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Controls on Permo-Carboniferous precipitation over tropical Pangaea: A GCM sensitivity study

Cheryl E. Peyser, Christopher J. Poulsen *

Department of Geological Sciences, University of Michigan, Ann Arbor, Michigan 48109 USA

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ABSTRACT

A series of Late Paleozoic climate model simulations was developed using the GENESIS atmospheric general circulation model to investigate the independent roles of Gondwanan deglaciation, atmospheric CO_2 rise, and regional tectonism on the long-term (10^6 yr) evolution of continental precipitation over tropical Pangaea. The model results indicate that either deglaciation or a CO_2 increase from 1× to 8× present-atmospheric levels could have caused substantial drying and warming at low latitudes, a result that is consistent with Late Paleozoic proxy records. Yet, the atmospheric processes that led to drying differ between these cases. The deglaciation of Gondwana reduces low-latitude temperature gradients in the Southern Hemisphere, decreasing by as much as 60% the meridional overturning in the Southern Hemisphere winter cell of the Hadley circulation. The decline in overturning reduces convective precipitation over equatorial Pangaea. In contrast, high levels of CO_2 have little effect on the large-scale meridional overturning circulation but increase continental temperatures, leading to high evaporation rates and reduced available soil moisture, the source of convective precipitation on land. In comparison to deglaciation and pCO_2, regional uplift/erosion of the Central Pangaean Mountains (CPMs) has a secondary effect on tropical precipitation in GENESIS and cannot explain the long-term aridification and warming of western Pangaea. We suggest that the deglaciation of Gondwana and a concomitant rise in atmospheric pCO_2 could explain much of the Late Paleozoic climate change over low-latitude Pangaea.

1. Introduction

Low-latitude Pangaea underwent profound climate change during the Permo-Carboniferous, marked in part by long-term drying over tens of millions of years. The occurrence of peat-forming forests, high-diversity paleoflora, paleosol composition and paleosol isotopic geochemistry indicate that the paleoequator was tropical with "ever-wet", "ever-warm" conditions in the Carboniferous (Cecil, 1990; Tabor and Montañez, 2002; Raymond and Metz, 2004). Throughout the late Carboniferous and early Permian, however, these conditions gave way to seasonally dry climates. Peat-forming forests were replaced by savannah-like flora (Phillips et al., 1985; Rowley et al., 1985; Cleal and Thomas, 2005); soil moisture decreased (Tabor and Montañez, 2004); and coal beds, paleosols, and fluvial facies gave way to eolian and evaporite facies (Cecil, 1990; Witzke, 1990; Rankey, 1997; Kessler et al., 2001; Tabor and Montañez, 2002; Ziegler et al., 2002). This drying trend is associated with a decrease in low-latitude floral diversity (Ziegler et al., 2002; Raymond and Metz, 2004) and a shift from spore-producing to seed-producing plants (Montañez et al., 2007). In addition to long-term aridification, emerging data suggest that low low-latitude temperature increased by ~10 °C (Tabor and Montañez, 2005; Montañez et al., 2007) and, in western Pangaea, winds shifted from Easterlies to Westerlies (Soreghan et al., 2002, 2007; Tabor and Montañez, 2002).

Several explanations have been given for the low-latitude Permo-Carboniferous aridity trend, emphasizing primarily tectonic controls. Importantly, equatorial Pangaea did not experience appreciable latitudinal drift during this period (Scotese, 1999; Ziegler et al., 2002; Loope et al., 2004), eliminating the possibility that continental drift into the subtropics caused the drying. It has been suggested that the uplift of the Central Pangaean Mountains (CPMs), a southwest–northeast trending mountain chain consisting of the Appalachian–Mauretanide–Hercynian orogenic belts that straddled the Pangaean paleoequator, created a rain shadow over western Pangaea (Rowley et al., 1985). However, climate model simulations of the Carboniferous show the opposite effect; high CPMs focus tropical precipitation on the equator by blocking the seasonal migration of the Intertropical Convergence Zone (Otto-Bliesner, 1998, 2003). Alternatively, the drying trend has been attributed to the development of mega-monsoons on Pangaea, resulting in equatorial aridity and marked seasonality (Parrish, 1993; Kessler et al., 2001). Ironically, mega-monsoon intensification may have been brought on by erosion of the CPMs (Tabor and Montañez, 2004). According to this idea, the

* Corresponding author. 2534 C.C. Little Building, Department of Geological Sciences, University of Michigan, Ann Arbor, MI 48109, USA. Tel.: +1 734 615 2236; fax: +1 734 615 4690.
E-mail address: POULSEN@UMICH.EDU (C.J. Poulsen).

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lowering of the mountain range would have allowed the Intertropical Convergence Zone (ITCZ) to seasonally migrate away from the equator, producing seasonally dry climates.

In addition to these possible tectonic mechanisms, the deglaciation of Gondwana has also been suggested as a possible cause of tropical climate change. The details of the Late Paleozoic glaciation, which began around 330 Ma, are not fully known. Traditionally the Permo-Carboniferous ice age has been viewed as a single uninterrupted event extending from the Early Carboniferous to the Late Permian (Veevers and Powell, 1987; Frakes and Francis, 1988; Crowell, 1999). However, in recent years, multiple glacial phases have been postulated (Mii et al., 1999; Isbell et al., 2003a, 2003b; Jones and Fielding, 2004), the final of which most likely ended in the middle Permian (Montañez et al., 2007) and probably coincided with increases in atmospheric pCO_2 (Royer, 2006; Montañez et al., 2007). Geological and oxygen isotopic evidence indicates that Late Paleozoic ice volume was as great as or greater than ice volume during the Pleistocene glacial maxima (Crowley et al., 1991; Joachimski et al., 2006).

On geological timescales, spanning millions of years in the Late Paleozoic, wet (arid) conditions in northern equatorial Pangaea coincide with the occurrence (absence) of continental ice sheets on southern Gondwana. This association of glacial intervals, commonly referred to as icehouse intervals, with humid (ever-wet, ever-warm) tropical conditions has long been recognized (e.g. Ziegler et al., 1987; Raymond et al., 1989; Raymond and Metz, 2004; Tabor et al., in press; Tabor and Poulsen, 2008). To explain this relationship between high and low-latitude climate, Ziegler et al. (1987) propose that high pressure systems created by glaciated poles pin the ITCZ and its associated tropical precipitation to the equator. Cecil et al. (2003) suggest a similar mechanism by which orbitally-driven fluctuations of Gondwana ice ice-sheet extent promote Carboniferous cyclothem development through their influence on the ITCZ and tropical precipitation. Though operating on different timescales, in both cases, the central idea is that high-latitude ice sheets constrain the position of the ITCZ through their influence on large-scale atmospheric patterns. This linkage between high-latitude ice sheets and tropical precipitation may be a general characteristic of the climate system that transcends the Late Paleozoic; for example, Pleistocene speleothem records document north–south migrations of the ITCZ that correspond to glacial–interglacial cycles (Wang et al., 2004). Alternatively, Miller and West (1993) and Miller et al. (1996) suggest that orbital-scale wet–dry cycles in the mid-continent of North America were linked to fluctuations in the intensity of the Pangaean monsoon. In their model, monsoonal low pressure systems intensified during interglacials, diverting the moisture-laden, low-latitude easterlies away from the equatorial region, causing equatorial drying. In support of a high to low-latitude climate linkage on Panagea, climate model simulations of the Permian demonstrate large changes in tropical climate and vegetation due to the deglaciation of Gondwana (Poulsen et al., 2007). Yet, in the single climate modeling study to test the influence of Gondwanan ice ice-sheet extent on tropical precipitation, Carboniferous polar ice had only a small effect on low-latitude precipitation (Otto-Bliesner, 2003).

This study is motivated by this observation that the tropical climate on Pangaea became arid as Gondwana deglaciation progressed. To our knowledge, the only explanations for this association between high-latitude ice sheets and tropical humidity (on any timescale) were proposed by Ziegler et al. (1987), Miller and West (1993), and Cecil et al. (2003) and require a large-scale reorganization of the general circulation of the atmosphere. In this contribution, we use an Earth system model, GENESIS version 2.3, to evaluate the influence of high-latitude continental ice on tropical climate during the Permo-Carboniferous transition through a series of sensitivity experiments. Because our objective is to evaluate the long-term (10^6 yr) evolution of Pangaean tropical precipitation, we do not consider the influence of orbital oscillations that occur on shorter timescales. During this time, changes in regional tectonics and atmospheric pCO_2 have also been reported and linked to changes in tropical precipitation. For this reason, we also quantify the influence of the CPMs and pCO_2 on tropical precipitation. Our model results indicate that the uplift and/or erosion of the CPMs have little influence on tropical precipitation. In contrast, the retreat of the Gondwana ice sheets and increase in atmospheric CO_2 could have led to substantial decreases in tropical precipitation, though for very different reasons. The mechanism for equatorial drying in each case is investigated.

2. Tropical precipitation

In contrast to extratropical regions, tropical precipitation is largely controlled by the large-scale Hadley circulation. In the modern climate, the highest precipitation rates are associated with the upwelling branch of the Hadley cell, a region of low pressure and low-level convergence (i.e., the ITCZ). The location of the ITCZ is largely determined by surface heating rates through solar insolation, a fact that is born out by the seasonal migration of the ITCZ. This surface heating is also responsible for spawning the convective updrafts that induce high rates of precipitation. On longer timescales, however, the mean location of the ITCZ is sensitive to interhemispheric temperature contrasts, and tends to shift towards the warmer hemisphere (Broccoli et al., 2006).

The Hadley overturning is driven by heating in the tropics and cooling in the subtropics. Subtropical cooling occurs through infrared radiative cooling to space and by energy transports to the extratropics through transient eddies (e.g., Pierrehumbert, 1995; Trenberth and Stepaniak, 2003). The intensity of the Hadley overturning is sensitive to the tropical heating gradient; enhanced tropical heating or subtropical cooling increases the Hadley overturning (e.g., Hou and Lindzen, 1992; Kim and Lee, 2001).

In this context, long-term (10^6 yr) drying of tropical Pangaea might be expected to result from either a persistent displacement of the Hadley cells or a persistent decrease in overturning intensity. However, either of these large-scale circulation changes requires an increase in tropical heating gradients. Alternatively, the drying may be unrelated to the large-scale circulation.

3. Methods

The Late Paleozoic experiments presented here were completed using GENESIS, an earth system model that has been used extensively for Late Paleozoic paleoclimate studies (e.g., PSUCLIM, 1999; Gibbs et al., 2002; Rees et al., 2002; Otto-Bliesner, 2003; Poulsen et al., 2007). The GENESIS version 2.3 consists of an AGCM coupled to multi-layer models of vegetation, soil or land ice, and snow (Pollard and Thompson, 1995; Thompson and Pollard, 1997). Sea-surface temperatures (SSTs) and sea ice are computed using a 50-m slab oceanic layer with diffusive heat flux, and a dynamic sea-ice model (Flato and Hibler, 1992). The AGCM grid is independent of the surface grid: the AGCM resolution used here is spectral T31 (~3.75) with 18 vertical levels; the surface model grid is 2×2°. The AGCM timestep is 30 min. A land-surface transfer model accounts for the physical effects of vegetation (Pollard and Thompson, 1995). Up to two vegetation layers (trees and grass) can be specified at each grid point, and the radiative and turbulent fluxes through these layers to the soil or snow surface are calculated. A six-layer soil model extends from the surface to 4.25 m depth, with layers thickening with depth. Physical processes in the vertical soil column include heat diffusion, liquid water transfer, surface runoff and bottom drainage, uptake of liquid water by plant roots for transpiration, and the freezing and thawing of soil ice. A three-layer snow model is used for snow cover on soil, ice sheet and sea-ice surfaces, including fractional cover when the snow is thin.

We conducted a series of sensitivity experiments to evaluate the influence of 1) Gondwanan glaciation, 2) the elevation of the Central