parameters like CO_2 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_2, 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_2 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_2 is extremely small. Indeed, if it should turn out that the tropics are thermostatically stabilized[10–12], 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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HOFFERT AND COVEY REPLY — Lindzen challenges our derivation of global climate sensitivity[1] 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 that the meridional temperature gradients decrease, and poleward heat flow increases, as global mean temperature increases[2–5]. 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[6] 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[7] by Lindzen is a negative feedback on temperature, whereas high-latitude ice albedo–temperature feedback is positive[8]. 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^{-2} (ref. 9). Our measured sensitivity of $\sim$ 2.3 K per CO_2 doubling (4.4 W m^{-2}) 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_2)[10]. Orbital forcing driving an atmosphere model alone cannot simulate the initiation of a glacial cycle[11], 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[13]. 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_2, a greenhouse gas[14–17]. Coupling with slow ice sheet and ocean feedbacks can account for orbitally-paced planetwide changes of temperature and CO_2 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[1]. With forcing and response known, whether CO_2 changes lead or lag climate changes[18] 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[19]. 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_2 changes.

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