

## Palaeoclimate sensitivity

SIR — Those studying global warming generally define climate sensitivity as the response of the globally and annually averaged temperature to a doubling of CO<sub>2</sub>. Such a quantity is, in theory, well defined, but to assume that major climate regimes in the past arose from such simple forcing is unjustified. To use past climate to infer sensitivity to a doubling of CO<sub>2</sub>, as was done recently by Hoffert and Covey<sup>1</sup>, is equally unjustified. In their Fig. 2, both the warmer and colder climates considered may have had tropical temperatures approximately the same as the current climate. But the differences in temperature between the tropics and high latitudes were very different. This, in turn, implies that these past climates were associated with very different north-south dynamic heat fluxes in the atmosphere-ocean system.

Such heat fluxes are important in at least two major respects: first, without them, the annually averaged pole-to-Equator temperature difference for the present climate would be about twice as great as it is<sup>2</sup>. Second, given that the Earth's major greenhouse gas, water vapour, varies greatly with latitude and altitude, it is impossible to calculate the net greenhouse effect without knowing where heat is deposited by the dynamic heat transports<sup>3</sup>. In addition, the atmospheric contribution to this heat transport is at least as great as that from ocean currents<sup>4</sup>, and is dominated by fluxes in winter<sup>5</sup>.

Dynamic fluxes depend on motions which in turn depend on spatial variations in heating. Thus, orbital variations are believed to have caused the cyclic glaciations of the past 700,000 yr (the Milankovitch hypothesis<sup>6</sup>). These variations involve very small changes in globally and annually averaged insolation, but give rise to major changes in the spatial distribution of heating. Atmospheric fluxes are likely to depend on the intensity of the Hadley circulation in the tropics<sup>7,8</sup>. This intensity, in turn, depends strongly on the displacement of the zonally averaged summer surface temperature maximum from the Equator<sup>9</sup>, and on the meridional sharpness of the zonally averaged temperature maximum<sup>8</sup>. The former is extremely sensitive to orbital parameters, whereas the latter depends greatly on the nature of monsoons. Monsoons clearly depend on the distribution of land and sea in the tropics; this was certainly very different during the mid-Cretaceous period considered by Hoffert and Covey<sup>1</sup>. Incidentally, neither of these two factors depends significantly on gross radiative

parameters like CO<sub>2</sub> concentration or solar constant — at least within the range of variation considered in ref. 1.

Hoffert and Covey's conclusion, that the existence of widely varying climatic states excludes the possibility of low sensitivity to doubling CO<sub>2</sub>, is only plausible for a one-dimensional Earth. For the real Earth, it ignores factors crucial to climate not included in the somewhat simplistic climate sensitivity appropriate to CO<sub>2</sub> increases. In particular, if an altered distribution of heating produces a large change in dynamic heat flux, then major changes in global climate may occur, even if the sensitivity to changing CO<sub>2</sub> is extremely small. Indeed, if it should turn out that the tropics are thermostatically stabilized<sup>10–12</sup>, then changes in forcing which are associated with little change in dynamic heat flux are likely to cause very little global change. The fact that the tropics appear to have remained at approximately the present temperature despite major changes in the Equator-to-pole temperature difference (and the associated heat flux out of the tropics) strongly suggests the presence of some stabilizing mechanism for the tropics.

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that the meridional temperature gradients decrease, and poleward heat flow increases, as global mean temperature increases<sup>2–5</sup>. This does not mean that changes in poleward heat flow cause significant warming, however.

The global energy balance must be satisfied. Near-linearity of longwave flux versus surface temperature<sup>6</sup> makes it unlikely that mere redistribution of surface temperature can affect global mean temperature much by changing planetary cooling. On the solar absorption side, the tropical cirrus shielding cited<sup>7</sup> by Lindzen is a negative feedback on temperature, whereas high-latitude ice albedo-temperature feedback is positive<sup>8</sup>. Because an increase in poleward heat flow cools the tropics while heating the poles, such heat flow could by itself lower planetary albedo. But how much would the Earth warm?

Fast albedo feedbacks are too weak to change global temperature significantly without global mean radiative forcing. That is why the 'old' Milankovitch theories fail (see below). Melting all the present-day sea ice can only increase global radiative forcing by ~ 2 W m<sup>-2</sup> (ref. 9). Our measured sensitivity of ~ 2.3 K per CO<sub>2</sub> doubling (4.4 W m<sup>-2</sup>) gives the corresponding global warming as ~ 1 K — too little to explain the ~ 9 K warmer Cretaceous without the greenhouse forcing used in our reconstructions. The much smaller sensitivities favoured by Lindzen could account only for a minuscule fraction of Cretaceous and Jurassic warmth.

Regarding the Hadley cell and monsoon conjectures, current research on Milankovitch forcing indicates a major role of feedbacks on the fast-response atmospheric variables (wind, temperature, moisture, snow and sea ice, clouds) from slowly-responding variables (ice volume, ocean currents, CO<sub>2</sub>)<sup>10</sup>. Orbital forcing driving an atmosphere model alone cannot simulate the initiation of a glacial cycle<sup>11</sup>, but can do so if the atmosphere is coupled to slow glacial dynamics (ref. 12 and M. E. Schlesinger, personal communication). Another serious problem with purely atmospheric dynamical models is that the hemispheres were out of phase with respect to the orbital precession cycle believed to have triggered the transition from the Last Glacial Maximum (LGM) deep freeze 11 kyr before present to Holocene warmth<sup>13</sup>. There is evidence that insolation changes somehow trigger changes in the ocean circulation, biological productivity and alkalinity carbon pumps regulating atmosphere/ocean partitioning of CO<sub>2</sub>, a greenhouse gas<sup>14–17</sup>. Coupling with slow ice sheet and ocean feedbacks can account for orbitally-paced planetwide changes of temperature and CO<sub>2</sub> recorded in ice cores in ways that

purely atmospheric models cannot.

We used reconstructions of ice sheets and compositions in ice cores to derive the albedo and greenhouse forcing of the LGM at zero solar mean forcing<sup>1</sup>. With forcing and response known, whether CO<sub>2</sub> changes lead or lag climate changes<sup>18</sup> is irrelevant for deriving the climate sensitivity of the LGM.

The most convincing test of any theory is comparison with observations. Our objective is to improve models for the prediction of climate change by tests against palaeoclimate data. We reported early findings that the ratio of global mean temperature change to global mean radiative forcing is very similar for two very different past climates. Our analysis has been expanded to meridional response patterns and additional palaeoclimates. Such validations are necessary regardless of one's disposition towards the current generation of global climate models<sup>19</sup>. We hope Lindzen supports his ideas with quantitative models whose assumptions can be compared with observations. At this point we find his conjectures implausible when compared with the view that global mean temperature is determined by global mean radiative forcing, including (but not limited to) greenhouse forcing from CO<sub>2</sub> changes.

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HOFFERT AND COVEY REPLY — Lindzen challenges our derivation of global climate sensitivity<sup>1</sup> by suggesting that large climate changes could have resulted from changes in poleward heat flow and/or the seasonal and latitudinal distribution of sunlight, that is, by moving heat from one location to another. Such factors could certainly be the pacemaker of climate change, as in Milankovitch forcing. We believe, however, that significant globally averaged temperature change would ensue only if additional feedbacks from slowly responding elements of the climate system altered the global mean radiative forcing.

Palaeoclimate reconstructions indicate

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