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Climate of the Past

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

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Abstract. Rapa Nui, an isolated island in the Southeast Pacific, was settled by the Polynesians most likely around 1200 AD and was discovered by the Europeans in 1722 AD. While the Polynesians presumably found a profuse palm woodland on Rapa Nui, the Europeans faced a landscape dominated by grassland. Scientists have examined potential anthropogenic, biological and climatic induced vegetation changes on Rapa Nui. Here, we analyse observational climate data for the last decades and climate model results for the period 800–1750 AD to explore the potential for a climatic-induced vegetation change. A direct influence of the ENSO phenomenon on the climatic parameters of Rapa Nui 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 Rapa Nui 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 Rapa Nui 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, Rapa Nui'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).

Although there are studies suggesting an early colonization of Rapa Nui around 800 AD or even earlier (Martinsson-Wallin and Crockford, 2001; Mieth and Bork, 2005; amongst others), recent studies indicate that the colonization took place most likely around 1200 AD (Hunt and Lipo, 2006; Wilmshurst et al., 2011). The ancient palm on Rapa Nui was congeneric with the Chilean wine palm (*Jubaea Chilensis*) known for its sweet sap and edible nuts, and for being frost and salt resistant, but slow growing and producing first flowers when 40 to 60 years old (Flenley and Bahn, 2003). The potential causes for 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 Rapa Nui 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 dated using the radiocarbon dating method. The authors assume that the Polynesians cleared the woodland by slashing and burning between 1250–1450 AD. The arguments that the aborigine population deforested the island before the first Europeans arrived are also provided by Flenley and King (1984), Flenley and Bahn (2003) and Rolett and Diamond (2004) amongst others. Furthermore, the Polynesian rat (*Rattus exulans*) might have played a significant role in Rapa Nui's vegetation change (Flenley et al., 1991; Hunt, 2006). Hunt (2006) hypothesizes that the Polynesian rat, which was brought on the canoes with the first Polynesians, could have played a major role in the deforestation of Rapa Nui by

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consuming the palm seeds and preventing palm trees from regeneration. He argues that the role of rats has often been underestimated.

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 Rapa Nui 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 hypothesis according to which climatic fluctuations caused or provided the decline of the palm woodland in prehistoric times. Orliac and Orliac (1997) analysed the fuel in earthen ovens and showed that there was a sudden switch from wood to grasses in the mid-17th century. The authors hypothesize that this indicates a sudden climatic fluctuation such as a severe drought due to the ENSO (El Niño/Southern Oscillation) 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 Rapa Nui could not be found. Another assumption is that the so-called “AD 1300 event” – taken as the transition between the Medieval Warm Period (MWP) and the Little Ice Age (LIA) in this region – caused the vegetation change on Rapa Nui due to uncommonly heavy precipitation associated with rapid cooling (Nunn, 2000). Reconstructions for the central Pacific, however, suggest that the MWP was cool and dry and the Little Ice Age was comparatively warm and relatively wet (Allen, 2006). Numerical experiments with the coupled Pacific ocean-atmosphere Zebiak-Cane model support paleoclimate evidence of an El Niño-like state in the tropical Pacific during the LIA and a La Niña-like state during the MWP (Mann et al., 2005).

In this paper, we explore the possibility of a climatic-induced vegetation change. Therefore, we reassess the climatic conditions on Rapa Nui in the last decades by analysing observational data for the years 1950–2000 AD and satellite data from the HOAPS-3 (Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite Data) precipitation climatology. We then analyse the climate variability in the Rapa Nui 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 Rapa Nui that might be triggered by the simulated climate changes.

2 Analysis of observational data

To reassess the climatic conditions on Rapa Nui – particularly for testing model results to be explored below –, we have analysed timeseries of monthly rainfall and monthly mean temperature data from Hanga Roa in the southwest of Rapa Nui (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 $P_{\text{obs}} \sim 1110\,\text{mm}\,\text{yr}^{-1}$, approximately). Climate variations are small presumably because Rapa Nui 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 Rapa Nui, 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 Rapa Nui. 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 Rapa Nui, we analysed the precipitation climatology between the years 1987–2005 from HOAPS-3 (Andersson et al., 2007). The dataset from HOAPS-3 provides a spatial resolution of 0.5° on a global grid. Figure 1 (top) shows that Rapa Nui lies on the verge of the SPCZ with precipitation rates of roughly $2\,\text{mm}\,\text{d}^{-1}$ ($730\,\text{mm}\,\text{yr}^{-1}$). 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 and uncertainties in the HOAPS-3 climatology.

To assess the uncertainty, Andersson et al. (2011) compare the precipitation climatology of HOAPS-3 with other climatologies like the atmospheric reanalysis dataset ERA-INTERIM, the satellite-derived product GPCP V2 and the TRMM 3B43 product. Around Rapa Nui, the ERA-INTERIM precipitation climatology is $\sim 0.12\,\text{mm}\,\text{d}^{-1}$ (6 %) higher compared to HOAPS-3 precipitation while TRMM 3B43 (GPCP V2) precipitation is $\sim 0.36\,\text{mm}\,\text{d}^{-1}$ or 18 % ($\sim$0.14 mm/d or 7%) lower. Since the differences of the precipitation rates in the HOAPS-3 climatology are relatively small compared to the ERA-INTERIM, GPCP V2 and TRMM 3B43 climatology, we think that the HOAPS-3 climatology is useful for the comparison with simulated rainfall around Rapa Nui. Moreover, HOAPS-3 is the only precipitation climatology which is consistently derived from the same type of satellite instrument.

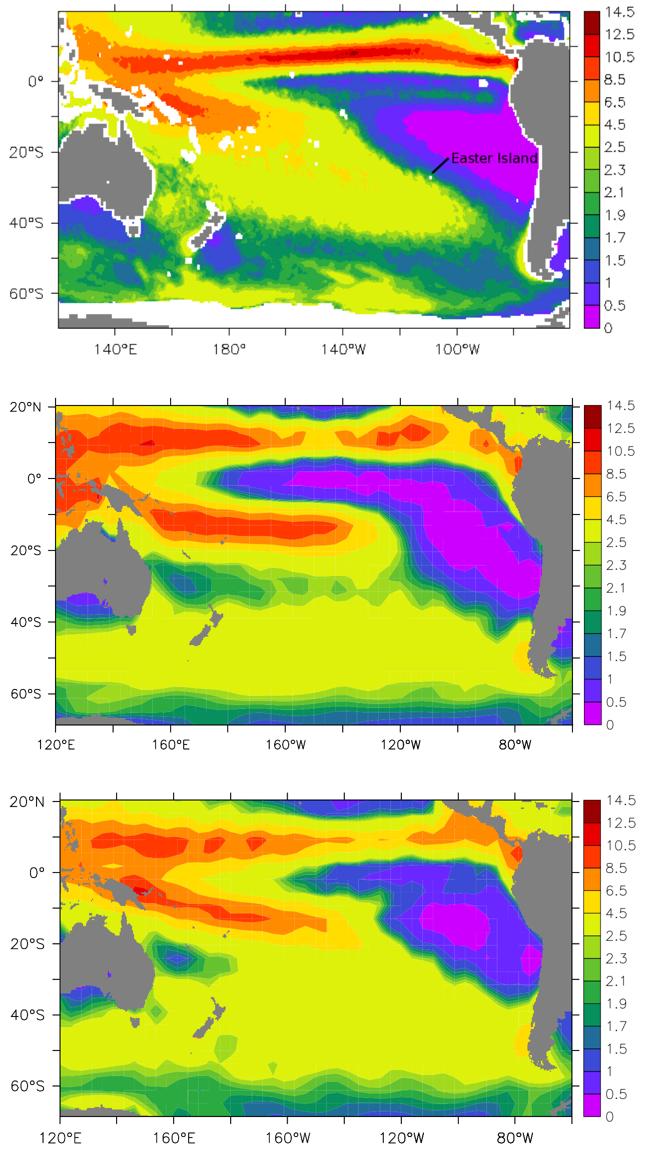

Fig. 1. Climatological mean of the precipitation rates [mm/d] in the Pacific region: (top) HOAPS-3 data for the period 1987–2005, (middle) ensemble mean of the Millennium experiments *mil0010*, *mil0012* and *mil0013* for the period 1987–2005, (bottom) ensemble mean of the ECHO-G experiments *Erik1* and *Erik2* for the period 1972–1990.

3 Analysis of model results

To explore possible climate changes on Rapa Nui in prehistoric times, we used model results of the past millennium because undisturbed proxies of precipitation and temperature are not available for Rapa Nui. Only very few simulations of the last millennium using comprehensive coupled climate models are available to address this topic (e.g. Ammann et al., 2007; Servonnat et al., 2010; Swingedouw et al., 2010). Therefore, the following analyses of the millennium ensemble simulations with the comprehensive Earth system models ECHAM5/MPIOM (Jungclaus et al., 2010) and ECHO-G (González-Rouco et al., 2006) are an important contribution for understanding pre-industrial climate variability in the Pacific region.

3.1 Ensemble simulations with ECHAM/MPIOM

First, we analysed model results from the Millennium project coordinated by the Max Planck Institute for Meteorology (Jungclaus et al., 2010). The millennium simulations with a fully interactive carbon cycle were carried out with the MPI Earth system model ECHAM5/MPIOM, consisting of the atmosphere model ECHAM5 (Roeckner et al., 2003) run at T31 resolution (horizontal resolution of $\sim 3.75° \times 3.75°$) with 19 vertical layers and the ocean model MPIOM (Marsland et al., 2003) with a horizontal resolution ranging from 22 km to 350 km. The carbon cycle model comprises the land surface scheme JSBACH and the ocean biogeochemistry module HAMOCC5 (Jungclaus et al., 2010).

The ensemble simulations carried out with ECHAM5/MPIOM reproduce the pre-industrial temperature variability consistent with the range of reconstructions (Jungclaus et al., 2010). The evaluation of a 300-yr control simulation with ECHAM5/MPIOM already showed that the tropical sea surface temperature climatology is well simulated and that global-scale heat and freshwater-transport are in agreement with observations (Jungclaus et al., 2006). Furthermore, ECHAM5/MPIOM has been successfully applied to different paleoclimate states such as Mid-Holocene climate and transient Holocene climate simulations (Fischer and Jungclaus, 2010; Otto et al., 2009; Dallmeyer et al., 2010; Vamborg et al., 2011), Last Glacial Maximum simulations (Mikolajewicz, 2011; Arpe et al., 2011), Eemian climate simulations (Fischer and Jungclaus, 2010; Schurgers et al., 2006) and Eocene climate simulations (Heinemann et al., 2009).

For this study we use the control run *mil0001* with constant climate forcing and the ensemble members *mil0010*, *mil0012* and *mil0013* with time dependent forcings such as the varying solar irradiance and volcanic activity (Jungclaus et al., 2010). The climatological precipitation rates (1987–2005) for the tropical and South Pacific from the ensemble mean are shown in Fig. 1 (middle). We argue that in comparison to the HOAPS-3 climatology, ECHAM5/MPIOM reproduces the ITCZ well and reveals the typical pattern of the SPCZ and the eastern Pacific dry zone. However, 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. Therefore, ECHAM5/MPIOM tends to underestimate precipitation in the region around Rapa Nui. The climatological precipitation rate (1987–2005) around Rapa Nui is $\sim 1.5\,\mathrm{mm\,d^{-1}}$ ($\sim 547.5\,\mathrm{mm\,yr^{-1}}$) which is 25 % less compared to the satellite-based estimates.

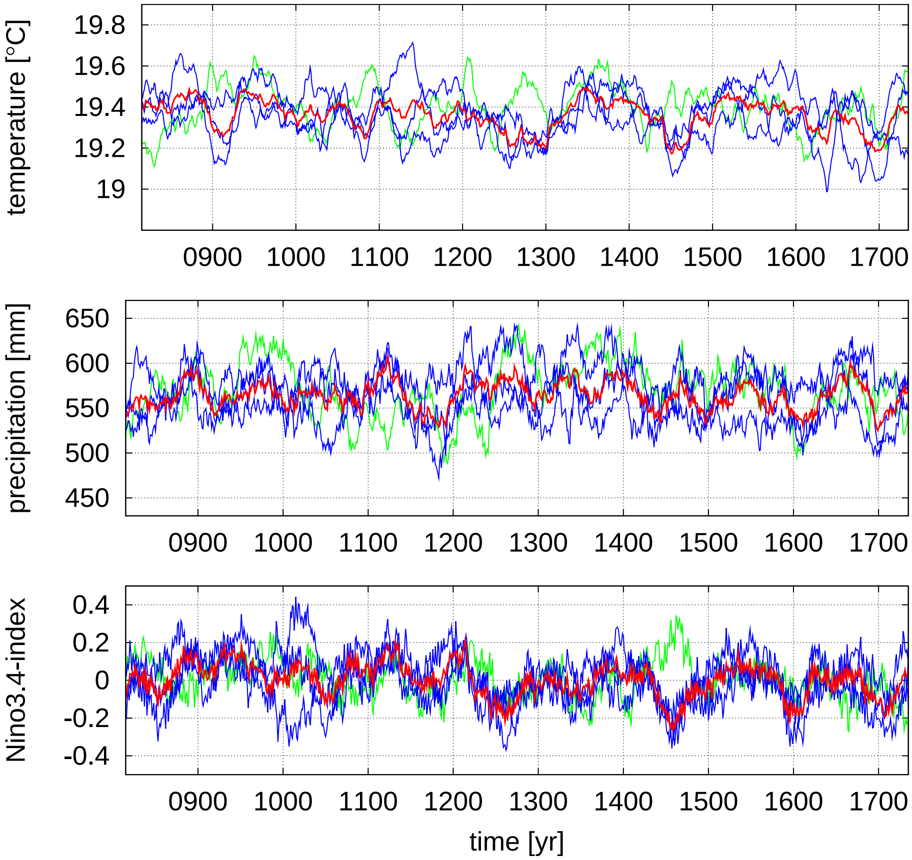

Fig. 2. 30-year running mean of simulated near-surface air temperature (top), precipitation (middle) and Niño3.4-index (bottom) around Rapa Nui for the period 800–1750 AD. Shown are the Millennium experiments *mil0001* (green), the ensemble members *mil0010*, *mil0012* and *mil0013* (blue) and the ensemble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

To test the model results for climatic trends for the period 800–1750 AD, we selected the near-surface air temperature and precipitation for the grid point covering Rapa Nui and calculated a 30-year running climate mean for this period. The timeseries of the control and ensemble simulations (Fig. 2) do not show any significant trend for the given period. A closer look at all eight grid cells surrounding the grid cell encompassing Rapa Nui (not shown here) confirms the result for the grid cell covering Rapa Nui: there are no significant trends in precipitation or temperature in any of these grid cells. 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 an associated precipitation change could have influenced the climate on Rapa Nui around 1300 AD. Likewise, a cool and dry MWP and comparatively warm and relatively wet LIA as seen in paleoclimate reconstructions for the central Pacific (Allen, 2006) cannot be found for the region around Rapa Nui in the model results.

To investigate the influence of the ENSO phenomenon on the climate of Rapa Nui 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 Rapa Nui 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 Rapa Nui in the model which is in line 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*,

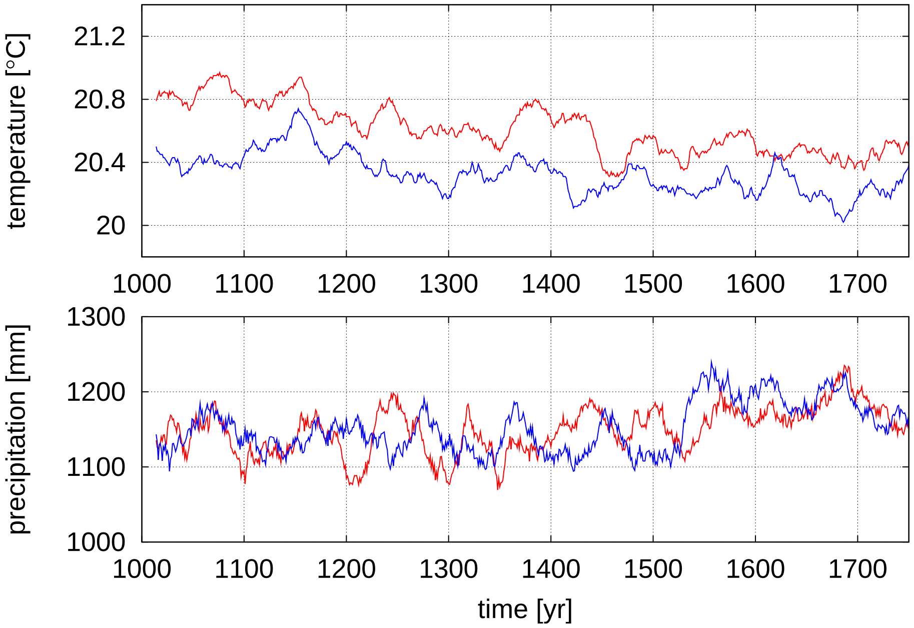

Fig. 3. 30-year running mean of simulated near-surface air temperature (top) and precipitation (bottom) for the period 1000–1750 AD. Shown are the ensemble simulations *Erik1* (red) and *Erik2* (blue) conducted with the atmosphere-ocean model ECHO-G.

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 Rapa Nui.

3.2 Ensemble simulations with ECHO-G

The model results from the ensemble simulations of the ECHAM5/MPIOM model show only small climatic trends from the Medieval Warm Period to the Little Ice Age in global mean temperature, in general, although some members of the simulation ensemble do capture the amplitude between MWP and LIA temperatures. Therefore, we analysed two ensemble simulations (*Erik1* and *Erik2*) with an earlier version of the model system, referred to as ECHO-G, consisting of the atmosphere model ECHAM4 run at T30 resolution (horizontal resolution of ∼3.75° × 3.75°) coupled to the ocean model HOPE-G run at T42 resolution (∼2.8°) with grid refinement at low latitudes for the ocean (González-Rouco et al., 2006). The simulations with this model system reveal a strong decrease of around 1.25 °C (*Erik1*) and 0.75 °C (*Erik2*) in the 2m-temperature (González-Rouco et al., 2006) from the MWP to the LIA for the Northern Hemisphere. This might be an unrealistically strong global cooling trend according to most reconstructions (IPCC, 2001).

Earlier studies with ECHO-G found that broad patterns of global temperature variability are well captured by the model compared with reconstructions (Zorita et al., 2004; 2005). Furthermore, ECHO-G reasonably simulates ENSO structures (like the tropical SST climate), atmospheric responses to ENSO and the subsurface ocean behaviour such as equatorial Kelvin and off-equatorial Rossby waves (Min et al., 2005). In addition, ECHO-G has been successfully applied to paleoclimate states such as Last Interglacial simulations (Felis et al., 2004) and Holocene simulations (Kim et al., 2004; Rimbu et al., 2004).

To evaluate the ability of the model to simulate the typical pattern in the tropical and South Pacific, we show the precipitation climatology from the ensemble mean of the simulations *Erik1* and *Erik2* for the period 1972–1990 in Fig. 1 (bottom). Since the ECHO-G simulations were not extended beyond 1990, we have to tentatively compare the ECHO-G climatology (1972–1990) with the HOAPS-3 and ECHAM5/MPIOM climatology (1987–2005). As for ECHAM5/MPIOM, ECHO-G reproduces the ITCZ well and reveals the typical pattern of the SPCZ and the East Pacific dry zone. However, ECHO-G tends to overestimate the precipitation around Rapa Nui, since the SPCZ reaches further southeastwards in this model. Therefore, the climatological precipitation rate around Rapa Nui is roughly 3 mm d^{-1} (1095 mm yr^{-1}) which is ∼50 % higher than the HOAPS-3 climatological precipitation.

To test the model results for climatic trends for the period 800–1750 AD, a 30-year running mean of near-surface air temperature and precipitation is depicted in Fig. 3 for the ensemble simulations *Erik1* and *Erik2* for the the grid point covering Rapa Nui. Both simulations with ECHO-G show a temperature decrease between the 12th and the 15th century, but the cooling trend of some $-0.4\,^{\circ}$C for the region of Rapa Nui is much weaker than the (simulated) Northern Hemispheric cooling trend (González-Rouco et al., 2006). 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. Furthermore, the trends in the eight grid cells surrounding the grid cell of Rapa Nui (not shown here) confirm the result for the grid cell covering Rapa Nui.

4 Sensitivity simulations with the BIOME-1.0 model

To tentatively explore possible effects of simulated climate variability on the vegetation of Rapa Nui, we carried out sensitivity simulations by using the model BIOME-1.0 (Prentice et al., 1992). BIOME-1.0, like its more recent version BIOME-4, is a model for global application. It is not specifically tuned to vegetation on sub-tropical islands. However, it captures the boundaries between tropical forests and grassland reasonably well. Therefore, we think this model can be used for a first tentative estimate of possible drastic changes between forest and grassland. As input variables for BIOME-1.0, near-surface air temperature, precipitation and cloud fraction are derived from the ensemble simulations *mil0010*, *mil0012* and *mil0013*. The mean annual cycle of the simulated climate variables around Rapa Nui were calculated for the period 800–1750 AD. Because the model precipitation from the Millennium experiments (around $550\,\mathrm{mm\,yr^{-1}}$) is much lower than observed local precipitation (around $1100\,\mathrm{mm\,yr^{-1}}$), 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 the soil-water capacity on Rapa Nui between soils with very low water holding capacities around 50 mm (Leptosols) and soils with water capacities exceeding 300 mm (Anthrosols) (personal communication with H.-R. 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 $1\,^{\circ}$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 et al., 2007; MARGO Project Members, 2009). In all cases, the BIOME model computes forest coverage, either as 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 analysed 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 Rapa Nui, 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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