Eocene-Oligocene boundary is estimated to be 75-100 kyr [*Kennett and Shackleton*, 1976]. If the climate forcing at that time might have been a decrease in the latitudinal heat transport towards the Antarctica, the timescale of the ice sheet growth could have been more than several million years because it would have been a gradual process corresponding to the northward movement of the Australia-Tasmania from the East Antarctica. Therefore, an ice cap of considerable size developed in a very short timescale might indicate the consequence of the small ice cap instability, although it cannot be concluded without further studies on the dynamical behaviors of the climate system.

Acknowledgments. We are grateful to L. A. Frakes and K. Caldeira for their critical reviews. We also thank to R. Tada, K. Masuda, and A. Ohmura for discussion. This research was partially supported by the grants-in-aid for Scientific Research (No. 09740363) of the Ministry of Education of Japan.

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(Received July 19, 1998; revised September 21, 1998; accepted November 30, 1998.)