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Evolution of tropical watersheds and continental hydrology during the Late Cretaceous greenhouse; impact on marine carbon burial and possible implications for the future

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ABSTRACT

Regional climate modelling for the Late Cretaceous greenhouse and high-resolution marine stratigraphic records from both sides of the low latitude Atlantic show that tropical South American and African hydrology and watersheds had a strong effect on freshwater transfer into the Equatorial Atlantic and subsequently the marine carbon record. This conclusion is derived from new detailed geochemical records from Demerara Rise off Suriname drilled at Ocean Drilling Program (ODP) Site 1261 combined with frequency analyses and climate simulations providing evidence for mainly eccentricity-driven changes in carbon burial in the western tropical Atlantic. Shorter orbital frequencies, in particular precession, clearly dominating black shale cycles off tropical Africa (ODP Site 959), are far less dominant at Demerara Rise despite comparable time resolution of the geochemical records. We suggest that these different frequency patterns in carbon burial were related to the regional evolution of Cretaceous watersheds and hydrology in tropical South America and Africa. River discharge deduced from simulations indicates higher and less variable discharge from South America compared to western Africa at that time. This runoff pattern would have supported more permanent anoxic conditions off South America compared to Africa, at least indirectly, and caused the lack of strong higher frequency geochemical cycles in the western sector of the Equatorial Atlantic. Furthermore, climate simulations show a general switch of primary runoff from either side of the Cretaceous Equatorial Atlantic every half precession cycle (i.e. every ~10 kyr). Similarities between the developments of Cretaceous and Holocene hydrology in the tropical Atlantic area imply that orbital-scale evolution of watersheds is a robust feature through time that is independent from the mean global climate state. Based upon the comparison of Cretaceous and Holocene trends in hydrology we infer that future hydrology in the study region may develop in a comparable direction to the one observed in the Cretaceous. If true, this suggests that the modern Amazon rain forest could shrink over the next millennium due to a ~30% loss of moisture while the Congo rain forest in Africa is likely to expand in response to a 14% gain in moisture.

1. Introduction

1.1. Climate-hydrology relationships—future, modern and past greenhouse

Earth's climate exhibits variations on a wide range of scales, both temporal and spatial. The regional feedbacks and consequences involved in these global variations provide the scope for research as the current discussion on global warming emphasizes the critical role of regional response to global climate trends (IPCC, 2007). One critical issue of the current debate on future global warming therefore centres on the hydrological cycle as primary driver of precipitation and freshwater, including flooding and droughts, nutrient and carbon flows within and between the terrestrial and marine environments (Bouwman et al., 2005; Milly et al., 2005). Modelling the future hydrological cycle and its impact on the marine environment is therefore one focal point of climate research (Held and Soden, 2006; Shindell et al., 2006), particularly because the mechanisms and relationships between the rate of global warming and the rate of increase in global precipitation are under

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debate (Gedney et al., 2006; Wentz et al., 2007). This is especially true for the tropical climate system because the temporal variability of the hydrological system in response to regional and global climate forcing still is not fully understood (Seidel et al., 2008).

While variation of Earth's water cycle is a robust and persistent feature of numerical simulations related to an increase in atmospheric pCO_2 it is difficult to assess model performance using observations of the recent past. It is even more difficult to transfer these processes to long time scales by calibrating numerical simulations to paleoclimate proxy records. Numerous modelling approaches have addressed the hydrological cycle in the geological past (e.g., Haupt and Seidov, 2001; Huber and Sloan, 2000; Park and Oglesby, 1991), though, not necessarily directly tested with paleoclimate proxy data. Paleoclimate records from marine sediments suggest that changes in the past hydrological cycle occurred at decadal–centennial, millennial and longer timescales and most data sets also display distinct orbital cyclicity. While the response of the hydrologic cycle to global warming seems to be proportionate on decadal time scales (Wentz et al., 2007), we still lack a well constrained theory of hydrologic evolution on long time scales. Paleoclimate studies may provide valuable constrains on the mechanisms that underlie modern and future climate change.

The Paleogene–Cretaceous greenhouse period has attracted much attention over the last decade (see review in Jenkyns, 2003). One focus is the investigation of organic carbon-rich marine black shales that mainly formed during a series of Oceanic Anoxic Events (OAEs; Schlanger and Jenkyns, 1976), as this period provides a natural example of the processes leading to massive and rapid fluctuations in sea surface temperatures (SSTs), ocean chemistry, and ecosystem response that may be applicable to better understanding dynamics in the future atmosphere– ocean system (IPCC, 2001, 2007). SST reconstructions, for example, for the Coniacian–Santonian (OAE 3), the Cenomanian–Turonian (OAE 2), and the early Albian (OAE 1b) utilizing isotopic and molecular fossil proxies (Bice et al., 2006; Bornemann et al., 2008; Forster et al., 2007; Norris et al., 2002; Schouten et al., 2003; Wagner et al., 2008) suggest that surface waters were around 32–33 °C in the low latitude Atlantic with peak values as warm as 37 °C and estimate temperatures exceeding 20 °C for the middle Cretaceous Arctic Ocean (Jenkyns et al., 2004). Such high SSTs, both at low and high latitudes are difficult to model and are not easily conceived given our current understanding of the physical processes driving the global ocean–atmosphere system. This, in part, is attributable to a general lack of knowledge of the cause–effect relationships controlling paleoclimate dynamics. A mechanism relevant for today's tropical climate is the hydrologic cycle by enhancing precipitation maxima in the tropics whereas the subtropical subsidence regions become drier (Seidel et al., 2008; Shindell et al., 2006).

Given the geological and paleoclimatic/paleoceanographic context of the Late Cretaceous tropical Atlantic it appears reasonable to expect comparable patterns in sediment geochemistry on both sides of the Equatorial Atlantic, in particular for carbon burial. In this study we understand the total organic carbon (TOC) record as the integrating sedimentary signal representing variations in continental climate, runoff, ocean circulation and redox. Other parameters including $CaCO_3$ and elements of terrestrial origin are considered to document more specific processes including ocean productivity and continental weathering. To identify similarities and differences across the Equatorial Atlantic we present new continuous biostratigraphic and bulk geochemical records from the South American continental margin off Suriname at ODP Site 1261. These new records are then compared to published records from ODP Site 959 off tropical Western Africa. Based on this comparison we aim to identify the underlying mechanisms that determined continental climate and marine organic carbon sedimentation and burial on both sides of the evolving Equatorial Atlantic Gateway (Wagner and Pletsch, 1999).

To further explore regional continental climate and land–ocean relationships we compare geochemical proxy data with numeric runoff volumes from both tropical continental catchment areas, extracted from GENESIS GCM for four orbital configurations covering one full precession cycle. We then examine extracted orbital timescale trends in Cretaceous continental runoff in comparison with general climate and runoff history of the Holocene for similarities and differences. In a final step we infer possible implications for hydrological cycling over future millennia.

1.2. The eastern tropical Atlantic in the Late Cretaceous

Geochemical proxy records for continental input (e.g., Silicium/Aluminium (Si/Al), Potassium/Aluminium (K/Al), Titanium/Aluminium (Ti/Al)), oceanic productivity (TOC, carbonate ($CaCO_3$)), and bottom water oxygenation (Nickel/Aluminium (Ni/Al), Zinc/Aluminium (Zn/Al), Vanadium/Aluminium (V/Al)) revealed periodic changes of orbital precession and its influence on marine circulation in the Deep Ivory Basin at ODP Site 959 (Beckmann et al., 2005a,b; Hofmann et al., 2003; Wagner et al., 2004). ODP Site 959 Hole D was drilled in 2102 m water-depth on the southern shoulder of the Deep Ivorian Basin at 3°37.656′N and 2°44.149′ W (Mascle et al., 1996). On the basis of their analysis on benthic foraminifera assemblages, Holbourn et al. (1999) attributed outer-shelf to upper slope conditions to deposits from the early Coniacian at Site 959, deepening to middle bathyal/lower bathyal conditions from the late Coniacian to early Santonian. Paleogeographic reconstructions place ODP Site 959 at approx. 11°S and 33°W 85 My ago (http://www.odsn.de/odsn/services/paleomap/paleomap.html) and at approx. 11°S and 30°W 80 My ago (Hay et al., 1999). Climate model simulations of that area have shown that Late Cretaceous continental runoff from tropical Africa was critical in stimulating short periods of enhanced organic carbon (OC) accumulation (Beckmann et al., 2005a; Floegel and Wagner, 2006). In particular, total continental freshwater discharge varied significantly over the course of one precessional cycle suggesting that peak OC deposition and thus ocean anoxia/euxinia was restricted to one specific orbital configuration. The model data suggest that maximum insolation occurred during spring, leading to highest freshwater discharge in the spring wet season and ultimately highest seasonal contrasts (Beckmann et al., 2005a). Although these results have been drawn for the Coniacian–Santonian (representing the OAE 3) they probably apply to other Cretaceous time periods of black shale formation as well, with similar profound effects on ocean–land–atmosphere dynamics and ocean redox.

1.3. The western tropical Atlantic in the Late Cretaceous

At ODP Site 1261 sediment cores through the Coniacian–Santonian OAE3 were retrieved during ODP Leg 207 (Demerara Rise off Suriname/French Guyana, Equatorial Atlantic; Erbacher et al., 2004). During this interval, Site 1261 was located on an open marine continental margin, with probable unrestricted connection to the early North Atlantic (Erbacher et al., 2004; Hetzel et al., 2006). The early North Atlantic itself, however, had no fully established deepwater connection to the South Atlantic (Wagner and Pletsch, 1999). Thus, it can be regarded as a (semi-)restricted basin. Since the Albian, Demerara Rise has experienced continuous deepening, and probably also some tilting, due to progressive opening of the Equatorial Atlantic Gateway, which has hampered estimations of paleo-water depths (Erbacher et al., 2004; Friedrich and Erbacher, 2006). Paleogeographic reconstructions place ODP Site 1261 at approx. 2°N and 58°W 85 My ago (http://www.odsn.de/odsn/services/paleomap/paleomap.html).

2. Materials and methods

2.1. Materials

ODP Site 1261 was drilled on the northwestern flank of the Demerara Rise, approx. 350 km north of Suriname in 1899 mbsl water-depth. Hole 1261A was drilled at 9°2.917′N and 54°19.038′W and hole