Initiation of a continental ice sheet in a global climate model (GENESIS)

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Abstract. The initiation and maintenance of a continental ice sheet are investigated using the GENESIS global climate model. A necessary condition for ice sheet initiation is to have snow cover survive through the summer. Model simulations examine the sensitivity of the maintenance of summer snow cover to the prescriptions of topography and solar luminosity. The time period chosen for this study is the Late Carboniferous (306 Ma) when an extensive continental ice sheet, as large if not larger than the Pleistocene glaciations, existed on a supercontinent in the southern hemisphere. This ice sheet, persisting for over 60 m.y., was one of the most prolonged periods of continuous glaciation in Earth history. Model simulations indicate that given the geography, solar luminosity (3% less than present), and atmospheric CO₂ (same as present) estimated for this time period, summer snow cover remains as far equatorward as 35°S latitude. Global mean temperature is -2.4°C, 17.2°C cooler than for present. Probable regions for the initiation of the Carboniferous ice sheet are apparent in analysis of the spin-up of the model to equilibrium. Summer snow cover first persists along the polar coastline of the supercontinent during year 4 of the simulation. Summer snow cover shows the greatest sensitivity to solar luminosity. Increasing the solar constant to its present value from the Late Carboniferous value results in a summer warming of southern hemisphere high-latitude land areas by as much as 37°C and complete melting of any summer snow cover. Topography plays a lesser role. Reducing land elevations to sea level causes persistent summer snow cover to retreat only 8° poleward. Conversely, initializing the model with an elevated land ice sheet has no effect on summer snow cover extent.

1. Introduction

Global climate models are an important tool in our quest to predict the ramifications of man’s pollution of the Earth’s atmosphere. These models, initially developed to understand present climate [Kasahara and Washington, 1971; Manabe and Broccoli, 1974] are now being asked to predict future climates. Consequently, they need to be critically evaluated in terms of their performance. One means of testing these models is to look at past climates. In conjunction with geologic proxy monitors, simulations of past climates allow an assessment of model capabilities under conditions much different than for which the models were developed, and they extrapolate our understanding of the natural variability of the climate system [Crowley and North, 1991; Crowley, 1993; Otto-Bliesner, 1995].

Earth’s history has been punctuated by periods of continental ice sheets. Major glaciations have been documented for the late Cenozoic (40-0 Ma), Permian-Carboniferous (320-245 Ma), Late Ordovician (440 Ma), and Late Precambrian (900-600 Ma) [Frakes and Francis, 1988; Crowley and Baum, 1991b]. Several factors, alone, or more probably, nonlinearly interacting, have been proposed to explain the initiation and maintenance of these ice sheets, including variations in levels of atmospheric CO₂, solar luminosity, and continental positions and topography. Simulating the initiation and maintenance of these ice sheets has been a challenge for climate modelers for the last 20 years. Early atmospheric modeling work for the Cenozoic, particularly the Pleistocene [Manabe and Broccoli, 1985; Kutzbach, 1987; Rind, 1987] suggests that the Laurentide ice sheet at Last Glacial Maximum was unstable and based on mass budget considerations should have melted in as little as 1000 years. Processes for the initiation of the Laurentide ice sheet are just as problematic. Analyses of faunal deep-sea records over the past 150 kyr point to a connection between Milankovitch variations in the solar forcing and interglacial/glacial climatic cycles [Imbrie et al., 1984]. It is generally thought that a cool-summer orbital regime is a necessary condition for ice sheet initiation. Rind et al. [Rind et al., 1989; Peteet et al., 1992] find that even with magnified reduction in summer and fall solar insolation and initial 10-m-thick ice sheet, their model could not retain this ice sheet, melting it within 5 years.

Recent modeling studies suggest that reductions in atmospheric carbon dioxide concentrations in conjunction with changes in sea surface temperatures and an extension of sea ice due to reduced summer solar insolation in the northern hemisphere may have played an important role in the inception of the Fennoscandian, Laurentide, and Cordilleran ice sheets [Peteet et al., 1992; Syktus et al., 1994; Dong and Valdes, 1995]. Better resolution of topographic features in northern Canada and Siberia as sites for glacial development is
also critical [Dong and Valdes, 1995]. Recent modeling studies suggest that the Laurentide ice sheet probably initiated on high regions of Baffin Island and that improvement in the resolution of this topographic feature plus the use of a ice sheet model may lead to a successful simulation of glacial initiation.

The mechanisms for the initiation, maintenance, and eventual demise of Permian-Carboniferous glaciation has been extensively studied with energy balance models and more recently using global climate models. Crowley et al. [Baum and Crowley, 1991; Crowley et al., 1994] find that small ice cap instability (SICI) associated with snow-albedo feedback, previously demonstrated in simple models of the climate system as a possible mechanism for glacial inception, is also a feature of more complex global climate models which explicitly include the hydrologic cycle. Under cold-summer orbital conditions, a reduction in solar luminosity by 0.5% from 98.5% to 98% of present levels results in a dramatic reduction in snow-albedo feedback, previously demonstrated in simple models of the climate system as a possible mechanism for glacial inception, is also a feature of more complex global climate models which explicitly include the hydrologic cycle. Under cold-summer orbital conditions, a reduction in solar luminosity by 0.5% from 98.5% to 98% of present levels results in a dramatic reduction in solar luminosity by 0.5% from 98.5% to 98% of present levels results in a dramatic act.

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The Late Ordovician (440 Ma) glaciation poses a climatic paradox for glacial maintenance in that atmospheric CO2, was high, estimated to be 13 times present. Crowley and Baum [1995] reconcile this paradox by demonstrating that the position of Gondwana tangential to the south pole in combination with reduced solar luminosity is sufficient to initiate and maintain the polar ice cap found in the rock record. The low thermal inertia of the nearby polar oceans is sufficient to cool summer temperatures of the adjacent land areas and allow accumulation of snow and ice. Late Precambrian simulations [Crowley and Baum, 1993a] illustrate that the response of modeled snow line to reduced solar luminosity depends on choice of paleogeography. A supercontinent located entirely in tropical latitudes will not trigger ice growth. Land areas at midlatitudes provide the “seed” area for summer snow cover and thus ice growth into lower latitudes.

In this study, the sensitivity of ice sheet initiation to several factors is considered. In particular, the ability of the model to retain summer snow cover over middle- and high-latitude land is assessed as a function of land elevation and solar luminosity given the land-sea distribution at 306 Ma. Results from the spin-up phase of the model as well as the mean climate for years 14-18 of the simulations are presented.

2. Details of Numerical Model

A set of sensitivity simulations for the Late Carboniferous is conducted using the National Center for Atmospheric Research (NCAR) GENESIS global climate model, version 1.02 [Thompson and Pollard, 1995a, b]. The model consists of components for the atmosphere, ocean, and land surface. The atmospheric component is based on the NCAR community climate model version 1 (CCM1). The atmosphere is described by the equations of fluid motion, thermodynamic equation, and mass continuity along with representations of radiative and convective processes, cloudiness, precipitation, and the orographic influence of terrain. The CCM1 code has been modified to incorporate new model physics for solar radiation, water vapor transport, convection, boundary layer mixing, and clouds. The horizontal resolution is R15 which corresponds to a 4.5° latitude by 7.5° longitude spectral transform grid, on average. A s-coordinate system is used in the vertical with 12 levels from s = 0.991 to 0.009.

The ocean component of GENESIS contains a 50-m-deep mixed layer ocean coupled to a thermodynamic sea ice model. The ocean representation crudely captures the seasonal heat capacity of the ocean mixed layer but ignores salinity, upwelling, and energy exchange with deeper layers. Poleward oceanic heat transport in present-day simulations is set to be 0.3 times the latitudinal variation from the “0.5 x OCNFLX” case of Covey and Thompson [1989] A six-layer sea ice model, patterned after Semtner [1976], predicts local changes in sea ice thickness through melting of the upper layer and freezing or melting on the bottom surface. Fractional sea ice coverage is included, as is a reduction in the albedo as the surface temperature of the ice approaches 0°C.

The land surface component [Pollard and Thompson, 1995] incorporates a land-surface transfer model (LSX) which accounts for the physical effects of vegetation, a six-layer soil model that diffuses heat linearly and moisture nonlinearly with a provision for soil ice, and a three-layer thermodynamic snow model. Snow cover can form on soil, ice sheets, and sea ice surfaces with changes in thickness due to snowfall and sublimation at the top layer and melting in each layer. A minimum snow thickness of 15 cm is imposed with fractional snow cover allowing for conservation of snow mass. Snow falls when the temperature is below freezing at the lowest atmospheric level. The average albedo of the snow varies from 0.75 for topmost snow-layer temperatures below -15°C to 0.55 at 0°C (e.g., wet snow). The effects of snow aging are ignored. Permanent land ice can be prescribed as a surface type in the model. As such, it cannot grow or ablate. The albedo of a snow-free ice sheet surface is the same as for sea ice. The average albedo varies from 0.65 for topmost layer temperatures below -5°C to 0.55 at 0°C. In present-day simulations, land ice is prescribed over Greenland and Antarctica.

The GENESIS model adequately reproduces observed present-day climate [Thompson and Pollard, 1995a]. Global and annual mean surface temperature is predicted to be 14.7°C, which is slightly warmer than observed estimates of 13.9°C. Much of this error is due to the model being too warm at the surface over Antarctica, land areas in high northern latitudes, and the topographic regions of the Andes, Rocky Mountains, and Greenland. The latitudinal location of the freezing isotherm over land and its seasonal migration match observed data.

The model’s global and annual mean precipitation (4.5 mm d⁻¹) is considerably greater than observed (3.2 mm d⁻¹). This overestimate occurs over both land and ocean and has been corrected in a newer version of GENESIS with decreased surface drag over oceans. Broad-scale patterns of precipitation are simulated correctly including the seasonal movement of the Intertropical Convergence Zone (ITCZ), the dry subtropics, and dry interior continents at middle and high latitudes in winter.

The model snow line compares favorably to observation, except for too little snow cover between the Black and the
Caspian Seas and too much just north of the Himalayas. The seasonal cycle of total snow mass and coverage over Eurasia and North America agree with the climatology derived from satellites. Over the ice sheets of Greenland and Antarctica the model produces a net annual accumulation of snow as observed.

3. Climate Sensitivity Simulations

The maintenance and initiation of the Late Carboniferous ice sheet are examined in a series of sensitivity simulations exploring the effects of (1) two different land elevations, (2) two different solar luminosities, and (3) prescribed land ice (ice sheet) from the south pole to approximately 45°S. The baseline Carboniferous simulation (hereinafter referred to as “no-ice”) is performed with no prescribed ice sheet (e.g., bare soil initially), land elevations ranging from 500 to 3000 m, present-day atmospheric CO₂ levels, and solar luminosity 3% less than present. The sensitivity simulations involve perturbing one of these components to test the stability of an ice sheet to uncertainties in the boundary conditions (Table 1).

3.1. Paleogeography

Paleogeography for the model simulations adopts the 306 Ma reconstruction (Figure 1) of C.R. Scotese and J. Golonka [Scotese, 1994]. The Late Carboniferous marks the beginning of the formation of Pangea. The southern supercontinent of Gondwana, consisting of South America, Africa, Australia, Antarctica, and parts of Asia, and the tropical continent of Laurussia, made up of North America and parts of Europe, have collided closing the seaway that had separated them earlier. As a result of this collision, a large tropical mountain range, Himalayan in scale, was formed. Data also indicate mountainous belts over the northern hemisphere land masses and at high southern latitudes. In the “no-ice” and “full-ice” simulations, mountain heights ranging up to 3 km are assigned using topographic and plate tectonic analogs (C.R. Scotese, personal communication, 1994). Nonmountainous land is set to an elevation of 500 m. In the “no ice-low” and “no ice-warm” simulations, all land points are assumed to be at sea level. These initial sensitivity simulations assume no vegetation and soil with texture intermediate between sand and clay and with intermediate color. At ocean points, poleward ocean heat transport is modified for the Late Carboniferous simulations by averaging Covey and Thompson’s [1989] data to make it symmetric about the equator. The values used are not multiplied by a factor of 0.3 as in the present-day runs.

3.2. Ice Sheet and Snow Cover

Glacial deposits (tillites) dated to the Late Carboniferous have been found on the continents of Australia, Africa, South America, and Antarctica as well as India [Crowell, 1983; Caputo and Crowell, 1985; Vevers and Powell, 1987] and suggest the possibility of four ice sheets with total areal extent of 18 X 10⁶ km² [Crowley and Baum, 1991a]. A more extensive single ice sheet covering nearly 70% of the continent of Gondwana from the south pole to roughly 45°S latitude and with areal extent of 42 X 10⁶ km² has been proposed by C.R. Scotese and J. Golonka (personal communication, 1994), (Figure 1). The rationale for a single massive ice sheet assumes extensive destruction of glacial evidence, especially during highly erosional postglacial environments. This massive ice sheet is prescribed in the full-ice simulation (Plate 1) and ice sheet heights ranging up to 3 km are assigned using the area-volume relationship employed in the Climate Mapping, Analysis, and Prediction (CLIMAP) studies [Paterson, 1972].

3.3. Atmospheric Carbon Dioxide

Models of the geochemical cycle [Walker et al., 1981; Garrels and Lerman, 1984; Budyko et al., 1987; Berner, 1994] and independent isotopic measurements of paleosols (ancient soils) and marine sediments [Freeman and Hayes, 1992; Yapp and Pothis, 1992; Mora et al., 1996] suggest that atmospheric CO₂ has varied considerably over the last 600 m.y. due to imbalances in the effects of weathering, organic burial, and metamorphism. The geochemical model of Berner estimates atmospheric CO₂ levels as high as 17 times present concentrations for some early time periods during the Phanerozoic [Berner, 1994]. For 306 Ma, atmospheric CO₂ concentrations are predicted to be similar to present. Input of CO₂ into the atmosphere by global degassing should have been low as seafloor spreading rates diminished with the formation of Pangea, while a significant drawdown of atmospheric CO₂ is expected to have occurred in response to enhanced burial of organic carbon as a consequence of the rise and spread of vascular land plants. Atmospheric CO₂ concentrations equal to those in the present-day control run of GENESIS (340 ppm) are adopted for these simulations.

3.4. Solar Luminosity

The solar constant can vary due to changes in the Sun’s output and the Earth’s orbital dynamics. Astrophysicists theorize that the Sun has brightened over the age of the Earth

Table 1. Summary of Model Simulations

<table>
<thead>
<tr>
<th>Simulation</th>
<th>No Ice</th>
<th>No Ice-Low</th>
<th>No Ice-Warm</th>
<th>Full Ice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar luminosity</td>
<td>3% less than present (1328.9 W m⁻²)</td>
<td>3% less than present (1370 W m⁻²)</td>
<td>present (1370 W m⁻²)</td>
<td>3% less than present</td>
</tr>
<tr>
<td>Atmospheric CO₂</td>
<td>1XCO₂</td>
<td>1XCO₂</td>
<td>1XCO₂</td>
<td>1XCO₂</td>
</tr>
<tr>
<td>Topography</td>
<td>500 m lowlands</td>
<td>0 m lowlands</td>
<td>0 m lowlands</td>
<td>500 m lowlands</td>
</tr>
<tr>
<td></td>
<td>1000-3000 m mountains</td>
<td>0 m mountains</td>
<td>0 m mountains</td>
<td>1000-3000 m mountains</td>
</tr>
<tr>
<td>Ice sheets</td>
<td>none prescribed</td>
<td>none prescribed</td>
<td>none prescribed</td>
<td>south pole to ~45°S</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>500-3000 m elevation</td>
</tr>
</tbody>
</table>

(see Figure 1 and text)
(~ 4.6 billion years), as hydrogen is converted to helium in the Sun’s core, being 30-40% dimmer when the Earth formed [Endal and Sofia, 1981]. Over the Phanerozoic, this translates to an approximate 6% increase in solar luminosity [Crowley et al., 1991]. The solar luminosity at 306 Ma has been set to 3% less than present in all but the no ice-warm simulation.

Milankovitch cycles of the Earth’s orbital dynamics have been documented in records for the Pleistocene, but the periods and magnitude of this forcing before the Pleistocene are uncertain [Berger, 1978; Berger et al., 1989]. An idealized circular solar orbit (eccentricity = 0) with present-day obliquity (23.4°) is assumed for this study. This orbital configuration means that the northern and southern hemispheres receive similar amounts of solar insolation in their respective seasons. This contrasts with the “cold summer” orbital configuration used in many glacial inception modeling studies which use a nonzero eccentricity and set the perihelion such that a minimum of summer insolation is received in the hemisphere in which land ice was known to have developed.

4. Results of Sensitivity Simulations

The sensitivity simulations for 306 Ma are started from a zonally symmetric wind and temperature initial state. The baseline no-ice simulation is integrated through 20 seasonal cycles, while all other simulations are integrated through 18 seasonal cycles, all with complete coupling of the atmosphere, ocean, and land surface. Mean climate statistics represent 5-year averages calculated from years 14-18 of the simulations. Results are summarized in Table 2.

4.1. Climatology of No-Ice Simulation

4.1.1. Approach to equilibrium. The simulation is initialized with a zonally and vertically uniform temperature of 30°C at the equator decreasing linearly to 2°C at the poles. Global mean temperature at the start of the simulation is 19.6°C. Global mean surface temperature (not shown) decreases rapidly during the first 10 years of the simulation. Although the simulation is not quite to equilibrium at year 20, the decreasing rate of change of surface temperature indicates an asymptotic approach with a mean global temperature at year 20 of -2.4°C, a 17.2°C cooling from the 14.7°C predicted for present day. Land surface temperatures and snow fraction show the dominating effect of the southern hemisphere landmasses on their seasonal variation. Land surface temperatures decrease from an average of 10.7°C in year 1 to an average of -17.5°C in year 20 (Figure 2a). This results in increasing amounts of snow cover with snow fraction for the globe as a whole approaching 0.58 (Figure 2b).

Southern hemisphere land areas cool substantially during the first winter with the freezing isotherm at 42°S and temperatures as low as -41°C at 88°S (Figure 3a). In addition, snow fraction increases to 1.0 at high southern latitudes (Figure 3b). Land areas at northern latitudes, being located at lower latitudes and less continental, cool less extensively during the first full winter although surface temperatures are still substantially below freezing (-25°C) and extensive snow covers these land areas. All snow cover melts during the respective summers in both hemispheres through year 3 of the simulation. During the summer of year 4, surface temperatures remain below freezing and a small area of snow persists over land and sea ice located near the south pole. This area of summer snow cover rapidly expands, due to snow-albedo feedback, with snow fractions greater than 0.8 from the south pole to 70°S during the summer of year 6. Summer land surface temperatures range from freezing at 62°S to -6°C at 88°S. Winter snow extent increases only slightly during this time period from maximum extent to 45°S during the first winter to 40°S during the summer of year 6.

By year 20 of the simulation, snow fraction over southern hemisphere land areas has come into quasi-equilibrium varying...
little between summer and winter and covering land areas from 90°S to 35°S. Winter to summer land surface temperatures vary from -83°C to -31°C at 88°S and -62°C to -18°C at 50°S. The smaller continent of Siberia at northern midlatitudes experiences greater seasonal variation in snow cover with total cover to 45°N in winter retreating to only those areas poleward of 60°N during summer.

Sea ice forms and thickens in both hemispheres remaining year-round in the southern hemisphere by year 3 and in the northern hemisphere by year 7 (Figure 3d). By year 20 of the simulation, sea ice extent varies little in latitudinal extent with a seasonal range from 42°S to 36°S and 55°N to 48°N. The advection of cooler air off the extensive snowpack covering Gondwana leads to greater sea ice extent over the

Plate 1. Modified Köppen classifications for no-ice, no ice-low, no ice-warm, and full-ice simulations. The color key is given in the first panel with climate types defined in Table 3. Dashed lines represent maximum summer sea ice extent for August in the northern hemisphere and February in the southern hemisphere. Thick solid line delineates prescribed ice sheet (Scotese and Golonka, personal communication, 1994) included in full-ice simulation only.
adjacent southern hemisphere oceans. Tropical ocean temperatures cool to approximately $23^\circ$C with maximum temperatures skewed toward the northern hemisphere (Figure 3c). Ocean surface temperatures and sea ice extent have not yet reached equilibrium in the model.

Current versions of climate models do not generally contain an explicit ice sheet model. Instead, a proxy for ice sheet initiation over land areas is the ability of snow cover to survive through the summer. An indication of where the Permian-Carboniferous ice sheet may have developed is apparent in the analysis of the spin-up of the model to equilibrium. The development of this Gondwana “ice sheet” is illustrated by February snow depths in the simulation. Snow depths are the product of the snow fraction and the snow heights.

Snow first persists over summer during year 4 of the simulation as a small patch at $75^\circ$S along the polar coastline of Gondwana with snow depths 0.1 m or less (Figure 4a). This area is conducive for summer snowpack due to the refrigerating effect of sea ice along this coastline as well as the availability of moisture for snowfall from the adjacent open ocean. By year 12, summer snow cover extends equatorward to $45^\circ$S over South America and Australia and with greatest depths (greater than 4.1 m) along the polar coastlines and extending over the adjacent sea ice. By year 20 of the simulation the equatorward extent of summer snow cover has come into equilibrium covering the landmass of Gondwana from the south pole to $35^\circ$ latitude. Maximum snow depths are located not only along the polar oceans but also along the midlatitude coasts where the adjacent oceans provide abundant moisture for precipitation. Lesser amounts of snow cover occur in interior regions.

### 4.1.2. Mean climate.

Surface temperatures cool from a maxima of $27^\circ$C in the tropics in the present-day simulation to $21^\circ$C in January and $23^\circ$C in July in the no-ice simulation (Figures 5 and 6). Maximum temperatures are found north of the equator ($\sim 10^\circ$N) in both months due to the extensive year-round snowpack and sea ice in the southern hemisphere and the presence of the tropical mountain belt just south of the equator. More dramatic cooling occurs at middle and high latitudes. Average surface temperatures at $88^\circ$S are $-76^\circ$C during southern winter (July) in the no-ice simulation, $24^\circ$C cooler than present, and $-28^\circ$C during the southern summer (January), $8^\circ$C cooler than present. Note that the present-day simulation includes permanent, prescribed ice sheets over Antarctica and Greenland as a lower boundary condition. Surface temperatures at $88^\circ$N are $2^\circ$C cooler than present in July but $11^\circ$C cooler in January.

### 4.1.3. Köppen climate classification.

Climate classification schemes permit characterization of the global patterns of surface temperature, precipitation, and evaporation. In this study, the Köppen climate classification scheme [Köppen, 1936], based on monthly mean surface temperature and precipitation, is employed. Specifics of the Köppen climate classification are given in Table 3. The scheme used for this study includes modifications similar to those of Guetter and Kutzbach [1990] to allow better

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**Table 2. Global Mean Statistics**

<table>
<thead>
<tr>
<th>Simulation</th>
<th>No Ice</th>
<th>No Ice-Low</th>
<th>No Ice-Warm</th>
<th>Full Ice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface temperature, $^\circ$C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>land+ocean</td>
<td>1.1</td>
<td>4.7</td>
<td>16.0</td>
<td>1.1</td>
</tr>
<tr>
<td>land</td>
<td>-14.0</td>
<td>-6.5</td>
<td>9.5</td>
<td>-15.0</td>
</tr>
<tr>
<td>ocean</td>
<td>6.0</td>
<td>8.3</td>
<td>18.1</td>
<td>6.3</td>
</tr>
<tr>
<td>Snow fraction, land</td>
<td>0.54</td>
<td>0.46</td>
<td>0.25</td>
<td>0.52</td>
</tr>
<tr>
<td>Southern hemisphere summer snow area, $10^6$ km$^2$</td>
<td>53.9</td>
<td>40.5</td>
<td>0</td>
<td>51.3</td>
</tr>
<tr>
<td>Percentage E climates</td>
<td>62</td>
<td>52</td>
<td>7</td>
<td>62</td>
</tr>
<tr>
<td>Ice fraction, ocean</td>
<td>0.24</td>
<td>0.20</td>
<td>0.02</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Averages for years 14-18 of the simulations.

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**Figure 2.** Time variations for no-ice simulation of global mean (a) surface temperature over land ($^\circ$C) and (b) snow fraction over land. Monthly average values are plotted.
agreement between climatic groups and the present-day vegetation they are meant to represent. In addition, small changes to the limiting temperatures of the climate classes and the formula to determine the location of the boundary between humid and dry climates are incorporated to improve the correspondence of the simulated present-day Köppen patterns and the observed patterns.

Of particular interest in this study are the polar (E) climates. Continental ice sheets are designated by the polar ice cap climate type (EF) in which surface temperatures remain below freezing year-round (in practice, regions of either land ice or year-round snow cover). Bordering the ice sheets is polar tundra (ET) which has at least 1 month above freezing but all months with average temperature below 10°C. The no-ice simulation has extensive polar (E) climates covering 62% of the land surface (Plate 1, Table 2). In the southern hemisphere, polar ice cap climates (EF) extend to about 35°S with polar tundra (ET) as far equatorward as 25°S. In the northern hemisphere the no-ice simulation suggests a permanent ice cap along the northern part of Siberia poleward of 56°N and over the mountainous regions in northeastern Siberia. Polar tundra (ET) climates are also simulated over the highest peaks in the tropical mountain belt.

4.2. Sensitivity to Land Elevation (No Ice-Low Simulation)

Lowering the land elevations to sea level results in a warming of global (land plus ocean) and annual mean surface temperature by 3.6°C and simulated increase of 7.5°C over continental regions (Table 2). The elimination of the tropical mountain range warms the land surface by 10.5°C at 7°S, the latitude with the highest peaks in the no-ice simulation. The climate type in this region changes from polar tundra (ET) and cool temperate (Df) climate to tropical (Aw) climate (Plate 1).

Larger surface temperature changes occur over high latitudes because of the ice-albedo feedback mechanism. At 88°S, land temperatures warm in January by 18°C and in July by 9°C (Figures 7c and 7d). The freezing isotherm retreats 8° poleward over Gondwana during the southern summer with a corresponding decrease in polar ice cap (EF) climates (Plate 1). Polar tundra (ET) climates along the northern fringes of Gondwana in the no-ice simulation are replaced by cool temperate (Df) climates in the no-ice-low simulation. Northern hemisphere high-latitude continental areas experience ~10°C warming with the lowering of the land elevations. Polar ice caps are now restricted to only the northern fringes of Siberia.

Figure 3. Time variations for no-ice simulation of zonal averages of (a) surface temperature over land (°C), (b) snow fraction over land, (c) surface temperature over oceans (°C), and (d) sea ice fraction over oceans. Monthly average values are plotted. Contour interval for temperature is 15°C with negative contours dashed and for fractional coverage is 0.25.
Surface temperatures over the oceans at low latitudes do not change with the lowering of land elevations. Although the latitudinal extent of southern hemisphere sea ice does not vary noticeably between the two simulations (Plate 1), the no ice-low simulation exhibits significantly warmer surface temperatures over the sea ice at high southern latitudes due to the advection of warmer temperatures off adjoining continental regions.

4.3. Sensitivity to Solar Luminosity (No Ice-Warm Simulation)

Solar luminosity at present levels (no ice-warm simulation) results in a significant warming of the global and annual mean surface temperature to 16.0°C (Table 1), warmer than present surface temperatures simulated by the GENESIS model, primarily due to much warmer temperatures over Antarctica and northern polar oceans. January surface temperatures are 19°C warmer at 88°S, 4°C warmer at the equator, and 49°C warmer at 88°N than the no ice-low simulation (Figure 7a). Snow cover has completely melted over Gondwana although some sea ice remains over the Panthalassic Ocean fringing Gondwana. Although Siberia exhibits subfreezing temperature poleward of 47°N, the northern polar oceans remain unfrozen.

In July the no ice-warm simulation is significantly warmer at high southern latitudes than the no ice-low simulation over both land (26°C warmer at 88°S) and the oceans (29°C at 83°S) although surface temperatures are still significantly below freezing. Northern hemisphere surface temperatures are also warmer although increases are only 14°C over high-latitude land areas and 6°C over the polar oceans. Tropical continental temperatures average 7°C warmer than with reduced solar input, while tropical ocean temperatures are 3°C warmer.

Figure 4. Simulated February snow depths in meters (south polar projection) for no-ice simulation for (a) year 4, (b) year 12, and (c) year 20. A maximum snow depth of 6 m is imposed on January 1 of each year.

Figure 5. Latitudinal distributions of zonally averaged surface temperatures (°C) for 306 Ma no-ice and 0 Ma (present day) simulations for (a) January land plus ocean and (b) July land plus ocean. Present-day simulation is a 5 year simulation with present-day forcing and geography started from an equilibrated simulation with fixed sea surface temperatures.

Surface temperatures over the oceans at low latitudes do not change with the lowering of land elevations. Although the latitudinal extent of southern hemisphere sea ice does not vary noticeably between the two simulations (Plate 1), the no ice-low simulation exhibits significantly warmer surface temperatures over the sea ice at high southern latitudes due to the advection of warmer temperatures off adjoining continental regions.
Table 3. Modified Köppen Climate Types

<table>
<thead>
<tr>
<th>Class</th>
<th>Type</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Af</td>
<td>Humid tropical climates. All months have an average temperature of at least 18°C. Tropical wet climate (rain forest) climate. Wet all seasons; all months have at least 4 cm of rainfall. Typical modern vegetation is evergreen tropical rain forest.</td>
</tr>
<tr>
<td></td>
<td>Aw</td>
<td>Tropical wet and dry (savanna) climate. Winter dry season; rainfall in driest month is less than 4 cm. Typical modern vegetation is savanna grasses and tropical deciduous forests.</td>
</tr>
</tbody>
</table>
| B     | BS   | Dry climates. Potential evaporation and transpiration exceed precipitation. These climates occur where the annual precipitation in centimeters is less than the amount \( R \) defined in the following formula (\( T \) is mean annual temperature in degrees Celsius; \( P_w \) is the percentage of precipitation occurring in the coolest six months of the year):
\[
R = 2.4 \ T - 0.36 \ P_w + 60.
\] Typical modern vegetation is low bushes, trees, and sagebrush. |
|       | BW   | Semiarid (steppe) climate. Rainfall exceeds 50% the amount given in above formula. Typical modern vegetation is low bushes, trees, and sagebrush. |
| C     | Cfa  | Warm temperate rainy climates. Average temperature of the coolest month is below 18°C but above -5°C. Typical modern vegetation is subtropical evergreen (pine) forests mixed with deciduous (oak) forests. |
|       | Cfb  | Humid subtropical climate. Wet year-round and summers hot. Average temperature of warmest month above 22°C. Typical modern vegetation is evergreen (fir) forests. |
|       | Cfc  | Marine climates. Wet year-round and summers cool. Average temperature of all months below 22°C. Typical modern vegetation is low growing, scrubby trees and shrubs called chaparral. |
|       | Cs   | Mediterranean climate. Summer drought; average winter monthly rainfall is at least 3 times that of the average summer monthly rainfall. Typical modern vegetation is evergreen (fir) forests. |
|       | Cw   | Winter drought. Average summer monthly rainfall is at least 10 times that of the average winter monthly rainfall. Typical modern vegetation is similar to Cf climates. |
| D     | Df   | Cool temperate (boreal) rainy climates. Average temperature of the coolest month is below -5°C; average temperature of warmest month is above 10°C. Typical modern vegetation is evergreen coniferous forests mixed with deciduous forests at equatorward boundary. |
|       | Dw   | Wet year-round. Symbols a-d indicate progressively cooler and shorter summers and colder winters. |
| E     | ET   | Polar climates. Average temperature of warmest month is below 10°C. Tundra climate. Average temperature of warmest month is above freezing (0°C). Typical modern vegetation is tundra vegetation consisting of lichens, mosses, and dwarf trees. |
|       | EF   | Ice cap climate. All months have average temperatures below freezing. |

4.4. Sensitivity to Prescribed Ice Sheet (Full-Ice Simulation)

The full-ice simulation evaluates the sensitivity of surface temperatures and summer snow cover to a permanent elevated ice sheet. In this simulation the presence of a prescribed land...

Figure 6. Simulated surface temperatures (degrees Centigrade) for no-ice simulation for (a) January and (b) July. Contour interval is 10°C with negative contours dashed.

OTTO-BLIESNER: CONTINENTAL ICE SHEET
These simulations support a single ice sheet covering Gondwana at least as large if not larger than the ice sheet proposed by C.R. Scotese and J. Golonka. The three simulations with reduced solar luminosity (no-ice, no ice-low, and full-ice) all develop a large single region of perennial snow cover of areal extent of at least 40.5 \times 10^6 \text{ km}^2. This result is fairly robust in terms of topography. The size of the Gondwanan ice sheet that developed in the no ice-low simulation is reduced by only 25% compared to the no-ice simulation with less equatorward extent in western Africa, Saudi Arabia, and northern Australia. Simulated perennial snow cover for the Carboniferous can be compared to size estimates for the Laurentide ice sheet at the Last Glacial Maximum (~21 kyr) of 11.6 \times 10^6 \text{ km}^2 and maximum Pleistocene extent of 23.5 \times 10^6 \text{ km}^2 [Crowley and Baum, 1991a]. Estimates of Carboniferous sea level variations of 100-200 m [Heckel, 1986] are also consistent with a single massive ice sheet.

5. Discussion and Conclusions

These simulations support a single ice sheet covering Gondwana at least as large if not larger than the ice sheet proposed by C.R. Scotese and J. Golonka. The three simulations with reduced solar luminosity (no-ice, no ice-low, and full-ice) all develop a large single region of perennial snow cover of areal extent of at least 40.5 \times 10^6 \text{ km}^2. This result is fairly robust in terms of topography. The size of the Gondwanan ice sheet that developed in the no ice-low simulation is reduced by only 25% compared to the no-ice simulation with less equatorward extent in western Africa, Saudi Arabia, and northern Australia. Simulated perennial snow cover for the Carboniferous can be compared to size estimates for the Laurentide ice sheet at the Last Glacial Maximum (~21 kyr) of 11.6 \times 10^6 \text{ km}^2 and maximum Pleistocene extent of 23.5 \times 10^6 \text{ km}^2 [Crowley and Baum, 1991a]. Estimates of Carboniferous sea level variations of 100-200 m [Heckel, 1986] are also consistent with a single massive ice sheet.

Perennial snow is also simulated in the northern hemisphere in the baseline no-ice simulation although considerably smaller than its southern hemisphere counterpart. The results suggest that the initiation of a continental ice sheet over northeastern Siberia is dependent on the elevation of the area. Removal of the mountains over western Siberia in the no ice-low simulation limits the ice
sheet to only the northern coastline of the continent. Lack of geological evidence of glaciation in this area makes any conclusions from these simulations tentative.

Lowering the solar luminosity to a level 3% less than present is sufficient to build a single massive ice sheet. From energy balance considerations which include only water vapor feedbacks, a 3% decrease in the solar constant can be expected to decrease global mean temperature by ~3.4°C [Crowley and North, 1991]. The Carboniferous no ice-low simulation gives a cooling of 11.3°C compared to no ice-warm simulation. Previous studies suggest that much of the cooling is a result of SICI (small ice cap instability) [Crowley and North, 1990; Baum and Crowley, 1991; Crowley et al., 1994]. Results suggest that, because of snow-albedo feedback, summer snow extent and therefore surface temperatures are highly sensitive to changes in solar input.

Summer snow area is also sensitive to the orbital configuration. For late Carboniferous luminosity (3% less than present), a cold summer orbit in the southern hemisphere produces large snow areas (62 X 10^6 km^2) [Crowley et al., 1994]. An orbital configuration favorable for hot summers in the southern hemisphere indicates that the entire Gondwanan land mass would become snow free during the summer [Crowley and Baum, 1993b]. With the results of the current study, this suggests that the transition point in SICI for the late Carboniferous occurs somewhere between the hot southern hemisphere summer orbit and the median orbit employed in this study.

The importance of solar luminosity for the initiation of the Permian-Carboniferous ice sheet is further confirmed by the no ice-warm simulation. At present levels of the solar constant, summer snow cover would not persist in either hemisphere. Surface temperatures are 16.0°C, actually slightly warmer than for the present-day simulation due to differences in geography, topography, and the present-day permanent ice sheets over Antarctica and Greenland. Several other sensitivity studies with the GENESIS model suggest that under present forcing the model might not retain permanent snow cover over Antarctica. GENESIS simulations [Crowley et al., 1993] with a pole-centered idealized continent extending to 45°S predict January temperatures in excess of 20°C at the south pole. A study for the Cretaceous [Otto-Bliesner and Upchurch, personal communication, 1996], when Antarctica had approximately the same location and size as present but lower topography, predicts a January (summer) surface temperature of 11°C at 88°S.

The demise of the Permian-Carboniferous ice sheet has yet to be simulated. Geologic evidence suggests that this ice sheet had probably disappeared by about 245 Ma [Frakes and Francis, 1988]. Energy balance model simulations support increasing solar luminosity and CO2 and changes in geography for decreasing ice extent during the Permian [Crowley and Baum, 1992]. Solar luminosity is expected to have increased by 0.75% and atmospheric CO2 estimates range from 3 to 9 times present levels by 245 Ma [Berner, 1994]. Sensitivity studies need to be done with an ice sheet model to separate the effects of these parameters on the melting of the Gondwanan ice sheet as well as the sensitivity to a single massive ice sheet versus a four-lobe ice configuration.

One parameter not considered in this study is the effect of vegetation on modifying the initiation and extent of the ice sheet. Many past paleoclimatic modeling studies have assumed that exposed land surfaces were uniform and lacking any vegetation. Reasons included missing or incomplete information on the global distribution of vegetation and no present-day analogs for past vegetation. Several recent studies have shown that surface temperatures are significantly affected by the prescription of vegetation, especially at middle and high latitudes [Bonn et al., 1992; Foley et al., 1994; Otto-Bliesner and Upchurch, personal communication, 1996]. A late Carboniferous simulation with mixed deciduous-coniferous vegetation stipulated for regions poleward of 40° latitude suggests that if high-latitude vegetation cover had been present, it would have substantially raised summer temperatures due to the altered albedo [Crowley and Baum, 1994]. Future sensitivity simulations will need to include a first approximation of vegetation for this period.

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