Climatic Fluctuations Due to Deep Ocean Circulation

Abstract. *A simple climate model that includes the effect of deep ocean turnover as a pure time delay exhibits an oscillatory behavior. The deep ocean signal contains frequencies characteristic of both the forcing function and the deep ocean delay.*

Schnitker has reported (*1*) evidence of rhythmic fluctuations in the faunal composition of deep-sea benthic foraminifera during the last 24,000 years. He suggested that fluctuations occur at periods that are the same order of magnitude as the turnover time of deep ocean water and that these fluctuations may therefore be linked to some internal mechanism involving deep ocean turnover. In this report we propose a simple climate model that includes the effect of deep ocean turnover and explore the possibility of periodic solutions. Our model solutions indicate that a strong oscillation in the temperature of the ocean mixed layer can occur with a period characteristic of the deep ocean turnover time and that the signal may last for several times the deep ocean turnover time.

We consider a zonally averaged energy balance model described by the following differential equation:

$$a(x)S(x)Q - [A + BT(x)] + \beta[\bar{T} - T(x)] = C\frac{dT}{dt} + \dot{m}''c[T(x_1,t) - T(x_1,t - t_d)] \quad (1)$$

The terms on the left side of Eq. 1 are those usually included in zonally averaged climate models (*2*). The first term is the solar radiation absorbed in any latitude band; x is the sine of the latitude, $a(x)$ is the co-albedo, $S(x)$ is a solar flux distribution term, and Q is the solar constant. The second term is the infrared flux leaving the atmosphere (*3*); A and B are taken to be constants, and $T(x)$ is the zonally averaged surface temperature at latitude $\sin^{-1}(x)$. The third term represents the divergence of the poleward energy flux in the form suggested by Budyko (*4*); β is a constant, and $\bar{T}$ is the hemispherically averaged temperature. The first term on the right represents the effect of the heat capacity of any latitude band; C is generally taken to be the heat capacity of the mixed layer of the ocean, and t is time. The final term does not appear in other zonally averaged, energy-balance climate models; $\dot{m}''$ is the mass flux of ocean water that sinks at some latitude $\sin^{-1}(x_1)$, c is its specific heat, and $T(x_1)$ is its temperature. We assume that this water flows along the bottom of the ocean, completely insulated from the mixed-layer water, and upwells at some fixed time t_d after sinking. Thus, the temperature of the water reentering the mixed layer is the same as that of the mixed layer at latitude $\sin^{-1}(x_1)$ t_d years ago—that is, $T(x_1, t - t_d)$. Although we realize that the real situation is much more complex than the one we are modeling, we emphasize that we seek here only to examine some of the effects the deepwater recirculation might have on climate fluctuations in an intermediate frequency range (periods of 200 to 2000 years). Schnitker has pointed out (*1*) that these fluctuations cannot be related in any obvious way to orbital changes (10^4 to 10^5 years) or sunspot activity (~ 10 years).

To investigate the nature of transient solutions of Eq. 1, we first assume that there is some equilibrium solution T_0 for which the sinking and upwelling water have the same temperature and for which $dT_0/dt = 0$. We further assume that the departure from equilibrium, $\theta = T - T_0$, can be written as the sum of a hemispherically averaged term $\bar{\theta}$ and a departure term $\Delta\theta$ whose hemispherically averaged value is zero: $\theta = \bar{\theta} + \Delta\theta$. If we assume also that the temperature distribution adjusts quickly to changes in $\bar{\theta}$ ($d\Delta\theta/dt \approx 0$), Eq. 1 can be averaged over latitude to yield a hemispherically averaged energy balance:

$$Q\left(\frac{d\bar{a}}{d\bar{T}}\right)\bar{\theta} - B\bar{\theta} = C\frac{d\bar{\theta}}{dt} + \dot{m}''c\left\{1 + \frac{Q}{B + \beta}\left[S(x_1)\frac{da(x_1)}{d\bar{T}} - \frac{d\bar{a}}{d\bar{T}}\right]\right\} \times [\bar{\theta} - \bar{\theta}(t - t_d)] \quad (2)$$

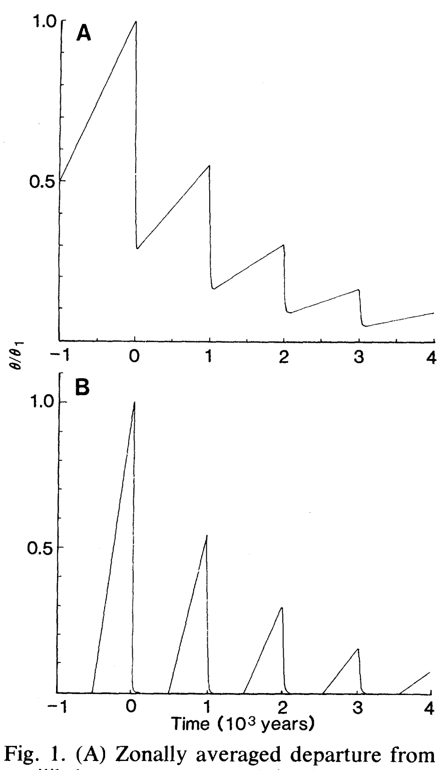

Fig. 1. (A) Zonally averaged departure from equilibrium temperature. Mixed-layer water sinks at latitude 70° at a rate of 2×10^7 m^3 sec^{-1}. The mixed layer is 70 m deep; $B = 1.8$ W m^{-2} °C^{-1}, $d\bar{a}/d\bar{T} = 0.0037$; $da(x_1)/d\bar{T} = 0.013$; $t_d = 1000$ years; $t_c = 2000$ years. (B) Same as (A), but with $t_c = 500$ years.

There are two terms in Eq. 2 that involve albedo feedback. The first term on the left represents the change in solar radiation due to global albedo change. The second term inside the pointed brackets accounts for the fact that the albedo feedback at high latitudes where deep ocean water is usually formed is larger than the average value. The albedo feedback has a more pronounced effect on the deep ocean feedback.

Owing to the term $\bar{\theta}(t - t_d)$, which is the hemispherically averaged departure from steady state at some time t_d before the present, solution of Eq. 2 requires a knowledge of the temperature history over a time t_d before the solution begins. To illustrate how this history affects the solution, we give solutions for two different histories. In each case, the ocean was initially in an equilibrium state and at some time t_c before the present $\bar{\theta}$ decreased linearly until $\bar{\theta} = \bar{\theta}_1$. This might have resulted, for example, from a glacial surge with subsequent calving of icebergs into the ocean as discussed by Ruddiman and McIntyre (*5*). We do not wish to obscure the issue by speculating about possible causes of a departure from equilibrium. Our purpose is to present a mathematical description of the nature of the oscillations that can result from the deep ocean delay.

The two solutions are shown in Fig. 1. In each case, the solution curve eventually returns to the steady-state value $\bar{\theta} = 0$. The solution curve in Fig. 1A ($t_c = 2000$ years) consists mainly of a slow approach to steady state with a superimposed signal that fluctuates with a period characteristic of the deep ocean delay (period ~1000 years). The solution curve in Fig. 1B also contains a fluctuation characteristic of past forcing ($t_c = 500$ years). In general, a solution curve will contain fluctuations characteristic of both the period of the forcing function and the deep ocean delay. An interesting feature of both cases is that the approach to equilibrium can be very much slower than would be predicted if one thinks of the deep ocean delay as a kind of time constant. The deep ocean signal can contain the memory of signals that occurred several delay times before the present.

The oscillatory nature of the solutions persists for fairly wide ranges of the various parameters. Changes in t_d and t_c only affect the frequency of $\overline{\theta}(t)$. The second term inside the pointed brackets in Eq. 2 is a positive number because the albedo feedback at high latitudes is larger than the average value. The oscillation tends to become more and more damped as this term is made smaller, but the solution retains its basic oscillatory character even when this term is set equal to zero (*6*).

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References and Notes

1. D. Schnitker, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, in press. A reviewer has pointed out that climate reconstruction from deep-sea cores for time scales shorter than a few thousand years is risky and that Schnitker's oscillations could be simply a measure of some sediment-mixing process. Although data from several cores do give similar spectra, both the data and the model presented here must still be regarded as somewhat speculative, of course.
2. S. H. Schneider and R. E. Dickinson, *Rev. Geophys. Space Phys.* **12**, 447 (1974).
3. R. D. Cess, *J. Atmos. Sci.* **33**, 1931 (1976).
4. M. I. Budyko, *Tellus* **21**, 611 (1969).
5. W. F. Ruddiman and A. McIntyre, *Quat. Res. (N.Y.)* **16**, 125 (1981).
6. We are presently studying a more complex model in which sinking and upwelling can occur at several locations and in which the several deepwater currents can communicate with each other as well as with the surface layer.
7. The original idea for this word came while one of us (R.G.W.) was at the Institute for Energy Analysis, Oak Ridge, Tenn., in 1976. We thank Drs. Ralph Rotty and Alvin Weinberg for their hospitality. This work is supported by NSF grant ATM-7916332.

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Biological Control of the Removal of Abiogenic Particles from the Surface Ocean

Abstract. *Concurrent measurements of particle concentrations in the near-surface water and of particle fluxes in the deep water of the Sargasso Sea show a close coupling between the two for biogenic components. The concentrations of suspended matter appear to follow an annual cycle similar to that of primary production and deepwater particle flux. Although the concentration of particulate aluminum in the surface water appears to vary randomly with respect to that cycle, the removal of aluminum to deep water is intimately linked to the rapid downward transport of organic matter.*

For the past 4 years we have continuously sampled the flux of particles to the deep Sargasso Sea at a site 45 km southeast of Bermuda (32°05′N, 64°15′W). Samples were recovered bimonthly from a sediment trap moored 3200 m below the surface and 1000 m above the sea floor (*1*). We have observed quite reproducible annual fluctuations in the total particle flux with a maximum range of a factor of 7 among sampling periods but generally less than that within 1 year. Quite similar fluctuations were observed in individual major constituents, such as organic carbon and calcium carbonate. We soon recognized a similarity between the timing and extent of these variations and the seasonal changes in primary production in the Sargasso Sea as reported by Menzel and Ryther 20 years earlier (*2*): highs in early spring and lows in late summer and fall. Not surprisingly, these seasonal changes affect the flux of such biologically important elements as calcium, because the production of coccoliths and foraminiferal tests (*3*) is closely linked to the cycle of photosynthetic carbon fixation. We were surprised, however, to find that the flux of particulate aluminum in the deep water also undergoes annual variations (*4*) and is, in fact, quite closely correlated to the flux of organic carbon (Fig. 1).

By a combination of scanning electron microscopy and energy-dispersive x-ray spectrometry, we determined that aluminum in the sediment-trap material is primarily associated with clay particles or at least with apparently nonbiogenic, silicon-containing particles. Similar aluminum-containing particles were identified in the suspended load of the surface water. Some silicon-aluminum spherules, most likely fly-ash particles (mullite) from industrial coal combustion (*5*), were also identified in the sediment-trap material. Deuser *et al.* had proposed (*4*) that the seasonal cycle of the aluminum flux and the close correlation of aluminum with organic carbon in the sediment-trap samples might be caused by biological removal of the clay particles from the surface water. Deuser *et al.* suggested that the subsequent rapid sinking of the particles could be accomplished as a result of their association with fecal pellets or other organic aggregates. It was not known, however, if by coincidence the input of clay to the surface water might also have an annual cycle similar to that of primary production.

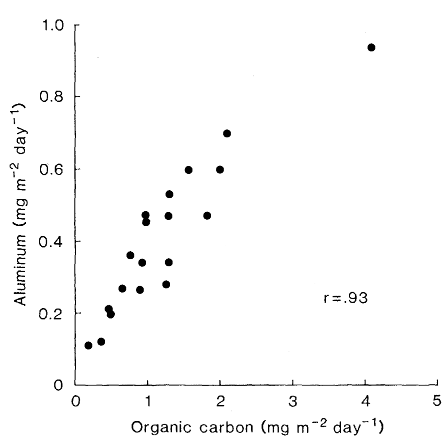

Fig. 1. Correlation between the fluxes of organic carbon and mostly abiogenic aluminum into a sediment trap at a depth of 3200 m in the Sargasso Sea. Points represent averages over 2-month collection periods between April 1978 and April 1982. Carbon and aluminum analyses were made on the < 37-μm fraction (after sieving) of material collected in the traps.

In order to obtain a measure of the particle input to, and formation in, the surface water, we subsequently began periodic sampling of the suspended matter in the top 200 m of the Sargasso Sea at a site near the sediment trap while also continuing the sediment-trap collections. Details of the sediment trap have been given in (*3, 4, 6*). Suspended matter was collected in 10- and 30-liter Niskin bottles, the contents of which were passed through Nuclepore filters (0.6-μm pore size) into evacuated carboys immediately upon arrival on deck. Depending on the suspended load, 2.5 to 12.5 liters passed through the filters before they became clogged. The calcium and aluminum concentrations in the material on the filters and in the < 37-μm size fraction of the sediment-trap samples were determined by instrumental neutron activation analysis (*7*). Samples were irradiated at the Rhode Island Nuclear Science Center in a neutron flux of 4×10^{12} neutron cm^{-2} sec^{-1} for 10 minutes and cooled for 5 minutes before counting on a Ge(Li) detector. We report here the results of the first year of concurrent measurements on suspended matter and sediment-trap samples.

For a comparison of the continuous flux measurements with the periodic concentration measurements we show on the left side of Fig. 2 juxtaposed plots of (i) the midpoints of seven 2-month sediment-trap accumulations, expressed as daily flux per square meter, and (ii) average suspended-matter concentrations in the surface water (sampling depths of 10, 25, 50, and 100 m) on 11