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Towards modeling the regional rainfall changes over Iran due to the climate forcing of the past 6000 years

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We present a climate modeling approach to reproduce the rainfall patterns over Iran due to the climatic forcings during the past 6000 years. The selected periods are simulated using a spatially high-resolved atmosphere General Circulation Model (GCM). Our results show that the winter rainfall patterns over Iran have changed due to the changes in solar insolation with a wetter condition starting around 3 ka BP and reaching its maximum during the Medieval Climate Anomaly ca. 1 ka BP. The rainfall variability can be explained by the changes in atmospheric conditions as a result of changing incoming solar irradiance based on the Milankovitch theory. A shift in the Earth's energy budget leads to the modulation of the West Asian Subtropical Westerly Jet (WASWJ). The investigations support the hypothesis that during the Holocene a northward shift in the WASWJ contributes to the less cyclonic activities over Iran. This brings less moisture into the region during the winter.

1. Introduction

Drastic climatic change was one of the major causes leading to the abandonment of ancient populations and rise and fall of different cultures in Iran especially at the fringe of the deserts (Berberian et al., 2012). Iran, an area with a complex topography, is located between arid Central Asia and the Mediterranean climate zone. It covers an area of 1,648,000 km^2 and is located in the region separating the continental climate of west Asia from Mediterranean climate. The Mediterranean climate governs large parts of Iran which is affected by changes in Westerly activities. Thus, except for the western parts and the northern coastal areas, Iran's climate is mainly arid and semiarid (Raziei et al., 2005; Sodoudi et al., 2010). In the inland area, the climate is characterized as continental hot and dry with annual temperatures of 22 °C–26 °C (Sodoudi et al., 2010). The Siberian High and Southwestern branch of summer Monsoon also contribute to the Iranian climate for the winter and summer seasons, respectively. The monsoon precipitation advances to south-eastern Iran during June to August with the highest amount of precipitation in June (Raziei et al., 2014). The fluctuations of the Westerlies equator-ward shift or strength lead to the climatic changes (more precipitation) in the westerly-dominated regions (Chen et al., 2010).

Ancient cultures in Mesopotamia were highly tuned to the availability of water resources. As an example, the archeological evidence shows an abrupt collapse of the developed Akkadian empire ca. 4.17 ± 0.15 ka BP (Cullen et al., 2000). This may be due to a shift to arid conditions.

The ostracod fauna of Lake Mirabad suggests a low lake level during the early Holocene and an increase during mid-Holocene (Griffiths et al., 2001). There is a lack of knowledge on past climate change in Iran compared to other regions of the globe (Kehl, 2009; Karimi et al., 2011). Kehl (2009) reviewed the state of the paleoclimate knowledge in Iran. He concluded that there is evidence of several Quaternary climate changes in this region. During interstadials of the Last and Penultimate Glacials, moisture increased over Iran. The climate of western Iran during the Younger Dryas and the Lower Holocene was probably characterized by dry climatic conditions (Kehl, 2009). However, their timing and location are controversial.

According to Djamali et al. (2009), human activity became more evident after 3.7 ka BP. Using geologic, geomorphic and chronologic data from the Qazvin Plain in northwest Iran, Schmidt et al. (2011) studied the cultural dynamics in the Central Iranian Plateau during the Holocene. Their multiproxy data suggest a peak in aridity at ca. 4550 BP in northwest of Iran which seems to be shifted from the "4.2 ka BP" drought event (Staubwasser et al., 2003).

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There are two classical approaches for the global climate simulations of the Holocene: (i) transient low resolution comprehensive coupled Atmosphere–Ocean General Circulation Models (AOGCMs) and (ii) highly resolved Atmosphere only General Circulation Models (AGCMs) for the selected episodes, the "time-slice simulations" (Berking et al., 2013). This is due to the high computational costs of the available computing systems that the second approach cannot be applied for the longer time periods (e.g. several thousand years). For producing a detailed climatic data which is comparable with the local proxy information, a downscaling technique is required. In this study we use a state-of-the-art AGCM to carry out the time-slice experiments for the Mid-to-late Holocene. The focus of our study is the climatic response to external forcings of the climate system since Mid-Holocene to present day in Iran.

To our knowledge, this is the first study using a combination of AOGCM and AGCM models with a time-slice approach to simulate the rainfall changes over Persian region for the period of Mid-Holocene to present time. Different selected time-slices are simulated by using a spatially finer resolved AGCM.

2. Materials and methods

In this paper, we used the ECHO-G model which consists of the atmospheric model ECHAM4 (Roeckner et al., 1996) and the ocean model HOPE (Wolff et al., 1997), at a spectral resolution of T31 (~3.7° × 3.7° at Eq.). The ECHO-G model has already been used in several studies (Zorita et al., 2005; Wagner et al., 2007; Strandberg et al., 2014). However, the horizontal resolution of the ECHO-G does not capture local patterns over Iran (totally 24 grid points within the domain).

Therefore, we utilized the "time slice simulations" technique (Cubasch et al., 1995; Berking et al., 2013) for reproducing the rainfall patterns over Iran. These simulations have been successfully applied for a climate-archaeological study over Sudan to reproduce heavy rainfall regimes in the ancient city of Naga (Berking et al., 2013). Twelve 30 year-long simulations for six different periods throughout the last 6000 years have been performed with the fifth-generation atmospheric general circulation model (ECHAM5) at two spectral horizontal resolution of T63 (~1.8° × 1.8° at Eq.) and T106 (~1.125° × 1.125° at Eq.). The lateral boundary conditions, Sea Surface Temperature (SST) and sea-ice cover distribution from the transient simulation of Wagner et al., 2007 (coupled ocean atmosphere model ECHO-G) are prescribed for time-slice experiments with ECHAM5 model. The climate forcings for ECHAM5 simulations are identical to the ECHO-G model set-up.

3. Results

3.1. Present time

The geographical distribution and the topography of the study area is shown in Fig. 1. The Iranian plateau is the continuation of the Tibetan Plateau. The topographical forcing plays a major role in the diverse climate of Iran (Sodoudi et al., 2010). Fig. 2 shows the climatology of seasonal rainfall over Iran from Global Precipitation Climatology Centre (GPCC) data-set provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/. There is a clear seasonal rainfall variability over Iran, especially between summer (Fig. 2(a)) and other seasons (Fig. 2(b)–(d)). The complex topographical condition which contains the Alborz range in the north and the Zagros mountains in the west and northwest and the latitudinal extent of Iran lead to the spatio-temporal variability of rainfall over this region.

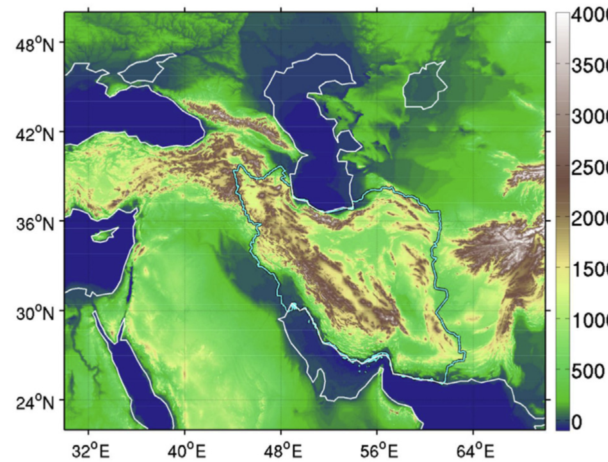

Fig. 1. Topography in meter over the study region. Cyan line indicates the recent time Iranian political boarder. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. ECHO-G simulations

According to Sundqvist et al. (2010) and Zhang et al. (2010), the changes in orbital forcing are the major driver of the climate change during the Holocene. The insolation due to orbital forcing shows different anomalous pattern during winter and summer from Mid-Holocene to present time. Fig. 3 shows the insolation difference between Mid-Holocene and present time. The Northern Hemisphere shows a positive insolation anomaly during summer (JJA) and a negative anomaly during winter (DJF). Given that the extreme anomalies in solar insolation between 6 ka BP and present time happen during summer and winter, we focus on these seasons in our analysis.

Fig. 4 presents the mean summer (JJA) rainfall (mm/month) over Iran region [25° N–41° N; 42.5° E–65.5° E] for 6 KBP to Pre-Industrial (PI) (blue line) from ECHO-G simulation and the solar insolation [W/m^2] at 31° N on 15th July (red line). During summer, the rainfall fluctuations over Iran region show a clear decrease from Mid-Holocene to present time. This can be explained by the changes in solar insolation due to varying orbital forcing. This result agrees well with the "moderate drying trend" from the study of Lauterbach et al. (2014) based on reconstructions of summer moisture using a sediment core from central Kyrgyzstan. By synthesizing the lake sediment records of mid-latitude arid Central Asia, Chen et al. (2008) found a moderate drying trend since the Mid-Holocene, caused by the Westerlies. They concluded that the summer insolation might be the major driver in controlling the moisture changes in arid Central Asia during mid-and late Holocene.

For winter, this pattern is reversed and the rainfall shows an increase since the Mid-holocene until present (Fig. 5). In contrast with the summer, the solar insolation indicates an increasing trend from Mid-Holocene until the present.

The time-series of rainfall from Mid-Holocene to present time show that during the Mid-Holocene (ca. 6 ka BP) the summer rainfall value was larger than winter. This regime is reversed for the recent observed climate (Fig. 3).

3.3. ECHAM5 simulations

The recent climate simulation of ECHAM5 reproduces similar large rainfall patterns as in GPCC but with about 4 (mm/moth) over-estimation in area-averaged rainfall during winter (not