phosphorylation? The cloning of the IκBα kinase present in the 700K complex should resolve this issue. ☐

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Climate change

Is the ocean at the helm?

Mike McCartney

The global climate heads off, unpredictably, into different regimes of behaviour for periods of years and decades. At middle latitudes, the central question is whether the ocean is a passive participant in climate change, merely responding to the atmosphere conditions above its surface, or a far more active component of the climate. On page 563 of this issue[1], Sutton and Allen present compelling evidence that the North Atlantic is an active participant in the decadally evolving regional climate, with vivid images of propagating and oscillating sea surface temperature (SST) distributions.

Sea surface temperature distributions are a critical link between the circulations of the atmosphere and the ocean. But the physics of this link is difficult. The question is whether the atmosphere and ocean circulations are truly coupled (rather than the atmosphere directing all the action), and if so, how. Sutton and Allen have analysed patterns of wintertime SST measured in the North Atlantic over several decades, together with records of the overlying atmospheric circulation, mapped through sea-level pressure (SLP) distributions. They find that the patterns evolve in a remarkably organized way over decade timescales, propagating with slow but steady persistence in the direction of the main ocean currents. Ocean circulation is ponderous compared with that of the atmosphere, but the huge heat capacity of water gains the ocean equal partnership in the movement of heat in the climate system.

The longest continuously measured property of the oceans is surface temperature. SST was once measured by ships' crews using insulated sampling buckets, more recently by thermometers fixed in intake pipes for engine cooling water. Winter SST anomalies (departures from monthly mean values) are the surface expression of temperature anomalies in the underlying bulk of the ocean's mixed layer: the cold and windy mid- to high-latitude winter atmosphere causes convective overturning of the water column down to at least a few hundred metres, and sometimes to more than 1,000 m. So an SST anomaly of just 1 °C represents a large amount of heat.

These heat anomalies are sequestered beneath a seasonally heated layer in summer, and re-exposed to the atmosphere in subsequent winters. This gives the ocean a 'memory' of atmospheric conditions. The repeated winter re-exposure of such accumulated thermal anomalies means that the atmosphere sees the anomaly for many winters — and there's the crux of the coupling question. If there *is* a feedback from anomalies in oceanic SST and heat content to the atmosphere, then recurring anomalies in atmospheric circulation should result. Is this borne out by the evidence in the North Atlantic?

One of the most robust modes of atmospheric variability is the North Atlantic Oscillation (NAO), a see-saw in the amplitudes of two centres of extreme pressure, the Icelandic low and Azorian high[2], which determines the strength of the westerly winds. The oscillation varies on timescales ranging from seasons to decades, and there are associated shifts in North American, European and northern Asian patterns of rainfall[3] and storm tracks[2,4], and also temperature[5] — which has a considerable effect on the measured pattern of 'global warming'[6].

Figure 1 shows the winter North Atlantic Oscillation[3] over 1864–1997. Are the longer timescales that predominate in this record a signature of ocean feedback to the atmosphere? Some numerical simulations have indicated that the atmosphere can oscillate decadally despite fixed SST conditions[7,8], so perhaps ocean memory need not be invoked to explain such low-frequency climate oscillations. But if the cause is an internal atmospheric oscillation, it must be a rather specialized one: J. W. Hurrell and I (in work in preparation) have found that, to accord with the observed changes in the pattern of SLP, the atmospheric oscillation would need to have a strong recurrent winter signal that fades in spring and is completely forgotten in the subsequent summer and autumn, and, moreover, has no precursor in the preceding autumn. It seems more likely that long-lasting SST anomalies do indeed feed back to force such atmospheric circulation anomalies on decade timescales.

The SST anomalies in question[9], now analysed by Sutton and Allen[1], propagate along with major ocean currents and circulation pathways, so that the sequestered heat anomalies are displaced downstream each time they are re-exposed to the atmosphere. This propagation is slow, but remarkably persistent. Sutton and Allen document a nine-year majestic march of SST anomalies, starting off the Carolinas of North America

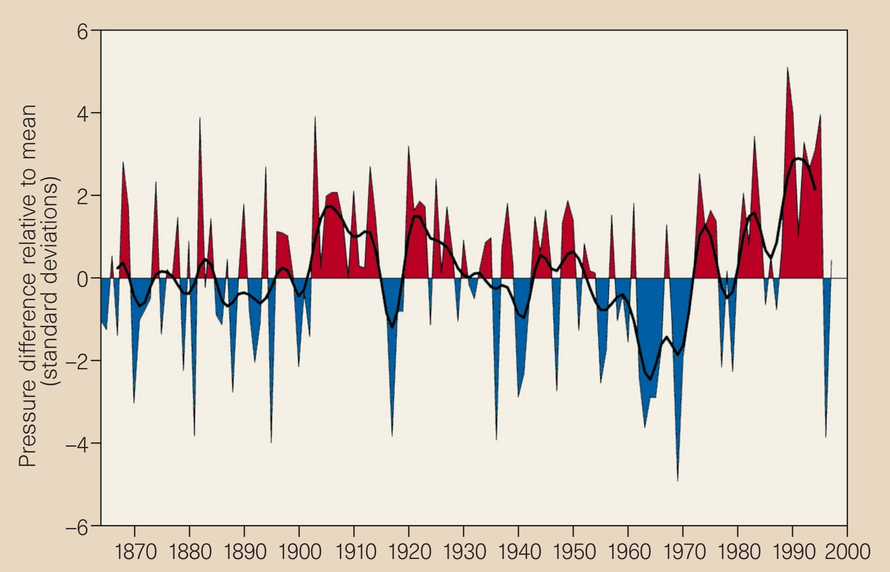

Figure 1 **Winter North Atlantic Oscillation index, based on the difference of normalized sea-level pressures (SLP) between Lisbon and Stykkisholmur (in Iceland) (ref. 3 and J. W. Hurrel, personal communication). The heavy curve is the same record smoothed with a low-pass filter to remove fluctuations with periods of less than four years. This long-term variability in the westerly winds may be driven by temperature variations in the ocean.**

and moving to southeast of Iceland. It would take a very contrived and special sequence of atmospheric conditions to produce air–sea heat-exchange anomalies that would yield this pattern. Comparing the NAO index of westerly wind strength (Fig. 1) with Sutton and Allen's time series of SST anomalies (Fig. 2a on page 565), I am struck by the remarkable correspondence of the period of declining NAO index from the 1940s until 1970 with the strongest propagating warm anomaly; and of the period of rising NAO index from 1970 to 1995 with the strongest propagating cold anomaly.

The SST evidence does have a somewhat curious aspect: the propagation speed of the SST anomalies, a few centimetres per second, is much slower than the principal currents involved, the Gulf Stream and North Atlantic Current. Three things contribute to that sluggishness. First, the SST anomalies are considerably wider than these currents; they span areas south of the currents where parts of the subtropical gyre are much slower and sometimes even flow westward rather than eastward, in compact recirculation cells adjacent to the main flow[10]. Second, because the strong currents meander over weeks to months, water parcels travelling in the current do not necessarily travel far eastward before being exchanged for other parcels to the south of the currents[11], and it is along such trajectories that parcels exchange heat with the air. Finally, water parcel speed and temperature propagation speed are not the same thing. Downstream cooling of the flow causes isotherms to be 'left behind'. Upstream or downstream isotherm displacements, and thus SST anomalies, could result from a fixed flow of water encountering increased or diminished cooling by the atmosphere, or from diminished or increased rate of flow of water with fixed atmospheric cooling, or a combination of both.

Climatologists have tended to think of the North Atlantic Oscillation as a mid-latitude-only phenomenon, disconnected from tropical Atlantic SST and climate change. Sutton and Allen's analysis shows wide-ranging SST anomalies that seem organized from Equator to subpolar sea. SST anomalies off the Carolinas of North America in the western subtropical gyre — the mid-latitude 'storm-formation region', as Sutton and Allen call it — appear to give rise to the slow-moving SST anomalies arriving in the eastern subpolar gyre about a decade later, and are correlated with the appearance of the same sign of anomalies in the tropical Atlantic after about six years. This has two important ramifications.

First, it shows that the SST anomalies and linked SLP anomalies are involved in a whole-ocean oscillation, a result anticipated in earlier studies[12,13]. Second, the linking of subtropical and tropical North Atlantic SSTs may be of particular relevance to climate forecasting. Warm conditions in the tropical North Atlantic since 1995 have been linked to the production of more tropical storms and hurricanes[14], and earlier work ties the same area to decadal changes in rainfall in north Africa and northeastern Brazil[15].

The demonstration of covarying SST and SLP fluctuations is evocative of a whole-ocean phenomenon, a North Atlantic atmosphere–ocean oscillation, against which attempts to simulate coupled atmosphere–ocean oscillations will be compared. Can a signal be extracted from observations that will finally confirm or deny the existence of ocean-to-atmosphere coupling? More tantalizingly, will the orderly behaviour of SST fluctuations help us to predict the aspects of climate over land that we really care about? ☐

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Carbon cycle

Inside the black box

Richard Norby

In an atmosphere in which levels of CO_2 are much higher than today, will terrestrial ecosystems accumulate more carbon or will they just process it faster? The answer to this apparently simple question has profound implications for the issue of how far the terrestrial biosphere can mop up carbon emitted to the atmosphere as CO_2 from fossil-fuel combustion. On page 576 of this issue[1], Hungate *et al.* conclude that, in two grasslands exposed to CO_2 at twice the ambient concentration, carbon cycles through the systems faster, but accumulation increases little. Consistent with model projections[2], the experimental results indicate that the net increase in carbon uptake observed in the short term probably does not reflect the potential for long-term carbon storage in grasslands.

The experiment was conducted on two different soil types at the Jasper Ridge Biological Preserve in northern California. After three years' exposure to ambient or twice-ambient CO_2, the CO_2-enriched systems contained significantly more carbon, primarily in roots, detritus (dead plant material) and soil microorganisms. But total soil carbon did not increase.

Could the transfer of carbon below ground eventually lead to a long-term increase in soil organic matter, or was the carbon mostly transferred to labile, short-lived pools? Using a mass-balance analysis of the annual carbon fluxes, Hungate *et al.* found that higher levels of CO_2 primarily stimulated the annual losses of carbon through root respiration, turnover and exudation of organic carbon. Direct observations of root turnover using miniature cameras in tubes inserted into the soil, and an independent assessment of respiration in a ^{13}C-labelled microcosm, suggested that the

Figure 1 **The Jasper Ridge CO_2 experiment, carried out by Hungate *et al.*[1], showing some of the field chambers on serpentine soil. (Photo by J. Canadell.)**