COMMENTARY

Hot climates, high sensitivity

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Climate sensitivity is the Holy Grail of climate science; because CO_2 is one of the principal control knobs for climate, sensitivity to changes in atmospheric CO_2 concentration is of particular interest. This sensitivity is typically characterized by the change in global mean temperature per doubling of concentration. Because the determination of climate sensitivity is plagued by uncertainties about the operation of various feedbacks in the climate system—notably cloud feedback—it is natural to look to the past for clues about how well we can model those feedbacks. The chilly climate of the Last Glacial Maximum has been extensively exploited for this purpose (1), but the high CO_2 hothouse climates such as the Pliocene (∼5 Mya) or Eocene (∼55 Mya) may be better analogs for where we are headed with our present adventure in turning fossil fuels into atmospheric CO_2. In this issue, Caballero and Huber (2) throw some cold water on this hot topic by providing evidence that hothouse states may have different climate sensitivity per doubling of CO_2 than the present state. None of this means that study of past hot climates is worthless in the Grail quest; it means only that the Parsifals of climate will have to work harder to extract the treasure. Better information about the past wouldn't hurt either. As Caballero and Huber note, there have already been great strides in understanding the magnitude and pattern of warmth in hothouse climates, which have helped resolve some earlier modeling paradoxes, but much remains to be done. In particular, narrowing the broad error bars on past atmospheric CO_2 is crucial to relating these climates to what is going on at present.

The origin of the state dependence of climate sensitivity is translated into geometric terms in Fig. 1. The temperature of the Earth is determined by the point at which the curve representing infrared loss to space [Outgoing Longwave Radiation (OLR)] as a function of temperature crosses the curve representing the amount of solar radiation absorbed; the latter depends on temperature through changes in clouds and ice cover. Increasing CO_2 brings down the OLR curve by an amount ΔF—the radiative forcing. The planet must then warm up to bring the energy budget back into balance. Climate sensitivity is determined by the relative slopes of the two curves at the crossing point; when the curves are nearly parallel, a large warming is required to make up for a given ΔF. Linear, or state-independent, sensitivity analysis treats the OLR and solar absorption curve as straight lines, whereas curvature allows the sensitivity

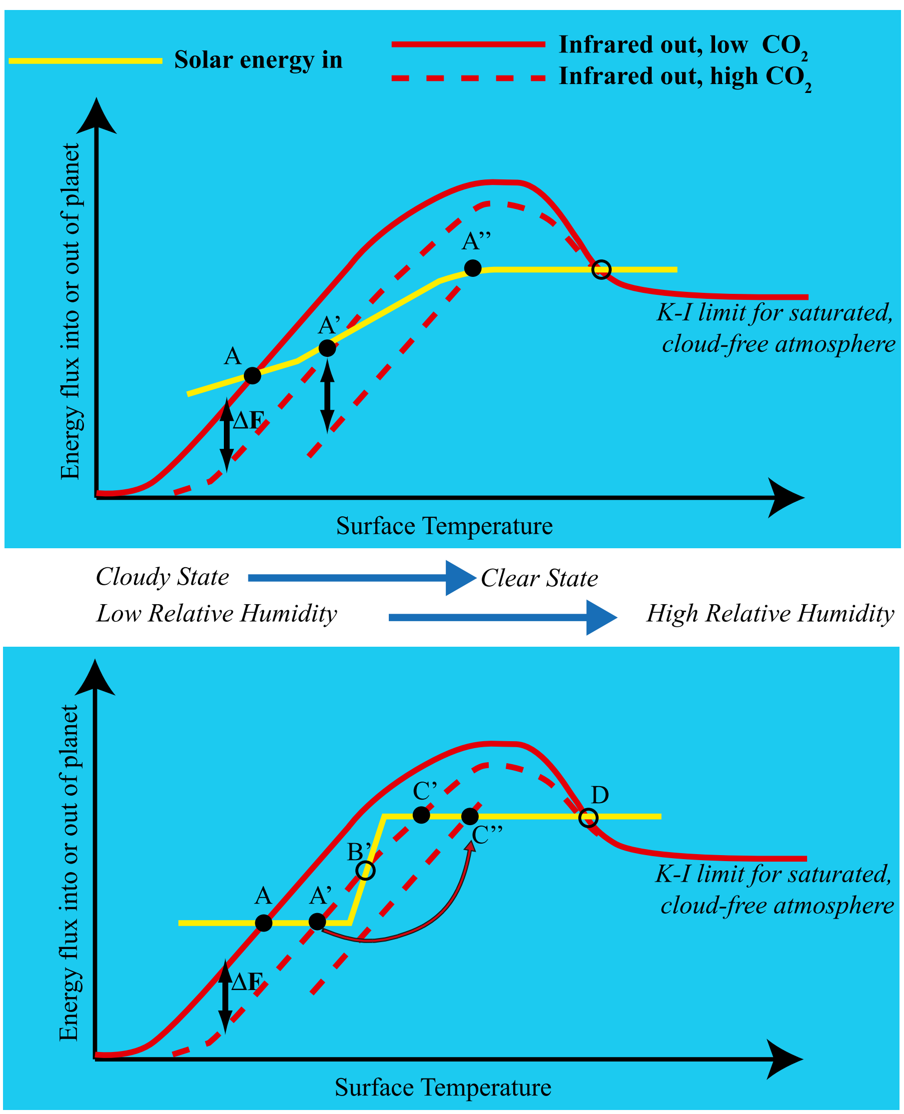

Fig. 1. Schematic of the way the Earth's energy budget introduces state-dependent climate sensitivity in ref. 2. Filled circles represent stable equilibrium climates, and open circles represent unstable equilibria. (*Upper*) Case in which the transition to a less cloudy state is smooth. (*Lower*) Hypothetical transition via a bifurcation, or "tipping point." The sharp reduction in outgoing infrared at high temperatures depicted here would occur as a result of relative humidity approaching 100% (saturation) in very warm climates. If the yellow solar absorption curve lies above the K-I limiting flux (which is a matter of speculation at present), then a runaway greenhouse would occur if the Earth's temperature was ever displaced beyond state *D*.

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to depend on the unperturbed state. In ref. 2, the state dependence arises primarily from curvature in the solar absorption curve, which in turn is tied to dissipation of low clouds when temperature increases. This situation is represented in Fig. 1, *Upper*, where it is seen that even if each doubling of CO_2 produced equal radiative forcing ΔF, the warming in going from state A to A' in the first doubling is less than that going from A' to A'' in the second doubling.

An additional factor in ref. 2 is that the radiative forcing ΔF per doubling of CO_2 is not constant as it would be for pure logarithmic behavior, but increases with CO_2. (Note that in ref. 2, "efficacy" refers to warming per doubling rather than the more conventional warming per unit radiative forcing as introduced in ref. 3). Deviations from the canonical logarithmic law arise mostly from the detailed spectral absorption properties of CO_2; they are well understood (4), but their importance has often been overlooked in earlier studies of hothouse climates. This effect can be easily allowed for when inferring climate sensitivity from hothouse climates, but Caballero and Huber find that, in addition, there is a contribution to the effective radiative forcing from "ultra-fast" cloud feedbacks, which are more problematic. The fast cloud feedbacks associated with the transition to the less cloudy state as the world warms are yet more problematic.

The transition to the less cloudy state needs not be smooth as depicted in Fig. 1, *Upper*. If the dependence of cloud albedo is sufficiently sharp, one gets a bifurcation or tipping point leading to multiple equilibrium states, in a manner analogous to the Snowball bifurcation (5), which arises from temperature-dependent ice-albedo feedback. In Fig. 1, *Lower*, a moderate increase in CO_2 leads to a smooth transition from state A to state A', but a further increase causes the continuation of A' to cease existing, whereafter the climate makes a discontinuous transition to the much warmer state C''. It is not clear yet whether the transition in ref. 2 is more like the upper or lower panel, but the character of the behavior is one of the things that are likely to differ from one model to another and would tend to cloud inferences of climate sensitivity from hothouse climates.

However, what lurks to the right of state D in Fig. 1? Here there (may) be dragons. At very high temperatures, the atmosphere is

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dominated by water vapor, and an extreme form of water vapor feedback causes the OLR to asymptote to a limiting value, which I prefer to call the Kombayashi-Ingersoll (K-I) limit, in honor of the investigators who first recognized the significance of a limiting OLR for the evolution of the climate of Venus (this is referred to instead as the Simpson-Nakajima limit in ref. 6). If the limiting solar absorption allowing for cloud dissipation was to lie above the K-I limit, then the Earth would be subject to runaway warming and succumb to the fate of Venus if the temperature were ever made warmer than state D. Although we are protected from runaway by water vapor subsaturation and cloud albedo in the present climate (and evidently in past hothouse climates as well), the disconcerting possibility that present Earth conditions could support a runaway as an alternate climate state has received support from recent revisions in calculations of the limiting infrared and solar fluxes (6, 7). The simulations of ref. 2 and other simulations cited therein do not show any indication of the transition to a runaway state even at very high CO_2, and simulations of post-Snowball hothouse climates similarly do not run away (5). In ref. 6, it is estimated that triggering a runaway under modern conditions would require CO_2 in excess of 30,000 ppm, and even that estimate is still speculative. The possibility of a runaway, however, highlights the need for a better understanding of the behavior of clouds and humidity in very warm climates. The answer would have implications for habitability of exoplanets, as well as for the distant (but hopefully not near) future of our own planet, as the sun continues to brighten.

One sure solution to the problem posed by uncertainty of climate sensitivity in hot climates is simply not to go there. Unfortunately, it looks increasingly like Nature will step in to answer some of our questions for us, and I doubt we'll like the answer. The highest emission scenario currently being considered by the Intergovernmental Panel on Climate Change is Representative Concentration Pathway 8.5 (8), which would bring CO_2 concentrations up to 2,000 ppm, which is in the upper reaches of the range considered in ref. 2. Even this scenario can be considered somewhat optimistic, in that it assumes that the annual growth in CO_2 emissions rate (which has been hovering around 3% for decades) will tail off by 2060 and that the emissions rate will cease growing altogether by 2100, whereafter emissions will trend to zero; unrestrained growth could easily dump twice as much carbon into the atmosphere. It is not known if there are actually enough recoverable fossil fuels to emit that much CO_2. Hoping that we run out of fossil fuels before bringing on a climate catastrophe does not seem like sound climate policy, but at present it seems to be the only one we have.

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