Modeling Obliquity and CO₂ Effects on Southern Hemisphere Climate during the Past 408 ka*  

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ABSTRACT  

The effect of obliquity and CO₂ changes on Southern Hemispheric climate is studied with a series of numerical modeling experiments. Using the Earth system model of intermediate complexity Loch–VECODE–ECBilt–CLIO–Agism Model (LOVECLIM) and a coupled general circulation model [Model for Interdisciplinary Research on Climate (MIROC)], it is shown in time-slice simulations that phases of low obliquity enhance the meridional extratropical temperature gradient, increase the atmospheric baroclinicity, and intensify the lower and middle troposphere Southern Hemisphere westerlies and storm tracks. Furthermore, a transient model simulation is conducted with LOVECLIM that covers the greenhouse gas, ice sheet, and orbital forcing history of the past 408 ka. This simulation reproduces reconstructed glacial–interglacial variations in temperature and sea ice qualitatively well and shows that the meridional heat transport associated with the orbitally paced modulation of middle troposphere westerlies and storm tracks partly offsets the effects of the direct shortwave obliquity forcing over Antarctica, thereby reinforcing the high correlation between CO₂ radiative forcing and Antarctic temperature. The overall timing of temperature changes in Antarctica is hence determined by a balance of shortwave obliquity forcing, atmospheric heat transport changes, and greenhouse gas forcing. A shorter 130-ka transient model experiment with constant CO₂ concentrations further demonstrates that surface Southern Hemisphere westerlies are primarily modulated by the obliquity cycle rather than by the CO₂ radiative forcing.

1. Introduction  

Presently, Earth’s rotation axis is tilted at an angle of 23°26′21.5° against the ecliptic plane. This value varies by about ±1.5° with a period of approximately 41 000 yr. The presence of the moon has played a key role in stabilizing Earth’s obliquity (Laskar et al. 1993) and hence climate. The last obliquity minimum was attained about 28 ka before present (BP)—about 7000 yr prior to the Last Glacial Maximum (LGM). Obliquity changes modulate the strength of the annual cycle of solar insolation. In contrast to precession, obliquity affects the amplitude of the seasonal cycle of insolation in both hemispheres synchronously. High obliquity also causes increased annual mean solar insolation at polar latitudes and a reduction of annual mean insolation equatorward of around 43° latitude (Loutre et al. 2004) (Fig. 1a). The largest Southern Hemisphere variations of the annual mean meridional insolation gradient \( \partial Q_0 / \partial y \) (with \( Q_0 \) and...
y representing the annual mean incoming shortwave radiation and latitude, respectively) occur at about 56.5°S (Fig. 1a, contour lines)—a region that overlaps with the Southern Hemisphere westerlies.

Annual mean insolation varies between high and low obliquity phases (Fig. 1a) with a maximum range (maximum to minimum insolation) of 15 W m⁻² at high polar latitudes (Loutre et al. 2004). Accounting for the mean present-day planetary albedo, the net shortwave forcing range in polar latitudes reduces to 2–3 W m⁻² (see Fig. 1b), attaining magnitudes similar to those in the low-albedo tropics and similar to the glacial–interglacial greenhouse gas forcing range of about 3 W m⁻² (Köhler et al. 2010).
Among the many paleo-evidences for obliquity forcing of Quaternary and Neogene high-latitude climate are obliquity signals in global ice volume, as captured in benthic δ¹⁸O variations (Imbrie and Imbrie 1980; Raymo et al. 2006), changes in high-latitude meridional temperature gradient (Vimeux et al. 2001), variations in CO₂ (Jouzel et al. 2007), the possible obliquity pacing of glacial terminations (Huybers and Wunsch 2005), and the obliquity signal of North Atlantic Deep Water and Antarctic Bottom Water ventilation changes, as recorded in benthic δ¹³C data from the Southern Ocean (Oppo et al. 1990). Clearly, obliquity cycles play an important role for climate, but a more detailed process-based understanding is needed to explain how they affect the individual climate components in tandem with time-varying greenhouse gas forcing variations [see Paillard (2001) and Berger et al. (1998, 1999) for a review of orbitally forced climate change in conceptual and intermediate complexity models]. Climate model simulations using coupled general circulation models (CGCMs) and Earth system models of intermediate complexity have further highlighted the importance of obliquity variations in driving tropical and extratropical climate during the late Pleistocene (e.g., Lee and Poulsen 2005; Timmermann et al. 2007; Lee and Poulsen 2008, 2009; Chen et al. 2011; Ganopolski and Roche 2009; Mantsis et al. 2011).

Here we will focus on the role of obliquity-driven insolation variations with regard to Southern Hemisphere climate, and in particular on the strength of the Southern Hemisphere westerlies. Our study has been partly motivated by a series of recent papers that postulated a deglacial poleward shift of Southern Hemisphere westerlies and an increase of Southern Ocean upwelling (Toggweiler et al. 2006; Anderson et al. 2009; Denton et al. 2010), potentially triggering the atmospheric CO₂ increase during Glacial Termination 1 and a positive feedback that further amplified the wind anomalies. This hypothesis is at odds with the results of climate model simulations run under LGM boundary conditions (Menviel et al. 2008; Rojas et al. 2009; Chavaillaz et al. 2012; Rojas 2013) that failed to simulate robust equatorward shifts or considerable changes in the amplitude of the Southern Hemisphere westerlies under glacial boundary conditions. In these modeling experiments, glacial–interglacial CO₂ changes do not affect the wind patterns in a way that would lead to a consistent strong positive atmosphere–carbon cycle feedback. While state-of-the-art CGCMs still have some difficulties in simulating certain aspects of the Southern Hemisphere westerlies (Wilcox et al. 2012), basic dynamical and thermodynamical processes, usually invoked to explain the hypothesized wind shifts (Toggweiler et al. 2006), are well captured and represented.

It is worth noting that LGM obliquity was similar to today’s and that if obliquity had been the main driver of variations in Southern Hemisphere westerlies, one would in fact expect only weak differences between LGM and present-day westerlies. This could help explain the finding that current Paleoclimate Modelling Intercomparison Project (phases 2 and 3; PMIP2 and PMIP3) LGM modeling experiments simulate only small changes in the characteristics of Southern Hemisphere wind patterns and large uncertainties (Rojas et al. 2009; Rojas 2013). Here we submit that obliquity variations are a key modulator for orbital-scale Southern Hemispheric wind changes. Our study complements recent studies (Lee and Poulsen 2005; Jackson and Broccoli 2003; Mantsis et al. 2011) that analyzed obliquity effects on atmospheric wind and surface temperature patterns in time-slice CGCM experiments.

The paper is organized as follows: after a brief discussion of the experimental setup of the Model for Interdisciplinary Research on Climate (MIROC) CGCM and the Earth system model of intermediate complexity (EMIC) Loch–VECODE–ECBilt–CLIO–Agism Model (LOVECLIM), the time-slice response of Southern Hemispheric climate to extreme idealized orbital configurations will be described. In the subsequent section we present numerical results that were obtained from transient climate model simulations conducted with LOVECLIM that include and exclude the effects of time-varying CO₂ concentrations. This section also entails a comparison of the transient model solutions with late Pleistocene Southern Hemisphere climate records and elucidates the mechanisms that lead to a muting of the direct obliquity shortwave forcing signal over Antarctica. The last section summarizes our key results and discusses potential implications for the interpretation of paleoclimate data and for previously suggested hypotheses on the driving forces of glacial terminations.

2. Experimental setup

To explore the role of obliquity in Southern Hemispheric climate, we first describe a series of idealized sensitivity experiments conducted with the MIROC CGCM (Hasumi and Emori 2004), version 3.2, and with the Earth system model of intermediate complexity LOVECLIM (Goosse et al. 2010), version 1.1. Thereafter, we discuss model experiments conducted with LOVECLIM that cover the entire orbital, ice sheet, and greenhouse gas forcing history of the past 408 ka. The suite of experiments analyzed here is summarized in Table 1.
The terrestrial vegetation model Vegetation Continuous Description (VECODE; Brovkin et al. 1997) consists of two plant functional types and nonvegetated desert zones. Each grid cell assumes a partial coverage by these three land cover types depending on the annual mean temperature and rainfall amount and variability. The present-day climate sensitivity of the model version used here is 2.2°C per CO2 doubling.

Two idealized fully coupled time-slice simulations were performed under present-day topographic and greenhouse gas boundary conditions with extreme obliquity values of 22.0° and 25.5° (abbreviated as OBL\textsubscript{low} and OBL\textsubscript{high}, respectively). We have chosen these extreme values, which lie outside the range of naturally occurring obliquity variations, to generate a more robust signal for our modeling experiments. The model comparison will mostly focus on the qualitative differences between high and low obliquity configurations.

### c. LOVECLIM transient model experiments

To study the time-evolving aspects of orbital and greenhouse gas–driven climate changes in the Southern Hemisphere over the last 408 ka, we analyze transient experiments conducted with LOVECLIM. Similar transient model experiments have been conducted with other more simplified Earth system models of intermediate complexity (Gallée et al. 1992; Ritz et al. 2011; Ganopolski and Calov 2011; Holden et al. 2010) and also with a coupled general circulation model (Smith and Gregory 2012). Focusing only on the last four glacial cycles, our transient experiment TR uses time-evolving orbital parameters, CO\textsubscript{2}, and Northern Hemispheric ice sheet forcing with a boundary acceleration factor (Timm and Timmermann 2007; Timm et al. 2008) of 5. The coupled model is driven by orbital parameter changes (Berger 1978) and reconstructed atmospheric concentrations of CO\textsubscript{2} (Lüthi et al. 2008), CH\textsubscript{4}, and N\textsubscript{2}O (Augustin et al. 2004). Orography, albedo,
and ice mask variations are obtained from a transient experiment conducted with the Climate and Biosphere Model, version 2 (CLIMBER-2), coupled to the Northern Hemisphere Simulation Code for Polythermal Ice Sheets (SICOPOLIS) ice sheet model (Ganopolski and Calov 2011). The simulated Northern Hemisphere ice volume (expressed in meters sea level equivalent) from the CLIMBER-2 run used here as forcing for LOVECLIM is depicted in Fig. 2. Compared to global sea level reconstructions from Waelbroeck et al. (2002) and Sidall et al. (2003), the timing of the simulated ice volume variations is captured well. A reduced amplitude of ice volume of 10%–20% is expected because CLIMBER-2 does not account for ice sheet variations in Antarctica. The CLIMBER-2 ice sheet resolution of $1.5^\circ \times 0.75^\circ$ was interpolated onto the ECBilt grid. The ice sheet–related variables in LOVECLIM (orography, albedo, and forest fraction) are updated every 1000 calendar years, which corresponds to 200 model years, using a boundary acceleration of 5. In the presence of land ice, gridpoint albedo in LOVECLIM is set to 0.7 and the vegetation mask is modified. The LOVECLIM experiment is conducted using an LGM bathymetry (Roche et al. 2007) in order to avoid internally generated Atlantic meridional overturning circulation (AMOC) oscillations as described in Friedrich et al. (2010). To save computing time, the 408-ka TR simulation was split up into four chunks that overlapped by about 10 ka (2000 model years). Each of these chunks (starting in interglacials at 408, 332, 239, and 125 ka BP and using a 5000-model-year-long spinup) ran in parallel on individual processors and the complete trajectory for TR is obtained by concatenating the data from the individual experiments and using sliding linear interpolation for the overlap periods. Freshwater forcing from the ice sheets is not taken into account.

Furthermore, we analyzed a transient experiment TRnoCO2 (see Table 1) with LOVECLIM that covers

![Figure 2](image-url)
the orbital and Northern Hemisphere ice sheet–forcing history of the last 130,000 years, but uses constant greenhouse gas concentrations from 130 ka BP onward. Except for using constant greenhouse gas concentrations and a lower boundary forcing acceleration factor of 5, the experiment TRnoCO2 follows the same setup as the transient 130-ka modeling experiments described in Timm et al. (2008). Note that in this simulation the present-day bathymetry and a slightly different Northern Hemisphere ice sheet evolution from TR were used. The effect of this mismatch between TR and TRnoCO2 on the Southern Hemisphere climate evolution is considered to be small.

3. Results

a. Idealized time-slice experiments

As documented in Figs. 3a and 3b, changing Earth’s obliquity from minimum to maximum values in OBLV_MI high and OBLV_MI low leads to polar warming of up to 5°C in the LOVECLIM and MIROC models. The warming is strongest near the Antarctic margin and in areas of large sea ice variability. The resulting changes in the Southern Ocean sea ice extent (not shown) and of surface albedo further contribute to the surface warming.

In LOVECLIM the meridional extent of the positive surface temperature anomalies is considerably larger than in MIROC, which exhibits the strongest response over Antarctica and the Weddell Sea. We observe that extreme phases of obliquity (experiments OBLV_low and OBLV_high) can induce temperature anomalies in West Antarctica that have a similar magnitude to those induced by glacial–interglacial changes of CO₂ (see Timmermann et al. 2009, their Fig. 6). Annual mean surface temperature changes equatorward of 40°S are relatively small.

In both models, and in response to an increase in obliquity, the simulated surface temperature response (Figs. 3a,b) and the sea ice albedo feedback lead to a considerable decrease of the magnitude of the meridional surface temperature gradient near 50°–60°S (Figs. 4c,d), and in turn a reduction of the Eady growth rate (not shown), a measure of the atmosphere’s baroclinicity. In LOVECLIM a reduction of baroclinicity in the region of the time-mean equivalent barotropic eddy-induced jet, which lies poleward of the subtropical jet (Fig. 4a, contours), causes a weakening of the storm track variance by approximately 20% (as measured by the kinetic energy of 2–8-day bandpass-filtered eddies; not shown), in accordance with idealized modeling experiments (Brayshaw et al. 2008). Figure 5 reveals that in LOVECLIM the simulated transient eddy momentum flux convergence weakens between 40° and 60°S. This is due to changes in tropospheric baroclinicity, which further induce an overall weakening of the eddy-induced jet at levels of 500 and 800 hPa (Fig. 4a, shading). This weakening in turn decelerates the zonal mean surface westerlies in the Southern Hemisphere by about 10%–20% in LOVECLIM (Figs. 3a and 4a) and in MIROC (Figs. 3b and 4b). A weakened storm track is associated with a reduction in the poleward transport of heat and moisture. The result is an increase of sensible cooling and latent cooling over Antarctica of about 2 W m⁻² (not shown), which opposes the local net short-wave flux anomaly because of increased net surface.
shortwave obliquity forcing. Hence the storm track adjustment plays an important role in partly offsetting the direct radiative effect of obliquity on Antarctic temperatures.

Experiments $OBL_{LV, MI}^{high}$ and $OBL_{LV, MI}^{low}$ are highly idealized simulations that were conducted for interglacial boundary conditions and extreme obliquity conditions. The main conclusions drawn from these experiments on

![Figure 4](image1.png)

**FIG. 4.** (a) Meridional section of annual mean zonally averaged zonal winds (contours; m s$^{-1}$) and annual mean difference between zonally averaged zonal winds (shading; m s$^{-1}$) simulated by LOVECLIM in $OBL_{LV}^{high}$ and $OBL_{LV}^{low}$. (b) As in (a), but for MIROC in $OBL_{MI}^{high}$ and $OBL_{MI}^{low}$. (c) Difference of zonally averaged annual mean temperature gradient between $OBL_{LV}^{high}$ and $OBL_{LV}^{low}$. (d) As in (c), but for $OBL_{MI}^{high}$ and $OBL_{MI}^{low}$. Negative (positive) values in the Southern (Northern) Hemisphere indicate a reduction of the magnitude of the surface temperature gradient.

![Figure 5](image2.png)

**FIG. 5.** Annual mean zonally averaged transient eddy momentum flux convergence anomaly ($10^{-6}$ m s$^{-2}$) between $OBL_{LV}^{high}$ and $OBL_{LV}^{low}$. The transient eddies are obtained by applying a 2–8-day bandpass filter to the simulated wind velocities.
the role of obliquity forcing on Southern Hemisphere westerlies and storm tracks are confirmed qualitatively by similar experiments conducted recently with the Fast Ocean Atmosphere Model (FOAM; Lee and Poulsen 2008, 2009) and the Geophysical Fluid Dynamics Laboratory Climate Model, version 2.1 (GFDL CM2.1; Mantsis et al. 2011).

To better understand how obliquity changes may have affected Southern Hemispheric climate under time-varying boundary conditions and CO₂ forcing, we analyze the transient model experiments TR and TRnoCO₂.

b. Transient glacial-cycle experiments

One key element of Southern Hemisphere glacial cycles is the variation of Southern Ocean sea ice extent. The bottom panel of Fig. 2 shows the simulated anomalies in Southern Hemisphere sea ice extent from TR in comparison with the sea salt flux from European Project for Ice Coring in Antarctica (EPICA) Dome C (Wolff et al. 2006), which is often considered to be a sea ice indicator. According to Wolff et al. (2006), high sea salt flux values correspond to large sea ice extent. We observe a good match between these two time series on all time scales. However, some notable differences occur during the Holocene. The model simulation shows a stable sea ice extent over the past 10 ka in contrast to the sea-salt proxy, which suggests an increase of sea ice during the past 9 ka. Furthermore, differences between the sea-salt flux and the simulated sea ice area occur during marine isotope stage 8 (MIS8) (250–300 ka). In addition to the dominant variations on time scales of 80–120 ka, both time series are also characterized by a considerable amount of spectral energy on precessional time scales. In the proxy data, the Eemian interglacial period around 125 ka stands out as the period with the smallest sea ice extent—a configuration that may have also impacted the West Antarctic ice sheet.

To further document the performance of the transient TR simulation in the Southern Hemisphere, we compare the simulated zonally averaged annual mean surface temperature anomalies at 75°S with a combined water-isotope-based Antarctic temperature proxy (Parrenin et al. 2013). As a result of transient CO₂ and orbital forcing in TR the Antarctic temperature evolution in LOVECLIM matches the reconstructions quite well in terms of timing (Fig. 6, top panel). However, the amplitude of the 100-ka signal in Antarctic temperatures is underestimated in TR compared to the reconstruction, as shown by the power spectrum of both time series in Fig. 6c. This mismatch may be a result of multiple sources of uncertainty, including uncertainty in the climate sensitivity and polar amplification mechanisms in LOVECLIM, the lack of anomalous Antarctic orographic forcing in the TR experiment, and also potential seasonal biases in the isotope-derived temperatures that can emerge from the overlap of high austral spring insolation changes and maximum snowfall in this season (Laepple et al. 2011). Furthermore, our model simulations do not capture the effects of meltwater pulses in the North Atlantic, which caused millennium-scale variability in Antarctica because of the bipolar seesaw mechanism. This type of variability may have contributed to the amplitude of some of the interglacial temperature anomalies in Antarctica, such as the initial rapid warming during the Eemian period, which coincided with the massive Heinrich event 11 (Hodell et al. 2008).

In addition to the dominant glacial–interglacial signals in TR with amplitudes of about 6°–7°C, the model also simulates obliquity-scale variations in annual mean temperatures at 75°S, in accordance with the observations. To further differentiate the orbital signal from the CO₂-induced changes in Antarctic temperature, we analyze the TRnoCO₂ transient sensitivity experiment that uses constant preindustrial CO₂ forcing. We find that when CO₂ forcing is neglected the obliquity variations become the dominant signal and the 100-ka signal is completely absent (Fig. 6a, dashed blue line). Comparing TR and TRnoCO₂ we conclude that the orbitally induced shortwave signal alone can explain about 50% of the total simulated amplitude of the glacial–interglacial surface temperature variations at 75°S.

To better understand the drivers of annual mean surface temperature variations poleward of the Southern Hemisphere westerlies, we studied the atmospheric heat budget for the zonally averaged latitude belt centered at 65°S (the southern extent of the westerlies) in experiment TR.

The individual contributions to the zonally averaged heat budget of the atmospheric column at 65°S for TR are shown in Fig. 6 (bottom panel). As documented by the power spectrum (Fig. 6d) there is a strong obliquity cycle in net shortwave radiation with a range of 8–12 W m⁻² and an equally strong peak at 100-ka eccentricity periods. Since clouds are climatologically prescribed in LOVECLIM, deviations from a perfect obliquity cycle and the enhanced amplitude of the net shortwave fluxes relative to Fig. 1b indicate that shortwave radiation anomalies include already significant contributions from the sea ice albedo feedback (Fig. 1c). This also explains the fact that both eccentricity (100 ka) and precessional (21 ka) components can be found in the power spectrum of the shortwave fluxes (Fig. 6d), in accordance with the CO₂ and orbitally driven variability in the Southern Hemisphere sea ice area (Fig. 2, bottom panel). By comparing Figs. 1b and 1c, we find that sea ice albedo changes α of just a few percent can already
induce large changes in the net incoming radiation of several watts per meter squared resulting from the term $Q_0(1 - \alpha')$, where $Q_0$ denotes the long-term annual mean insolation reaching the surface. This forcing is larger in polar latitudes than the anomalies of the top-of-the-atmosphere outgoing longwave radiation (Fig. 6b, blue line), which in TR are mostly determined by the effect of the greenhouse gas forcing on surface temperatures.\footnote{Water vapor changes only play a minor role at 65°S.}

Figure 6b further reveals that in TR the atmospheric heat transport convergence, which is largely driven by atmospheric circulation changes (see Fig. 7a), partly compensates the net annual mean shortwave radiation changes, in particular on obliquity and precession time scales (see also power spectrum in Fig. 6d). These findings are consistent with the notion that, during phases of low obliquity, middle tropospheric Southern Hemisphere westerlies (Figs. 4 and 7a) and storm tracks (Fig. 5) intensify, which leads to an enhancement of the heat transport convergence at 65°S relative to the long-term mean (see Fig. 7a). These changes weaken the influence of the direct obliquity shortwave forcing on surface temperatures. Our results explain that in spite of similar amplitudes of CO$_2$ longwave and obliquity shortwave forcings, Antarctic temperatures are dominated much more by the 100-ka sawtooth signal captured in CO$_2$ variations, than by the direct obliquity signal (Fig. 6c).

The simulated variations of the lower troposphere 800-hPa Southern Hemisphere westerlies in TR and TRnoCO2 (Fig. 7b) document that a large fraction of...
the orbital-scale wind variability is determined by the obliquity forcing, as demonstrated by the power spectrum in Fig. 7e. Although the simulated temperatures around Antarctica differ considerably between experiments TR and TRnoCO2 (Fig. 6a), their respective simulated 800-hPa wind changes are very similar (Fig. 7b), which supports our conclusion from the snapshot experiments that changes of lower troposphere Southern Hemisphere westerlies are driven by the surface temperature gradients, rather than by the overall Southern Hemisphere temperature. This is further corroborated with the high correlation between the simulated temperature gradient in TR (cyan) and the strength of the zonal mean winds at 800 hPa averaged between 45°S and 60°S (Fig. 8). In addition to the obliquity signal, our model solution also displays some changes in the 500-hPa winds on the 100-ka cycle (Fig. 7d), which can be traced back to the contributing effects of CO₂ forcing and possible nonlinear rectification processes between precession-driven seasonal insolation changes and the seasonal cycle in sea ice cover (Timmermann et al. 2009).

Given the fact that our simulated temperature gradient compares well with a deuterium-excess based reconstruction of this quantity from Vimeux et al. (2001), Stenni et al. (2010), and Uemura et al. (2012) (Fig. 8), and that simulated sea ice variations correlate well with paleo-proxy data (Fig. 2), we conclude that at least the surface climate conditions that cause changes in atmospheric circulation in the Southern Hemisphere are realistically represented in TR. More experiments with higher vertical resolution models are needed to determine whether the atmospheric response to these boundary conditions is robustly captured in LOVECLIM.
4. Summary and discussion

Based on a transient climate model simulation covering the past 408 ka, a 130-ka sensitivity experiment without varying CO₂, and idealized snapshot experiments for high and low obliquity conducted with the three-dimensional Earth system model of intermediate complexity LOVECLIM and the coupled general circulation model MIROC, we have documented the following:

- In addition to greenhouse gas forcing, obliquity-paced changes in net shortwave fluxes determine the time evolution of temperature variations over Antarctica (Figs. 6a,b);
- Obliquity forcing effectively modulates the meridional SST gradient in the Southern Ocean region, in accordance with the ice core deuterium excess data (Vimeux et al. 2001; Uemura et al. 2012) (Fig. 8);
- Obliquity-driven variations in the meridional SST gradient induce changes in the strength of lower and middle troposphere Southern Hemisphere westerlies and storm tracks, with low obliquity corresponding to stronger westerlies and storm tracks (Figs. 3a,b, 5, and 7); and
- Obliquity-paced changes of the lower and middle troposphere Southern Hemisphere westerlies weaken the effects of direct shortwave obliquity forcing on surface temperatures via changes in atmospheric heat transport, thus enhancing the relative contribution of greenhouse gas forcing in orbital-scale Antarctic temperature change (Fig. 6b).

Complementary to our time-slice experiments (section 3a), which confirm previous results of stronger Southern Hemisphere westerlies for low obliquity (Mantsis et al. 2011), a new perspective on the joint effects of obliquity and greenhouse gas forcing on Southern Hemisphere climate is provided here through a transient modeling approach that covers several glacial cycles. Our transient climate model simulation compares well with Southern Hemisphere climate proxies, such as water isotope-based Antarctic temperature reconstructions, deuterium-excess data, and sea-salt fluxes.

The transient model simulations described here are based on a three-layer atmospheric model with a horizontal resolution of 5.6°. Admittedly this is not the optimal choice to simulate details of Southern Hemispheric westerlies, including their dynamics and response to external forcings. Our choice was motivated by the fact that LOVECLIM simulates the basic dynamics of westerlies and their interactions with the sea ice and Southern Ocean in a computationally efficient manner that allows us to conduct simulations that cover several glacial cycles, albeit with orbital acceleration. The dynamical mechanisms identified here from the LOVECLIM experiments are qualitatively similar to those identified by our idealized time-slice experiments conducted with the more sophisticated MIROC CGCM.

Our finding of stronger marine isotope stage 2 (MIS2) surface winds in the Southern Ocean as well as stronger Southern Ocean upwelling (Fig. 7, bottom panel) challenges recent interpretations of paleoceanographic data (e.g., Anderson et al. 2009; Denton et al. 2010), which call for weaker and/or equatorward-shifted westerlies and weaker Southern Ocean glacial upwelling to explain variations in Southern Ocean opal fluxes and other proxies. Our simulated Southern Ocean upwelling (Fig. 7c) reveals a more complicated dynamics on orbital timescales, with both wind-driven obliquity and sea ice–driven precession components present (see power spectrum in Fig. 7f). The origin of the precessional-scale Southern Ocean upwelling and its link to sea ice variability will be explored in a forthcoming study.

Given the apparent mismatch between simulated upwelling changes, which are dominated by precessional-scale variability (Fig. 7f) and atmospheric CO₂ (Fig. 7c), we conclude that the anomalous upwelling of carbon-rich waters from the deep ocean (Toggweiler et al. 2006) is an unlikely candidate to explain the magnitude and timing of orbital-scale CO₂ changes. This conclusion adds to the existing uncertainties and ambiguities in interpreting Southern Hemisphere paleo-proxy data in terms of...
changes in the Southern Hemisphere westerly winds (Kohfeld et al. 2013).

As shown previously (Lamy et al. 2007; Timmermann et al. 2010; Lee et al. 2011), millennial-scale variability in the North Atlantic associated with Heinrich events and reductions of the AMOC can also induce changes in the Southern Hemisphere westerlies. The existing discrepancies among Southern Hemispheric wind proxies discussed in detail in Menviel et al. (2008) and Denton et al. (2010; see their supplementary material) may very well reflect the fact that the North Atlantic–Southern Ocean atmospheric bridge projects more on higher-order stationary wave patterns, as suggested in Timmermann et al. (2010), than on the southern annular mode (wave-number 0 response). The horizontal and vertical response, both to millennial-scale events and external forcings, is very likely to be more complex and diverse than often assumed when interpreting regional paleo-proxy data just in terms of shifting and intensifying/weakening Southern Hemisphere westerlies.

Summarizing, our model experiments have demonstrated that both CO₂ and obliquity forcing are important drivers of Southern Hemispheric glacial–interglacial climate change.

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