Atmósfera (1994), 7, pp. 173-178

SHORT CONTRIBUTION

Discontinuous auto–oscillations of the ocean thermohaline circulation and internal variability of the climatic system

B. A. KAGAN, N. B. MASLOVA and V. V. SEPT

St. Petersburg Branch, P. P. Shirshov Institute of Oceanology,
30, Pervaya Liniya, 199053 St. Peterburg, Russia

(Manuscript received Nov. 26, 1992; accepted in final form August 24, 1993)

It is believed by many investigators that the cause of Quaternary glacial cycles is the variation of astronomical parameters the climatic impacts of which are amplified by changes of the atmospheric CO_2 concentration. Here, we examine the alternative hypothesis that ice age/interglacial transitions arise from internal variability of the climatic system. Within the framework of a model consisting of the atmosphere, a three–layer ventilated ocean and continental ice we show that the ocean thermohaline circulation in the intermediate/deep water masses can admit discontinuous auto–oscillations. These auto–oscillations are due to discontinuous changes of the salinity difference between the above–mentioned water masses. At the same time, the temperature difference as well as ocean average temperature and salinity, atmospheric CO_2 partial pressure and continental ice mass remain continuous and undergo asymmetric oscillations with periods close to those of astronomical parameter variations.

Judging from spectra of the solar radiation and paleoclimatic indicators ($\delta^{18}O$ and $\delta^{13}C$ in shells of planktonic and benthic foraminifera, see Hays *et al.*, 1976; Shackleton and Pisias, 1985) the periods of oscillations in the atmospheric CO_2 concentration and global ice volume coincide with those of variations in the eccentricity of the Earth's orbit and obliquity and orientation of its axis of rotation. In addition, solar radiation changes precede some atmospheric CO_2 concentration changes, and the latter, in turn, precede changes in the continental ice volume. These observations have been interpreted as proof of the astronomical origin of Quaternary ice ages.

There exists, however, another possibility concerning the cause of the alternating glacial and interglacial epochs expressed by Lorenz (1968), i.e. that long–term climatic changes can be explained by internal variability of the climatic system without necessarily invoking externally varying factors. This idea gains new support in view of recent paleontological and geochemical data (Crowley and North, 1988; Broecker and Denton, 1989) and studies of the non–uniqueness of the ocean thermohaline circulation (Bryan, 1986; Welander, 1986; Marotzke *et al.*, 1988) indicating the existence of long-period discontinuous auto–oscillations of the climatic system.

As the basis for illustrating this possibility, we take a simple model of the climatic system including description of the ocean themohaline circulation. Following Kagan and Maslova (1991) we represent the ocean by a system of three water masses–surface, intermediate and deep. We assume also that heat and salt exchange between these water masses is performed by diffusion and organized transports, both being parameterized in terms of temperature and salinity differences in the neighbour water masses. In this ocean, the thermohaline circulation has 16 stable steady states but has neither limit cycles nor other closed phase trajectories (Kagan and Maslova, 1991). However, joining the ocean, atmosphere and continental ice in a single climatic system leads to a loss of stability of the steady states and gives rise to discontinuous auto–oscillations with a period of the order of 10^5 years (Kagan *et al.*, 1993). The distinctive property of these auto–oscillations is an alternation of the slow and abrupt changes in direction and intensity of the ocean thermohaline circulation associated with abrupt changes of the salinity difference in the intermediate/deep water masses. Contrary to this, the temperature difference, ocean average temperature and salinity as well as continental ice mass remain continuous and perform asymmetric oscillations.

As in Kagan *et al.* (1993), we determine the air surface temperature with the help of the quasi–stationary atmospheric heat budget equation. Then we approximate the meridional distribution of the air surface temperature by the first two terms of the series in even Legendre polynomials, and the equator–to–pole difference of temperature as a linear function of intensity of thermohaline circulation in the intermediate/deep water masses and of the global average air surface temperature. Suppose also that the sea ice boundary coincides with the −10°C isotherm and that the area and mass of the continental ice are interconnected by a linear relationship. To determine the continental ice mass, we use the evolution equation in which the source of the ice mass is water flux at the atmosphere–ocean interface parameterized in terms of the air–water difference of temperature and the sink is ice degradation due to iceberg discharge and ablation. The iceberg discharge rate is assumed to be a prescribed constant and the ablation rate is an unknown to be determined by the equation of the heat budget at the continental ice surface.

Let us add to above system an equation for total inorganic carbon concentration in surface, intermediate and deep water masses and an expression for the CO_2 flux at the ocean–atmosphere interface. Further, we suppose that the sources and sinks of organic carbon equalize each other, the integral (over the ocean surface) flux of CO_2 vanishes and that the atmospheric CO_2 partial pressure is not changed with latitude. Then, after transforming to dimensionless variables and rejection of small terms we have the following equations describing the evolution of the climatic system on the scale of slow time defined by the continental ice relaxation time:

$$\frac{dM}{d\tau} = -(q_2 - q_2^*) - a_1(\overline{T}_\alpha - \overline{T}_\alpha^*), \tag{1}$$

$$a_2 + a_3(q_2 - q_2^*) + a_4(\overline{T}_\alpha - \overline{T}_\alpha^*) = \kappa\varphi(\kappa^{-1}q_2,\ \beta), \tag{2}$$

$$\overline{H}(\overline{T}_\alpha,\ M) + a_5 \ln(P_\alpha^{CO_2}/P_{\alpha^*}^{CO_2}) = 0, \tag{3}$$

$$\sum_\kappa A_{j\kappa}\frac{V_o}{V_j}(|\, q_\kappa \,| + \kappa)(C_{[\kappa/2]} - C_\kappa) - \frac{V_o s_j}{V_j s_o} a_6 \left(C_{sj} - [CO_2]_j\right) = 0, \tag{4}$$

$$\sum_j (V_j/V_o)C_j = a_7. \tag{5}$$

The system (1)–(5) is a generalization of the degenerate system considered in Kagan *et al.* (1993) with allowance for interaction between thermodynamic and carbon cycles. Here M is the continental ice mass; $\overline{T}_\alpha$ is the global average air surface temperature; q_2 is the intensity of the thermohaline circulation in the intermediate/deep water masses; $\varphi(\kappa^{-1}q_2, \beta) = \kappa^{-1}q_2 + \beta(\kappa^{-1} \mid q_2 \mid +1)^{-1}$; κ and β are dimensionless parameters characterizing the effects of diffusion and the haline constituent of the circulation, respectively; $\overline{H}(\overline{T}_\alpha,\ M)$ is a planetary average radiation budget at the upper boundary of the atmosphere; $P_\alpha^{CO_2} = \sum_j s_j[Co_2]_j/\sum_j s_j k_g$ is the atmospheric CO_2 partial pressure; C and $[CO_2]$ are the total inorganic carbon concentration and dissolved carbon dioxide concentration connected between themselves by relationships of chemical equilibria of various carbon compounds at the ocean–atmosphere interfaces; k_g is a gas exchange rate at the ocean–atmosphere interface; C_s is CO_2 solubility in sea water depending on the atmospheric CO_2 partial pressure and sea water temperature and salinity; V is the ocean volume; V_j and s_j are the volume and area of ventilation domain for the j–th water mass; indexes j and k are equal to 0, 1, 2 and 1, 2, respectively, with $j = 0$ corresponding to surface, $j = 1$, to intermediate and $j = 2$, to deep water masses; $[k/2]$ is the integral part of the number k; A_{jk} are elements of the matrix

$$(A_{jk}) = \begin{pmatrix} -1 & 0 \\ 1 & -1 \\ 0 & 1 \end{pmatrix},$$

$a_1, \ldots a_7$ are constants; τ is the slow time; subscripts * refer to stationary values of the functions.

The results of numerical solution of system (1)–(5) is outlined in Figure 1 in the form of long–linear spectra of temperature in the surface (Fig. 1a), intermediate (Fig. 1b) and deep (Fig. 1c) water masses, continental ice mass (Fig. 1d) and the atmospheric CO_2 partial pressure (Fig. 1e). Note that the most remarkable features are the following: firstly, the presence of strong spectral peaks at periods of $80 \cdot 10^3$, $41 \cdot 10^3$, $21 \cdot 10^3$ and $18 \cdot 10^3$ years close to the eccentricity period ($\sim 100 \cdot 10^3$ years), obliquity period ($\sim 41 \cdot 10^3$ years) and the precessional periods ($\sim 23 \cdot 10^3$ and $\sim 19 \cdot 10^3$ years); secondly, a decrease in the amplitudes of the ocean temperature oscillations with periods of $21 \cdot 10^3$ and $18 \cdot 10^3$ years with increasing depth (or latitude) and, thirdly, the lead of the atmospheric CO_2 partial pressure changes over the continental ice mass changes (*cf.* Figs. 2a and 2b).

These features of the solution are similar to the data obtained from geochemical studies (Broecker and Denton, 1989; Imbrie, 1982; Ruddiman and McIntyre, 1984) but are in no way connected with variations of the astronomical parameters. In particular, $80 \cdot 10^3$ years is a period of discontinuous auto–oscillations, $41 \cdot 10^3$ and $21 \cdot 10^3$ years are periods of their harmonics, and $18 \cdot 10^3$ years is a period definied by the difference between the lifetime of the normal (present) and abnormal (reverse) circulation (Fig. 2c). In other words, in our case the cause of the features mentioned above is internal variability of the climatic system resulting from the existence of discontinuous auto–oscillations of the ocean thermohaline circulation.

The period of the discontinuous auto–oscillation proves to be dependent on interaction of the thermodynamic and carbon cycles. Thus, in the presence of this interaction, and taking into consideration the chemical reactions of CO_2 and $CaCO_3$ with sea water, the period of discontinuous auto–oscillations amounts to $80 \cdot 10^3$ years. However, without allowance for the $CaCO_3$ solubility process it equals $104 \cdot 10^3$ years, and in the absence of interaction of the thermodynamic and carbon cycles, to $133 \cdot 10^3$ years. The decreasing discontinuous auto–oscillation period is explained by the decreasing lifetime of normal and abnormal circulations, and this, in turn is

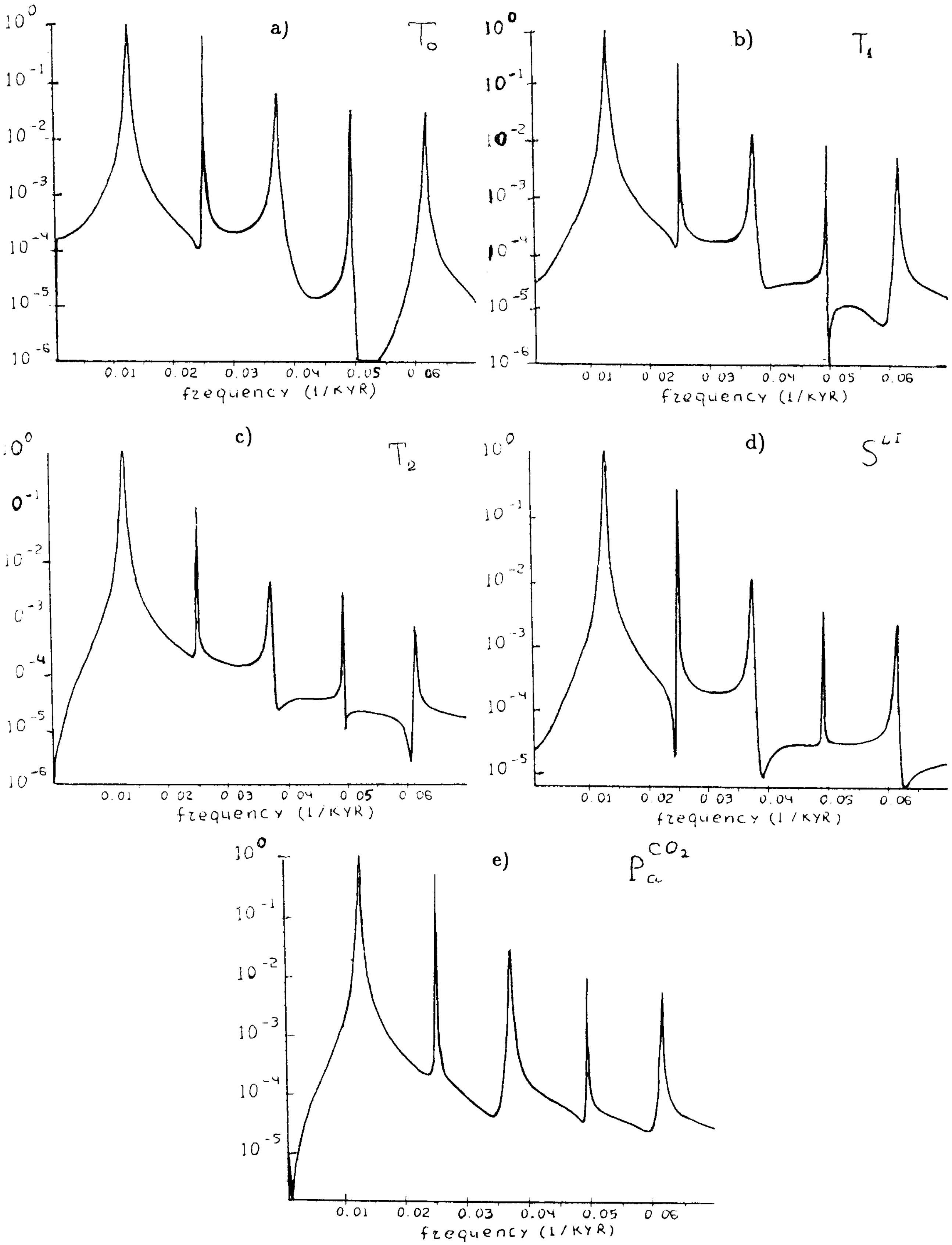

Fig. 1. Spectra of temperature in the surface (a), intermediate (b) and deep (c) water masses, continental ice mass (d) and the atmospheric CO_2 partial pressure (e).

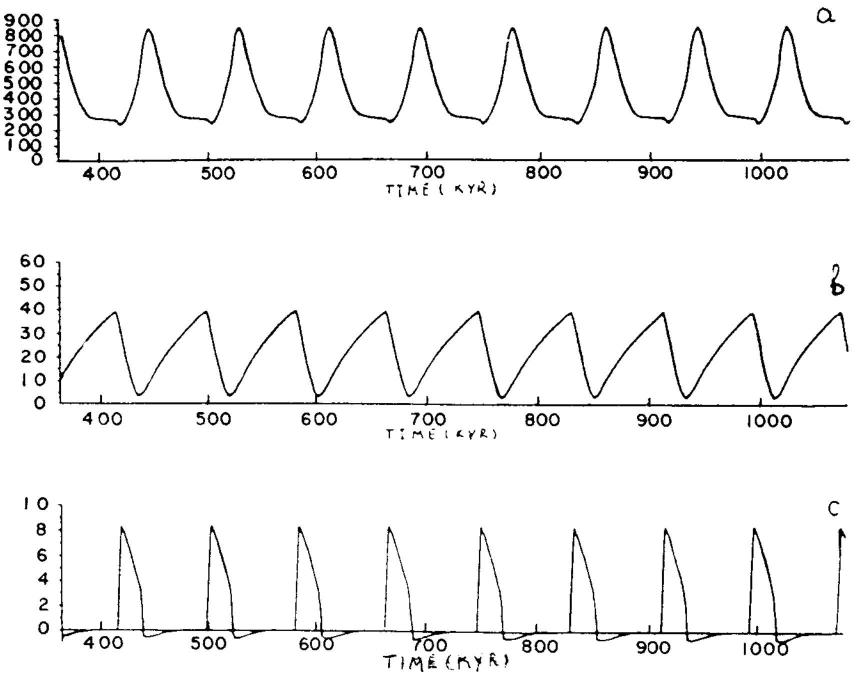

Fig. 2. Evolution of the atmospheric CO_2 partial pressure (a), continental ice mass (b) and the intensity of thermohaline circulation in the intermediate/deep water masses (c).

explained by amplification of the negative feedback between the continental ice mass and the global average air surface temperature. It fillows that a consistent description of the thermodynamic/carbon cycle interaction is the necessary condition for a better understanding of various manifestations of long-term climatic variability and, in particular, Quaternary glacial cycles.

REFERENCES

Broecker, W. S., and G. H. Denton, 1989. The role of ocean-temperature reorganization in glacial cycles, Geochimica et Cosmochimica Acta., 53, 2456-2501.

Bryan, F., 1986. High-latitude salinity effects and interhemispheric thermohaline circulation, *Nature*, **323**, 301-304.

Crowley, T. J., and G. R. North, 1988. Abrupt climate change and extinction events in Earth history, *Science*, **240**, 996-1002.

Hays, J. D., J. Imbrie and N. J. Shackleton, 1976. Variations in the Earth's orbit: pacemaker of the ice ages, *Science*, **194**, 1121-1132.

Imbrie, J., 1982. Astronomical theory of the Pleistocene ice ages: a brief historical review, *Icarus*, **50**, 408-422.

Kagan, B. A., and N. B. Maslova, 1991. Non-uniqueness of the thermohaline circulation in a three-layer ventilated ocean, *Fluid Dyn. Res.*, **8**, 287-295.

Kagan, B. A., N. B. Maslova and V. V. Sept, 1993. Discontinuous auto-oscillations in a coupled atmosphere-ocean-continent ice model, *Atmósfera*, **6**, 199-214.

Lorenz, E. N., 1968. Climatic determinism, *Meteorol. Monographs*, **8**, 1-3.

Marotzke, J., P. Welander and J. Willebrand, 1988. Instability and multiple steady states in a meridional–plane model of the thermohaline circulation, *Tellus*, **40A**, 162-172.

Ruddiman, W. F., and A. McIntyre, 1984. Ice–age thermal response and climatic role of the surface Atlantic Ocean, 40 N°to 63 N°, *Bull. Geol. Soc. Am.*, **95**, 381-396.

Shackleton, N. J., and N. G. Pisias, 1985. Atmospheric carbon dioxide, orbital forcing, and climate, In: The Carbon Cycle and Atmospheric CO_2: Archean to Present (Eds. E. T. Sundquist and W. S. Broecker). *Geophys. Monogr. Ser.*, **32**, 303-317.

Welander, P., 1986. Thermohaline effects in the ocean circulation and related simple models, In: Large–scale Transport Processes in Oceans and Atmosphere (Eds. J. Willebrand and D. L. T. Anderson). D. Reidel Publ. Co., Dordrecht, 163-200.