JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 100, NO. D1, PAGES 1093–1101, JANUARY 20, 1995

Reconciling Late Ordovician (440 Ma) glaciation with very high (14X) CO_2 levels

Thomas J. Crowley and Steven K. Baum

Department of Oceanography, Texas A&M University, College Station

Abstract. Geochemical data and models suggest a positive correlation between carbon dioxide changes and climate during the last 540 m.y. The most dramatic exception to this correlation involves the Late Ordovician (440 Ma) glaciation, which occurred at a time when CO_2 levels may have been much greater than present (14-16X?). Since decreased solar luminosity at that time only partially offset increased radiative forcing from CO_2, some other factor needs to be considered to explain the glaciation. Prior work with energy balance models (EBMs) suggested that the unique geographic configuration of Gondwanaland at that time may have resulted in a small area of parameter space permitting permanent snow cover and higher CO_2 levels. However, the crude snow and sea ice parameterizations in the EBM left these conclusions open to further scrutiny. Herein we present results from four experiments with the GENESIS general circulation model with CO_2 levels 14X greater than present, solar luminosity reduced 4.5%, and an orbital configuration set for minimum summer insolation receipt. We examined the effects of different combinations of ocean heat transport and topography on high-latitude snow cover on Gondwanaland. For the no-elevation simulations we failed to simulate permanent summer snow cover. However, for the slightly elevated topography cases (300-500 m), permanent summer snow cover occurs where geological data indicate the Ordovician ice sheet was present. These results support the hypothesis based on EBM studies. Further results indicate that although average runoff per grid point increases substantially for the Ordovician runs, the decreased land area results in global runoff 10-30% less than present, with largest runoff reductions for flat topography. This response has implications for CO_2-runoff/weathering parameterizations in geochemical models. Finally, simulated tropical sea surface temperatures (SSTs) are the same or only marginally warmer than present. This result is consistent with evidence from other warm time intervals indicating small changes in tropical SSTs during time of high CO_2.

1. Introduction

One of the most significant developments in geology during the past 10 years has been emergence of the paradigm suggesting that variations in CO_2 have played an important role in the evolution of past climates. This relationship applies to both Pleistocene glacial cycles [*Barnola et al.*, 1987] and pre-Pleistocene time periods of altered land-sea distribution. The pre-Pleistocene conclusions represent a convergence of results from climate [*Barron and Washington*, 1985] and geochemical [*Berner*, 1991] models and proxy data for higher CO_2 levels [*Berger and Spitzy*, 1988; *Cerling*, 1991; *Freeman and Hayes*, 1992]. There is generally good agreement between the geochemical models and the proxy CO_2 indices [*Berner*, 1992], at least in terms of the sign of the response. The geochemical model calculations also agree well [*Crowley and Baum*, 1991] with the distribution of glacial deposits (Figure 1) through the Phanerozoic (last 540 m.y.).

Despite the gratifying convergence of evidence from a number of different approaches, a troubling exception to the CO_2-climate correlation involves evidence for Late Ordovician (440 Ma, million years ago) glaciation in North Africa and adjacent regions (Figure 1). At that time these areas were part of the Gondwanan supercontinent and in high southern latitudes (Figure 2). The most direct evidence for glaciation is based on tillites and striated terrain typical of glacial deposits [*Hambrey and Harland*, 1985; see also *Crowley and North*, 1991, Figure 11.6], although the initial suggestion of glaciation was based on equatorward displacements of marine biota [*Spjeldnaes*, 1961]. The estimated area of the deposits, if they represented a contiguous ice sheet, would be of the order of 6-10 X 10^6 km^2 [*Hambrey*, 1985; *Crowley and Baum*, 1991], about the same size as the present East Antarctic Ice Sheet [cf. *Long*, 1993]. Analysis of nearshore marine sediments indicate a sea level fall of 50-100 m for this event [*Brenchley and Newell*, 1980]. The areal estimates of ice cover would be consistent with the lower estimate for magnitude of sea level fall [*Crowley and Baum*, 1991]. The glaciation also coincides with the second largest extinction event in the Phanerozoic, when an estimated 85% of all species became extinct [e.g., *Brenchley*, 1984; *Jablonski*, 1991].

In the context of the CO_2 paradigm the problem with Late Ordovician glaciation involves geochemical model calculations that CO_2 levels may have been very high for the Late Ordovician [*Berner*, 1991], on the order of 14X present values. This calculation agrees with CO_2 estimates from proxy data of a ~16X CO_2 increase [*Yapp and Poths*, 1992]. These values seem incompatible with glaciation of any type. Although $\delta^{13}C$ data suggest there may have been a "brief"

Paper number 94JD02521.

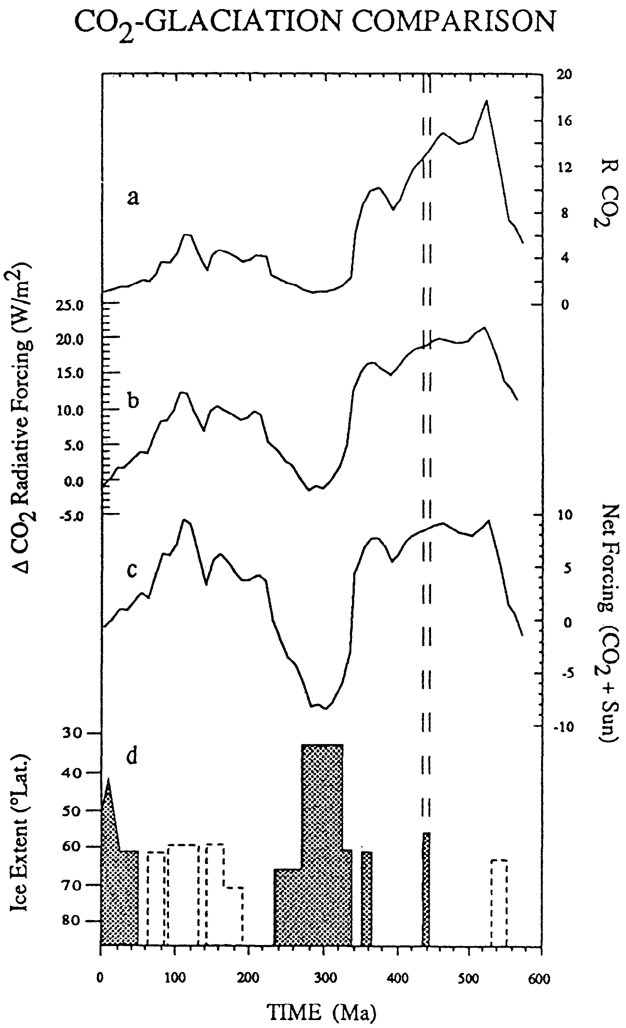

Figure 1. (a) Phanerozoic CO_2 variations as calculated by a geochemical model [from *Berner*, 1990]; (b) radiative departures from present of Figure 1a, based on CO_2 concentration/radiative forcing relationship discussed by *Kiehl and Dickinson* [1987]; (c) combined effect of radiative forcing (Figure 1b) and solar luminosity variations versus time, with values for the luminosity being interpolated between two limits determined by *Endal and Sofia* [1981] and with a planetary albedo of 0.3 applied to all adjustments; (d) area of glaciation versus time as estimated by *Frakes and Francis* [1988]. Dashed areas represent evidence for ice but not necessarily continental glaciation; hachured areas represent times of continental glaciation. Long-dashed lines at ~440 Ma represent the subject of this study. [After *Crowley and Baum*, 1991.]

(0.5–1.0 m.y.) interval of lower CO_2 levels in the Late Ordovician [*Brenchley et al.*, 1994], these results need to be further validated and may apply only to changes that occurred after initiation of glaciation (see also discussion section).

It is therefore of interest to determine what processes may have triggered glacial inception in the Late Ordovician. Two factors in addition to CO_2 that need to be considered involve solar evolution and paleogeography. Solar models predict a gradual increase in the average output of the Sun over time [*Endal and Sofia*, 1981], and thus the energy received by the Earth would have been less in the Ordovician than at present. The solar models suggest a decrease in the solar constant for the late Ordovician in the range of 3.5-5.0% less than for present [*Crowley and Baum*, 1991]. This decrease serves to partially counteract the heating effect of the high CO_2 concentrations, although if we adjust the increase in radiative forcing from CO_2 for the decrease in radiative forcing due to solar change, an effective "net" atmospheric CO_2 concentration about 4 times greater than present is still obtained (Figure 1). This latter value is the same as used by *Moore et al.* [1994] for the mid-Silurian (425 Ma).

The second factor to consider is paleogeography. Studies with energy balance climate models (EBMs, *Crowley et al.* [1987]) suggest that the unique geographic configuration in the Late Ordovician, a large landmass nearly tangent to the pole (Figure 3), provided a scenario where the large heat capacity of the surrounding waters may have suppressed summer warming on the landmass, thereby allowing preservation of summer snowcover. Some support for this idea was obtained from both linear and nonlinear EBM simulations [*Crowley et al.*, 1987; *Crowley and Baum*, 1991]. However, the snow and sea ice parameterizations in the EBMs are dependent on temperature only; that is, an explicit hydrologic cycle is not included in the model. Because of the importance of snow-albedo feedback for snowline retreat, this crude parameterization raises concern about the validity of the EBM conclusions.

In this paper we reexamine the topic of Late Ordovician glaciation by repeating the EBM experiments with a general circulation climate model (GCM) that enables explicit calculation of moisture and sea ice fields. CO_2, elevation, and ocean circulation effects can also be more accurately incorporated into the GCM. Utilization of the GCM also enables calculation of moisture budgets, an option which in turn yields results that have implications for the role of weathering feedbacks under altered CO_2 levels.

An important assumption in this study is that summer temperature is the constraining factor for ice sheet initiation.

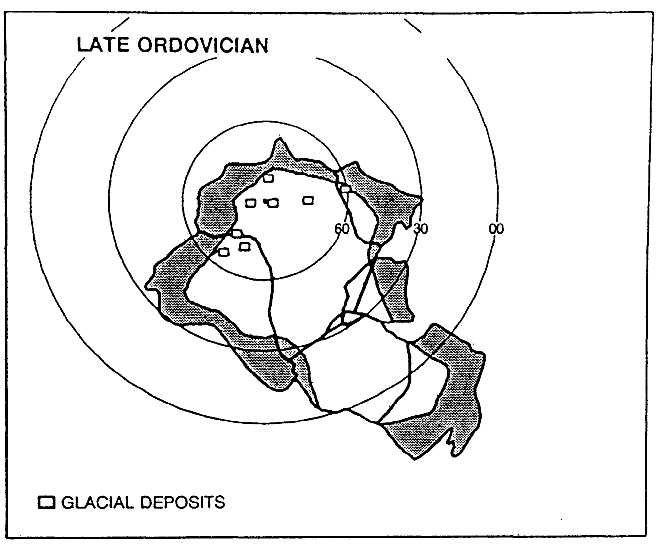

Figure 2. Late Ordovician paleogeography of Gondwanaland. Circular contours are lines of latitude. The shaded region indicates areas of continents flooded by shallow seas. The rectangles are glacial deposits from *Caputo and Crowell* [1985]. [After *Crowley et al.*, 1987.]

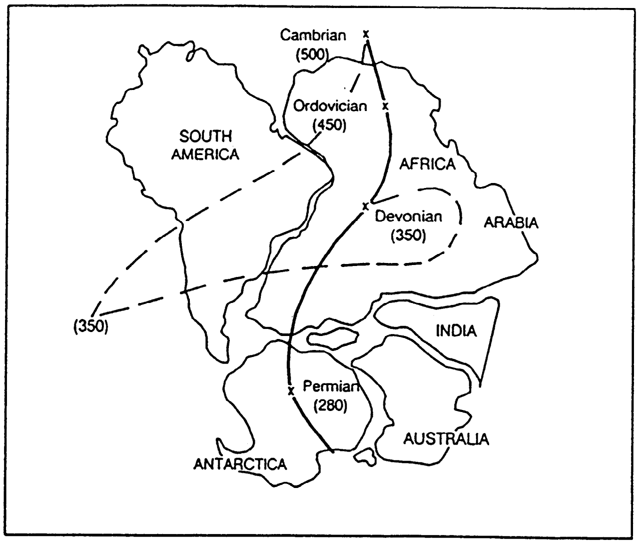

Figure 3. Postulated Paleozoic apparent polar wander paths of the south pole with respect to Gondwanaland. Dashed curve indicates alternate path based on different data sources. Different paleomagnetic studies yield variations on these two possible paths [cf. *Bachtadse and Briden,* 1991]. Numbers in parentheses are ages in Ma. Note the "landfall" of Gondwanaland at ~440 Ma. [From *Crowley et al.,* 1987; adapted from *Morel and Irving,* 1978.]

That is, we assume it is not possible to initiate ice cap formation if it gets too hot in the summer. By addressing the problem in this manner, we are able to focus on a critical boundary condition necessary for glacial inception, without introducing the significantly more complicated problem of subsequent growth of the ice sheet. We assume that permanent summer snow cover will lead to ice cap development within a geologically short interval (few thousand years).

2. Model and Boundary Conditions

The new climate model [*Thompson and Pollard,* 1994], termed GENESIS (version 1.02.A) is based on the NCAR Community Climate Model (CCM) but features new treatments of clouds, diurnal forcing, penetrative plume convection, boundary layer mixing, and water vapor transport. A major extension of the CCM for GENESIS was the inclusion of a land-surface transfer model (LSX) that allows for the inclusion of the effects of spatially variable vegetation, soil texture, and color [*Pollard and Thompson,* 1994]. This is combined with a six-layer soil model, standard three-layer snow and six-layer sea ice thermodynamic models, and a thermodynamic slab ocean to account for processes occurring at or near the surface of the Earth. GENESIS has the same number of vertical levels (12) and horizontal resolution (4.5° by 7.5°) as the CCM, and the horizontal and vertical variables are discretized using spectral transformation and finite difference methods, respectively, except for the water vapor transport scheme, which uses a semi-Lagrangian method. More detailed discussion of the model is given by *Thompson and Pollard* [1994] and *Pollard* and *Thompson* [1994]. Additional comparisons with data and other GCMs can be found in *Yip and Crowley* [1994].

GENESIS requires more boundary conditions than most other GCMs because of the addition of the aforementioned land surface model and its attendant requirements. Since the land surface had not been colonized to any great extent in the Late Ordovician [cf. *Gray et al.,* 1982; *Retallack,* 1992; *Horodyski and Knauth,* 1994], we specify a bare surface with uniform median values of soil texture and color, with the land surface package run at the same resolution as the atmospheric model (4.5° X 7.5°). Although the median values of soil parameters are a compromise choice reflecting lack of knowledge of soil types, they fortuitously allow for a slight muting of albedo below that of highly reflective bare soils, as might be consistent with any incipient vegetation cover.

A mixed layer slab ocean of constant depth was specified for the simulation. GENESIS also allows for a zonally symmetric specification of ocean heat transport. For our four simulations (see below) two were run with present ocean heat transport in the model and two were run with values increased by 50% (Figure 4). Use of a value greater than present is consistent with inferences that ocean heat transport may have increased during past times when CO_2 levels were higher [e.g., *Rind and Chandler,* 1991; *Crowley,* 1993]. Because there is an asymmetry at present between poleward heat transport in the northern and southern hemispheres, all Ordovician experiments symmetrized ocean heat transport latitudinally.

The EBM experiments suggested that permanent snow cover was possible only with a set of orbital parameters that minimizes the amount of insolation received in the austral summer. Lacking any explicit knowledge as to how to modify these for the Paleozoic, we used the parameter range developed by *Berger* [1978] for the Pleistocene to specify this

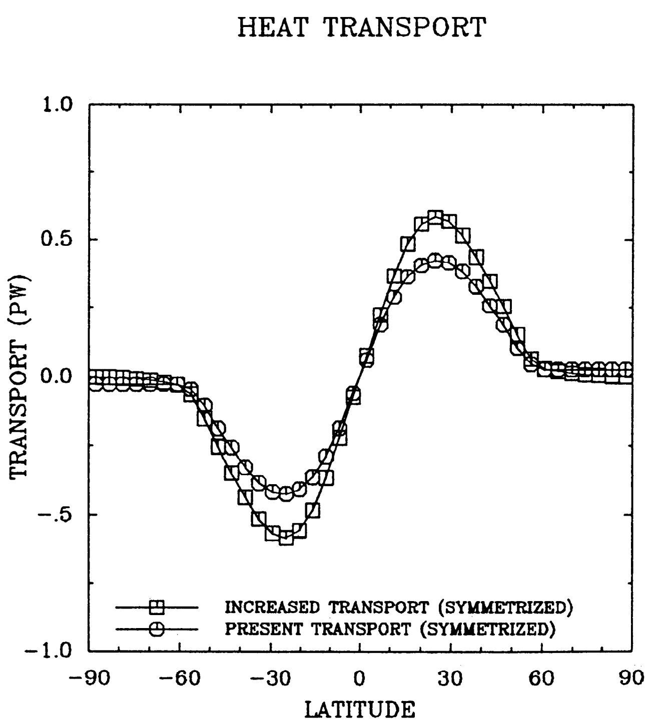

Figure 4. Heat transport distribution in petawatts (1 PW = 10^{15}W) used for Ordovician run. Runs symmetrized transport around the equator and were equivalent either to present average transport in the control run or present transport increased 50%.

configuration, which is termed a "cold summer orbit" (CSO). These values are eccentricity (0.06), obliquity (22.0°), and longitude of perihelion (180°). Four main simulations were conducted. All simulations used 14X CO_2 levels, -4.5% solar luminosity, and a cold summer orbit. Adjusted parameters for the different runs involved ocean heat transport and topography (see below).

Two paleogeographic distributions were used as boundary conditions during the course of this investigation. The first was that of *Scotese and Golonka* [1992] for the Silurian period (Wenlockian epoch, 433 Ma). The second, which more accurately reflects the geographical distribution at the time at which the evidence for glaciation has been found, the Latest Ordovician (Ashgillian), was obtained by modifying the 433 Ma geography, since no reconstructions were available for 440 Ma. The 433 Ma reconstruction, along with another by *Scotese and Golonka* [1992] for 458 Ma, indicated that the Gondwanan landmass was moving south (toward the pole) from 458 to 433 Ma. Therefore we rotated the 433 Ma Gondwana about 5° north to a position more tangential to the south pole for 440 Ma. A similar line of reasoning led to moving the northwestern Europe landmass (Baltica) at 433 Ma slightly farther away from North America than for 440 Ma. The two geographies are compared in Figure 5.

The simulations for Gondwana were specified as having either no topography or a 500-m elevation, ramping downward to 300 m at the grid points nearest the oceans. The remaining areas had low relief. This feature is in contrast to the locally high relief utilized by *Moore et al.* [1994] for the equatorial Caledonide Mtns. at ~425 Ma, after Baltica collided with North America (see above). Thus the four experiments test the various combinations of altered heat transport and topography on summer snow area. This latter feature is considered the critical index as to whether glaciers will grow.

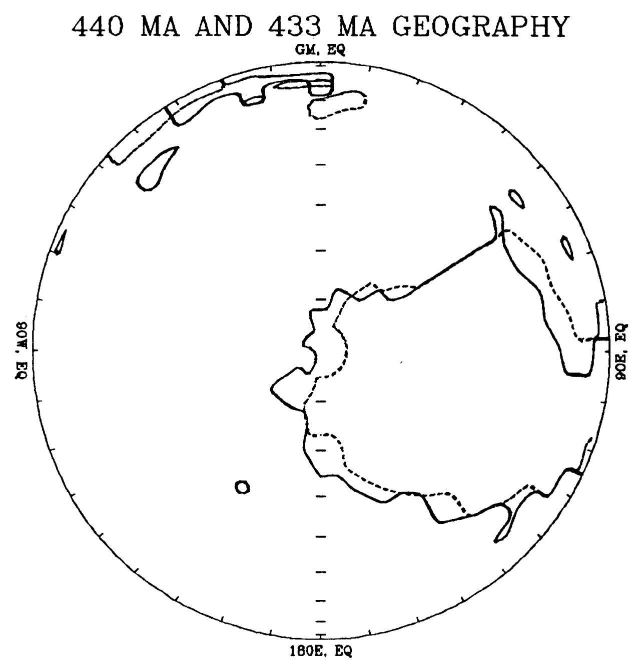

Figure 5. Original geography (solid line) of *Scotese and Golonka* [1992] before minor rotation (dashed line). See text for further discussion.

3. Results

The principal results are summarized in Figure 6 and Table 1. The figure shows simulated January snow area and depth for the various combinations of ocean heat transport and topography used in our simulations. For comparison we also show simulated January and July temperature fields for one of these runs (Figure 7). Except in areas of altered topography, regional temperatures are fairly similar for the four runs.

The only simulations yielding significant summer snowcover are those with some elevation (Figure 6). Ocean heat transport has only a minor effect on simulated snow area. This latter response may seem surprising but could reflect one of two possible explanations: (1) the 50% increase in ocean heat transport is not large enough to significantly influence the results; some support for this idea can be derived from the relatively small differences between the 1X and the 2X ocean heat transport runs of *Barron et al.* [1993] with the GENESIS model; or (2) significant compensation occurs in the ocean-atmosphere system [cf. *Stone*, 1978] that results in increases in one medium (ocean) being offset by decreases in the other medium (atmosphere).

Also shown in Figure 6 is the distribution of glacial deposits from *Caputo and Crowell* [1985]. The agreement between model-simulated snowcover and glacial deposits is quite encouraging, especially considering the fact that additional glaciological feedbacks would occur once permanent summer snowcover was initiated.

Because there is some evidence that the Late Ordovician ice sheet was at or near sea level [D. Rowley, personal communication, 1994], we examined the potential effects of changes in forcing on lowering the snow line to sea level. Because of the prohibitive time required to do this exercise with a GCM, we chose the EBM developed by *Hyde et al.* [1990] and used by *Crowley and Baum* [1991] in their Ordovician simulations. This is a two-dimensional (latitude-longitude) EBM with snow feedback. The EBM has been validated many times against observations and other models [e.g., *Hyde et al.*, 1990; *Crowley and Baum,* 1991], so it yields a reasonable first-order estimate of the effects of changes in forcing.

The purpose of the EBM exercise was to estimate how much of a change in forcing would be required to decrease summer temperatures about 2°-3°C on the flat topography continent. Lapse rate considerations suggest such a decrease could allow a snowline present at a 300-500 m (Figure 6) elevation to persist if lowered to sea level. Results (Figure 8) indicate that a reduction of CO_2 to about 12X present levels and a reduction of luminosity to 5% could effect such a change. These values are well within the uncertainties of lower Paleozoic CO_2 estimates [*Berner*, 1994] and luminosity values [*Crowley and Baum,* 1991].

The zonal temperature profile of sea surface temperatures (SSTs) for the four runs is illustrated in Figure 9 and compared to the control run of *Thompson and Pollard* [1994]. This figure indicates that despite the increase in global temperatures (Table 1) due to an approximate net fourfold increase of CO_2, tropical SSTs were about the same as present [cf. *Railsback et al.,* 1990]. These results are interesting in the sense that they represent one of the first (to our knowledge) indications that some climate simulations for high CO_2 do not produce tropical SSTs significantly warmer than the present, a result more in accord with the geologic record [*Crowley,* 1993]. Preliminary

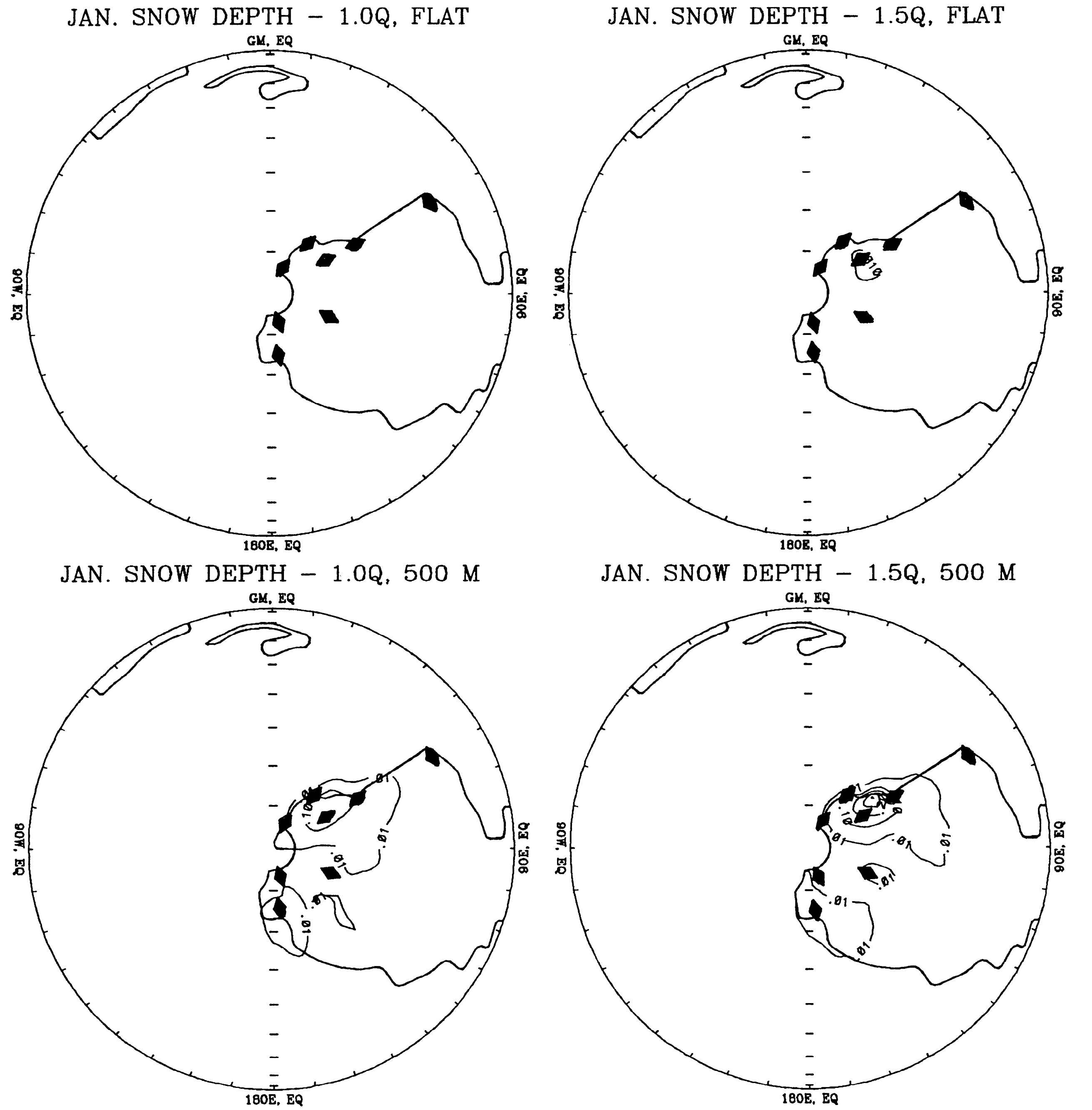

Figure 6. Simulated Late Ordovician (440 Ma) January snowcover (south polar projection) with 14X CO_2 and solar constant reduced 4.5% for the last three years of model runs. Q represents the ocean heat transport term; flat means no elevation for the Gondwanan landmass. Filled diamonds represent glacial deposits as illustrated in Figure 2.

assessment of the reason for this response involves higher levels of cloudiness (results not shown).

The global average temperature increase of 3.4°C (average for the four runs) is ~25% less than can be estimated with the ~8.6 W/m^2 "net" CO_2 forcing (Figure 1) and the model sensitivity of ~2.0 $W/m^2/°C$ for a doubling of CO_2 with present geography [*Thompson and Pollard*, 1994]. The different sensitivity reflects either the substantially different Ordovician geography or limitations in calculation of the "net CO_2" forcing.

Calculated zonal average precipitation minus evaporation (P - E) profiles indicate that the intertropical convergence zone (ITCZ) and flanking subtropical highs may have been enhanced in the Ordovician (Figure 10). This pattern may reflect one or more processes, which we cannot separate at present without more extensive model simulations. One process is the enhanced orbital forcing of an eccentricity value of 0.06, which may strengthen overturn in the ITCZ. Another factor involves smaller seasonal migrations of the ITCZ due to decreased land area in low latitudes. A third factor is that

Table 1. Areas of Simulated Snow Enclosed by 0.1-m and 0.01-m Contours and Maximum Snow Depth for each Simulation Configuration

Heat Transport Q	Gondwana Elevation m	Number of Years in Run	January Snow Area ($x 10^6 km^2$) >0.1m	>0.01m	Maximum Snow Depth m	Global Average Temperature °C
1.0	0	10	0.0	0.0	0.00	17.7
1.5	0	10	0.0	0.1	0.05	18.7
1.0	500	15	1.3	7.2	0.15	17.9
1.5	500	13	2.2	12.9	0.30	17.9

Note that the global average temperature for the control run is 14.6°C [*Thompson and Pollard*, 1994]. Q refers to the ratio of ocean heat transport with respect to the present control run.

greater precipitation with elevated CO_2 levels may have strengthened the hydrologic cycle. Whatever the explanation, zonal average P-E was increased in the ITCZ. The peak at 7°-8°N presumably reflects increased insolation receipt in the northern hemisphere due to our choice of orbital parameters. For one of the runs (Figure 11), there is an equatorward dip of the ITCZ over the North American landmass, however. The strong convective uplift over North America may explain some of the very depleted $\delta^{18}O$ values measured for that area that were inferred to indicate a strong monsoonal circulation [*Yapp*, 1993].

4. Discussion and Conclusion

To summarize, it is possible to simulate permanent summer snowcover with a GCM for the Late Ordovician. Although the present results succeeded only when a slight elevation increase was specified for Gondwanaland, additional EBM sensitivity experiments suggest that rather small changes in forcing (12X rather than 14X CO_2 and -5.0% rather than -4.5% luminosity) could lower Ordovician snow lines to sea level. These differences are well within the uncertainties of the forcing terms. Other uncertainties not considered involve, for

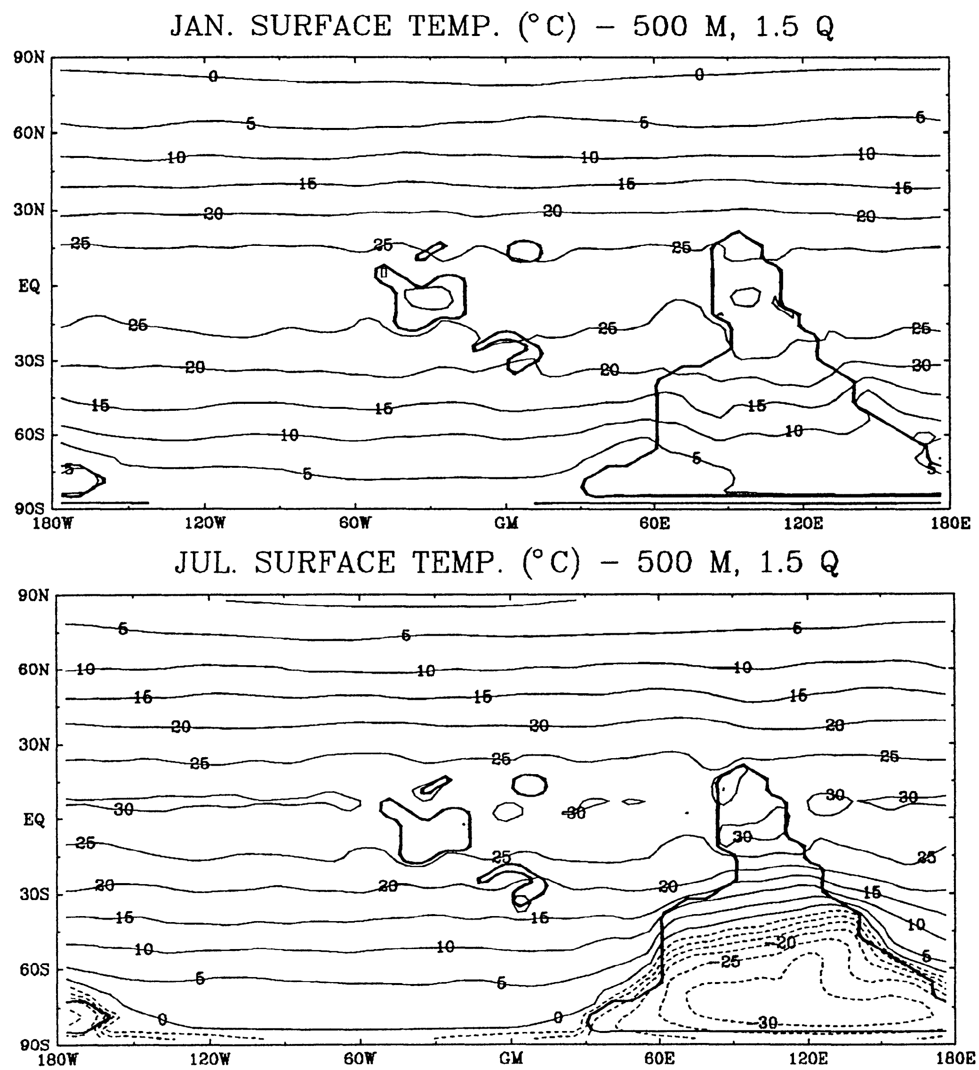

Figure 7. Simulated Late Ordovician (440 Ma) temperatures with 14X CO_2, solar constant reduced 4.5%, elevated topography, and ocean heat transport increased 50% for (a) January and (b) July.

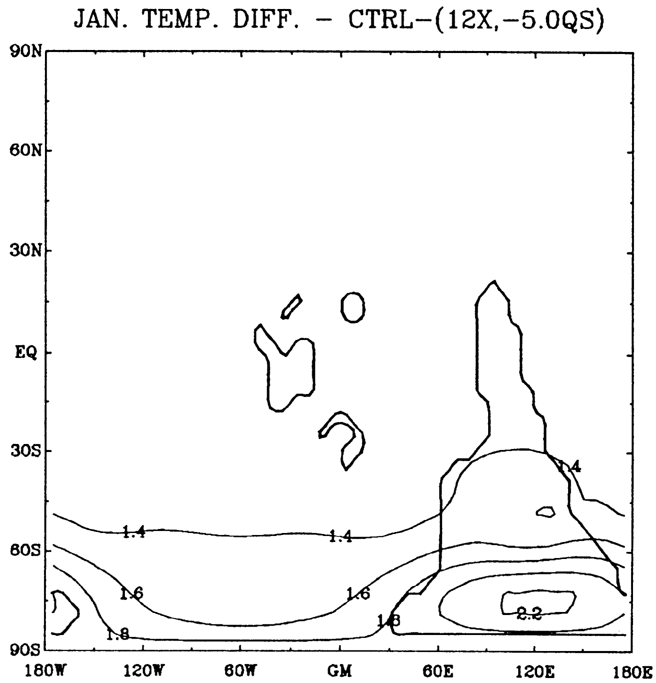

Figure 8. Energy balance model calculated January temperature difference between Ordovician baseline run (14X CO_2 -4.5% luminosity, cold summer orbit) and run with 12X CO_2 -5.0% luminosity, and cold summer orbit. This calculation helps constrain potential changes in boundary conditions required to get glaciation at sea level.

example, the cooling effect in high latitudes of increased Earth rotation rate [*Jenkins et al.*, 1993] and slight changes in the spectrum of incoming insolation due to decreased solar output. It is also necessary to recall that other models, with different sensitivities, should yield cutoff levels different than the ones we determined.

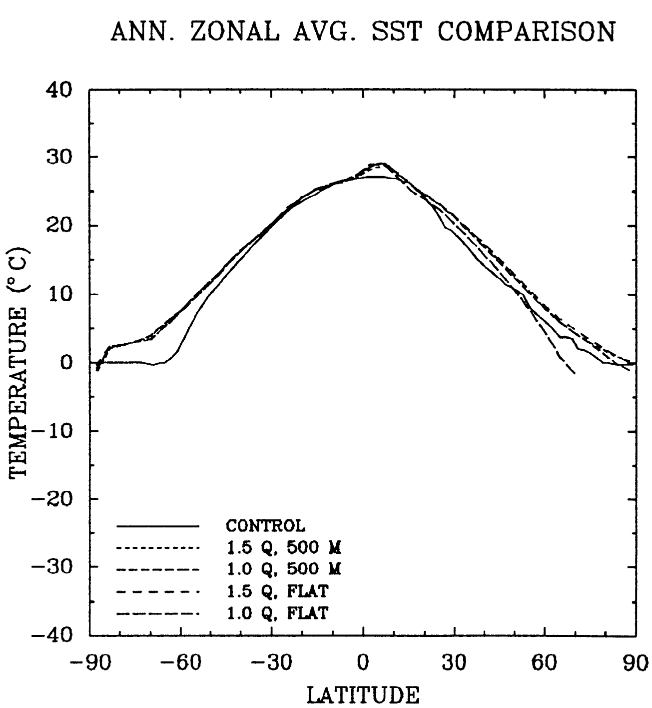

Figure 9. Annual, zonal average sea surface temperatures (SSTs) from control run of *Thompson and Pollard* [1994] compared to SSTs from Late Ordovician runs.

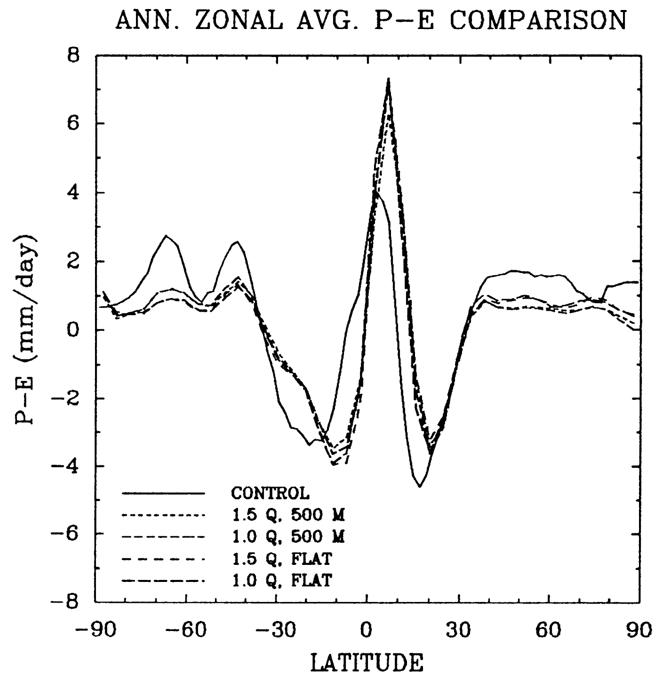

Figure 10. Annual, zonal average P-E from control run of *Thompson and Pollard* [1994] compared to P-E from Late Ordovician runs.

The important point of our results is that with reasonable changes in forcing we can obtain a result that reconciles an apparently perplexing paleoclimate paradox in a straightforward manner. This conclusion is not at variance with recent observational results of *Brenchley et al.* [1994],

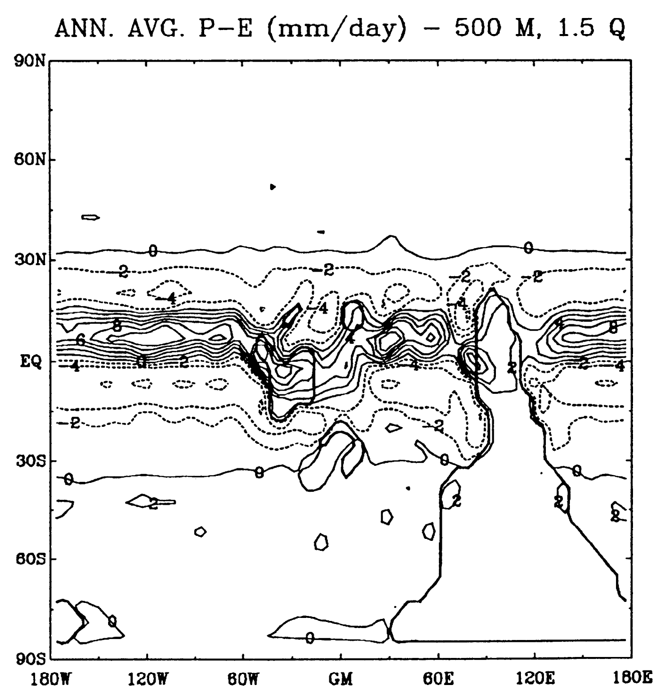

Figure 11. Areal distribution of Late Ordovician annual average P-E for runs with elevated topography and ocean heat transport increased 50%. Other runs yielded similar patterns of P-E.

who suggested that carbon changes may have lowered CO_2 in the latest Ordovician. Such changes may have happened, but our results are consistent with the idea that glaciation may have started at high CO_2 levels. Such an event may then have triggered the ocean carbon changes that may have subsequently lowered the pCO_2 levels, as conjectured by *Brenchley et al.* [1994].

With respect to termination of the Ordovician glaciation, *Brenchley et al.* [1994] further suggest that CO_2 levels may have subsequently risen after the conjectured flushing of the ocean carbon reservoir by onset of glaciation [cf. *Long*, 1993; *Wang et al.*, 1993]. Although such a mechanism is possible, another explanation may involve the rapid movement (23 cm/yr) of Gondwanaland across the pole in the Ordovician [*Bachtadse and Briden*, 1990]. Previous studies suggest that pole-centered supercontinents may be ice free, even at low CO_2 levels, because the large land area isolated from the waters allows significant summer heating [*Crowley et al.*, 1993]. However, such results are sensitive to landmass size, and since high sea level in the Silurian resulted in a relatively "small supercontinent," it is necessary to test such a conjecture with a GCM. We plan to conduct such experiments in the future.

Our results may explain one problem with the original *Crowley et al.* [1987] hypothesis that was pointed out by *Barron* [1987], namely that some Cretaceous near-pole-edged configurations do not have any evidence for glaciation. Based on the experience gleaned from our Ordovician simulations, this response could reflect slightly higher net-CO_2 forcing in the Cretaceous (cf. Figure 1), lower topography, or the fact that vegetated land surfaces at high latitudes [*Bonan et al.*, 1992; *Crowley and Baum*, 1994] have significantly lower albedo than bare surfaces (the present group of flowering plants evolved in the Cretaceous). For example, Carboniferous (300 Ma) simulations suggest that the lower albedo of vegetated surfaces can increase summer temperatures as much as 10°C [*Crowley and Baum*, 1994], thus potentially eliminating permanent snowcover.

Implications for Geochemical Weathering Estimates

A further element of our analysis involves the effect of P-E, runoff, and temperature on weathering. *Berner* [1991, 1994] has used such information for estimating the feedback role of climate change on runoff, weathering, and atmospheric CO_2 levels. Our values (Table 2) indicate that P-E (land) and runoff during the Ordovician increased as much as 100% on average for all grid points. However, because land area was only 43% of present (due to very high sea levels), total runoff was 10-30% less for the Ordovician simulations, with the largest decreases occurring in the no-elevation simulations. By comparison, calculated runoff [*Thompson and Pollard*, 1994] for the present is ~0.9 Sv (1 Sverdrup = 10^6 m^3/s), a result that agrees reasonably well with total estimated runoff from the continents of 1.1 Sv [*Broecker and Peng*, 1982], and average P-E (land) for the emerged Pangean supercontinent (300 Ma) is 38% less than present [*Crowley and Baum*, 1994]. These results indicate that the nature of the runoff/weathering feedback for CO_2 calculations may be different than originally conceived [*Berner et al.*, 1983]; cf. (B.L. Otto-Bliesner, Continental drift, runoff and weathering feedbacks: Implications from climate model experiments, submitted to *Journal of Geophysical Research,* 1994) and used at present [*Berner*, 1994] in geochemical calculations. Although the importance of the weathering feedback has been downgraded in the more recent version of this geochemical model [*Berner*, 1994], our results nevertheless may warrant further reexamining the role of this feedback in the model. The global temperature increase of about 3.5°C (Table 1) may also have implications for CO_2 temperature/weathering feedbacks.

Table 2. Simulated Global Average Runoff and P-E (Land) for Both the Control and the Late Ordovician

Simulation	Global Average Land P-E mm/d	Global Average Runoff mm/d	Total Runoff 10^6 m^3/s
Control	0.96	0.53	0.91
1.0 Q, Flat	1.29	0.86	0.64
1.5 Q, Flat	1.31	0.86	0.64
1.0 Q, 500	1.91	1.13	0.84
1.5 Q, 500	1.83	1.09	0.81

The average values are for individual grid points, while the total runoff values are integrated for all land areas. Land area in control run is 149.1 X 10^6 km^2 and for the Ordovician 64.5 X 10^6 km^2.

Concluding Remarks

As with any climate model simulation, there are always caveats and concerns. Other climate models have different sensitivities, so it is desirable to test our conclusions with other models. Likewise, ocean heat transport may well have differed from what was specified [cf. *Rind and Chandler*, 1991]. The CO_2 values are also open to uncertainty, probably by a factor of at least 50%. Despite these uncertainties we believe our results have taken another step in closing the gap between theory and observation. We therefore conclude that the perplexing paradox of Late Ordovician glaciation may be explicable in a relatively straightforward manner and does not represent a major impediment to accepting the hypothesis that CO_2 has played an important if not dominant role in the evolution of climate on tectonic timescales.

Acknowledgments. This research was supported by NSF grants ATM-9224833 and ATM-9396320. We thank S. Thompson and D. Pollard for access to their model, R. Berner, C. Scotese, D. Rowley, and A. Ziegler for discussions, and the reviewers for their comments. Computing was done at NCAR, which is supported in part by the National Science Foundation.

References

Bachtadse, V., and J. C. Briden, Palaeomagnetic constraints on the position of Gondwana during Ordovician to Devonian times, in *Palaeozoic Palaeogeography and Biogeography*, edited by W.S. McKerrow and C.R. Scotese, pp. 43-48, Geological Society, London, 1990.

Bachtadse, V., and J. C. Briden, Palaeomagnetism of Devonian ring complexes from the Bayuda Desert, Sudan—New constraints on the apparent polar wander path for Gondwanaland, *Geophys. J. Int., 104,* 635-646, 1991.

Barnola, J. M., D. Raynaud, Y. S. Korotkevich, and C. Lorius, Vostok ice core provides 160,000-year record of atmospheric CO_2, *Nature, 329,* 408-414, 1987.

Barron, E. J., Explaining glacial periods, *Nature, 329,* 764-765, 1987.

Barron, E. J., and W. M. Washington, Warm Cretaceous climates: High atmospheric CO_2 as a plausible mechanism, in *The Carbon Cycle and Atmospheric* CO_2*: Natural Variations Archean to Present, Geophys. Monogr. Ser.*, vol. 32, edited by E. T. Sundquist and W. S. Broecker, pp. 546-553, AGU, Washington, D. C., 1985.

Barron, E. J., W. H. Peterson, D. Pollard, and S. Thompson, Past climate and the role of ocean heat transport: Model simulations for the Cretaceous, *Paleoceanography, 8,* 785-798, 1993.

Berger, A. L., Long-term variations of caloric insolation resulting from the earth's orbital elements, *Quat. Res., 9,* 139-167, 1978.

Berger, W. H., and A. Spitzy, History of atmospheric CO_2: Constraints from the deep-sea record, *Paleoceanography, 3,* 401-411, 1988.

Berner, R. A., Atmospheric carbon dioxide over Phanerozoic time, *Science, 249,* 1382-1386, 1990.

Berner, R. A., A model for atmospheric CO_2 over Phanerozoic time, *Am. J. Sci., 291,* 339-376, 1991.

Berner, R. A., Palaeo-CO_2 and climate, *Nature, 358,* 114, 1992.

Berner, R. A., GEOCARB II: A revised model of atmospheric CO_2 over Phanerozoic time, *Am. J. Sci., 294,* 56-91, 1994.

Berner, R. A., A. C. Lasaga, and R. M. Garrels, The carbonate-silicate geochemical cycle and its effect on atmospheric carbon dioxide over the last 100 million years, *Am. J. Sci., 283,* 641-683, 1983.

Bonan, G. B., D. Pollard, and S. L. Thompson, Effects of boreal forest vegetation on global climate, *Nature, 359,* 716-718, 1992.

Brenchley, P. J., Late Ordovician extinctions and their relationship to the Gondwana glaciation, in *Fossils and Climate*, edited by P. Brenchley, pp. 291-315, John Wiley, New York, 1984.

Brenchley, P. J., and G. Newall, A facies analysis of Upper Ordovician regressive sequences in the Oslo region, Norway—A record of glacio-eustatic changes, *Palaeogeogr., Palaeoclimatol., Palaeoecol., 31,* 1-37, 1980.

Brenchley, P. J., J. D. Marshall, G.A. F. Carden, D. B. R. Robertson, D. G. F. Long, T. Meidla, L. Hints, and T. F. Anderson, Bathymetric and isotopic evidence for a short-lived Late Ordovician glaciation in a greenhouse period, *Geology, 22,* 295-298, 1994.

Broecker, W. S., and T.-H. Peng, *Tracers in the Sea*, 690 pp., Eldigio Press, New York, 1982.

Caputo, M. V., and J. C. Crowell, Migration of glacial centers across Gondwana during the Paleozoic era, *Geol. Soc. Am. Bull., 96,* 1020-1036, 1985.

Cerling, T. E., Carbon dioxide in the atmosphere: Evidence from Cenozoic and Mesozoic paleosols, *Am. J. Sci., 291,* 377-400, 1991.

Crowley, T. J., Geological assessment of the greenhouse effect, *Bull. Am. Meteorol. Soc., 74,* 2363-2373, 1993.

Crowley, T. J., and S. K. Baum, Towards reconciliation of Late Ordovician (~440 Ma) glaciation with very high CO_2 levels, *J. Geophys. Res., 96,* 22,597-22,610, 1991.

Crowley, T. J., and S. K. Baum, General circulation model study of late Carboniferous interglacial climates, *Palaeoclimates,* in press, 1994.

Crowley, T. J., and G. R. North, *Paleoclimatology,* 339 pp., Oxford University Press, New York, 1991.

Crowley, T. J., J. G. Mengel, and D. A. Short, Gondwanaland's seasonal cycle, *Nature, 329,* 803-807, 1987.

Crowley, T. J., S. K. Baum, and K.-Y. Kim, General circulation model sensitivity experiments with pole-centered supercontinents, *J. Geophys., Res. 98,* 8793-8800, 1993.

Endal, A. S., and S. Sofia, Rotation in solar-type stars, I, Evolutionary models for the spin-down of the sun, *Astrophys. J., 243,* 625-640, 1981.

Frakes, L. A., and J. E. Francis, A guide to Phanerozoic cold polar climates from high-latitude ice-rafting in the Cretaceous, *Nature, 333,* 547-549, 1988.

Freeman, K. H., and J. M. Hayes, Fractionation of carbon isotopes by phytoplankton and estimates of ancient CO_2 levels, *Global Biogeochem. Cycles, 6,* 185-198, 1992.

Gray, J., D. Massa, and A. J. Boucot, Caradocian land plant microfossils from Libya, *Geology, 10,* 197-201, 1982.

Hambrey, H. A., and W. B. Harland, The late Proterozoic glacial era, *Palaeogeogr., Palaeoclimatol., Palaeoecol., 51,* 255-272, 1985.

Hambrey, M. J., The Late Ordovician--Early Silurian glacial period, *Palaeogeogr., Palaeoclimatol., Palaeoecol., 51,* 273-289, 1985.

Horodyski, R. J., and L. P. Knauth, Life on land in the Precambrian, *Science, 263,* 494-498, 1994.

Hyde, W.T., K.-Y. Kim, T.J. Crowley, and G.R. North, On the relation between polar continentality and climate: Studies with a nonlinear energy balance model, *J. Geophys. Res., 95,* 18,653-18,668, 1990.

Jablonski, D., Extinctions: A paleontological perspective, *Science, 253,* 754-757, 1991.

Jenkins, G. S., H. G. Marshall, and W. R. Kuhn, Precambrian climate: The effects of land area and Earth's rotation rate, *J. Geophys. Res., 98,* 8785-8794, 1993.

Kiehl, J. T., and R. E. Dickinson, A study of the radiative effects of enhanced atmospheric CO_2 and CH_4 on early Earth surface temperatures, *J. Geophys. Res., 92,* 2991-2998, 1987.

Long, D. G. F., Oxygen and carbon isotopes and event stratigraphy near the Ordovician–Silurian boundary, Anticosti Island Quebec, *Palaeogeogr., Palaeoclimatol., Palaeoecol., 104,* 49-59, 1993.

Moore, G. T., S. R. Jacobson, C. A. Ross, and D. N. Hayashida, A paleoclimate simulation of the Wenlockian (Late Early Silurian) world using a general circulation model with implications for early land plant paleoecology, *Palaeogeogr., Palaeoclimatol., Palaeoecol., 110,* 115-144, 1994.

Morel, P., and E. Irving, Tentative paleocontinental maps for the early Phanerozoic and Proterozoic, *J. Geol., 86,* 535-561, 1978.

Pollard, D. and S. L. Thompson, Use of a land-surface-transfer scheme (LSX) in a global climate model: The response to doubling stomatal resistance, *Global Planet. Change*, in press, 1994.

Railsback, L. B., S. C. Ackerly, T. F. Anderson, and J. L. Cisne, Palaeontological and isotope evidence for warm saline deep waters in Ordovician oceans, *Nature, 343,* 156-159, 1990.

Retallack, G. J., What to call early plant formations on land, *Palaios, 7* 508-520, 1992.

Rind, D., and M. Chandler, Increased ocean heat transports and warmer climate, *J. Geophys. Res., 96,* 7437-7461, 1991.

Scotese, C. R., and J. Golonka, *Paleogeographic Atlas,* Paleomap Project, University of Texas-Arlington, Arlington, 1992.

Spjeldnaes, N., Ordovician climatic zones, *Norsk Geologisk Tidesskrift, 21,* 45-77, 1961.

Stone, P. H., Constraints of dynamical transports of energy on a spherical planet, *Dyn. Atmos. Oceans, 2,* 123-139, 1978.

Thompson, S. L., and D. Pollard, A global climate model (GENESIS) with a land-surface-transfer scheme (LSX), 1, Present-day climate, *J. Clim.*, in press, 1994.

Wang, K., C. J. Orth, M. Attrep Jr., B. D. E. Chatterton, X. Wang, and J.-J. Li, The great latest Ordovician extinction on the South China Plate: Chemostratigraphic studies of the Ordovician–Silurian boundary interval on the Yangtze Platform, *Palaeogeogr., Palaeoclimatol., Palaeoecol., 104,* 61-79, 1993.

Yapp, C. J., Paleoenvironment and the oxygen isotope geochemistry of ironstone of the Upper Ordovician Neda Formation, Wisconsin, USA, *Geochim. Cosmochim. Acta, 57,* 2319-2327, 1993.

Yapp, C. J., and H. Poths, Ancient atmospheric CO_2 pressures inferred from natural goethites, *Nature, 355,* 342-344, 1992.

Yip, K-J. J., and T. J. Crowley, *Selected circulation Statistics and Sensitivity Experiments for the GENESIS GCM.* Texas Center for Climate Studies, Technical Report No. 1, Texas A&M University, College Station, Texas, 1994.

S. K. Baum and T. J. Crowley, Department of Oceanography, Texas A&M University, College Station, TX 77843-3146.

(received September 27, 1993; revised September 2, 1994; accepted September 13, 1994.)