Comments and Reply on " 'Equable' climates during Earth history?"

COMMENT

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In their conclusions, Sloan and Barron (1990, p. 492) stated that "if unequivocable [sic] data indicating warmth well within continental boundaries at high or middle latitudes can be found, these data would be crucial and would indicate either a fundamental flaw in our knowledge of the climate system or a lack of understanding of the factors that have influenced climate in Earth history."

Sloan and Barron seem to have overlooked the wealth of published paleontology and paleobotany studies that demonstrate emphatically that there were "warmer winters" in the western interior of North America for at least the later Cretaceous through much of the Cenozoic. There are so many published data, in fact, that it is difficult to decide what to mention.

To cite just one such paper, Hutchison (1982) tracked turtle, crocodilian, and champsosaur diversity through the Cenozoic in western North America. His study area was within lat 40° to 48°N and long 99° to 111°W. Although he discussed various aspects of the ecology of these reptiles through the Cenozoic, the most important (relative to the ideas of Sloan and Barron) pertain to the temperature tolerances of large (>30 cm), nonburrowing tortoises. Referring to the tolerances of these large, terrestrial tortoises, Hutchison noted that "The average winter temperatures are therefore interpreted to be well above freezing (13 °C or above) and produce only light frosts. . . ." There is no basis to believe that tortoises and myriad other animals and plants have greatly modified their temperature tolerances in recent time. Accordingly, the subfreezing winter lows proposed by the simulations of Sloan and Barron are greatly at odds with what is well known from paleontologic data.

COMMENT

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On the basis of four computer simulations, Sloan and Barron (1990) suggested that continental interiors experienced climates with a high degree of seasonal temperature fluctuation during Cretaceous and Eocene time. They also stated that "actual continental-interior data that could be used to test this hypothesis are rare" (p. 492), even though the premise of their article is to challenge previous "hypotheses of warm, equable climates in mid-latitude continental interiors" (p. 489). We summarize here some published paleontological data and conclusions that prompted earlier hypotheses of climatic equability, but that were largely ignored by Sloan and Barron. These data refute Sloan and Barron's simulation cases 1–3, and cast doubt on case 4 because they indicate warm winters and relatively high mean annual temperature in continental interiors.

There are more than 560 Late Cretaceous and Paleogene fossil localities in western interior North America between paleolatitudes 30° and 55°N (Cretaceous mammals—25, Clemens et al., 1979; Paleocene-Eocene mammals—160, Archibald et al., 1987; Krishtalka et al., 1987; Cretaceous plants—78, McClammer and Crabtree, 1989; Paleocene-Eocene plants—300, Brown, 1962; Wing, 1987). Observations and paleoclimatic inferences based on these localities (Table 1), provide a test of Sloan and Barron's prediction that the −3 °C isotherm would have crossed western interior North America at about lat 45°N (Sloan and Barron, 1990, Fig. 2, cases 1–3).

Overall, paleontological evidence from the northern Rocky Mountain region, at ~45°N, strongly implies minimum temperatures of ~0 °C, cold-month mean temperatures of 4.4–13 °C, mean annual temperatures of 13–17 °C, and only moderate temperature seasonality during the 55–50 Ma period. The presence of large nonburrowing tortoises, palms, tree ferns, and dicot trees lacking strong seasonal growth rings cannot be reconciled with Sloan and Barron's prediction of sustained temperatures below freezing and a high degree of seasonal temperature fluctuation. These forms are currently excluded from such climatic regimes by basic anatomical and metabolic features that almost certainly would have limited the ranges of their early Cenozoic relatives. In particular, paleobotanical evidence for climatic equability from the Yellowstone-Absaroka volcanic region strongly refutes Sloan and Barron's estimates, because the area probably had significant altitude during the early Eocene (Axelrod, 1968).

These paleoclimatic inferences for the northern Rocky Mountains pertain to the acme of Tertiary warmth based on the marine oxygen isotope record (Miller et al., 1987). Terrestrial fossils from the region imply cooler climate during the late Paleocene (e.g., Hickey, 1980; Rose, 1981) and mid- to late Eocene (e.g., Wing, 1987; Stucky, 1989) than during the early Eocene. However, the paleontological evidence for the entire Tertiary prior to ca. 34 Ma is for warm, equable climate with little frost in the low to moderate paleoaltitude areas of the northern Rocky

TABLE 1. OBSERVATIONS AND PALEOCLIMATIC INFERENCES, WESTERN NORTH AMERICA

Observation	Paleoclimatic inferences	Data source
Cretaceous and Paleogene palms in northern Wyoming	Minimum temperature >-4.5 °C	Brown (1962), Wing (1987)
Early Eocene tree-ferns in northern Wyoming, Yellowstone National Park, and North Dakota	Minimum temperature about 0 °C, even at paleoaltitude of about 1 km	Hickey (1977), Wing (1987)
Strong taxonomic similarity between Eocene northern Rocky Mountain floras and extant subtropics	Generally warm-temperate to subtropical climate	MacGinitie (1974), Hickey (1977)
35%-65% entire-margined species in late Paleocene to early Eocene floras of northern Rocky Mountains	Estimated mean annual temperatures of 13-18 °C	Hickey (1977, 1980), Wing (1987)
Mixed seasonal and aseasonal growth patterns in early Eocene woods from Yellowstone National Park	Moderate seasonality at paleolatitude of about 45°N and paleoaltitude of about 1 km	Wheeler et al. (1977, 1978)
Large aquatic ectotherms in Paleogene southern Montana and Wyoming	Minimum cold-month mean temperature >4.4 °C	Hutchison (1982)
Diverse and large terrestrial ectotherms in early Eocene of northern Wyoming	Minimum cold-month mean temperature >13 °C; temperature rarely <0 °C	Hutchison (1982)
High mammalian diversity (>60 species in local faunas) in Paleocene-Eocene of northern Rocky Mountains	Subtropical to tropical climate; moderate seasonality of temperature and precipitation	Stucky (1989), Rose (1981)
Specialized arboreal and volant fruit eaters in Paleocene-early Eocene of northern Rocky Mountains	Year-round fruit production, moderate seasonality of temperature and precipitation	Olson (1987), Stucky et al. (1990)

Mountains. Paleocene and later Eocene paleontological evidence may be compatible with Sloan and Barron's case 4 climate simulation, which gives a value of 7 °C for the 100 day January simulation at ca. 45°N.

Although there is compelling evidence for warm, equable climate in the continental interior of North America, Pacific Coast floras probably grew in wetter, warmer conditions than roughly coeval floras of the northern Rocky Mountains (e.g., MacGinitie, 1941). Thus, paleontological data and climate models differ in the magnitude rather than the existence of cooler, more seasonal interior climates.

Sloan and Barron (1990, p. 492) closed their article by stating that "unequivocable data indicating warmth well within continental boundaries at high or middle latitudes . . . would indicate either a fundamental flaw in our knowledge of the climate system or a lack of understanding of the factors that have influenced climate in Earth history." Such data already exist in the paleontological literature. Paleoclimate models have increased our understanding of how climate systems work, and have raised the level of debate by providing testable quantitative predictions. However, it is counterproductive for paleontologists and climate modelers to proceed in isolation from, or ignorance of, each other.

REPLY

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We thank Archibald and Wing for their data citations. However, careful reading of our paper indicates that we are well aware of the abundance of existing data and their climatic interpretations. Indeed, this information provides the basis for the hypothesis that we addressed in our modeling study. Due to the succinct nature of papers published in *Geology*, we could not summarize or list all of the data, although we described the general character of such interpretations in our Introduction.

That data exist is not in dispute; Wing has catalogued 460 Paleocene-Eocene fossil localities to demonstrate this point. However, there is a question, and a key to this argument, regarding the significance and robustness of conclusions from the data. The Comments of Archibald and Wing illustrate the lack of understanding that exists between the subdisciplines of paleontology and paleoclimate modeling. Disagreement ultimately lies within *interpretations* of the paleontological data in a climatic context. We do not feel that this wealth of geologic information is beyond reinterpretation in light of paleoclimate modeling studies, just as we feel that our modeling efforts and understanding could be improved by consideration of robust paleontological data interpretations.

To more clearly illustrate the possible need for reinterpretation of both models and geologic evidence, and to illustrate the need for unequivocal data, we have mapped the Eocene positions (Sloan and Barron, unpublished) of three data sites in our original Figure 2 (Fig. 1 here). The study areas of Hickey (1977), MacGinitie (1974), and Hutchison (1982) are represented by a box in Figure 1 and referred to here as the "data site."

Examining cases 1 and 2, which, of the cases presented, most closely resemble reconstructed early Eocene surface conditions, the data site is located just inside the region bounded by the 270 K isotherm for average January conditions (Fig. 1). The lack of agreement between model results and data interpretations becomes uncertain under these conditions for several reasons that arise from both model and data considerations. In terms of the model, we noted in our original paper that "perpetual" January simulations may produce unrealistically cold surface temperatures because of the lack of a seasonal radiation cycle. We estimated a difference of ~4 °C for the continental interior in this area for the present day (warmer for a January simulated with a seasonal cycle) (Sloan and Barron, 1990, p. 492). A temperature difference of 4 °C would be important in the cases depicted here, because the data located at the freezing margin would then be located in a region with temperatures between about -3 and +2 °C. Whereas these temperatures are lower than the minimum temperature of 13 °C suggested by Hutchison (1982) for this region, they are nearly in agreement with other estimates of minimum surface temperature at this time.

January temperature estimates of -3 to +2 °C are close to the low end of the range of minimum temperatures estimated by Hickey (1977) from plant fossils for this region (6–13 °C), and are in keeping with at least one observation of winter temperature tolerance of +2 °C of modern alligators (*A. mississippiensis*) (Hagan et al., 1982). Interpretations of minimum temperatures from fossil plant data generally are closer to model estimates than are interpretations of the same condition from animal data. In addition, model estimates of mean annual temperature with the same surface boundary conditions as case 1 (Sloan and Barron, 1990) produce temperatures for the continental interior of North America that closely match paleobotanically derived estimates of mean annual temperature for the same region by both MacGinitie (1974) and Hickey (1977) (Sloan and Barron, unpublished). This correlation supports temperature results produced by the model, or at least demonstrates that model results are not "greatly at odds" with all paleoclimate interpretations from geologic data. Furthermore, the maps (Fig. 1) illustrate the importance of geographic position of the data sites for comparing observations with model results. Many of the data observations are near the margin of the 270 K isotherm predicted by the model. Clearly, our results have greater significance for regions well within the continental interior.

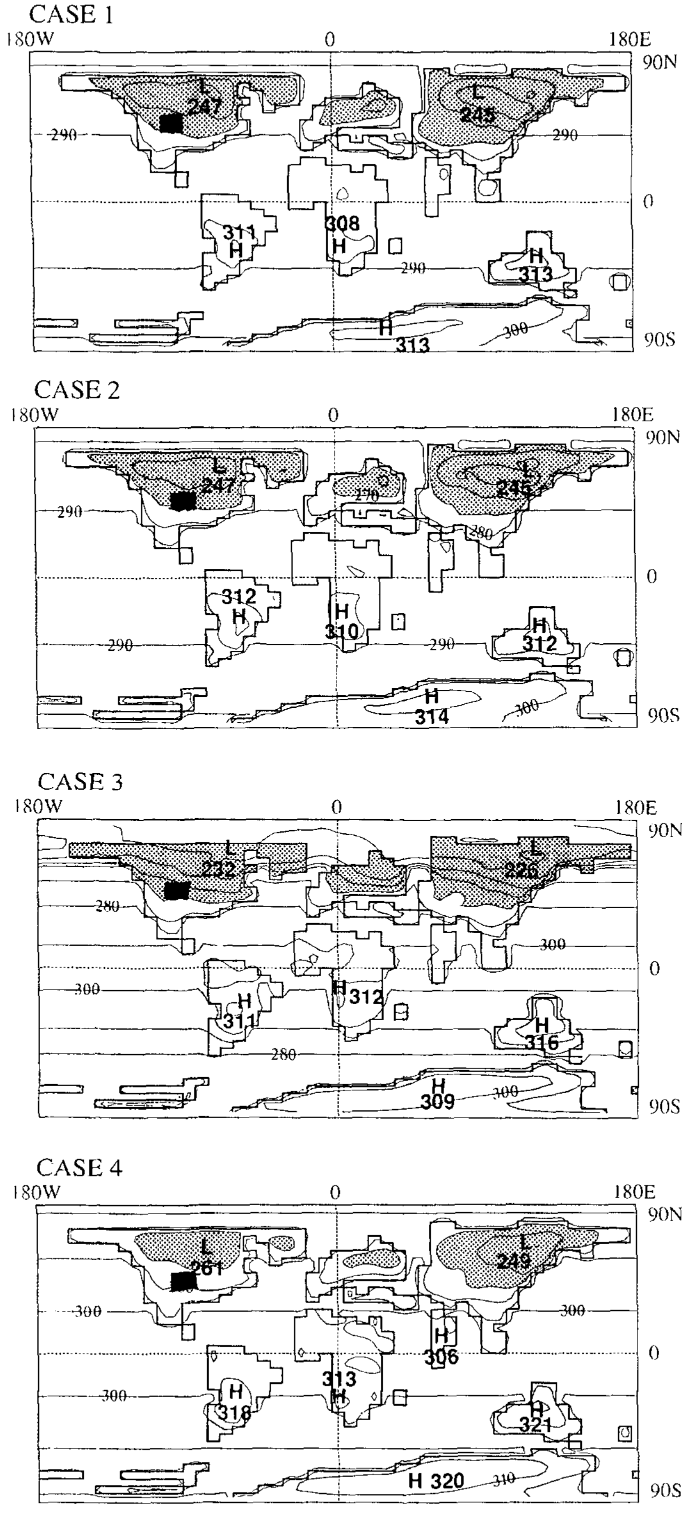

Figure 1. Surface temperature distributions for Eocene cases 1 through 4. Temperatures represent 100-day, time-averaged, model results. Dark rectangle on each map represents paleolocation of "data site" referred to in text. Shaded areas indicate surface temperatures less than 270 K. Temperatures are contoured at 10 K intervals; relative maximum (H) and minimum (L) temperatures are indicated in kelvin.

Both Archibald and Wing responded to our call for data to further define minimum surface temperature conditions for midlatitudinal continental interiors during the Eocene, but they do not, in our opinion, provide data of unequivocal nature. Whereas paleoclimatic interpretations from some of the data of Wing's Table 1 seem robust (e.g., the correlation between terrestrial turtles with carapaces greater than 30 cm in length and a 13 °C winter isotherm), empirical relations based upon correlation between modern climate conditions and fauna are characterized by many often-stated uncertainties with regard to their application to the geologic past. Many of the other observations and paleoclimate inferences either provide ambiguous climatic description, are based on weak assumptions, or are less than quantitative.

Unequivocal climatic indicators are needed because the conclusions regarding Eocene climate characteristics that have been drawn separately by paleontological studies and by climate modeling studies appear to be individually reasonable, and yet are not completely compatible. As shown by this example, and as noted by Wing, paleontological data and model results differ more in magnitude than in character of interpretations, at least for most issues. If we are to further our understanding of past climate systems and clarify discrepancies between paleontological interpretations and model-derived predictions, data from well within the continental interior (e.g., as defined by the regions bounded by the 280 K isotherm in Fig. 1) that are of an undisputable interpretive nature would be most helpful. We agree wholeheartedly with Wing's closing statement; an integrated approach to defining and deciphering past climate systems would be an ideal way to proceed.

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