Are There Any Satisfactory Geologic Analogs for a Future Greenhouse Warming?

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ABSTRACT

There have been numerous attempts to propose past warm time periods as "analogs" for a future greenhouse warming. In this paper it is argued that, although paleoclimate studies may provide important insights into processes operating in the climate system, there may be no warm time period that is a satisfactory past analog for future climate. The future greenhouse warming may represent a unique climate realization in earth history. This conclusion is based on the following considerations: 1) comparisons with Holocene (9000 BP) or Eemian climates (120 000 BP) may be inappropriate because much of the variations in these climates can be explained in terms of seasonal rather than mean-annual forcing; it has yet to be demonstrated that increased warmth for these intervals involved mean annual temperature increases that were globally synchronous, 2) comparisons with older and warmer climates (ex., Pliocene, Eocene, or Cretaceous) can be misleading because these warm periods had reduced polar ice cover, whereas future air temperatures will be very warm, but ice sheets will persist because of their large thermal inertia. Due to the different time scales for the atmosphere, deep ocean, and ice sheets, this significant nonequilibrium component to the future climate response is probably very different than the long time-averaged picture representative of past warm periods. Furthermore, changes in geography have probably significantly modified the atmosphere and ocean circulation during the earlier warm periods resulting in regional climates significantly different than what might occur in the future. It is therefore suggested that future discussions on geologic analogs be restricted to study of processes operating in the climate system and that continued use of the term for past warm time periods be abandoned.

1. Introduction

The future greenhouse warming threatens to be a climate change of large magnitude, with CO_2 doubling estimates for global temperature increases ranging from 1.8–5.2°C (Mitchell et al. 1989; Schlesinger 1989). Other radiatively important trace gases should also have a significant climate effect (Dickinson and Cicerone 1986). In the quest to determine what the climate might be like in the future scientists have sometimes suggested or cited past warm periods as a frame of reference or even possible analogs for our future warming (Kellogg 1977; Hansen and Lebedeff 1987; Budyko and Sedunov 1988; Zubakov and Borzenkova 1988). Regional climates for these warm periods have been thought of as snapshot views as to how regional climate may vary in the future.

Although the above suggestion seems reasonable, advances in our understanding of past and present climates have uncovered some significant problems in continued use of the term analog (c.f., Schneider 1984). This paper reviews the time periods most often cited as analogs and argues that, although paleoclimate studies can contribute much valuable insight into mechanisms of climate change, continued efforts to identify past, warm periods as analogs rest upon often unstated assumptions that are probably not valid. The future greenhouse warming may, therefore, represent a unique climate realization in earth history. These conclusions are based on analysis of the time intervals most frequently cited as analogs: 1) the early Holocene (6000 BP, years before present) and last interglacial (sometimes known as the Eemian, 120 000 BP), and 2) pre-Pleistocene warm periods—the Pliocene (about 3–4 Ma, million years ago), Eocene (~50 Ma) or mid-Cretaceous (~100 Ma). There are serious shortcomings in invoking any of these time periods as geologic analogs.

2. Comparisons with Pleistocene warm periods

a. Early Holocene (6000–9000 BP)

The geologic literature is replete with discussions that the early part of the present interglacial and also the past interglacial were warmer than the present. However, extensive studies of the early Holocene (COHMAP 1988) suggest that the warmth may have been primarily seasonal in nature over much of the northern hemisphere land masses, that times of greater warmth were not always globally synchronous, and that much of the warmth can be explained by variations in the

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seasonal cycle of insolation at the top of the atmosphere—the Milankovitch effect (Fig. 1). Modeling studies (Kutzbach and Guetter 1986; COHMAP 1988) indicate that changes in the seasonal cycle of insolation can cause significant seasonal changes of land temperature (1–3°C) in continental interiors (Fig. 2).

Statements about early Holocene warmth sometimes assume that conditions were uniformly warm globally. However, the geographic extent of early Holocene warmth needs to be better documented (Webb and Wigley 1985). Save for a few regions, sea-surface temperatures (SST) do not seem to be significantly warmer than the present. There is clear evidence for temperatures 1.0–2.0°C warmer in the high latitudes of the southern hemisphere (Hays et al. 1976; Jouzel et al. 1987; Clapperton et al. 1989), but these changes could also be due to Milankovitch forcing. Although it is sometimes assumed that orbital forcing is out-of-phase between the hemispheres this statement is true only for precessional forcing (~20 000 year period) during times of low eccentricity such as the last 80 000 years [during time of high eccentricity, precession response could theoretically dominate obliquity (tilt) response at high southern latitudes; c.f., Short et al. 1990]. Since forcing at the obliquity period (41 000 years) is in phase with the Northern Hemisphere, synchronous warming in the high-latitudes of the Southern Hemisphere may reflect this process. This point is illustrated in Fig. 3 by means of an energy balance climate model that has been used to calculate the surface temperature response to changes in orbital forcing at 80°S.

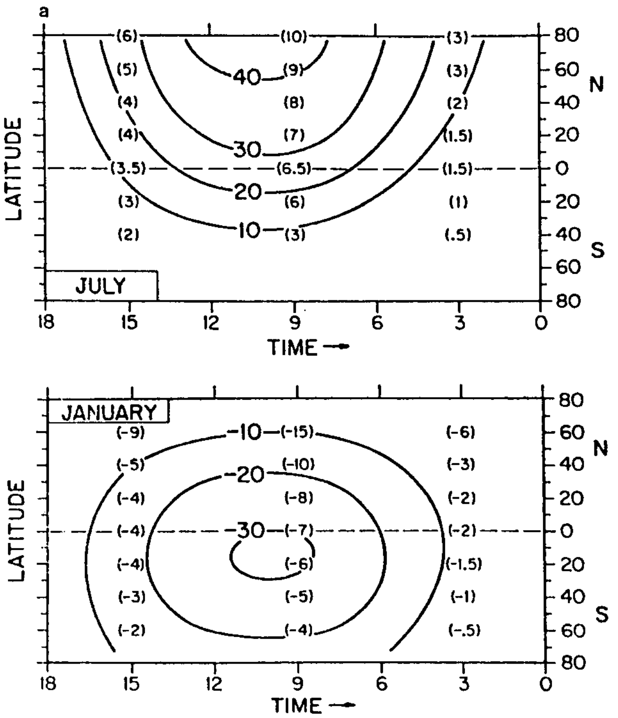

FIG. 1. Solar radiation departures (past-minus-present, in W/m^2) for July and January as a function of latitude and time (18 000 BP to present). The numbers in parentheses are the departures from present expressed in percent. [From Kutzbach and Guetter 1986]

Climate model studies indicate that the same orbital changes that caused summer warming in the northern hemisphere were associated with winter cooling in these regions and also a 0.1–0.3°C mean annual cooling in tropical SSTs (Kutzbach and Gallimore 1988; Hyde et al. 1989). The winter cooling has been only marginally documented, perhaps because many proxy climate indices may be biased toward recording a summer signal. The tropical cooling is below the detection limits of geologic data, but because of the area involved it can affect estimates of global mean annual temperatures. Figure 4 illustrates global mean temperatures over the last 18 000 years as calculated from two different modeling studies (Kutzbach and Guetter 1986; Hyde et al. 1989). Both studies show that even though Antarctic mean annual and northern hemisphere summer temperatures were warmer at 9000 BP the global mean temperature was within 0.1°C of the present value.

In order to get higher global mean temperatures at 6000–9000 BP the planetary energy balance would have to be modified, perhaps due to higher CO_2 levels, greatly reduced ice cover, or changes in clouds. Ice cores do not provide any strong evidence for large changes in either of the first two variables (Fig. 5) and the fluctuations of the latter are so problematical that we cannot say anything with confidence. Unless there are some other means to change the planetary energy balance it, there is at present no good theoretical justification for concluding that the global average annual temperature of the early Holocene was significantly different from the present.

To summarize, much of the Holocene temperature response may be explainable in terms of orbital forcing variations that in general had little effect on mean annual temperatures. Where increases in temperature were mean annual, changes could still reflect a localized circulation response to seasonal forcing. This analysis can be carried one more step to identify another potential problem with assumed greater warmth in the early Holocene; if global mean temperatures were warmer at 9000 BP we have no explanation for the warmth. That is, the climate system would be even more sensitive to forcing than indicated by models. Finally, even if the warmth were mean-annual it might still not be justifiable to use the interval as an analog for the seasonal cycle of insolation was clearly different from the present.

b. Last interglacial (120 000 BP)

The above reasoning applies equally well to the last interglacial (c.f., MacCracken and Kutzbach 1990). Seasonal changes in orbital forcing were greater than in the early Holocene, so climate models simulate larger summer warming in continental interiors (greater than

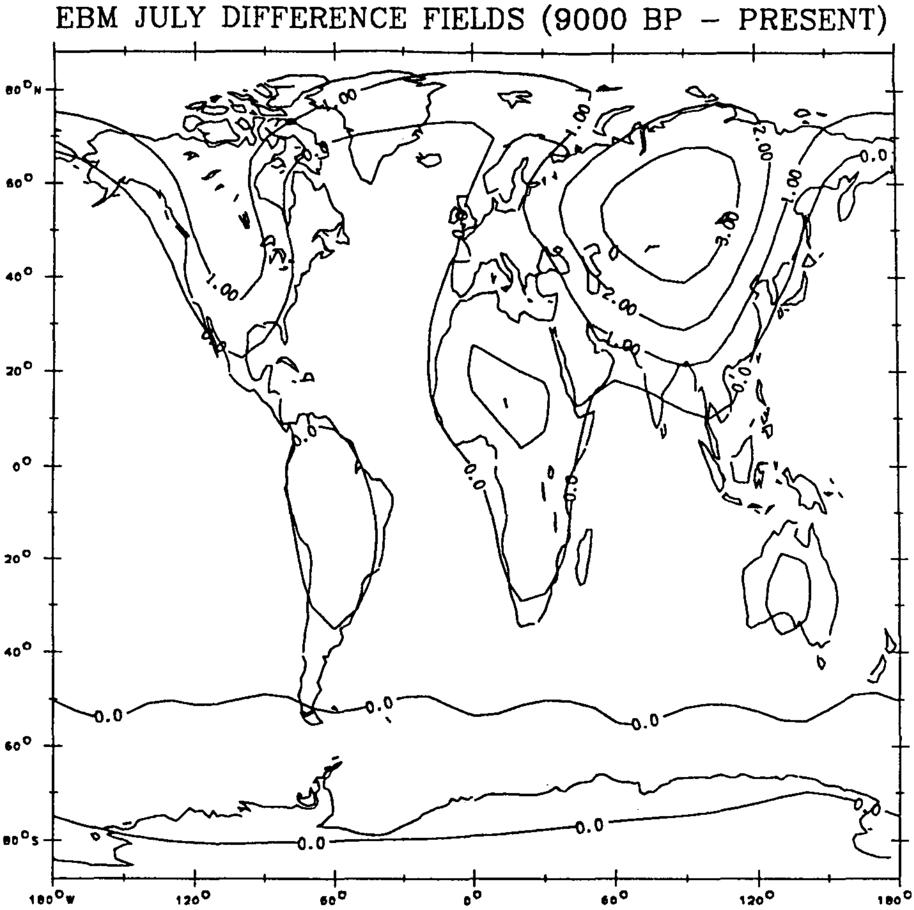

FIG. 2. Effect of altered radiation field at 9000 BP on surface temperatures. Figure illustrates temperature differences July temperatures (9000 BP minus present) as calculated by an energy balance model. July 9000 BP was warmer than the present in northern midlatitudes. Similar results are obtained from GCM runs (c.f., Kutzbach and Guetter 1986). [From Hyde et al. 1989]

4°C over a large part of Eurasia; c.f., Fig. 6). There also seems to have been some significant mean annual warming along the coast of northwest Europe (see summary in CLIMAP 1984) and Antarctica (Fig. 7). However, there is also evidence that these northern and southern hemisphere warming events were not synchronous (CLIMAP 1984). For example, southern hemisphere warming seems to have peaked very early in the interglacial while in some areas North Atlantic warming was significantly later (Fig. 8).

SSTs exert a strong influence on global average temperatures. Taken as a whole, SSTs for the last interglacial (Fig. 9) were not significantly different from the present (CLIMAP 1984). For the sites illustrated in Fig. 9, the average difference in SSTs (present minus 120 000 BP) is -0.05 ± 2.06°C ($n = 52$). There are a few regions (eastern boundary currents of North Atlantic and North Pacific) where last interglacial SSTs seemed to have been below present values (Crowley 1981; Muhs and Kyser 1987). Regional changes in mean-annual SSTs may reflect changes in the ocean circulation. For example, changes in the thermohaline circulation (c.f., Manabe and Stouffer 1988) can alter heat exchange between hemispheres; at present, export of cold North Atlantic Deep Water (NADW) across the equator is associated with import of approximately 1.0×10^{15} W of warm water from the South Atlantic to the North Atlantic (Hastenrath 1980). Since NADW production appears to have been less than the present during the last interglacial (Boyle and Keigwin 1985/1986), heat storage in the southern hemisphere should have increased. The above process might well apply to explaining some regional differences in SSTs between the present and past interglacials.

In some cases annual changes in SSTs could also result from Milankovitch forcing. For example, in high latitudes increased summer insolation results in net mean annual increases in insolation. GCM studies suggest that such changes reduce sea ice cover, leading to mean annual increases in SSTs (Kutzbach and Gallimore 1988; Mitchell et al. 1988). Changes in cloudiness might also increase midlatitude SSTs (Mitchell

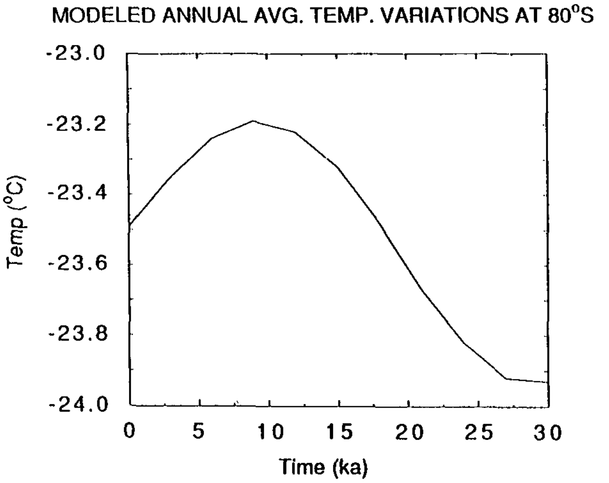

FIG. 3. Simulation of mean annual temperature changes in the high latitudes of the southern hemisphere (80°S) over the last 30 000 years. Calculation is from a two-dimensional energy balance model and refers to changes due only to orbital insolation forcing (c.f., Short et al. 1990). Note that the magnitude of the temperature range is probably less than would occur in more complicated models (c.f., Short et al. 1990), that the calculated temperatures do not include the effect of topography, and that the temperature peak in the early Holocene is in phase with northern hemisphere warming and consistent with ice core measurements from the same location (Jouzel et al. 1987).

et al. 1988). Finally, intense seasonal heating over land can lead to greater subsidence over the ocean (Prell and Kutzbach 1987), possibly causing a spinup of the wind-driven ocean circulation. Such a pattern was inferred for the North Atlantic gyre during the last interglacial (Crowley 1981), and could explain both increased transport of Gulf Stream waters into the Norwegian Sea (c.f., Kellogg 1980) and greater equatorward transport along the eastern boundary current. This response would cause net warming and cooling in these regions, respectively, thereby possibly explaining some of the regional differences in last interglacial temperature response previously described.

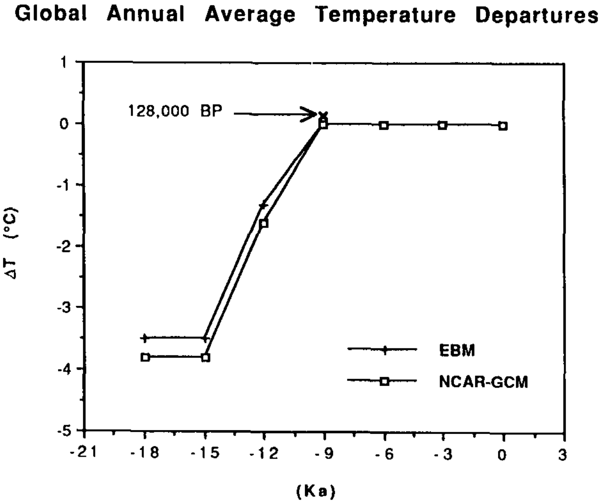

FIG. 4. Comparison of energy balance model and NCAR general circulation model simulations of global mean annual temperature departures from 18 000 to the present. Even though seasonal temperature changes at 9000 BP can be significantly different than the present (Fig. 2) global average temperatures at 9000 BP are essentially the same as present. The same is true for the last interglacial (= cross; 128 000 BP was chosen because this is the time of maximum departures of solar insolation forcing—c.f., Fig. 1). [9000 BP results from Hyde et al. 1989; 128 000 BP results from this study]

Utilizing the same energy balance climate model that agrees well with the NCAR model at 9000 BP (Fig. 4), calculated global mean temperatures at 125 000 BP are only 0.2°C warmer than the present. This conclusion assumes no significant changes in CO_2—an assumption consistent with ice core studies indicating that last interglacial CO_2 levels (Fig. 7) were comparable to the Holocene (280–290 ppm), except for a brief interval (1000–2000 years) when they were slightly higher (~300 ppm; Barnola et al. 1987) but still ~50 ppm less than present values. In order to find times when it was significantly warmer than the present the pre-Pleistocene era must be examined (section 3).

3. Comparisons with pre-Pleistocene climates

It is often stated in paleoclimate reviews (e.g., Crowley and North 1990) that climates were warmer during much of the 100 million year time period preceding the Pleistocene ice ages. This conclusion is based on evidence for displacement of fauna and flora into high latitudes and from ^{18}O measurements of benthic (bottom-dwelling) foraminifera, which show a steady decline through time (Fig. 10). The decline has been interpreted in terms of decreasing bottom water temperatures. Although some of the above climate changes have also been interpreted in terms of seasonal and geographic redistributions of heat (Shackleton and

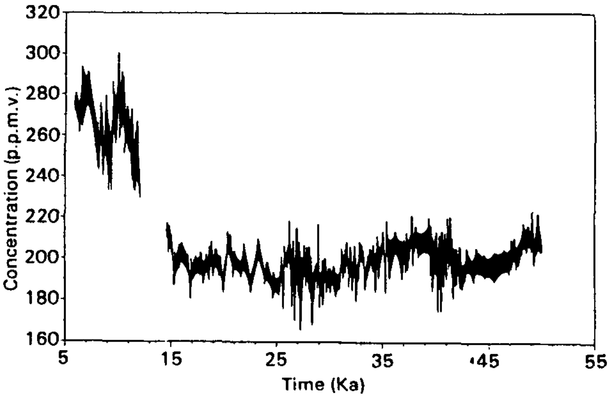

FIG. 5. Atmospheric CO_2 concentration in Byrd (Antarctica) ice core. Early Holocene levels (290 ppm) are only about 10 ppm higher than pre-industrial levels (c.f., Friedli et al. 1986). [From Neftel et al. 1988]

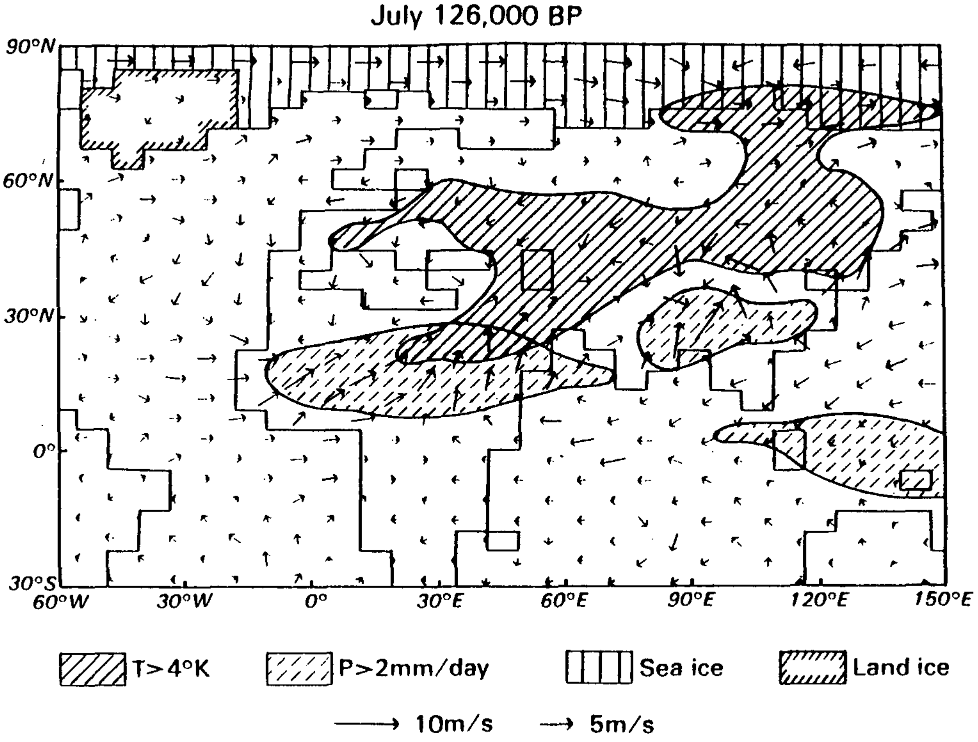

FIG. 6. Departures (experiment minus control) of surface temperature (T), winds (arrows), and precipitation (P) for the Indian Ocean sector for July 126 000 BP, illustrating the effect of increased summer insolation on T and P. [After Prell and Kutzbach 1987]

Boersma 1981; Crowley et al. 1986) most discussions conclude that global mean annual temperatures were probably higher (an important caveat to this conclusion is that our knowledge of past tropical SST changes, which strongly influence global mean temperatures, needs to be better constrained). If we accept the above conclusion we can use Fig. 11 to project back in time when it may be possible to find a suitable time period to examine as an analog.

a. General considerations

Even if some pre-Pleistocene time intervals were warmer than the present they still do not represent satisfactory analogs for future warming. This conclusion is based on two main lines of reasoning:

1) The time intervals being analyzed or proposed as "greenhouse analogs" presumably represent long time-averaged equilibrium climates with much reduced ice cover, whereas the future greenhouse perturbation will likely be out-of-equilibrium for a significant duration of its total effect (thousands of years). For example, polar ice sheets will still be present at least during the initial stages of warming (e.g., first millennium). The nonequilibrium nature of the future climate reflects the fact that the atmosphere and mixed layer ocean are being perturbed at a very high rate (~2–4°C/century). Yet the deep oceans and ice sheets, with response times one to three orders of magnitude longer than the atmosphere, are changing more slowly (e.g., Stouffer et al. 1989). The response time of the east Antarctic ice sheet is so long (perhaps tens of thousands of years; c.f., Whillans 1981) that this ice sheet may only start responding to the greenhouse warming *after* the CO_2 perturbation has been washed out of the system by buffering with the deep ocean carbonate reservoir.

Because the future climate will be out of equilibrium with the greenhouse gas radiative perturbation, which itself will be continuously changing, the planet will almost assuredly experience the bizarre combination of warm atmosphere/mixed layer ocean and polar ice sheets; i.e., a nonglacial atmosphere with glacial-age polar regions (because of its intermediate response time the deep ocean should be somewhere in-between in its adaptation to changing boundary conditions). There may be only one time period when polar ice caps and higher CO_2 levels may have co-existed—the Late Ordovician, 450 million years ago (c.f., Crowley et al. 1987). Even here the sequence of events, time scale considerations, adequacy of geologic deposits, and continental positions are so different from the present that we cannot feel secure in citing this time as an analog.

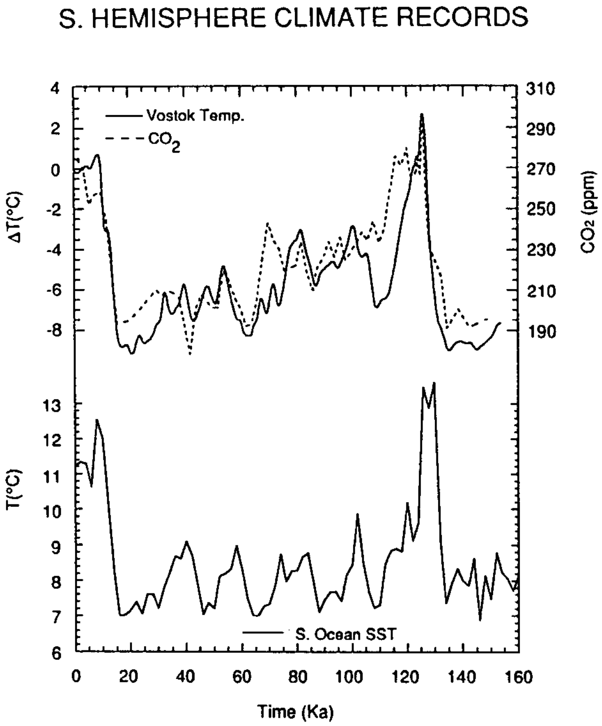

FIG. 7. Comparison of high latitude southern hemisphere records for the present and last interglacial with the ice core CO_2 record from Vostok, Antarctica. Both the Southern Ocean SST and ice core temperature record indicate warmth greater than the present at the last interglacial. However, the warmth was apparently not synchronous with some of the best documented examples of warmth in the northern hemisphere (c.f., Fig. 8). Note that CO_2 values are comparable for both the present and past interglacial. [SST record from Martinson et al. 1987; ice core deuterium record from Jouzel et al. 1987; CO_2 record from Barnola et al. 1987; ice core chronology plotted according to revisions of Petit et al. 1990]

2) There were significant differences in geography 330that raise serious questions about the appropriateness of past warmer climates as analogs for the future. During the last 100 million years there has been a general drift of land into the high latitudes of the northern hemisphere and changes in continental areas (e.g., Fig. 12) which should have had a significant effect on atmospheric temperatures (Barron 1985; Crowley et al. 1986). Opening and closing of "oceanic gateways" has also probably significantly affected ocean heat transport. For example, ocean GCM calculations (Fig. 13) indicate that an open Central American isthmus may have greatly reduced poleward ocean heat transport and thermohaline overturn in the North Atlantic (Maier-Reimer et al. 1990). Finally, there has been uplift of major mountain ranges such as the Alps, Himalayas, and Rocky Mountains in the time interval under consideration (Ruddiman et al. 1989). Uplift of the mountains could have a significant effect on the atmospheric circulation (Kutzbach et al. 1989; c.f., Mullen 1989). When all of these geographic effects are considered together it is evident that, even if global temperatures were warmer, the regional climate patterns may have been significantly different than what we might experience in the future.

b. *Application of general arguments to some pre-Pleistocene warm intervals*

The above general statements can be applied to the most commonly cited warm intervals of the last 100 million years—the Early Pliocene (~3-5 Ma), the Early Eocene (~50 Ma), and the mid-Cretaceous (~100 Ma). The Middle Miocene (~15-17 Ma) is another warm interval, but we have less information on global syntheses from both land and sea for this time than for some of the other three time intervals.

1) EARLY PLIOCENE (~3-5 Ma)

The Early Pliocene warm interval preceded slightly the rapid onset of midlatitude northern hemisphere glaciation at about 2.5 Ma. Various geologic evidence indicates that conditions were perhaps at least seasonally 10°C warmer than the present in high northern latitudes (c.f., summaries in Zubakov and Borzenkova 1988 and Raymo et al. 1990), Greenland and Arctic ice cover were probably reduced, and circum-Antarctic SSTs were perhaps 6°-10°C greater than present (Cieselski and Weaver 1974). Sea level may have been at least 30 m higher (c.f., Haq et al. 1987)—a result consistent with inferred decreases in both Greenland and Antarctic ice cover (Webb et al. 1984; Funder et al. 1985).

Despite its relative closeness to the present the Early Pliocene would differ from a future greenhouse warm-

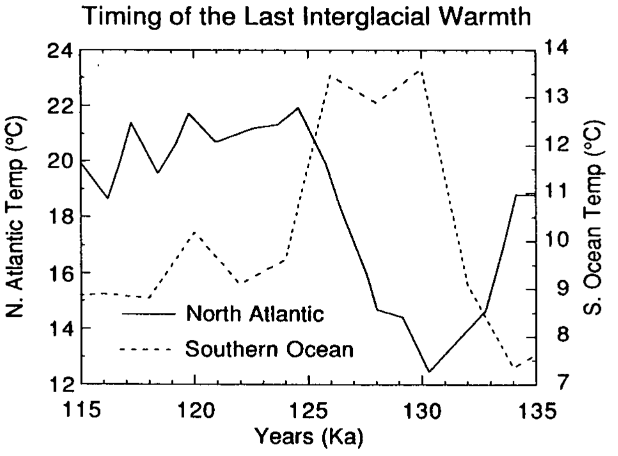

FIG. 8. Comparison of the timing of peak warmth during the last interglacial in the North Atlantic and southern hemisphere. North Atlantic record from Ruddiman and McIntyre (1981), southern hemisphere record from Martinson et al. (1987). Peak warmth does not occur synchronously in the two cores, a response that may reflect redistributions of heat by the ocean–atmosphere system. Note that this separation in timing may not be as dramatic in all records.

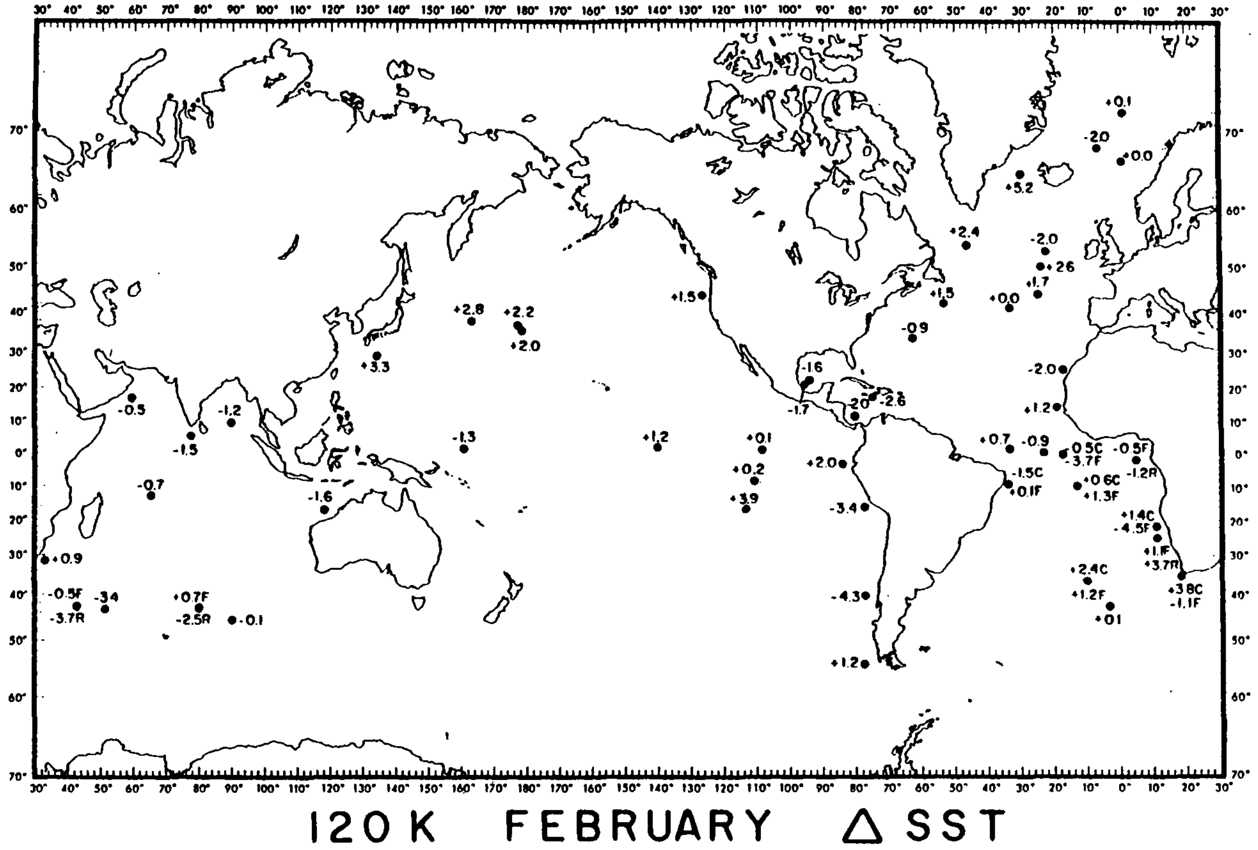

FIG. 9. Difference between modern sea-surface temperature and estimated February sea-surface temperature (in °C) at the last interglaciation 120 000 years ago. Negative values mean that the last interglacial ocean was colder than today. Most SST values are similar to present; any spatially coherent increases in one region are more or less offset by equivalent decreases in other areas. [From CLIMAP 1984]

ing in the following respects: 1) reduced ice sheet cover would not occur in the near future, 2) there may have been substantial uplifts in western North America and the Tibetan Plateau in the last few million years (Ruddiman et al. 1989), 3) the Central American isthmus was just on the verge of closing (c.f., Maier-Reimer et

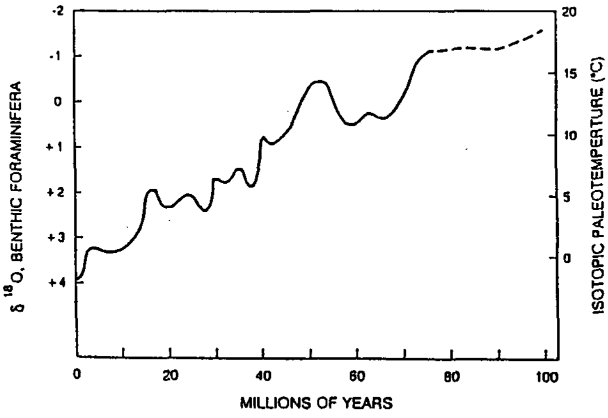

FIG. 10. Oxygen isotope record over the last 100 million years. The record has been interpreted primarily to indicate past changes in deep water temperature. It is assumed that very warm deep waters are incompatible with extensive ice cover in polar regions, a conclusion consistent with other geologic data from high latitudes (c.f., Crowley and North 1990). [After Douglas and Woodruff 1981]

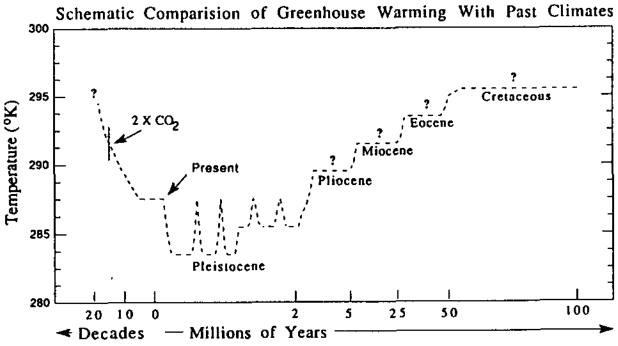

FIG. 11. Schematic comparison of future greenhouse warming with past changes in temperature. Note that Pleistocene climate oscillations are idealized and that interglacial temperatures were probably not significantly warmer than present (see text). Pre-Pleistocene changes are not well-fixed in magnitude, but their relative warmth is approximately correct. Maximum warming in the Cretaceous based on estimates by Barron and colleagues (Thompson and Barron 1981; Barron and Washington 1985). Time intervals in between have been scaled accordingly. [From Crowley 1989]

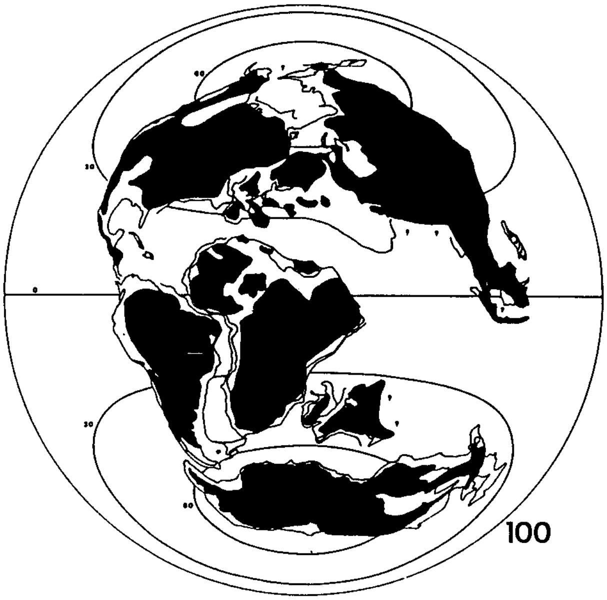

FIG. 12. Paleogeographic reconstruction at 100 Ma. Light areas on continents indicate regions flooded by shallow seas (maximum depth 100–200 m). [After Barron et al. 1980]

al. 1990); i.e., there may have been some differences in ocean circulation response between the Pliocene and future warm periods (Fig. 13). Thus, the criteria laid out as critiques for pre-Pleistocene analogs has been met.

2) EARLY EOCENE (~50 Ma)

This interval is a particularly interesting time from an observational viewpoint. Temperatures were substantially warmer in high latitudes of both hemispheres (see summary in Crowley and North 1990) and bottom waters were ~15°C—results incompatible with extensive high latitude ice cover. Sea level was at least 75 m greater than the present, flooding a number of low-lying regions especially in North America and Europe. In addition, there was an extensive seaway south of Europe and Asia—the Tethys Sea (c.f., Fig. 12). Perhaps the most astonishing feature of Early Eocene climates is the oxygen isotope evidence for nearly uniform values in low and high latitudes and in the deep ocean (Zachos et al. 1990). If the oxygen isotope values can be translated into temperatures (a translation that requires independent validation) then latitudinal and depth temperature gradients in the ocean were only about one-fifth of the present. There are some indications that CO_2 levels may have been greater (2–4×?) during this time (Lasaga et al. 1985; Owen and Rea 1985; Berger and Spitzy 1988).

As with the Pliocene a number of significant differences from the present mitigates the use of the Eocene as a future greenhouse analog. Again, we have the absence of high latitude ice, higher sea level, significantly lower orography (Ruddiman et al. 1989), and presence of an open Central American isthmus (c.f., Fig. 13). There are also some indications that the deep-water circulation may have been different in the Eocene (Barron and Sloan 1990), in that bottom water may have formed in the subtropics due to excess evaporation. This conjectured bottom water, termed "warm, saline bottom water" (WSBW; Brass et al. 1982), would form in much the same way that Mediterranean Intermediate Water forms today (initial density of this water is greater than Antarctic Bottom Water; however, mixing with ambient water masses rapidly reduces its density). Eocene WSBW may have formed as a result of some combination of higher CO_2 levels increasing evaporation in the subtropics and an enlarged Tethys creating more favorable sites for bottom water formation especially in expanded shelf areas (c.f., Fig. 12). Although formation of extensive WSBW needs more empirical support it is clear that Eocene oceanographic conditions present some fascinating opportunities for modeling (Barron and Sloan 1990). However, it is unlikely that an Eocene oceanographic analog will be repeated in the future because the existence of high latitude ice should maintain deep water formation in these regions. Less extensive shelf areas in the subtropics might also reduce production of a future WSBW.

3) MID-CRETACEOUS (~100 Ma)

The mid-Cretaceous is another time interval that has been the focus of many studies (Barron et al. 1981; Barron and Washington 1982, 1985). This was probably the warmest time interval of the last 100 million years, with little if any evidence for high latitude ice. The general consensus is that CO_2 levels several times

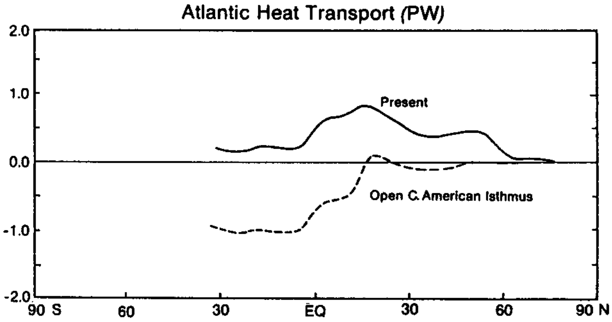

FIG. 13. Example of how altered solid earth boundary conditions may have resulted in regional climate patterns significantly different from the present during pre-Pleistocene warm periods. Comparison of poleward ocean heat transport in the Atlantic for an ocean GCM simulation with present boundary conditions and with an open Central American isthmus. An open isthmus results in an almost complete collapse of the North Atlantic thermohaline cell. [After Maier-Reimer et al. 1990]

higher than the present (5–7×?) were responsible for Cretaceous warmth (Berner et al. 1983; Barron and Washington 1985). In the future such levels could be approached if we burned all available fossil fuels and decreased the rate of CO_2 sequestering in the ocean.

As with the other warm intervals the general criticisms outlined for the pre-Pleistocene are applicable to the mid-Cretaceous; lack of extensive (or any) high latitude ice in the Cretaceous would be substantially different from the situation encountered during the early stages of a greenhouse warming. The significantly different geography (Fig. 12) would present boundary conditions for orographic and ocean forcing greatly different than what would occur in the future. Although it is important to better understand the origin and regional patterns of Cretaceous warmth these conditions do not justify its use as an analog.

4. Summary and conclusions

a. Summary

Examination of the paleoclimate record indicates that there may not be any satisfactory geological analogs for a future greenhouse warming. In terms of global mean temperature Pleistocene interglacials may not have been significantly warmer than the present. If pre-Pleistocene intervals were warmer, changes in geography would almost certainly have created regional climates different than what might occur in the future. Finally, because future temperatures may be increasing at a very high rate (2–4°C/century) we will have the unique combination of warm atmospheres and polar ice sheets—a condition very different from the pre-Pleistocene warm periods.

b. "Time period analogs" vs. "process analogs"

It is important to note that, although there may be no individual geologic time periods that are true analogs for future warming, paleoclimate studies may still give valuable insight into certain processes that may operate in the future. For example, Oerlemans (1982) has conjectured that a future warming might be associated with increased snow accumulation on Antarctica as a result of enhanced water vapor levels in the warmer atmosphere. Such a response is consistent with ice core observations on Antarctica, which demonstrate that Holocene snow accumulation rates were greater than during the last glacial maximum (Lorius et al. 1985). Likewise, conjectures about abrupt changes in future climate, due to instabilities in the ocean–atmosphere system (Broecker et al. 1985; Broecker 1987), receive some support from the geologic record (Dansgaard et al. 1984; Broecker and Denton 1989). Finally, geologic time periods provide an excellent opportunity to validate climate models against an independent set of boundary conditions. In the future, experiments with pre-Pleistocene time periods may provide sturdy tests of critical parameterizations in coupled ocean–atmosphere models (e.g., flux adjustments between the atmosphere and ocean—c.f., Sausen et al. 1988).

c. Conclusion

The above arguments therefore suggest that there may not be any time periods that are satisfactory geologic analogs for a future greenhouse warming. The warming may represent a unique climate realization in earth history. From a geologic perspective mankind will be sailing into the future on uncharted waters. Thus, although paleoclimate data can be very valuable in their own right and can be used to validate atmosphere and ocean models, caution should be exercised in order not to overemphasize data usefulness when attempting to construct "snapshot" scenarios for future warming.

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