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A regional climate model study of the impact of tectonic and orbital forcing on African precipitation and vegetation

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ABSTRACT

The development of the East African Rift System (EARS) caused by tectonic forcing during the past 20 million years is believed to influence the regional climate in Africa. However, changes in the Earth's orbital parameters also have an influence on climate on these timescales. To analyze the influence of both tectonic and orbital forcing, we applied the non-hydrostatic regional climate model COSMO-CLM (COSMO model in Climate Mode, CCLM). The regional simulations are driven by different global simulations performed with the coupled ocean–atmosphere general circulation model ECHO-G. To analyze the impact of tectonic forcing a different topography representing a possible past stage of the development of the EARS is applied in the model. The results indicate that tectonic forcing has a strong impact on precipitation in Africa caused by circulation changes. To analyze the impact of orbital forcing, which means the impact of changing insolation patterns, we chose configurations of the Earth's orbit that result in significantly different patterns of insolation. One example is the orbital configuration of the last interglacial at 125,000 years before present, when the seasonality of insolation in the Northern Hemisphere was greatly enhanced, whereas in the Southern Hemisphere it was substantially weakened compared to preindustrial conditions. The simulation of this time slice shows a strong impact of orbital forcing on precipitation in large parts of Africa, caused by altered moisture transport. The application of a biome model helps in analyzing the impact of the two forcing factors on vegetation for a more direct comparison with proxy data.

1. Introduction

East Africa is a region of special interest concerning the hominid evolution during the past five to six million years. During this time, various external forcing factors influenced the East African climate and vegetation. Due to tectonics the East African Rift System (EARS) started developing roughly 20 million years ago (Maslin and Christensen, 2007), and it is still an active system with diverging plates. The development of the EARS led to a change in the region's topography from relatively flat terrain to mountainous areas including the highest peaks of the African continent. This change in topography has strongly contributed to the aridification of East Africa since the middle Pliocene, and may therefore also be connected to hominid evolution (Pickford, 1990; Kingston, 2007; Maslin and Christensen, 2007). Besides this tectonic forcing, changes in the Earth's orbital parameters also play a significant role in climate change over these long time scales. Changes in Earth's orbital parameters lead to variations in the seasonal and regional distribution of solar insolation.

The influence of the East African highlands on climate has been analyzed in various studies using global climate models (Rodwell and Hoskins, 1995; Slingo et al., 2005; Sepulchre et al., 2006; Chakraborty et al., 2009; Kaspar et al., 2010). Rodwell and Hoskins (1995), Slingo et al. (2005) and Chakraborty et al. (2009) concentrate on the impact on monsoonal flow and climate over the Western Indian Ocean. They all show that the East African Highlands are essential for focusing the summer monsoonal flow along the East African coast and therefore for its intensity. Slingo et al. (2005) and Chakraborty et al. (2009) also looked at the impact on East African climate, which is the focus of Sepulchre et al. (2006) and Kaspar et al. (2010). The results of Slingo et al. (2005), Sepulchre et al. (2006) and Kaspar et al. (2010) show that for the removed topography case an increase in precipitation in East Africa is due to a stronger moisture transport toward the continent, whereas Chakraborty et al. (2009) find a precipitation decrease due to the absence of orographic rainfall. Sepulchre et al. (2006) also applied a dynamic global vegetation model showing an increase in total vegetation cover over East Africa and a shift from herbaceous-dominated to arboreal-dominated vegetation with decreasing elevation.

The impact of orbital forcing on African climate can be analyzed by simulating selected time slices with orbital parameters substantially different from present-day conditions. Global simulations have been

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used to analyze orbital forcing with a focus on the tropics (e.g. Clement et al., 2004) and on Africa (Herold and Lohmann, 2009; Kaspar et al., 2010). They all show a substantial impact of different orbital parameters on climate. Both simulations with focus on Africa look at the last interglacial, known as the Eemian, roughly 125,000 years before present (BP). They find an increase in summer temperature over the northern Sahara due to stronger insolation, leading to a meridional pressure gradient and a strong zonal flow transporting moisture from the Atlantic Ocean toward northern Africa, which leads to an increase in precipitation in this region.

The global simulations by Kaspar et al. (2010) concerning the impact of tectonic and orbital forcing on African climate have a relatively coarse resolution of ~3.75°. Therefore, their results can only be interpreted at the continental scale. Smaller-scale topographic features like the western and eastern branches of the EARS and the Turkana Channel are not resolved in the global model, but have a substantial impact on precipitation patterns. To consider these small-scale effects and to obtain more regional details of the impact of tectonic and orbital forcing on African climate, we applied numerical downscaling by nesting a regional climate model (RCM) into the global model as suggested by Kaspar et al. (2010). In general, the explicit simulation of smaller-scale processes and the more detailed representation of orography in an RCM are expected to yield more realistic simulations than a global model with a coarser resolution (Denis et al., 2002; Wang et al., 2004). This is the first time an RCM is used to analyze the impact of tectonic and orbital forcing over Africa.

Applications of RCMs for simulating past climates are rare. Simulations adapting the orbital parameters to the desired time slice include those of Hostetler et al. (2000), Renssen et al. (2001), Zheng et al. (2004), Diffenbaugh et al. (2006) and Patricola and Cook (2007). Renssen et al. (2001) directly compare the ability of the regional model and the driving global climate model to represent the European climate during the Younger Dryas as indicated by proxy data. They find that, for most climate variables and seasons, the results of the regional simulation are closer to the reconstructions than the results of the global simulations. They conclude that the advantage of an RCM over a GCM is its more detailed information due to the higher resolution, which corresponds better to paleoclimate reconstructions. Renssen et al. (2001) therefore deduce that the comparison of regional proxy data with RCM simulations is more suitable than that with the global simulations.

2. Model description

In this study we use the COSMO model in Climate Mode (CCLM) (Böhm et al., 2006; Rockel et al., 2008), which is a non-hydrostatic RCM. It is based on the COSMO model (see http://www.cosmo-model.org) that is used for operational mesoscale weather forecasting in the Consortium for Small-scale Modeling (COSMO), including the German meteorological service DWD. CCLM is developed as a community effort of several universities and research centers (see http://www.clm-community.eu). It uses a regular latitude/longitude grid with a terrain-following height coordinate.

The model domain of our simulations covers large parts of Africa ranging from 14.5°W to 67.0°E and from 37.5°S to 25.0°N (Fig. 1a). A spatial resolution of 0.5° (approx. 50 km) on 32 atmospheric levels and 10 soil levels is used. With this configuration and different convection parameterization schemes Kaspar and Cubasch (2008) validated present-day CCLM simulations for precipitation against the GPCC (Global Precipitation Climatology Centre) full data reanalysis product (Rudolf et al., 1992; Rudolf and Schneider, 2005). They obtained the best results with a good agreement between simulated and observed precipitation for the Tiedtke convection scheme (Tiedtke, 1989) with a two-category ice scheme (Doms et al., 2005) which is therefore used in the present study. The study by Kaspar and Cubasch (2008) showed that the seasonal cycle of precipitation over Africa is well captured by the regional model except for some underestimation over the equatorial EARS. However, the spatial pattern is less well represented, especially the maxima over Central Africa. Kaspar and Cubasch (2008) point out that no observations are available for large areas in this region and conclude that the bias in this region does not necessarily show shortcomings of the model. To allow model applications for past orbital configurations, we implemented a routine that calculates the seasonal and latitudinal pattern of insolation based on the three Earth's orbital parameters eccentricity, obliquity and longitude of the perihelion. This implementation is consistent with that in the global climate model ECHO-G (Legutke and Voss, 1999; Min et al., 2005).

The tectonic forcing is represented in the model by a change in topography in Southern and Eastern Africa and the Arabian Peninsula. In this region, the elevation is reduced by 50%, with an altitude threshold of 650 m. This simple scenario has been chosen to allow a clear interpretation of the results, and the experiment should therefore be considered as a sensitivity test. Detailed regional information on past stages of

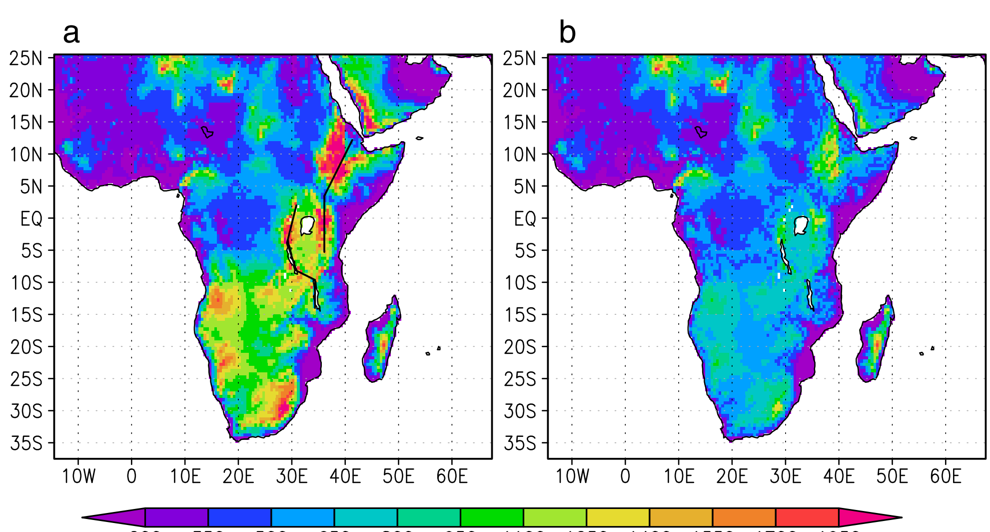

Fig. 1. Model domain with orography in m for (a) the preindustrial control simulation CTRL and (b) the simulation TECT with an orography reduction of 50%. Black lines indicate the location of the EARS with its western and eastern branches around Lake Victoria.