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Influence of orbital forcing and solar activity on water isotopes in precipitation during the mid and late Holocene

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Abstract

In this study we investigate the impact of mid and late Holocene orbital forcing and solar activity on variations of the oxygen isotopic composition in precipitation. Our study is based on a set of novel climate simulations performed with the atmosphere general circulation model ECHAM5-wiso enhanced by explicit water isotope diagnostics. From the performed model experiments we derive the following major results: (1) the response of both orbital and solar forcing lead to changes in surface temperatures and $\delta^{18}\text{O}$ in precipitation with similar magnitudes during the mid and late Holocene. (2) Past $\delta^{18}\text{O}$ anomalies correspond to changing temperatures in the orbital driven simulations. This does not hold true if an additional solar forcing is added. (3) Two orbital driven mid Holocene experiments, simulating the mean climate state approximately 5000 and 6000 yr ago, yield very similar results. However, if an identical additional solar activity-induced forcing is added, the simulated changes of surface temperatures as well as $\delta^{18}\text{O}$ between both periods differ. From our findings we conclude that the Holocene variability of $\delta^{18}\text{O}$ in precipitation, as stored in many paleoclimate archives, is rather complex to understand since the combined effect of different external forcings on $\delta^{18}\text{O}$ in precipitation is non-linear.

1 Introduction

Numerous European proxy archives demonstrate consistent strong millennial scale climate variability during the mid and late Holocene (Wanner et al., 2008). Some of these records demonstrate an influence of orbital forcing (e.g. Davis and Brewer, 2009). However, a larger number of records show a high variability on a millennial scale that does not clearly correspond with the orbital forcing. Such high Holocene variability is for instance recorded in the calcite oxygen isotope signal of several European speleothems (McDermott et al., 2011). It has been suggested that past changes in solar activity might have influenced the European climate, too (e.g. Shindell et al.,

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2001). Nonetheless, observed proxy variability and its relation to large-scale Holocene climate changes are not fully understood for many European records, yet.

5 The signature of the orbital forcing on surface temperatures and other climate variables is quite elaborated from proxy data (Kim et al., 2004; Leduc et al., 2010; Lorenz et al., 2006), modeling studies (e.g. Lorenz and Lohmann, 2004) as well as theoretical concepts (Laepfle and Lohmann, 2009) of past climate changes. For Europe, transient climate simulations for the Holocene show a change in the mean state of the North Atlantic Oscillation/Arctic Oscillation (NAO/AO; Hurrell, 1995) with associated high-latitude temperature and sea ice changes (Lorenz and Lohmann, 2004). This matches results from proxy data and indicates a trend from a more positive phase of the NAO/AO during the mid Holocene to a more negative one during the late Holocene (Rimbu et al., 2003; Rimbu et al., 2004).

10 The influence of the solar activity on Earth's climate is still under discussion (Gray et al., 2010; Haigh, 1994; Lockwood, 2012; Wanner et al., 2008). Several reviews on this topic have recently been published (Beer et al., 2006; Gray et al., 2010; Haigh, 2003, 2007; Jager, 2008; Lockwood, 2012; Rind, 2002). A plausible physical mechanism how solar activity might alter the state of the middle atmosphere via UV radiation and how this change is transported to the troposphere is explained by a number of studies (Gray et al., 2010; Ineson et al., 2011; Kuroda and Kodera, 2002; Shindell et al., 2001; Spanghel et al., 2010). These studies conclude that an increase of UV radiation during periods of high solar activity heat the middle atmosphere due to photochemical reactions with stratospheric ozone. This leads to an altered stratospheric circulation that propagates pole- and downwards to affect tropospheric jet streams and thus atmospheric circulation on a synoptic scale. As a plausible consequence the studies by Lockwood et al. (2010) and Wolling et al. (2010) found an increase of atmospheric blocking during solar minima that accounts for unusual low temperatures over Europe and simultaneous warming over Greenland, emphasizing that solar activity might trigger climate on a regional scale, only. Further studies (e.g. Martin-Puertas et al., 2012)

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have shown the occurrence of atmospheric circulation pattern similar to a negative NAO phase during periods with less solar activity.

In this study we investigate the impact of orbital forcing and solar activity on variations of the oxygen isotopic composition (typically expressed as $\delta^{18}\text{O}$), which is recorded in many paleoclimate archives. In general it is safe to assume that the stable oxygen isotope composition of most terrestrial proxy archives, e.g. the calcite oxygen isotope signal in speleothems, is controlled by the isotopic composition of the local precipitation. Changes of this composition are related to a variety of factors, such as local temperature changes, variations of the precipitation amount, the isotopic composition of the evaporated source water and the atmospheric transport from the source to the archive location (Dansgaard, 1964). Limitations on the traditional interpretation of $\delta^{18}\text{O}$ precipitation values as a pure temperature proxy at mid to high latitudes have been identified in several studies (e.g. Jouzel, 1999; Fricke and O'Neil, 1999). Like for other terrestrial records, regional effects may also influence the oxygen isotope records of speleothems (Scholz et al., 2012).

Our study is motivated by recent findings from the speleothem BU4 (Fohlmeister et al., 2012) from the well-monitored Bunker Cave in Germany (Riechelmann et al., 2011). The core BU4 is investigated as part of the research work performed by the DFG research unit 668 (DAPHNE, <http://www.fg-daphne.de>). It has been selected as a typical example of a European $\delta^{18}\text{O}$ record. In this core, enriched $\delta^{18}\text{O}$ values reflect lower winter temperature and less winter rainfall (Fohlmeister et al., 2012). Dominating periods in this record that are suggested to represent rather cold and dry winter climate in Central Europe center around 7.5 k (7500 yr before present), 6 k, 3.5 k, and the Little Ice Age (LIA) around 0.5 k (Fig. 1a). During the mid and late Holocene, the $\delta^{18}\text{O}$ signal of BU4 seems not to be clearly dominated by the orbital forcing (typically expressed as a change in incoming solar radiation at 65°N). For past solar activity changes, the most recent reconstruction of total solar irradiance (TSI) based on measurements of the cosmogenic isotope ^{10}Be in ice cores (Steinhilber et al., 2012) indicate a possible coherence with the $\delta^{18}\text{O}$ values of BU4 during LIA (Fig. 1b). The reconstructions of

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TSI and sunspot numbers (Solanki et al., 2004; not shown) show another sequence of solar minima around 5.5 ka that appears similar to the solar minima of the Little Ice Age. However, while the $\delta^{18}\text{O}$ signal of the speleothem record from the Bunker cave seems to correspond to the solar radiation during the LIA, an equivalent correspondence is not detected for the mid Holocene (Fig. 1c).

Due to these findings from BU4, we focus in this study on three Holocene climate periods: the pre-industrial climate (late Holocene) as well as the mean 5 k and 6 k climate (mid Holocene). Although orbital driven insolation changes between 6 k and 5 k are rather small, a strong influence on the $\delta^{18}\text{O}$ signal in Central Europe cannot be excluded a priori. For past solar activity, to our knowledge no investigations of this external forcing on the Holocene $\delta^{18}\text{O}$ signal in precipitation exist, yet. Furthermore, although it is obvious that both external forcing infer with each other, it is unclear how the combination of them is imprinted in the various continental $\delta^{18}\text{O}$ records.

Our study is based on a set of novel climate simulations performed with the atmosphere general circulation model (AGCM) ECHAM5-wiso. This model is able to simulate the isotopic composition within all compartments of the model's hydrological cycle (Werner et al., 2011). As recently demonstrated by Wackerbarth et al. (2010, 2012), the $\delta^{18}\text{O}$ values of precipitation simulated with ECHAM5-wiso can subsequently be used to drive a calcification model to successfully simulate the $\delta^{18}\text{O}$ value of BU4 cave drip water and speleothem calcite. However, in this study we simulate and analyze mean values of $\delta^{18}\text{O}$ in precipitation, only, but with a focus on central Europe.

2 Methods and model-setup

In this section we first explain the isotope model we use in this study. Then we present the setup of the model experiments to account for influences of orbital parameters and solar activities as well as the interaction between both. Hereafter, we explain our choice of analyzed climate parameters.

2.1 ECHAM5-wiso

We apply the atmospheric general circulation model ECHAM5-wiso that explicitly allows the simulation of the three isotopic water species H_2^{16}O , H_2^{18}O , and HDO (Werner et al., 2011). This model has its origin in the fifth version of the atmospheric general circulation model ECHAM5 (Roeckner et al., 2003, 2006) and is enhanced by including a water isotope module in the model's hydrological cycle, following the work of Joussaume et al. (1984), Jouzel et al. (1987), and Hoffmann et al. (1998). The isotope module computes changes of the composition of different water masses within the entire hydrological cycle, including evaporation from the ocean, cloud condensation, precipitation, surface water reservoirs, and river runoff.

Until now, no fully coupled ocean-atmosphere model (AOGCM) is available that uses the isotope version ECHAM5-wiso. Thus, mean monthly sea-surface temperatures (SST) and sea-ice cover (SIC) as well as orbital parameters and greenhouse gas concentrations (GHG) are prescribed to force this atmosphere model. As a further boundary condition, the $\delta^{18}\text{O}$ values of ocean and lake surface waters have to be prescribed.

In prior studies ECHAM5-wiso has already demonstrated the capability to simulate the present-day isotopic composition of precipitation in good agreement with observational data of the Global Network of Isotopes in Precipitation (GNIP), both on a global (Werner et al., 2011) as well as on an European (Langebroek et al., 2011) scale.

2.2 Experimental setup

All ECHAM5-wiso simulations are computed in a high spatial resolution (T106L31) with an approximate horizontal grid size of $1.1^\circ \times 1.1^\circ$ and 31 vertical layers. All simulations are run for 10 yr after spin-up.

To distinguish between the orbital and solar activity forcing effects on the simulated atmospheric state, we perform two sets of model experiments. A first set contains a standard control simulation under pre-industrial climate conditions (PI) as well as a 5 k

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and 6 k simulation, each, where only changes of the orbital forcing and greenhouse gases are applied. The second set of simulations additionally accounts for positive and negative changes in the solar activity.

The applied orbital parameters and atmospheric concentrations of greenhouse gases (CO_2 , CH_4 , N_2O) are given in Table 1. All experiments are computed with a fixed solar constant. The $\delta^{18}\text{O}$ values of the ocean surface waters are set to observed modern values, derived from the global gridded dataset (LeGrande and Schmidt, 2006). The surface waters of large lakes were set to a constant value of +0.5‰. As the oceanic $\delta^{18}\text{O}$ distribution during the mid Holocene is unknown but most likely very similar to today, identical isotope values of lakes and ocean surface waters are used for all simulations.

Required boundary fields of SST and SIC for the first set of simulations (denoted with the suffix “orb”) are derived from a transient Holocene run of the coupled atmosphere-ocean model ECHO-G (Lorenz and Lohmann, 2004). For the three time-slices PI, 5k and 6k climatological means were calculated using 50 model years. Since this ECHO-G experiment was run with an orbital acceleration factor of 10 (see Lorenz and Lohmann, 2004, for details), every 50-yr period represents 500 calendar years. The three selected ECHO-G periods are listed in Table 1. From these ECHO-G SST and SIC fields the anomalies 5 k-PI and 6 k-PI were calculated. The anomalies were added to mean pre-industrial SST and SIC fields (observational period: 1870–1899) derived from an AMIP2 climatology (Taylor et al., 2000) to avoid any ECHO-G related model bias in the prescribed mean state of SST and SIC.

To account for solar induced effects originating in the stratosphere a second set of ECHAM5-wiso simulations is performed. This time, the according SST and SIC boundary fields are derived from a transient simulation of the last 500 years performed with the EGMAM model (ECHO-G with Middle Atmosphere Model; Spanghehl et al., 2010). This transient simulation (denoted as EGMAM2 in Spanghehl et al., 2010) is driven by changes in total solar irradiance due to solar activity as well as volcanic eruptions and changes in greenhouse gas concentrations. It includes changes in short-wave heating

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due to prescribed photochemical changes in ozone in the stratosphere. For our study, we selected two time slices from this EGMAM transient simulation: one with a rather low solar irradiance, denoted as sol(-), and one with a rather high solar irradiance, denoted as sol(+). For the sol(-) case climatological means are calculated for the time slice 1675–1715 AD, covering the late Maunder Minimum as defined by Spanghel et al. (2010). The sol(+)-boundary conditions were calculated from the years 1750–1790 AD of the EGMAM simulation, respectively. Both chosen time periods have an almost equal, nearly constant CO₂ level. The SST and SIC anomalies of the sol(-) and sol(+) time slices are calculated as the deviation from the arithmetic mean state of sol(-) and sol(+). These anomaly fields are then combined with the PI, 5 k and 6 k SST and SIC fields from the first set to account for the additional forcing due to low (high) solar activity. These ECHAM5-wiso experiments are denoted with the suffix “sol(-)” and “sol(+)”, respectively.

In summary, we compute and analyze nine ECHAM5-wiso simulations to study the orbital and solar activity forcing effects on the mid and late Holocene climate: PI, 5 k_orb, 6 k_orb, PI_sol(-), 5 k_sol(-), 6 k_sol(-), PI_sol(+), 5 k_sol(+), and 6 k_sol(+).

In our analyses we focus on modeled surface temperatures as one of the key paleoclimate variables, and $\delta^{18}\text{O}$ of precipitation, which is recorded in many paleoarchives. If not stated otherwise, all changes are reported as anomalies compared to the pre-industrial control simulation (PI). Thus, statements about depletion of isotopic values or cooler temperatures should always be interpreted as relatively depleted values in the isotopic composition or relatively cooler temperatures in the past as compared to the PI simulation.

3 Results

In the first three sections of this chapter we examine the simulated annual mean climate of our various experiments. First, we present the influence of changed orbital forcing for the investigated different Holocene periods. Next, we analyze the influence

of solar activity on the late and mid Holocene climate. In the third section we study the combined influence of orbital and solar activity forcing on mean annual surface temperatures and $\delta^{18}\text{O}$ in precipitation. Since it is suggested that the $\delta^{18}\text{O}$ signal in European speleothems is dominated by the winter climate (Wackerbarth et al., 2010, 2012), the simulated influence of winter (DJF) versus summer (JJA) climate on $\delta^{18}\text{O}$ in precipitation is briefly presented in the last section of this chapter.

3.1 Influence of orbital forcing on surface temperatures and $\delta^{18}\text{O}$

For the pre-industrial control simulation (PI), surface temperatures as well as $\delta^{18}\text{O}$ of precipitation are characterized by strong meridional gradients. Warmest temperatures (Fig. 2a) and most-enriched $\delta^{18}\text{O}$ values (Fig. 3a) are found in the tropics, while coolest temperatures and strongest $\delta^{18}\text{O}$ depletion occur in the polar regions. The PI simulation shows a corresponding pattern of temperature distribution and $\delta^{18}\text{O}$ values, indicating a strong dependence of $\delta^{18}\text{O}$ to local temperatures. Focusing on the European continent, a west-east gradient of decreasing $\delta^{18}\text{O}$ values can be observed.

Both mid Holocene experiments show similar patterns, indicating that orbital driven climate changes between 6 k and 5 k are not very large, neither on a global nor European scale. In general, a change to mid Holocene orbital parameters with higher contribution of the obliquity-related part of incoming solar insolation results in high-latitude warming and low-latitude cooling (Fig. 2b and c). This is resembled by enrichment of $\delta^{18}\text{O}$ in high latitudes and depletion in the tropics, respectively (Fig. 3b and c). However, even if most parts of the high latitudes are warming, some spatial heterogeneity is detected. E.g. the Labrador Sea as well as the region south of Greenland show some cooling and thus $\delta^{18}\text{O}$ depletion. In addition, the longitudinal temperature gradient and $\delta^{18}\text{O}$ depletion in Central Russia is enhanced during 5 k in comparison to 6 k. In both mid Holocene time slices orbital forcing results in distinct cooling patterns south of the Sahel zone and over India as well as Southeast Asia. This can be related to a shift of the Intertropical Convergence Zone (ITCZ; Herold and Lohmann, 2009).

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Over Europe, the temperature response due to the changed orbital forcing is less than $+2^{\circ}\text{C}$ for the mid Holocene. Changes in $\delta^{18}\text{O}$ are on average quite small (less than $\pm 1\text{‰}$) and for most regions no substantial change can be observed. Central Europe is, however, partly characterized by higher values whereas Scandinavia and Morocco is depleted in $\delta^{18}\text{O}$.

3.2 Influence of solar forcing on surface temperatures and $\delta^{18}\text{O}$

First, we analyze the PI simulation. To evaluate the influence of changing solar activity on the pre-industrial climate the following two PI simulations are examined: (1) PI_sol(-) takes into account a negative solar forcing and thus resembles similar conditions as during the Maunder Minimum. (2) PI_sol(+) represents a (hypothetical) counterpart of PI_sol(-) with an equivalent, but positive solar forcing. To isolate the solar effect on temperature and $\delta^{18}\text{O}$, we calculate the anomalies induced by the assumed changed solar activity between corresponding simulations, e.g. PI_sol(+)-PI.

Negative solar forcing during the PI climate leads to decreasing annual mean temperatures especially at mid to high northern latitudes (Fig. 4a). In particular the polar regions south of Greenland, the Labrador Sea, the Barents Sea, the Sea of Okhotsk, and the Hudson Bay are affected by the negative solar forcing. This results in substantially reduced annual mean temperatures with a local cooling of up to -2°C . However, sol(-) forcing also results in increased annual mean temperatures over Europe, North America, and parts of Western Siberia. On the opposite, a positive solar forcing sol(+) leads to slightly increasing temperatures with a maximum warming of around $+1^{\circ}\text{C}$ (Fig. 4b).

Interestingly, the sol(+) and sol(-) results are not completely opposite to each other, neither spatially nor in absolute temperature anomalies (Fig. 4), although the applied SST forcing setup has been symmetrical. The cooling driven by the sol(-) forcing is much higher than the response of warming due to sol(+) forcing. This can be in particular observed in the North Atlantic and the Labrador Sea. The effect on low latitude

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temperature changes is in both cases rather small. For Europe, the sol(-) and sol(+) conditions lead to cooler and warmer surface temperatures in Scandinavia, respectively. Furthermore, we observe a unique warming over western Europe and a slight cooling at the Carpathians in the sol(+) experiment.

5 The solar forcing effect on the PI distribution of $\delta^{18}\text{O}$ in precipitation does result in a rather noisy anomaly pattern with no clear trend (Fig. 5). The isotope anomalies are in most regions around $\pm 1\text{‰}$ and a clear temperature influence is only observed in the PI_sol(-)-simulation. Here, the strong cooling of the polar regions correlates with more depleted $\delta^{18}\text{O}$ values in precipitation. Over Europe, the $\delta^{18}\text{O}$ changes (Fig. 5c and
10 d) are quite similar for both experiments and do not reflect the European temperature anomalies (Fig. 4c and d).

Next, we analyze the two mid Holocene simulations. Again, to isolate the effects by changing solar activity during the mid Holocene anomalies are calculated between the experiment with additional solar influences boundary conditions and with out for each
15 time-slice, e.g. 5 k_sol(-)-5 k_orb.

Negative solar forcing, sol(-), leads to decreasing annual mean temperatures especially at mid to high northern latitudes, both at 5 k and 6 k (Fig. 6a and b). However, in both time slice simulations a few areas are characterized by slight warming. On a global scale most patterns of temperature anomalies are similar to the findings of the
20 PI simulations (Fig. 4a), e.g. the additional cooling south of Greenland. However, some major differences exist, too, for instance over Europe. In comparison to the PI_sol(-)-simulation (Fig. 4c) the cooling over Europe is stronger in the mid Holocene simulations (Fig. 6c and d). Nevertheless, a consistent anomaly pattern is observed in all three simulations with a strong temperature decrease in Eastern Europe and Scandinavia as
25 well as no temperature changes (or even a slight warming) in Central Europe. For the simulated mid Holocene changes in $\delta^{18}\text{O}$ we find on a global scale (Fig. 7a and b) a similar anomaly pattern as for the PI simulation (Fig. 5a), but like for the surface temperatures, regional, differences exist. In parts of Europe, the simulated small isotopic

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changes in the 5 k and 6 k simulation often disagree and even switch between depletion and enrichment (Fig. 7c and d).

Similar behavior as for the sol(−) experiments exists for the sol(+) forcing results. Again, on a global scale the temperature and $\delta^{18}\text{O}$ anomaly pattern are similar between 6 k and 5 k (Figs. 6e and f and 7e and f). However, most regions of Europe are affected by slightly increased temperature during 5 k (Fig. 6g), whereas an increased solar forcing during 6 k leads to slight cooling of Eastern Europe (Fig. 6h). For the isotopic composition of precipitation in Central Europe, a depletion of $\delta^{18}\text{O}$ in the 5 k simulation (Fig. 7g) and an enrichment of $\delta^{18}\text{O}$ in the 6 k experiment (Fig. 7h) occur.

3.3 Combined influence of orbital and solar forcing on surface temperatures and $\delta^{18}\text{O}$

In this section we present the simulated surface temperatures and $\delta^{18}\text{O}$ of precipitation values of the ECHAM5-wiso simulations that were forced by SST and SIC changes induced by the combination of orbital parameter and solar activity variations.

For both the 5 k and 6 k simulations, an assumed additional increase (decrease) of solar activity leads to an amplification (weakening) of the orbital temperature response during the mid Holocene (Fig. 8, as compared to Fig. 2). The obliquity driven global temperature anomalies with cooling in the tropics and warming at high latitudes during the mid Holocene are preserved in both scenarios. In the sol(−) case the meridional temperature gradient is reduced due to the solar activity-induced cooling. In particular the polar regions south of Greenland, the Labrador Sea, the Barents Sea, the Sea of Okhotsk, and the Hudson Bay are influenced by the additional forcing. In the sol(+) case the combined forcing leads to further increased temperatures, especially on the Northern Hemisphere. A warming of similar strength, but less geographical expansion is observed for the Southern Hemisphere with highest temperature anomalies over South America and South Africa. For the (sub)tropical regions, the orbital driven shift of the ITCZ is not substantially affected by any additional solar activity-induced forcing. For Europe, we find for both sol(−) and sol(+) cases a warming of Western

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and Central Europe, which can be related to the dominating orbital forcing in these areas (Fig. 8c, d, g, h). However, in Scandinavia and Eastern Europe the regional cooling due to a negative solar-activity induced forcing dominates over the orbital-induced warming, and the combined effect results in PI-similar temperatures during 6 k and a slight cooling of approx. $-1\text{ }^{\circ}\text{C}$ relative to PI during 5 k.

In comparison to the experiments forced by orbital parameter changes, only, an additional solar activity-induced forcing has regionally a high potential to alter the distribution of $\delta^{18}\text{O}$ in precipitation (Fig. 9, as compared to Fig. 3). The global meridional trends from more negative values in low to mid latitudes to increased values in high latitudes that correspond to the obliquity driven temperature evolution during the Holocene (Sect. 3.1) is regionally disturbed by the additional solar activity-related forcing. For Western Europe, an assumed decrease in solar activity leads to an enrichment in $\delta^{18}\text{O}$ in precipitation during both 5 k (Fig. 9c) and 6 k (Fig. 9d) as compared to the simulation with orbital-induced forcing (Fig. 3e), only. However, an equivalent depletion is not detected for the related sol(+) simulations (Fig. 9g and h). Neither for increase nor decreased solar activity, the simulated European $\delta^{18}\text{O}$ anomalies (Fig. 9c, d, g, h) can be clearly linked to corresponding simulated surface temperature anomalies (Fig. 8c, d, g, h).

3.4 Relative influence of winter versus summer climate on $\delta^{18}\text{O}$

Cave monitoring and speleothem analyses suggest that Northern Hemisphere winter is the dominating season for leaving an imprint in the isotopic composition of the precipitated calcite at Bunker Cave (Wackerbarth et al., 2010; Fohlmeister et al., 2012). Analyses of our simulation results reveal that the additional solar activity-induced forcing is not only affecting annual mean climate conditions during the mid and late Holocene, but that these changes strongly differ with season. The largest part of the Northern Hemisphere temperature changes found in the analyses of annual mean values can be traced back to the simulated winter (DJF) temperatures while the summer season (JJA) shows minor temperature changes (Fig. 10a and b). As for the annual mean

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values, an asymmetric behavior of the sol(-) and sol(+) simulations is also observable during winter season: low solar activity has a much stronger influence on Northern Hemisphere winter temperatures than an equivalently high solar activity. The simulated seasonal change of $\delta^{18}\text{O}$ in precipitation shows the strongest link to seasonal temperature changes between 30°N – 70°N . For the winter season, a slight zonal decrease in $\delta^{18}\text{O}$ of approximately -0.5‰ can be seen for the winter season in the case of decreased solar activity (Fig. 10c). However, the equivalent enrichment of $\delta^{18}\text{O}$ is absent for an assumed equal increase in solar activity. For the Northern polar regions above 70°N , the ECHAM5-wiso simulations result in an ambiguous pattern of zonal $\delta^{18}\text{O}$ changes. Isotope anomalies are of similar magnitude for both winter and summer season (Fig. 10 c and d) and no clear correspondence to the modeled temperature changes can be detected.

For Europe, the simulated winter $\delta^{18}\text{O}$ anomalies (Fig. 11) are in many regions similar to the annual mean ones (Figs. 5 and 9) but strengthened in magnitude. This complies with a general stronger influence of winter versus summer changes on the annual mean climate in Europe. As for the annual mean, the wintertime $\delta^{18}\text{O}$ patterns over Central Europe are rather noisy with many small-scale regions of isotope enrichment and depletion that cannot be clearly linked to winter temperature changes (not shown). Again, an assumed strengthening or weakening of solar activity does not result in equivalent isotope anomalies, neither for the PI nor the 5 k and 6 k simulations.

4 Discussion

In the following discussion we focus on two questions: (1) how strong is the linkage between temperature and $\delta^{18}\text{O}$ variations for Holocene changes of orbital parameters and solar activity? (2) How large is the impact of the two forcing mechanisms on past atmospheric circulation changes over Europe?

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4.1 Holocene temperature and $\delta^{18}\text{O}$ changes

The oxygen isotope composition of an atmospheric water mass is altered by every phase change of the water. As a consequence, the final isotopic composition of precipitation reaching the Earth's surface is determined by several factors: the isotopic composition of the initial water source, temperature and climate conditions during evaporation, mixing and partially rainout of the water during its transport, as well as temperature and precipitation amount at the precipitation location. Despite this complexity, it is well known since the early work by Dansgaard (1964) that spatial variations of local temperature and $\delta^{18}\text{O}$ in precipitation can be linked for many mid- and high-latitude regions of the Earth. Many isotope-enabled AGCMs can reproduce this temperature- $\delta^{18}\text{O}$ relation both on the global as well as on a regional scale (see Sturm et al., 2010, for more details on this topic). This strong spatial temperature- $\delta^{18}\text{O}$ linkage has also been shown for present-day ECHAM5-wiso simulations, both on a global and European scale (Werner et al., 2011; Langebroek et al., 2011). For Europe, the temperature effect on $\delta^{18}\text{O}$ is superimposed by the so-called continental effect. The latter describes an observed west-east gradient in $\delta^{18}\text{O}$ with a decreasing isotope composition over Europe. It reflects the impact of progressive rainout of easterly-advected moisture-bearing air masses on the isotopic composition of precipitation. This continental effect is not only found in present-day observations, but also in different Holocene isotope records, e.g. a collection of European speleothems (McDermott et al., 2011).

For temporal changes of $\delta^{18}\text{O}$, a clear correspondence of temperature and isotope variations does not always exist. For the present-day climate numerous studies (e.g. Noone and Simmonds, 2002; Werner and Heimann, 2002; Schmidt et al., 2007; Herold and Lohmann, 2009; Pfahl et al., 2012; Field, 2010) have shown that changes of $\delta^{18}\text{O}$ in precipitation often do not correspond well with local temperature changes. The isotopic signal is rather influenced by atmospheric circulation changes, which do not alter surface temperatures at the precipitation site in a comparable manner. For the Holocene climate, LeGrande and Schmidt (2009) come to a similar conclusion.

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They have systematically analyzed the simulated isotopic composition of precipitation for eight different Holocene time slices using the GISS ModelE-R. According to their findings, Holocene changes of the isotopic composition of precipitation should better be interpreted in terms of regional hydrological cycle changes rather than as indicators of local climate. Our mid Holocene $\delta^{18}\text{O}$ results derived from the 5 k and 6 k ECHAM5-wiso simulations with changed orbital parameter forcing (Figs. 2 and 3) agree with these findings.

Our mid and late Holocene results with solar activity-induced forcing, only, show little influence of local temperature changes on the isotopic composition of meteoric water, both on a global as well as on a regional scale (Figs. 4–7). For Holocene temperature changes, the model results consistently show a much stronger response to an assumed decrease in solar activity than to an increase for all three time slices investigated (Figs. 4 and 6). This is remarkable as the applied SST and SIC anomaly fields derived from the EGMAM simulation have the same pattern and magnitude, but opposite sign for the case of increased or decreased solar activity. For $\delta^{18}\text{O}$, a similar asymmetry between the sol(–) and sol(+) simulations is partially detected in northern high latitude regions.

For the mid Holocene climate, the differences in orbital forcing between the 5 k and 6 k are rather low and lead to minor, but consistent differences in the $\delta^{18}\text{O}$ signal (Fig. 2). However, if an additional solar activity-induced forcing is applied (Fig. 8), the resulting changes in $\delta^{18}\text{O}$ pattern between 5 k and 6 k are not consistent any longer: In high northern latitudes the effect of a decreased solar activity is stronger during 5 k than during 6 k. This is noteworthy as the applied SST and SIC changes have been identical in both experiments.

We conclude from our simulation results that non-linear effects and feedbacks of the orbital and solar activity forcing substantially alter the $\delta^{18}\text{O}$ in precipitation pattern and its relation to temperature changes. As some of the strongest temperature and $\delta^{18}\text{O}$ changes occur in northern high latitude regions, sea ice feedbacks might account for part of this non-linear behavior. As sea surface temperatures in the polar regions

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are near the threshold of freezing (around -1.8°C) little cooling is required for sea ice formation. The occurrence of sea ice in a region, which was previously characterized by open seawater, leads to strong changes of surface albedo, near-surface temperatures and sea level pressure. In our experiments the largest response to changes in the North Atlantic sea ice cover are placed south of Greenland and the Labrador Sea. Here, strong cooling is consistently observed in the ECHAM5-wiso simulations with SST and SIC anomalies related to reduced solar activity. The counterpart experiments, where an increased solar activity is assumed, show only minor warming in these regions. Our results are in agreement with the reported simulations results of both models used to compile our boundary conditions to force ECHAM5-wiso. In the transient EGMAM simulation, a strong cooling over the western North Atlantic has been detected and related to an increase in sea ice and a salinity anomaly (Spanghehl et al., 2010). In the Holocene ECHO-G experiment, increased eastward wind pattern occur during 6 k relative to the PI climate, which enhance southward sea ice transport along the eastern coast of Greenland resulting in an increased sea ice concentration and a temperature drop south of Greenland (Lorenz and Lohmann, 2004). The combination of the SST and SIC anomalies derived from these both experiments has led to an amplification of this effect in our simulation, in particular during the winter months. All ECHAM5-wiso simulations with an assumed decrease in solar activity consistently show a larger influenced area with more sea ice in the Northern Hemisphere in comparison to the simulations with increased solar activity and less sea ice (not shown). This leads to a stronger effect on simulated surface temperatures and $\delta^{18}\text{O}$ changes in the case of decreased solar activity in comparison to the one with increased activity.

Although a sea ice feedback might explain the simulated $\delta^{18}\text{O}$ changes in the northern high latitudes, such feedback cannot account for simulated changes of $\delta^{18}\text{O}$ in precipitation in other regions. E.g. most simulations show a slight isotopic enrichment over the southwestern part of North America. Over Australia, strong isotope enrichment is detected in three out of four mid Holocene simulations with solar activity-induced

forcing fields, only (Fig. 7a, b, e, f). Further analyses beyond the scope of this study are required to explain these simulated changes in $\delta^{18}\text{O}$.

4.2 Past atmospheric circulation changes over Europe

Earlier studies based on both data analyses (Baldini et al., 2008; Wackerbarth et al., 2010) and model experiments (Field, 2010; Langebroek et al., 2011) suggest that the winter climate dominates the $\delta^{18}\text{O}$ signal in precipitation in central Western Europe. The previous model studies demonstrated that the annual $\delta^{18}\text{O}$ values are a combination of a strong winter and a weak summer signal. Since evapotranspiration of soil water is enhanced during summer (Trenberth, 1999), the recharge rate of the karst water that may enter any underlying cave system is much lower in summer than winter (Wackerbarth et al., 2010).

For the present-day climate, changes of the winter dominated signal can be linked to a NAO/AO-like pressure pattern, which dominates European winter temperatures and $\delta^{18}\text{O}$ values (Baldini et al., 2008; Field, 2010). In agreement with these findings, Langebroek et al. (2011) showed for a present-day ECHAM5-wiso simulation that $\delta^{18}\text{O}$ precipitation values at the Bunker Cave location can be correlated to large-scale sea level pressure fields with a strong projection onto the NAO relation with temperature, but with an eastward shift of the northern center of action.

Boreal winter insolation due to orbital parameter variations did not change very much from mid to late Holocene. However, different proxy data indicate a trend from a more positive phase of the NAO/AO during the mid Holocene to a more negative one during the late Holocene (Rimbu et al., 2003, 2004). This is consistent with findings from the transient ECHO-G experiment, which we have used to derive our SST and SIC boundary fields. The ECHO-G simulation displays a change in the mean state of the NAO/AO and associated high-latitude temperature and sea ice changes during the Holocene (Lorenz and Lohmann, 2004).

For solar activity variations, previous investigations show a subtle influence on European winter circulation in reanalysis (Lockwood et al., 2010; Woollings et al., 2010)

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and long-term instrumental (Lohmann et al., 2004) data. Lohmann et al. (2004) show a blocking-like circulation for boreal winter and low solar activity, in line with Woollings et al. (2010) who report on a statistically significant higher frequency of cold winters is associated with a low solar activity. Further studies have shown negative phases of NAO-like pattern during periods with a less active sun (Martin-Puertas et al., 2012; Rimbu et al., 2004; Scholz et al., 2012).

Our modeling results also suggest that a solar activity-induced forcing can alter the atmospheric circulation in the Northern Hemisphere. Sea level pressure anomalies simulated by our PI_sol(-) experiment are similar to those found in the EGMAM simulation of Spanghel et al. (2010) that explicitly includes stratospheric short-wave heating (Fig. 12). Both ECHAM5-wiso and EGMAM simulations cover similar conditions that resemble the anomaly between a pre-industrial period with a low solar activity (e.g. the Maunder Minimum) and a succeeding pre-industrial climate period with a high solar activity. It is noteworthy that our ECHAM5-wiso simulation can reproduce these SLP anomalies of the transient EGMAM experiment by prescribing related SST and SIC anomalies, only. These model results indicate that low solar activity might lead to a negative phase of a NAO-like pattern for a mean pre-industrial climate.

For both 5 k and 6 k mid Holocene periods, our simulations with a combined orbital and solar activity-induced forcing result in atmospheric circulation patterns that show large differences between the simulated periods (not shown). Similar to the simulated temperature and $\delta^{18}\text{O}$ values, we find a non-consistent, non-linear impact of the additional solar forcing on the simulated sea level pressure fields. Unfortunately, proxy data of Holocene atmospheric circulation changes is very rare, which hampers a more detailed evaluation of these model results.

5 Concluding remarks

The influence of orbital-driven insolation and solar activity changes on the distribution of stable water isotopes in meteoric precipitation is investigated for the mid and late

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Holocene. In particular, we have analyzed different time slice experiments with sea surface temperature and sea ice boundary conditions perturbed by both orbital parameter and solar activity-induced changes. All experiments were calculated with the isotope-enhanced AGCM ECHAM5-wiso (Werner et al., 2011).

5 According to our model experiments, both orbital as well as solar forcing lead to alterations of similar amplitude of $\delta^{18}\text{O}$ in precipitation. Changes of the orbital configuration lead to isotopic changes at mid and high latitudes, which are in correspondence with the simulated variations of local surface temperatures. Only little changes are simulated between the two mid Holocene periods, 6000 and 5000 yr ago. However, this
10 temperature-isotope relation diminishes if an additional solar activity-induced forcing is applied. The distribution of $\delta^{18}\text{O}$ in precipitation becomes more random and does not show a clear correlation to surface temperatures any longer. As a consequence perturbations by additional solar forcing are able to change even the sign of overall
15 $\delta^{18}\text{O}$ anomaly patterns, in particular over Europe. This non-linear result of a combined orbital plus solar activity-induced forcing might explain some of the complex variability in $\delta^{18}\text{O}$ observed in various Holocene proxy records. Our results indicate that a quantitative interpretation of single $\delta^{18}\text{O}$ Holocene proxy records in terms of regional climate variability remains difficult. A simple relation between local changes of surface temperatures and measured $\delta^{18}\text{O}$ changes cannot be safely assumed a priori for the
20 Holocene.

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Table 1. Orbital (eccentricity, obliquity, perihelion) and greenhouse gas (CO₂, CH₄, N₂O) forcing of the three periods investigated. Boundary conditions were derived from a transient simulation with the AOGCM ECHO-G (Lorenz and Lohmann, 2004). The used specific model years from this experiment are given in the last column.

	Ecc.	Obl.	Perihel.	CO ₂	CH ₄	N ₂ O	ECHO-G
PI	0.016804	23.04725	278.734	280	760	270	1926–1976
5 k_orb	0.018424	24.0239	197.594	275	650	260	1446–1496
6 k_orb	0.018682	24.1048	180.918	280	650	270	1346–1396

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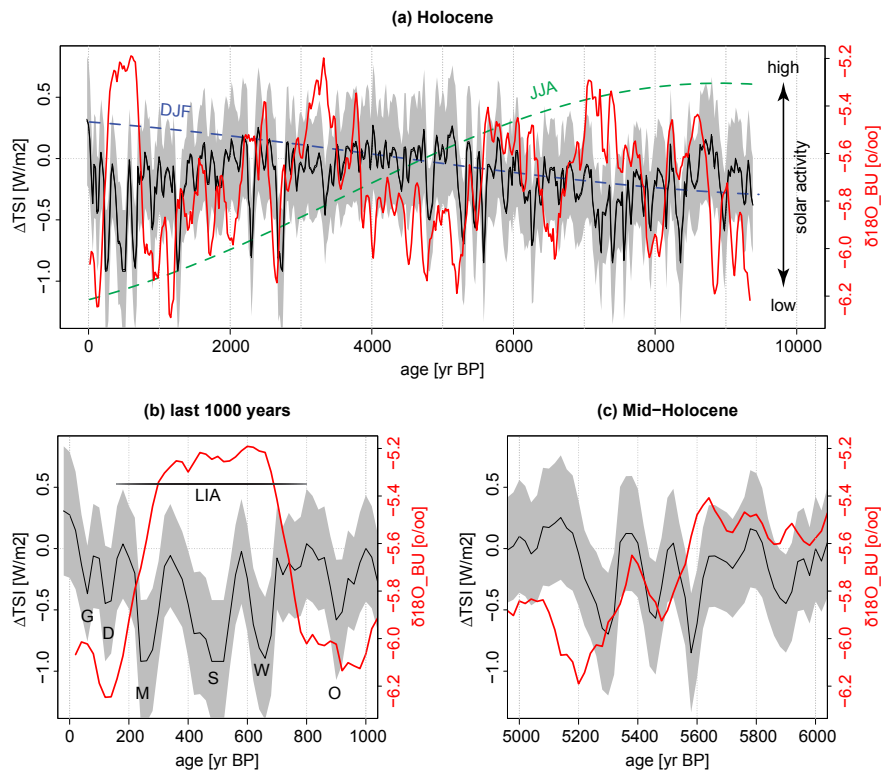


Fig. 1. (a) Reconstructions of solar activity (black) and measured $\delta^{18}\text{O}$ changes of the BU4 record (red) at the Bunker Cave (Germany) during the mid to late Holocene. The plot shows the solar activity as the difference of total solar irradiance from the value during the solar cycle minimum of the year 1986 AD (1365.57 Wm^{-2} ; Steinhilber et al., 2012). Grey bands represent the 1-sigma uncertainty. (b) and (c) same as (a) but focusing on the last 1000 yr and the mid Holocene, respectively. Capital letters mark grand solar minima: G: Gleissberg, D: Dalton, M: Maunder, S: Sprorer, W: Wolf, O: Oort.

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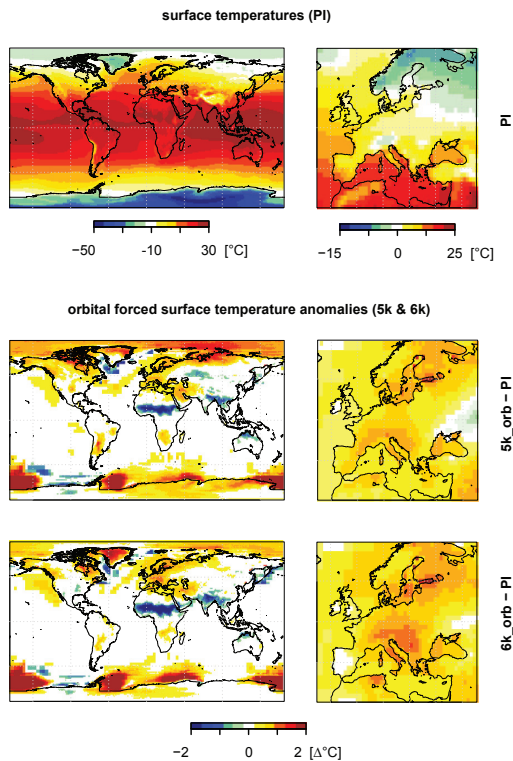


Fig. 2. Upper row: simulated surface temperature for the pre-industrial climate simulation (PI). Middle and lower row: simulated temperature anomalies for both orbital-driven experiments of the mid Holocene (5 k_orb, 6 k_orb) as compared to the PI simulation. Anomaly values with less than 0.5 of the standard deviation are shaded in white. The right column shows the results for Europe, enlarged.

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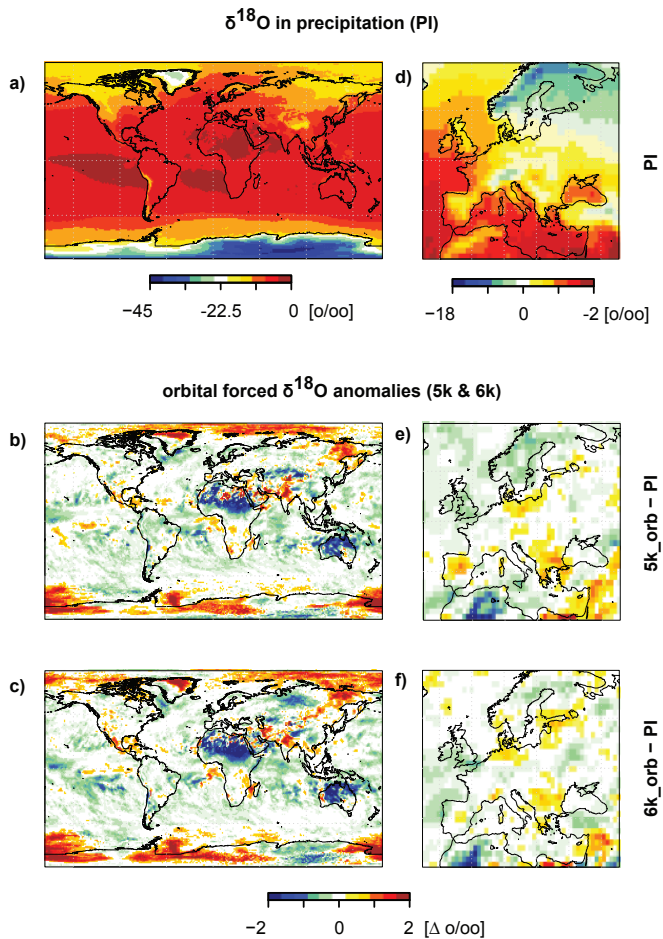


Fig. 3. Same as Fig. 2 but for $\delta^{18}\text{O}$ in precipitation values.

solar forced surface temperature anomalies (PI)

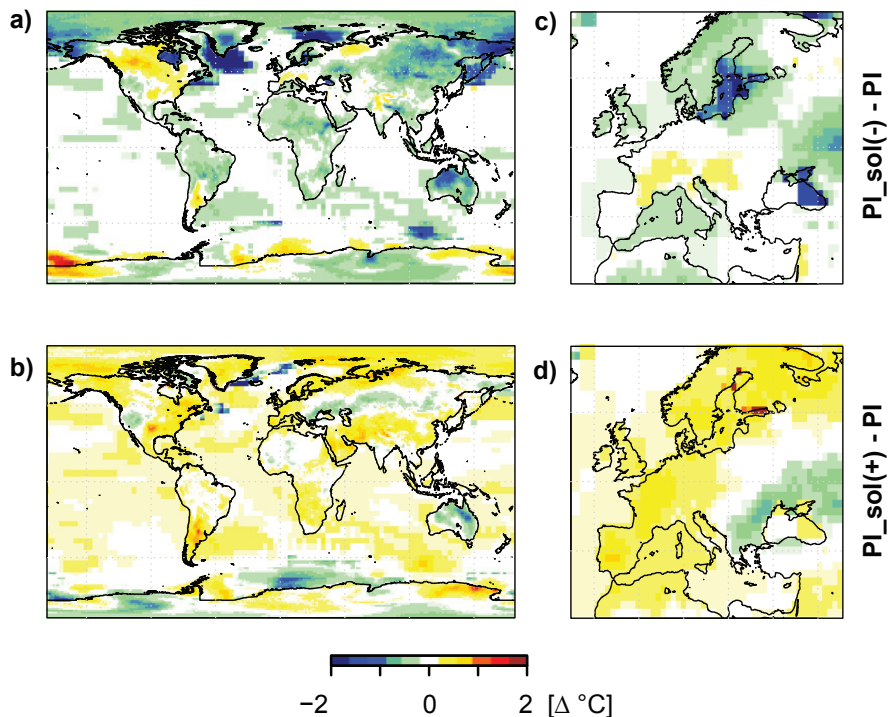


Fig. 4. Simulated solar activity-induced changes of PI surface temperatures. The temperature anomalies are calculated between the experiment with additional solar influence boundary conditions ($PI_{sol(-)}$ and $PI_{sol(+)}$, respectively) and the undisturbed PI climate simulation. Plot details are similar to Fig. 2.

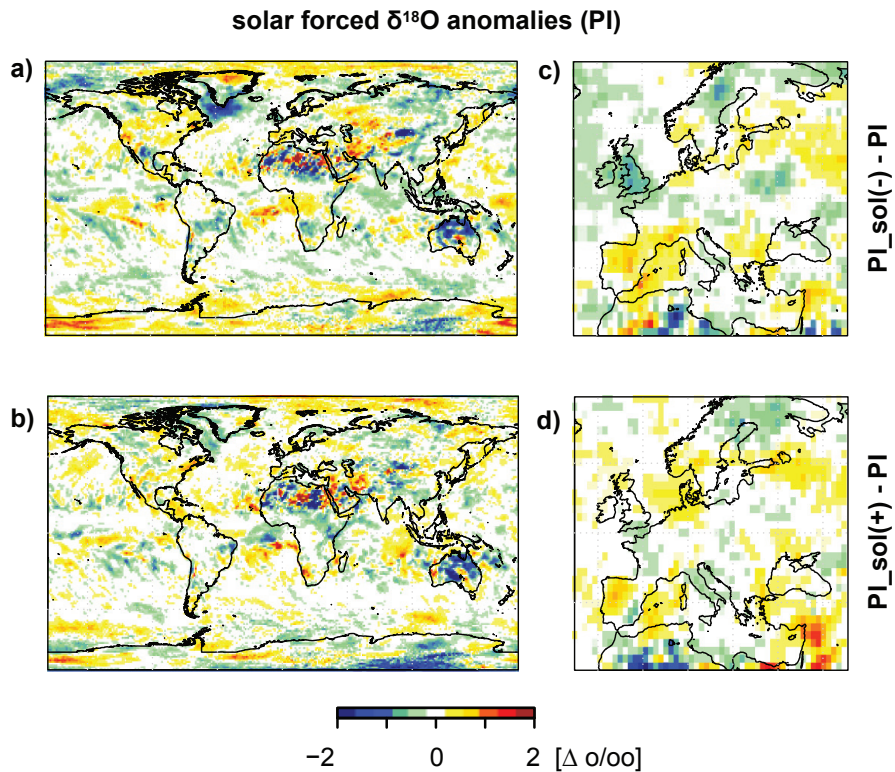


Fig. 5. Same as Fig. 4 but for $\delta^{18}\text{O}$ in precipitation values.

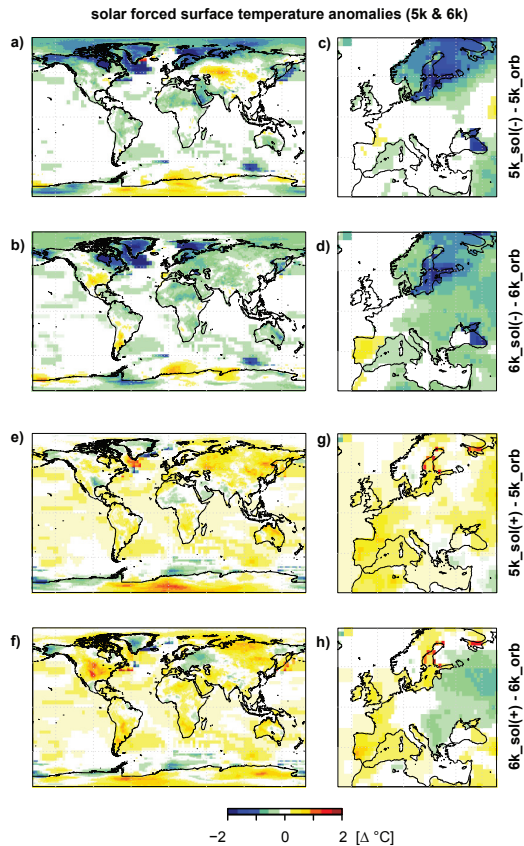


Fig. 6. Simulated solar activity-induced changes of mid Holocene (5k, 6k) surface temperatures. The temperature anomalies are calculated between the experiment with additional solar influence boundary conditions (sol(-) and sol(+), respectively) and the undisturbed 5k and 6k climate simulations. Results for low solar activity forcing are shown in panels (a–d), and for high solar activity in panels (e–f). Plot details are similar to Fig. 2.

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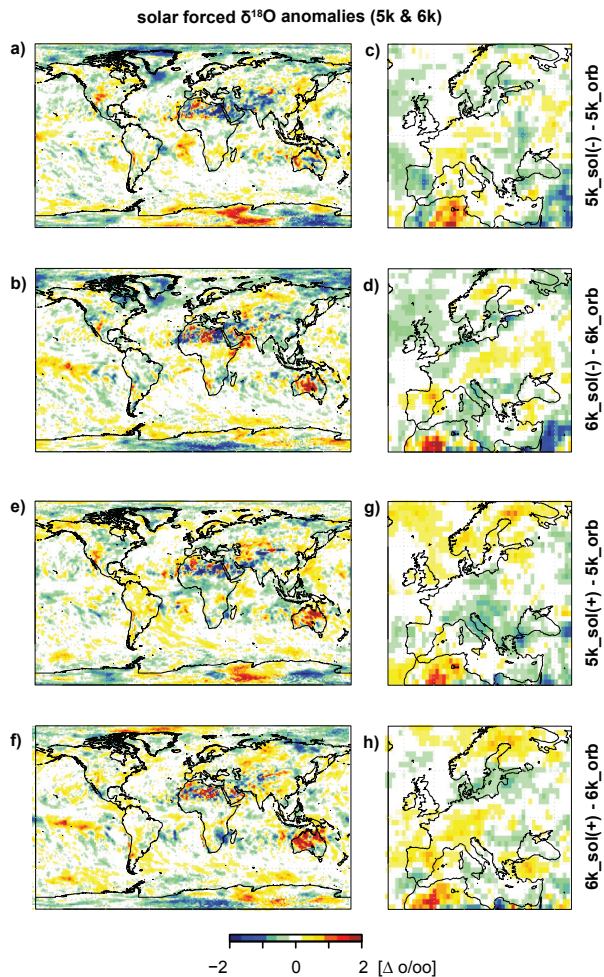


Fig. 7. Same as Fig. 6 but for $\delta^{18}\text{O}$ in precipitation values.

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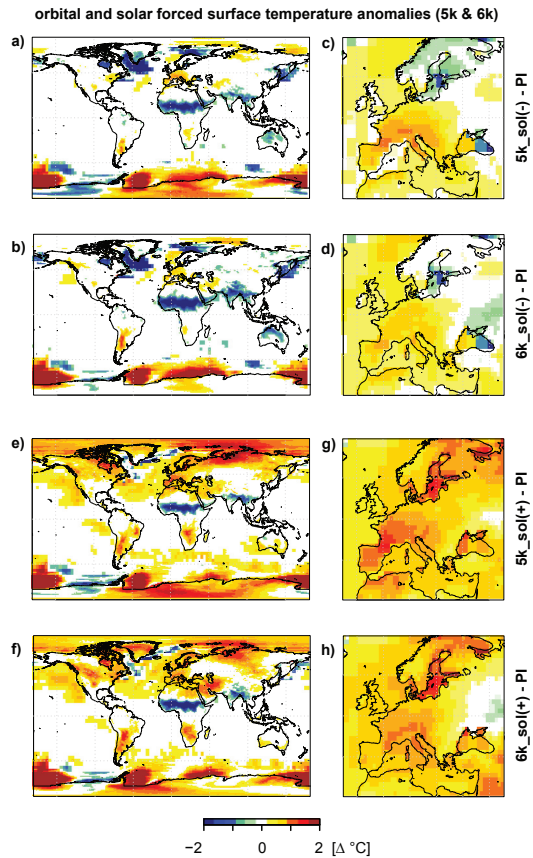


Fig. 8. Same as Fig. 6 but for the combined effect of orbital-driven insolation and solar activity changes.

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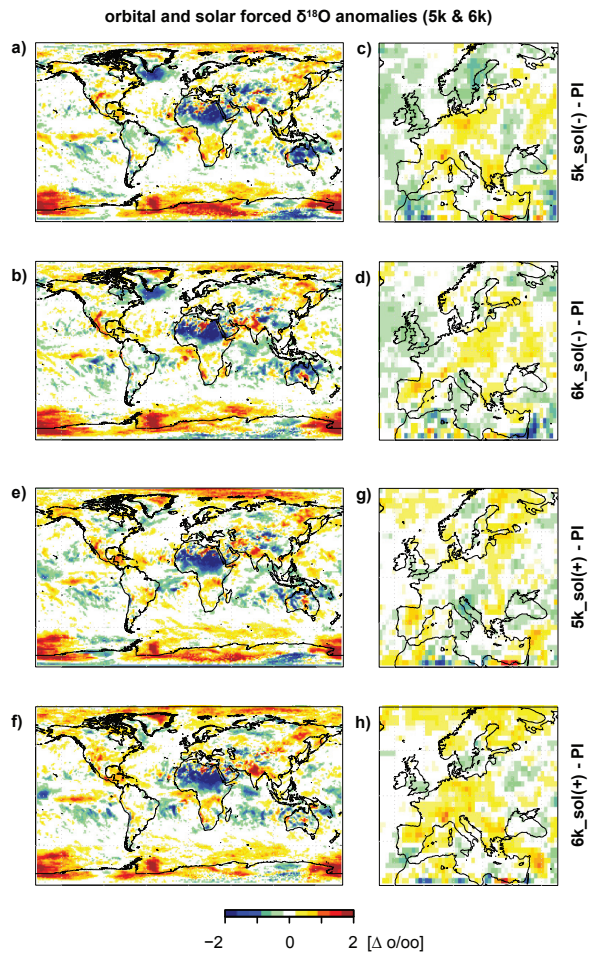


Fig. 9. Same as Fig. 8 but for $\delta^{18}\text{O}$ in precipitation values.

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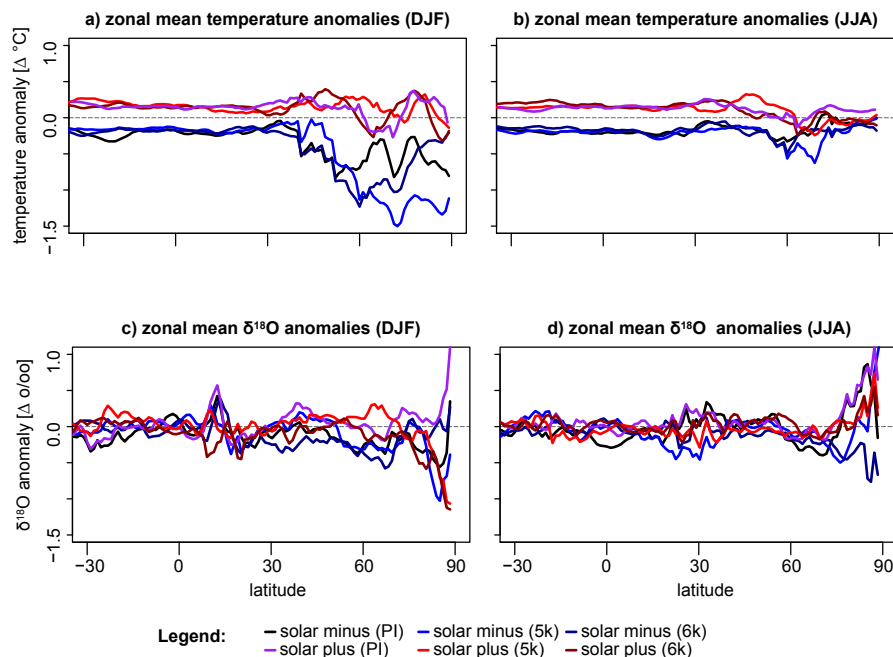


Fig. 10. Zonal mean temperature and $\delta^{18}\text{O}$ precipitation anomalies during boreal summer (JJA) and winter (DJF) due to changes in solar activity (see text). Reddish lines visualize the influence of an increased solar activity, bluish lines represent a weak activity of the sun.

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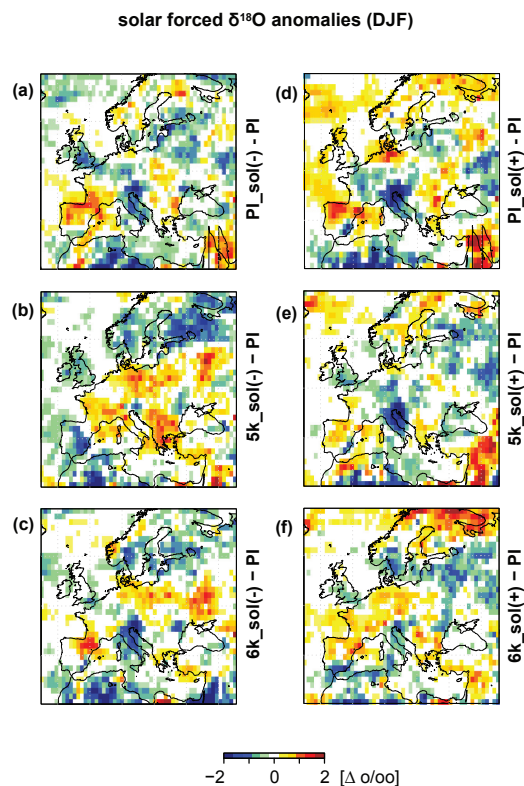


Fig. 11. Combined orbital-driven insolation and solar activity-induced winter (DJF) $\delta^{18}\text{O}$ anomalies for PI, 5k, and 6k. The left column (a–c) shows simulation results for weak solar activity, the right column (d–f) for high solar activity.

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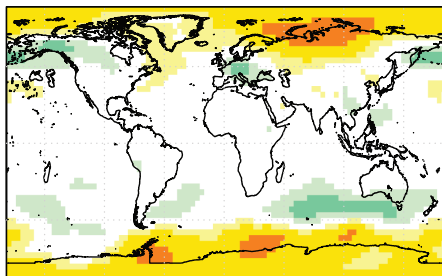
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sea level pressure anomalies

EGMAM: sol(-) - sol(+)



ECHAM5-wiso: PI_sol(-) - PI

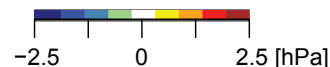
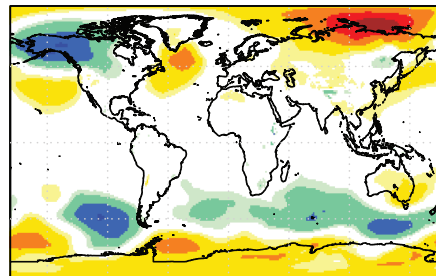


Fig. 12. The simulated annual mean sea level pressure pattern (SLP) of **(a)** the EGMAM experiment (after Spanghehl et al., 2009) and **(b)** the corresponding ECHAM5-wiso simulations. Shown are the anomalies between a phase with low solar activity, sol(-), and a phase of default solar activity. This is the sol(+) phase in the case of EGMAM, which is derived from a period with pre-industrial conditions (see Sect. 2.2), and the pre-industrial climate (PI) in the case of ECHAM5-wiso.