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Climate of the Past Discussions

Simulated climate variability in the region of Rapa Nui during the last millennium

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Abstract

Easter Island, an isolated island in the Southeast Pacific, was settled by the Polynesians probably between 600 and 1200 AD and discovered by the Europeans in 1722 AD. While the Polynesians presumably found a profuse palm woodland on Easter Island, the Europeans faced a landscape dominated by grassland. Scientists have examined potential anthropogenic, biological and climatic induced vegetation changes on Easter Island. Here, we analyze observational climate data for the last decades and climate model results for the period 800–1750 AD to explore potential causes for a climatic-induced vegetation change. A direct influence of the ENSO phenomenon on the climatic parameters of Easter Island could not be found in the model simulations. Furthermore, strong climatic trends from a warm Medieval Period to a Little Ice Age or rapid climatic fluctuations due to large volcanic eruptions were not verifiable for the Easter Island region, although they are detectable in the simulations for many regions world wide. Hence we tentatively conclude that large-scale climate changes in the oceanic region around Easter Island might be too small to explain strong vegetation changes on the island over the last millennium.

1 Introduction

Easter Island (in Polynesian language: *Rapa Nui*) is located at 27°9′ S and 109°26′ W in the Southeast Pacific consisting mainly of three extinct volcanoes covering an area of 166 km^2. When the Europeans arrived at the isolated island in 1722 AD, Easter Island's landscape was dominated by grassland; in contrast, at the time of the Polynesian settlement the landscape was presumably covered with palm trees and shrubs, combined with grasses (Flenley et al., 1991; Mieth and Bork, 2005). Though the date for the settlement remains controversial, one hypothesis suggests 800 AD or even earlier (Martinsson-Wallin and Crockford, 2001; Mieth and Bork, 2005; amongst others), while research by Hunt and Lipo (2006) indicates a later primary arrival of the Polynesians

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around 1200 AD. There is a high probability the ancient palm on Easter Island was congeneric with the *Jubaea Chilensis*, a palm endemic to central Chile (Mieth and Bork, 2005). The change from a vegetation which was dominated by palm trees to mainly grass dominated vegetation led to a controversial discussion about the causes of Rapa Nui's vegetation decline.

A detailed sediment-stratigraphic analysis on Poike Peninsula located in the eastern part of Easter Island revealed a charcoal layer which covers the old surface of the garden and the palm soil (Mieth and Bork, 2006). In this layer, Mieth and Bork found several carbonized fossil nuts which were analysed by ^{14}C radiocarbon dating. The authors assume that the Polynesians cleared the woodland by slashing and burning between 1250–1450 AD. The hypothesis that the Rapa Nui deforested the island before the first Europeans arrived is also noted by Flenley and King (1984), Flenley and Bahn (2003) and Rolett and Diamond (2004) amongst others. In contrast, Hunt (2006) hypothesized that rats which arrived with the canoes of the first Polynesians played a major role in Rapa Nui's ecological catastrophe by consuming the palm seeds and other parts of the trees.

In recent studies, Mann et al. (2008) and Saez et al. (2009) provide a detailed sedimentological and geochemical study of the Raraku Lake sediments to give new insights into the environmental and climate evolution of Easter Island during the last millennia. According to Saez et al. (2009), the lake sedimentary record from 34 to 17.3 cal kyr BP supports a scenario of cooler and wetter conditions along with a reduced vegetation cover. A depositional hiatus in the sediments of Rano Raraku between 3990 and 1180 cal yr BP (Mann et al., 2008) and between 4200 and 800 cal yr BP (Saez et al., 2009) suggests that a drought occurred during these periods. This gives rise to a third hypothesis which assumes that climatic fluctuations caused or provided the decline of the palm woodland in prehistoric times. In 1997, Orliac und Orliac analyzed the fuel in earthen ovens and showed that there was a sudden switch from wood to grasses in the mid-17th. The authors hypothesize that this indicates a sudden climatic fluctuation such as a severe drought due to the ENSO (El Niño/Southern Oscillation)

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phenomenon. However, the analysis of climate variability in the Southeast Pacific between 1985–1993 AD did not support the hypothesis of significant ENSO-related inter-annual climate variability at Rapa Nui (MacIntyre, 2001a,b). Similar to these studies, the effects of recent El Niño and La Niña events between 1950 and 2000 AD were explored by Genz and Hunt (2003). An effect of the ENSO phenomenon on the present climate of Easter Island could not be proven. Another assumption is that the so-called "AD 1300 event" – taken as transition between the Medieval Warm Period and the Little Ice Age in this region – caused the vegetation change on Easter Island due to uncommonly heavy precipitation associated with rapid cooling (Nunn, 2000).

In this paper, we explore the possibility of a climatic-induced vegetation change. Therefore, we reassess the climatic conditions on Easter Island in the last decades by analyzing observational data for the years 1950–2000 AD and satellite data from HOAPS-3 (Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite Data). We then analyze the climate variability in the Easter Island region from recent simulations with global climate models for the period 800–1750 AD. Finally, we use the BIOME 1.0 model by Prentice et al. (1992) to tentatively explore potential changes in plant functional types on Easter Island that might be triggered by the simulated climate changes.

2 Analysis of observational data

To reassess the climatic conditions on Easter Island – particularly for testing model results to be explored below –, we have analyzed timeseries of monthly rainfall and monthly mean temperature data from Hanga Roa in the southwest of Easter Island (Genz and Hunt, 2003). The data indicates a weak annual cycle of monthly mean temperature (between 18.0–23.8 °C) and a humid island's climate (total annual precipitation $P_{obs} \sim 1110$ mm/y, approximately). Climate variations are small presumably because Easter Island lies in the Southeast Pacific at the edge of the subtropical gyre which barely shifts during the year. The relatively constant position of the subtropical gyre is due to the small seasonal displacement of the ITCZ (Inter Tropical Convergence Zone) over the pacific.

To account for the humid climate on Easter Island, we assume two effects to be relevant. First, the island effect which includes effects due to the land-sea breeze and convection induced by the orography of Easter Island. Second, the interplay of the SPCZ (South Pacific Convergence Zone), the subtropical gyre and the westerly storm tracks centered at 34° S (Saez et al., 2009). According to Vincent (1993), the SPCZ is an extended and persistent cloud band which axis stretches from New Guinea east-southeastward to about 30° S and 120° W. To investigate the effect of the SPCZ on the climate of Easter Island, we analyzed the climatological mean of the precipitation rate between the years 1987–2005 from HOAPS-3 (Andersson, 2007). The dataset from HOAPS-3 provides a spatial resolution of 0.5° on a global grid. Figure 1 shows that Easter Island lies on the verge of the SPCZ with precipitation rates between 1.8–2.2 mm/d (657–803 mm/y). Because the dataset from HOAPS-3 explicitly excludes land areas and, hence, does not include topographic effects, we tentatively attribute the difference between precipitation measured at Hanga Roa and estimated from HOAPS-3 to the island effect.

3 Analysis of model results

To explore possible climate changes on Easter Island in prehistoric times, we used model results because undisturbed proxies of precipitation and temperature are not available for Easter Island. First, we analyzed model results from the Millennium project coordinated by the Max Planck Institute for Meteorology (MPI-M). The simulations were carried out with the MPI Earth system model ECHAM5/MPIOM, consisting of the atmosphere model ECHAM5 (horizontal resolution of $\sim 3.75^\circ \times 3.75^\circ$), the ocean model MPIOM and modules for land vegetation (JSBACH) and for ocean biogeochemistry (HAMOCC). For this study we use the control run *mil0001* with constant climate forcing (Jungclaus, 2007) and the ensemble members *mil0010* (Haak, 2008), *mil0012* (Botzet,

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2008a) and *mil0013* (Botzet, 2008b) with time dependent forcings such as the varying solar irradiance and volcanic activity. From the model results, we selected the near-surface air temperature and precipitation for the grid point around Easter Island between the years 800–1750 AD. To test the model results for climatic trends, we calculated a 30-year running climate mean of the timeseries.

The timeseries (Fig. 2) do not show any significant trend. Therefore, the model results do not corroborate the assumption of Nunn (2000) that a temperature decrease associated with a large-scale cooling from the Medieval period to the Little Ice Age and associated precipitation change could have influenced the climate on Easter Island around 1300 AD.

The mean annual precipitation in the model is 564.2 mm. This value is smaller than the satellite-based estimates for the precipitation in the oceanic region around Rapa Nui, and it is smaller than the observed precipitation of approximately 1110 mm on the island itself. This discrepancy can presumably be attributed to the local island effect, which is not resolved in the global-scale model. Secondly, the location of the SPCZ in the model deviates from the observation such that the area under consideration is just outside the range of the SPCZ due to a more zonally orientated SPCZ in the model.

To investigate the influence of the ENSO phenomenon on the climate of Easter Island during the last millennium, we calculated the correlations between the simulated time series of the Niño3.4-index and the simulated timeseries of near-surface air temperature and precipitation as suggested by Genz and Hunt (2003). The Niño3.4-index can be obtained by selecting the sea surface temperature (SST) for the tropical pacific between 120° W–170° W and 5° N–5° S from the model results and calculating the SST anomalies as well as a 5-month running mean. A trend analysis of the timeseries of the Niño3.4-index confirmed that there is no climatic trend in the SST anomalies. The empirical correlation between the Niño3.4-index and the near-surface air temperature on Easter Island is $r = 0.421$, and between the Niño3.4-index and the precipitation $r = 0.282$. We conclude that there is no significant correlation between the ENSO-phenomenon and the climate variability near Easter Island in the model which is in line

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with earlier analyses for present-day climate (MacIntyre, 2001a,b).

Around 1258 AD, a strong volcanic eruption occurred in the tropics. According to Oppenheimer (2003), ice cores from both the Antarctic and the Arctic indicate a volcanic eruption at that time which could have been the strongest of the last millennium. The ensemble simulations *mil0010*, *mil0012* and *mil0013* include the effect of this volcanic eruption (as well as other reconstructed eruptions during the last millennium) on the atmospheric radiation and energy budget. While the impact of the eruption in 1258 AD is clearly seen in global and hemispheric mean temperature values in the model, hardly any change can be detected for the region near Easter Island.

The model results from the ensemble simulations of the ECHAM5/MPIOM model show only small climatic trends from the Medieval Period to the Little Ice Age in global mean temperature. Therefore, we analyzed two simulations with an earlier version of the model system, referred to as ECHO-G, consisting of the atmosphere model ECHAM4 (horizontal resolution of $\sim 3.75^\circ \times 3.75^\circ$) coupled to the ocean model HOPE-G. The simulations with this model system reveal a strong decrease of around 1 °C in the global mean temperature for the period 1000–1750 AD (Zorita et al., 2005) which might be an unrealistically strong global cooling trend according to most reconstructions (IPCC, 2001).

The 30-year running mean near-surface air temperature and precipitation simulated by ECHO-G for the the grid point around Easter Island for 1000–1750 AD are depicted in Fig. 3. Both simulations with ECHO-G show a temperature decrease between the 12th and the 15th century, but the cooling trend of some −0.4 °C for the region of Easter Island is much weaker than the global cooling trend. The simulated precipitation remains at a nearly constant, but high level until 1500 AD, with a yearly mean precipitation of about 1150 mm (Fig. 3). After around 1500 AD, a small, but significant increase in simulated precipitation can be detected.

Precipitation simulated by the ECHO-G model is larger than the precipitation estimated for the oceanic region around Easter Island, and is close to the measured value on the island. Like in the ECHAM5/MPIOM, there is no island effect in ECHO-G. Hence

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we conclude that ECHO-G tends to overestimate precipitation in the region around Easter Island. In ECHO-G, the SPCZ reaches further south than in ECHAM5/MPIOM and it covers the grid point around Easter Island.

4 Sensitivity simulations with the BIOME 1.0 model

To tentatively explore possible effects of simulated climate variability on vegetation of Easter Island, we carried out sensitivity simulations by using the model BIOME 1.0 (Prentice et al., 1992) and near-surface air temperature, precipitation and cloud fraction derived from the ensemble simulations *mil0010*, *mil0012* and *mil0013*. The mean annual cycle of the simulated climate variables around Easter Island were calculated for the period 800–1750 AD. Because the model precipitation from the Millennium experiments (around 550 mm/y) is much lower than observed local precipitation (around 1100 mm/y) we added the difference between model results and observational data to the annual cycle of precipitation and increased the cloud fraction by 0.1.

First, the simulated climatology was varied within the range of simulated decadal fluctuations of the ensemble simulations, and these values were used as input for the BIOME 1.0 model. In a second set of sensitivity simulations, the values of the water holding capacity (watc) in the BIOME model was varied between 50–350 mm with the climatology held constant. This range of values of watc was chosen to represent the spatial variability in soil water capacity on Easter Island between soils with very low water holding capacities around 50 mm (Leptosols) and soils with water capacities exceeding 300 mm (Anthrosols) (personal communication with Bork, unpublished data, 2009). Finally, we tested the sensitivity of the BIOME 1.0 model results to climate changes stronger than our climate simulations indicate. Hence we prescribed a cooling trend of some 1 °C which presumably is as large as the temperature difference between present-day climate and the climate around the Last Glacial Maximum (LGM) for the Southeast Pacific area (Ganopolski et al., 1998; Braconnot, 2007; MARGO Project Members, 2009). In all cases, the BIOME model computes forest coverage, either as

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warm-temperate evergreen forests or tropical raingreen or tropical evergreen forests. No shifts to shrub or grassland were found in the simulations.

5 Conclusions

Climate simulations with two different climate models have been analyzed with respect to simulated temperature and precipitation in the region around Rapa Nui between 800 and 1750 AD. The climate models represent present-day global climate patterns and climate variability reasonably well. They agree with each other in many respects, but they also differ. The models represent the location and strength of the SPCZ differently: one model tends to simulate less rainfall than reconstructed for the region around Rapa Nui, while the other tends to overestimate rainfall. One model produces a weak global and northern hemispheric mean cooling from the Warm Medieval Period towards the Little Ice Age, while the other model reveals a strong trend in comparison with reconstructions. Both models reveal a clear response of global and regional climate to the strong volcanic eruption around 1258 AD. Despite these differences, both models show qualitatively similar results with respect to long-term climate change near Rapa Nui: they either reveal no statistically significant or marginally small trends in simulated temperature and precipitation. Furthermore, no strong climate change over Easter Island in response to the strong volcanic eruption around 1258 AD has been seen in the models.

Some first, very preliminary sensitivity studies on the effect of (simulated) climate variations on the vegetation change indicate no significant change in forest coverage on Rapa Nui. Hence, we tentatively conclude that large-scale climate changes in the region of Rapa Nui might be too small to explain strong vegetation changes on the island over the last millennium. We cannot exclude, however, small-scale, local effects on precipitation over the island in response to changes in the local atmosphere–ecosystem system of the island.

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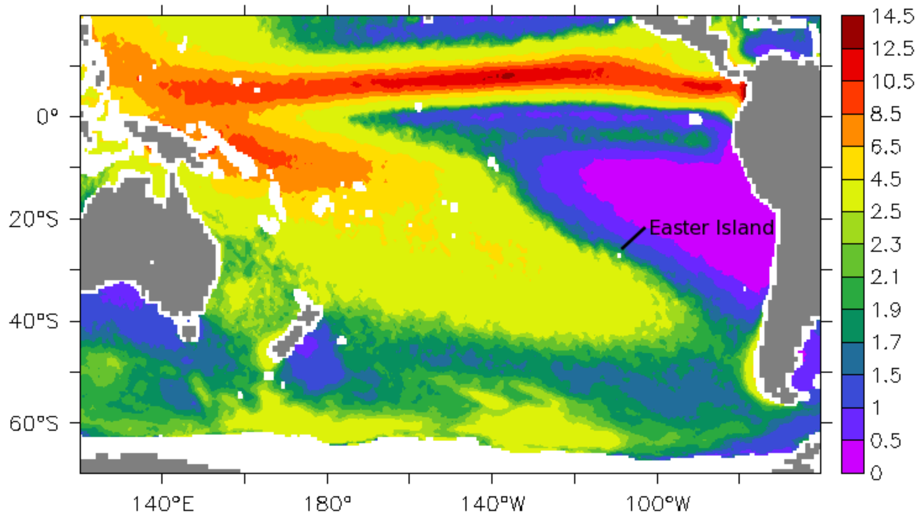

Fig. 1. Climatological mean (1987–2005) of the precipitation rates [mm/d] in the pacific region from HOAPS-3 data (Andersson, 2007).

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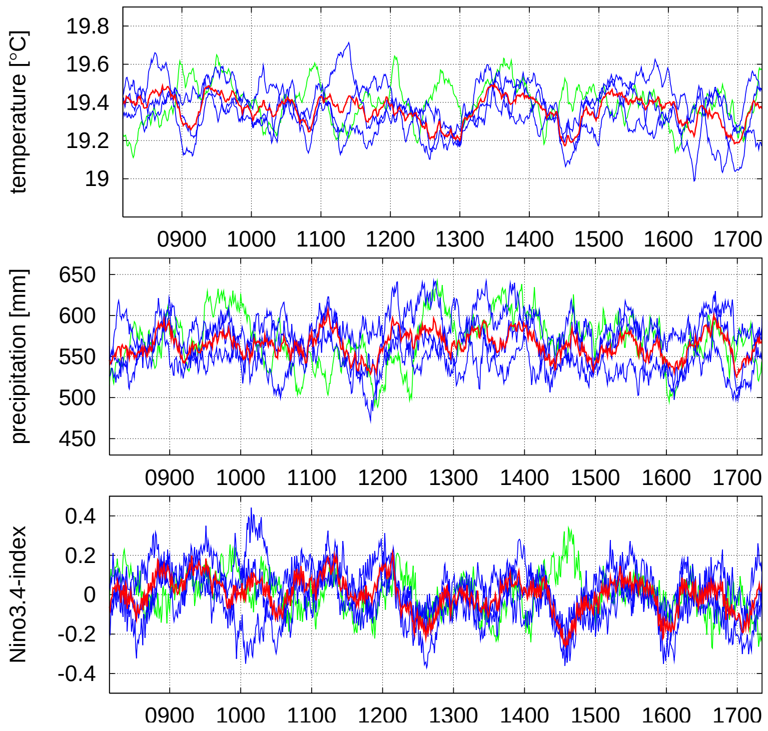

Fig. 2. 30-year running mean of simulated near-surface air temperature (top), precipitation (middle) and Niño3.4-index (bottom) around Easter Island for the period 800–1750 AD. Shown are the Millennium experiments *mil0001* (green), the ensemble members *mil0010*, *mil0012* and *mil0013* (blue) and the ensemble mean (red).

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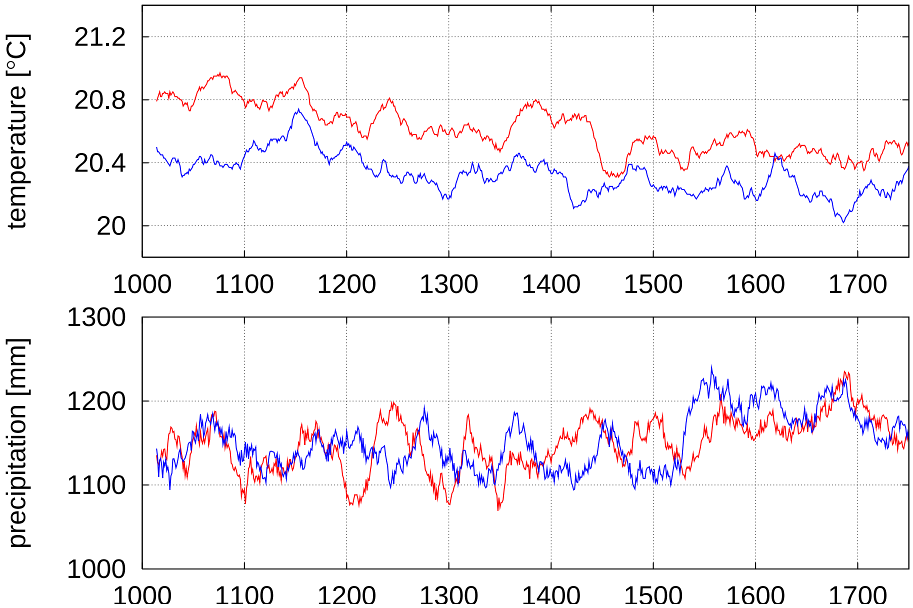

Fig. 3. 30-year running mean of simulated near-surface air temperature (top) and precipitation (bottom) for the period 1000–1750 AD. Shown are the ensemble simulations *Erik1* (red) and *Erik2* (blue) conducted with the atmosphere-ocean model ECHO-G (Zorita et al., 2005).