CLIMATE CHANGE

The variable ocean

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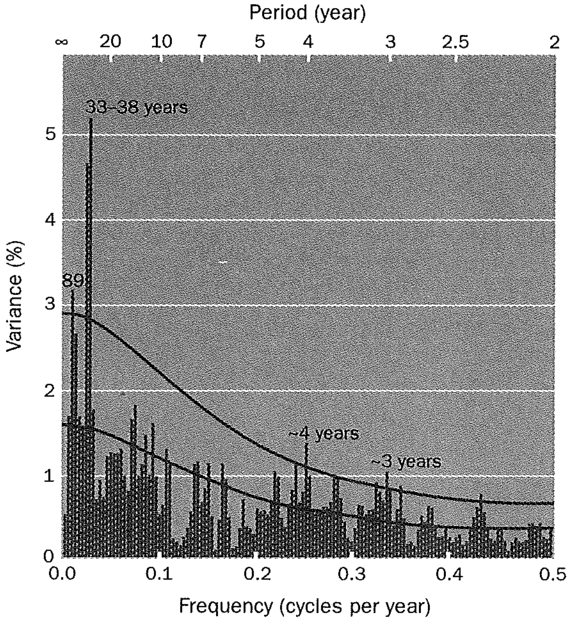
NATURAL variability in the climate system still hampers the unequivocal detection of increasing air temperatures as the emission of CO_2 into the atmosphere continues. Understanding such fluctuations is thus a great challenge to climate researchers, three of whom — Delworth, Manabe and Stouffer[1] — have now found natural variability in a 600-year integration of their general circulation model simulating the present climate. Irregular but organized 40- to 60-year oscillations about a mean state are localized in the northwest Atlantic region and are associated with a subtle interplay between the thermohaline circulation of the ocean and the advection of heat and salt. The timescale of 40–60 years is especially interesting because it coincides with the typical timescales of anthropogenic climate modification and may hide changes for some years to come, unless advanced statistical methods are used[2].



Statistical methods allow the reconstruction of summer temperatures from tree-ring widths of pine trees. Spectral analysis of a 398-year series of this climate proxy from the northern regions of Fennoscandia shows there to be strong variability on a timescale of 30–40 years. The lower line represents red noise with equal variance and the upper is the 95 per cent confidence limit (after ref. 8; courtesy of K. R. Briffa). Natural fluctuations of the thermohaline circulation in the North Atlantic as found in a coupled atmosphere–ocean general circulation model[1] may well induce cycles of temperature in northwestern Europe.

The model, a three-dimensional simulation with atmosphere–ocean coupling developed at NOAA's Geophysical Fluid Dynamics Laboratory, is one of the standard tools in climate research to assess the consequences of global warming[3]. Delworth and colleagues go further by analysing the natural variability of the modern-day, quasi-steady state and, in doing so, learning more about how the conspicuous interannual and interdecadal variability seen in long-term climate records is generated. The broad-band variability in the North Atlantic over a 600-year run compares favourably with that of observations from Weather Ship Station I (59° N, 19° W) and has the typical red-noise character. Superimposed on this random component is a broad peak at the interdecadal timescale, and the model results suggest a new form of interaction between ocean and atmosphere, occurring mainly in the Atlantic Ocean northeast of the maritime provinces of Canada.

The modelled interdecadal oscillation has its most noticeable effect on the North Atlantic 'conveyor belt', which carries vast quantities of surface water towards the pole where it cools and sinks to form deep water. There, its peak-to-peak amplitude is about 2×10^6 m^3 s^{-1}, more than ten per cent of the long-term mean. Such fluctuations in the rate of deep-water formation influence the strength of the surface flow into the sinking regions and with it the advection of heat and salt. By relating time series of sea surface temperature to a lagged time series of the conveyor strength, Delworth *et al.* demonstrate the succession of processes that are at the heart of the simulated variability.

The schedule is as follows. When the thermohaline circulation is weak, decreased advection of lower-latitude warm and saline waters into the central region of the North Atlantic generates a pool of anomalously cold and fresh water. As the impact on density of the thermal anomaly is about three times stronger than the haline, the anomaly induces a geostrophically controlled cyclonic circulation at the surface, exchanging colder, fresher waters near the northeast coast of America with warmer, saline mid-ocean waters. This anomalous buoyancy-driven gyre is actually superimposed on the upper branch of the time-mean conveyor belt which flows northeast at that latitude and enhances it. As the associated increased salt transport brings denser water into the sinking region and so helps the conveyor intensify, more heat is advected from lower latitudes by the same mechanism. This erodes the cold anomaly and eventually creates a warm pool in the same region. Geostrophy now requires an anticyclonic gyre which weakens the thermohaline circulation by carrying fresher and colder waters in the mid-ocean southwards, against the direction of the time-mean conveyor belt.

Budget calculations in this region indicate that the fluctuation is mainly due to periodically varying meridional fluxes of heat and salinity. Ocean-to-atmosphere exchange is important for heat (it slowly removes temperature anomalies) but not for salt; surface fluxes of fresh water vary only slightly during a cycle. This indicates that the fluctuation is mainly oceanic and could, with suitable surface boundary conditions, be simulated in ocean-only models. But classical 'mixed boundary conditions' (where heat fluxes are proportional to temperature anomalies, freshwater fluxes are constant) will not do the trick, as it is known that they thermally couple the atmosphere too tightly to the ocean. As Delworth and colleagues show, the persistence of sea-surface-temperature anomalies is a central part of the proposed mechanism and also acts to stabilize the North Atlantic circulation.

Although the fluctuations in the model are initiated at the sea surface, their effects can be traced both in the deep Atlantic and in the atmosphere of the Northern Hemisphere. Salinity and temperature profiles show changes that reach beyond 3 km depth in the sinking region between 52° and 72° N in the Atlantic. Surface air temperatures also follow the oceanic oscillation, and distinct anomaly patterns are expected, especially in winter months when a stronger thermohaline circulation transports enough heat northward to reduce ice cover. During that phase of the oscillation a negative pressure anomaly develops, centred southeast of Greenland, bringing a warming of about 1 °C over the northern North Atlantic and a significant cooling of about 1.5 °C over the Labrador Sea.

The modelled oscillation is distinctly irregular, a common feature in nonlinear dynamical systems. Although the first 200 years of the integration show a quasi-periodic cycle of 40–50 years, the periods are longer in the following 400 years. It seems that some preconditioning of the ocean at a particular location is required, and that the fluctuation itself may remove or add to it. Other model calculations also point at a centre of action in the northern North Atlantic and Labrador Sea[4,5], and they also show oscillations on timescales of 10–40 years, although these are due to somewhat different mechanisms.

What adds weight to the model results is that observational studies indicate distinct and coherent changes in the ocean and atmosphere in this century. A hard look at global-mean temperature records reveals interdecadal (60–70 year) cycles and increased variability in the region of the North Atlantic[2]. A long-term cooling trend from the late 1950s to early 1970s, in the top 1,500 m of the Atlantic Ocean at 34° N, follows patterns of sea surface temperature and salinity anomalies[6,7] that are similar to the modelled differences between times of strong and weak thermohaline circulation. Waters in the central Labrador Sea, too, have become cooler and fresher at intermediate depths during the past 25 years[8], but with the coarse resolution of present models a direct comparison is not yet possible.

Perhaps the most intriguing piece of evidence for interdecadal cycles comes from a 1,480-year time series of summer temperatures reconstructed from tree-ring widths of pine from northern Fennoscandia[9]. The past 400 years of this proxy indicator show significant variance in the band of 30–40 years (see figure). Spectral analysis of sub-intervals indicates that these periods themselves are variable[10], as in the numerical simulation. Delworth and colleagues' model could provide a natural mechanism for such cycles (previous interpretations have had to invoke some nonlinear interaction between solar forcing and atmospheric temperatures).

Given the paramount importance of the thermohaline circulation and its variability for the climate system, what should the next steps be? Enlarging the observational data set in key regions such as the North Atlantic and Labrador Sea area must be one priority. And numerical models must be refined to give a better representation of how deep water masses are formed and distributed, plus improved compatibility of atmospheric and oceanic heat, freshwater fluxes, and air–sea interaction. We will then gain more of a feel for the robustness of such cycles. ☐

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