The effect of obliquity-driven changes on paleoclimate sensitivity during the late Pleistocene

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We reanalyze existing paleodata of global mean surface temperature ΔT_g and radiative forcing ΔR of CO_2 and land ice albedo for the last 800,000 years to show that a state-dependency in paleoclimate sensitivity S, as previously suggested, is only found if ΔT_g is based on reconstructions, and not when ΔT_g is based on model simulations. Furthermore, during times of decreasing obliquity (periods of land-ice sheet growth and sea level fall) the multi-millennial component of reconstructed ΔT_g diverges from CO_2, while in simulations both variables vary more synchronously, suggesting that the differences during these times are due to relatively low rates of simulated land ice growth and associated cooling. To produce a reconstruction-based extrapolation of S for the future we exclude intervals with strong ΔT_g-CO_2 divergence and find that S is less state-dependent, or even constant (state-independent), yielding a mean equilibrium warming of 2–4 K for a doubling of CO_2.

Keypoints:

- Proxy-based reconstructions and model-based simulations of global mean surface temperature over the last 800000 years differ in detail
- During periods of decreasing obliquity and sea level the proxy reconstructions show a temperature-CO2 divergence missing in simulations

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• Elimination of these periods leads to a more linear paleoclimate sensitivity and to equilibrium warming for CO2 doubling of 2–4 K

Plain Language Summary

Anthropogenic carbon dioxide (CO_2) emissions will lead to rising global mean temperature through the greenhouse effect. The amplitude of this warming, as estimated with computer simulations for the equilibrium climate response to a doubling of atmospheric CO_2 concentration, is called climate sensitivity. It is necessary to verify these simulation-based quantifications of climate sensitivity with independent alternative approaches. One such approach is the analysis of past (paleo) climates, which has indicated a state-dependent paleoclimate sensitivity. Here, we compare different data-based reconstructions and computer-based simulations of paleoclimate sensitivity of the last 800,000 years and find that they disagree. In data-based reconstructions global mean temperature and CO_2 diverge during intervals when land ice growth is particularly pronounced. This temperature-CO_2 divergence is not observed in simulations, probably due to an underestimation of the rate of land ice growth and the associated cooling. However, these periods of pronounced land ice growth are not of relevance for a warming future and can therefore be neglected when estimating climate sensitivity from reconstructions of the past. Consequently, we find that paleoclimate sensitivity derived from reconstructions is less state-dependent than previously thought and agrees with warming estimates of 2–4°C as derived from simulated equilibrium climate response for CO_2 doubling.

1. Introduction

Analyses of paleo reconstructions [*Köhler et al.*, 2015] (K2015 in the following) and paleo climate simulations [*Friedrich et al.*, 2016] (F2016 in the following), covering the late Pleistocene, have suggested that climate sensitivity might not be a constant param-

eter of the climate system, but a state-dependent variable that increases towards warmer climates. Most other studies on this topic indicate a similar behavior, including a review that covers a wide range of colder and warmer climate states [*von der Heydt et al.*, 2016]. However, there have also been studies using general circulation models (GCMs) or Earth system models of intermediate complexity (EMICs) which simulate an increase in climate sensitivity for colder than present-day climate [e.g. *Colman and McAvaney*, 2009; *Kutzbach et al.*, 2013; *Pfister and Stocker*, 2017].

Fueled by this ambiguity we wanted to test the robustness of the conclusions in earlier studies (K2015, F2016). Here we investigate whether this, previously found, state-dependency of climate sensitivity can be reproduced in other setups, we reanalyze the proxy-based reconstructions of global temperature change (ΔT_{g}) published in the last few years [*Snyder*, 2016, in addition to K2015 and F2016], investigate transient 800-kyr simulation results obtained with the EMICs, CLIMBER [*Ganopolski and Calov*, 2011] and LOVECLIM (F2016), and analyze the only available transient GCM simulation across the last glacial/interglacial transition provided by the CCSM3 model [*Liu et al.*, 2009; *He*, 2011] (Fig. 1).

A direct comparison of today's anthropogenic warming with paleodata-based reconstructions is not possible, due to the lack of a direct analog in the magnitude of the rate of changes. However, we can evaluate the general climate system response to radiative forcing anomalies. For such efforts, the specific equilibrium climate sensitivity $S_{[\mathrm{X}]}$ (or paleoclimate sensitivity) has been defined as the ratio of the global and annual mean surface temperature change (ΔT_{g}) over the change in radiative forcing ($\Delta R_{[\mathrm{X}]}$) caused by

the process(es) X [*PALAEOSENS-Project Members*, 2012]

$$S_{[\mathrm{X}]} = \frac{\Delta T_{\mathrm{g}}}{\Delta R_{[\mathrm{X}]}} \tag{1}$$

Here, we calculate radiative forcing for processes including the greenhouse gas (GHG) effect (CO_2, CH_4 and N_2O), but also other processes, such as the (planetary) albedo effects from land ice (LI), vegetation (VG) and aerosols (AE). The time-dependency of the climate to those forcing or feedback processes is not of particular interest in the following, but has been addressed elsewhere [e.g. *Zeebe*, 2013; *Rohling et al.*, 2018]. This concept of calculating $S_{[\mathrm{X}]}$ was introduced in *PALAEOSENS-Project Members* [2012] to clarify which forcing is explicitly included when estimating climate sensitivity from paleodata, not to test causation. Furthermore, this approach assumes that different forcing processes have a similar impact on ΔT_{g}, which is a simplification [e.g. *Yoshimori et al.*, 2011; *Stap et al.*, 2018], that is difficult to overcome in analyses of mainly proxy-based reconstructions. Within the context of Earth system model analysis this ratio $\Delta T_{\mathrm{g}}/\Delta R_{[\mathrm{X}]}$ is also called the *climate sensitivity parameter* [e.g. *Yoshimori et al.*, 2011].

The emergence of state-dependency in $S_{[\mathrm{X}]}$ implies that the best fit to a scatter plot of ΔT_{g} versus $\Delta R_{[\mathrm{X}]}$ is not linear, but some non-linear function, e.g. a higher order polynomial (Fig. 2a). While the detection of such a non-linearity is rather straight forward, the quantification of $S_{[\mathrm{X}]}$ is more complicated, as describted in detail by *Köhler et al.* [2017a].

In F2016 two independent estimates of ΔT_{g} were generated: a purely proxy-based reconstruction based on SST data from 63 records and a simulation with the LOVECLIM model. The estimates of ΔT_{g} were then averaged and confirmed the state-dependency

in $S_{[X]}$ for the last ∼800 kyr as deduced by K2015. Since this state-dependency in $S_{[X]}$ suggests that during warm interglacials a relatively small change in ΔR leads to a relatively large change in ΔT_g (Fig. 2a), it is crucial to know how robust this conclusion is. Recently, a new proxy-based reconstruction of global mean temperature changes constructed from 61 records of SST anomalies has been published [*Snyder*, 2016]. These two proxy-based reconstructions of ΔT_g [F2016, *Snyder*, 2016] are not fully independent with respect to the underlying data, but differ in details and in the upscaling methodologies.

Finally, we discuss how our findings for paleoclimate sensitivity can be extrapolated to the future and compare a rough approximation of equilibrium global warming caused by $2\times CO_2$ with other approaches.

2. Methods

In K2015 deconvolution of the LR04 benthic $\delta^{18}O$ stack [*Lisiecki and Raymo*, 2005] was used to provide mutually consistent contributions from sea level (or land ice volume) and deep ocean temperature (ΔT_O) using 3-D ice sheet models of *de Boer et al.* [2014]. Temperature change over land in the high latitude northern hemisphere (about $40-85°N$, ΔT_{NH}) where most glacial/interglacial changes in land ice occurred during the late Pleistocene, is linearly related to ΔT_O on a multi-millennial timescale. However, ΔT_{NH} also contains changes due to elevation changes (lapse rate) and considers seasonality. ΔT_g and ΔT_{NH} are then related to each other via a non-constant polar amplification factor (f_{pa}) that has been determined from PMIP3 output. Sensitivity analyses [*de Boer et al.*, 2014, K2015] have shown that ΔT_g has a relative uncertainty of ∼10% over the last 800 kyr. This setup is a model-based interpretation of proxy data. It is a mixture

between a purely proxy-based reconstruction and model-based simulations. However, while full climate models are driven by temporal changes in various boundary conditions (e.g. insolation, GHG), and then calculate all other variables internally, here only the ice sheet dynamics are simulated. Therefore, we consider our approach to be more similar to those of the proxy-based reconstructions than of the model-based simulations. From the three alternative time series, based on different assumptions for the polar amplification factor f_{pa} in K2015, we use the standard case (ΔT_{g1}), in which f_{pa} is linearly related to ΔT_{NH}. However, our conclusions are not dependent on this choice of f_{pa} and ΔT_{g} (see the application of the alternative temperature time series in Fig. S1). The fact that three alternative formulations of ΔT_{g} can be connected to the same $\Delta R_{[\mathrm{LI}]}$, shows that there are some degrees of freedom in the connection of both variables.

In K2015 the radiative forcing of CO_2 ($\Delta R_{[\mathrm{CO_2}]} = 5.35 \cdot ln(\mathrm{CO_2}/(278\mathrm{ppm}))\mathrm{W/m^2}$, *Myhre et al.* [1998]) and land ice albedo was considered explicitly — leading to $\Delta R_{[\mathrm{CO_2,LI}]}$ and to the state-dependency in $S_{[\mathrm{CO_2,LI}]}$. It should be noted that, when following the revised formulation of *Etminan et al.* [2016], $\Delta R_{[\mathrm{CO_2}]}$ differs by less than 0.01 $\mathrm{W/m^2}$ [*Köhler et al.*, 2017b]. Furthermore, we assume that radiative forcing is state-independent, which might be a simplification [e.g. *Forster et al.*, 2016]. We will analyze similar variables based on alternative ΔT_{g} from proxies (F2016, *Snyder* [2016]), and simulations (LOVECLIM (F2016), CLIMBER [*Ganopolski and Calov*, 2011], CCSM3 [*Liu et al.*, 2009; *He*, 2011]). We will first analyze these different ΔT_{g} in relation to the same $\Delta R_{[\mathrm{CO_2,LI}]}$ as derived in K2015, but for in-depth investigations of simulations we only use the internally applied radiative forcing. The use of these alternative ΔT_{g} for identical $\Delta R_{[\mathrm{CO_2,LI}]}$ has the poten-

tial to introduce a bias because temperature and land ice distribution are firmly linked through deconvolution of the LR04 benthic δ^{18}O stack. This potential bias is not investigated any further here, although alternative land ice distribution [e.g. ICE-5G of *Peltier*, 2004] agree well with our results (K2015). Alternative approaches to estimate $\Delta R_{[\mathrm{LI}]}$ from sea level changes have shortcomings, since they omit the latitudinal effect of land ice distribution on radiative forcing (see K2015 for further details). Chronological misfits between the different records, that might also be introduced in that way, should not be of importance here, as our final interpretations are based on 8-kyr running means. Details of both alternative $\Delta R_{[\mathrm{LI}]}$ estimates and chronological issues have been discussed previously [K2015, *Köhler et al.*, 2017a]. For the CLIMBER simulations additional processes (CH_4, N_2O, vegetation, aerosols) in the radiative forcing term $\Delta R_{[\mathrm{X}]}$ are also considered.

Time series are standardized before analysis. Due to very high variability in calculated ratios (Figs. 3b,c, S1b,c) data far away from the mean ($|\Delta T_\mathrm{g}/\Delta R_{[\mathrm{CO_2,LI}]}| > 0.25\sigma$; $|\Delta R_{[\mathrm{LI}]}/\Delta R_{[\mathrm{CO_2}]}| > 1\sigma$) are considered as outliers and removed. The chosen cut-off thresholds mainly influence the peak height in the standardized time series, but not the dynamics contained in the time series. Due to the rather linear behaviour of the simulations, no outliers in $\Delta T_\mathrm{g}/\Delta R_{[\mathrm{CO_2,LI}]}$ have been removed from the LOVECLIM and CLIMBER results. Finally, the outlier-free time series are standardized a second time to enable comparison between the different approaches. This outlier selection during standardization is illustrated for K2015 in Fig. S2.

The land ice dynamics simulated in CLIMBER (which are also used in LOVECLIM via offline coupling) are restricted to northern hemisphere ice sheets, Antarctic land ice is

kept fixed at present day configuration, while in K2015 the dynamics of ice sheets and ice shelves in both hemispheres have been investigated. The CCSM3 simulations [*Liu et al.*, 2009; *He*, 2011] were driven by the ICE-5G land ice distribution, which was compared to *de Boer et al.* [2014] in K2015. This ICE-5G-based $\Delta R_{[\mathrm{LI}]}$ is also used here when investigating CCSM3 results.

We use the internal fitting routines of the software package GLE, the Graphics Layout Engine (http://www.gle-graphics.org) and use F-tests to determine whether a second order polynomial fits the scattered ΔT_{g}-ΔR-data better than a linear approach (Table S1). For all fits the pre-condition of meeting the origin is applied (no temperature change for no forcing change), leading to the following two regression equations to be tested: either $y = b \cdot x$ (linear) or $y = b \cdot x + c \cdot x^2$ (non-linear).

In cases where uncertainties in both ΔT_{g} and $\Delta R_{[\mathrm{X}]}$ are available, more elaborate statistics might be applied (e.g. Monte-Carlo approaches have been used in K2015). Uncertainties in ΔT_{g} are only available for K2015 and Snyder. In Fig. S3, we show that non-linear fits are very similar when considering or ignoring uncertainties in these two data sets. We take this as support for the more simplistic approach in our main analysis: all data sets are treated identically and fits are calculated without considering uncertainties in the scattered data.

3. Results and Discussions

3.1. Proxy-based reconstructions versus model-based simulations

The main difference between proxy-based reconstructions and model-based simulations to estimate global temperature changes, is that the proxy-based reconstructions capture

the impacts of all Earth system processes active in the considered time window, while in the model-based approaches only those processes implemented in the model can leave their imprint in the simulation results. Simulated time series of ΔT_{g}, therefore, have to be questioned critically for any serious omissions. In other words, any persisting difference between proxy-based reconstructions and simulated ΔT_{g} might be caused by those processes not included in the models. Alternatively, proxy-based reconstructions might be systematically biased, although this seems unlikely if independent reconstructions come to similar conclusions.

Here we compare results of others to the approach of K2015 (Fig. 1a) in order to understand when the proposed state-dependency in $S_{[\mathrm{CO_2,LI}]}$ is sustained or when it needs to be rejected. If we replace ΔT_{g} with an alternative time series (F2016, Snyder, CLIMBER, LOVECLIM, CCSM3, Fig. 1b,c), we find a similar state-dependency in $S_{[\mathrm{CO_2,LI}]}$ — with higher values for warmer conditions — when the applied ΔT_{g} time series is based on proxy-based reconstructions (Fig 2b). This holds for the temperature data set of Snyder, as well as for proxy-based ΔT_{g} derived in F2016 (Fig 2b). The non-linearity in the ΔT_{g}-$\Delta R_{[\mathrm{CO_2,LI}]}$ scatter plots is less pronounced in these alternative calculations, when compared to K2015.

If temperature anomalies are taken from CLIMBER simulations, a non-linear relationship between ΔT_{g} and $\Delta R_{[\mathrm{CO_2,LI}]}$ is generated that is inverse to that found by K2015 (Fig. 2c), suggesting a smaller paleoclimate sensitivity for warmer climates. Similarly, if we base this analysis on the ΔT_{g} simulated in LOVECLIM, we find an inverse non-linear relationship — opposite to the proxy-based results (Fig 2c). Since the ΔT_{g}-$\Delta R_{[\mathrm{CO_2,LI}]}$

relationship of the proxy-based reconstructions of F2016 and the transient LOVECLIM simulations show the opposite slope, it is natural that an averaged ΔT_g based on both (as used in F2016) contains a rather linear relationship (Fig. 2d). Finally we analyzed the only available transient GCM-simulation, the Trace21K scenario of the CCSM3 model for the last 21 kyr. Using their ΔT_g, we again find the same results as from the EMIC runs (Fig. 2d) — a state-dependent paleoclimate sensitivity with steeper slopes in the ΔT_g-$\Delta R_{[CO_2,LI]}$ data during colder climates, pointing to a higher $S_{[CO_2,LI]}$, which is inverse to the results from the proxy-based approaches.

If we analyze internally consistent EMIC simulation results using the radiative forcing of CO_2 and land ice applied in the model runs together with the simulated ΔT_g (instead of $\Delta R_{[CO_2,LI]}$ based on K2015), we find a linear relationship between ΔT_g and $\Delta R_{[CO_2,LI]}$ for LOVECLIM (Fig. 2e). In CLIMBER we find a similar non-linear relationship between ΔT_g and $\Delta R_{[CO_2,LI]}$ — with steeper slope during cold climate— as in the approaches in which the CLIMBER-simulated ΔT_g was analyzed together with $\Delta R_{[CO_2,LI]}$ of K2015 (Fig. 2e). Further details on the differences in $\Delta R_{[LI]}$ for the different approaches can be found in Fig. S4.

3.2. Obliquity-driven changes and the $\Delta T_g - CO_2$ relationship

How can we understand this strong state-dependency of S found in proxy-based approaches and the difference to the model-based approaches? It has recently been deduced, from ice core data covering the last 800 kyr, that the multi-millennial trend of atmospheric CO_2 concentration and Antarctic temperature diverge when obliquity decreases [*Hasenclever et al.*, 2017]. One way of perceiving this divergence is that the reduced incoming

insolation at high latitudes causes land ice sheet growth and cooling, while there is a coexisting process that keeps CO_2 at a relatively constant level. Solid Earth modeling experiments have indicated that falling sea level might lead to enhanced magma and CO_2 production at mid ocean ridges [e.g. *Lund and Asimow*, 2011]. *Hasenclever et al.* [2017] suggested, that the combination of marine volcanism at mid ocean ridges and at hotspot island volcanoes might react to decreasing sea level and be a potential cause for this $\Delta T_g - CO_2$ divergence. Alternatively, the divergence implies that processes other than CO_2 radiative forcing or land ice albedo (potentially radiative forcing from non-CO_2 GHGs, or albedo change caused by aerosols, or vegetation) dominate during these phases — leading to a cooling with little reduction in CO_2. The evidence so far [e.g. *Köhler et al.*, 2010] does not indicate that the latter was the case, although potential impacts of different forcing efficacy [e.g. *Yoshimori et al.*, 2011; *Stap et al.*, 2018] have so far not been investigated. One study analyzed the contribution of the terrestrial carbon cycle to the divergence of CO_2 and ΔT_g at the end of the present (Holocene) and the previous (Eemian or MIS 5e) interglacial [*Brovkin et al.*, 2016]. Processes which seemed to explain the reconstructed divergence in the Holocene failed to explain similar dynamics during MIS 5e, pointing to model deficiencies in the representation of the land carbon cycle, or suggesting that other processes are at work. All modeling results used in here (CLIMBER, LOVECLIM, CCSM3) were obtained in simulations with prescribed observed CO_2 concentrations, and thus include all effects of the Earth system feedbacks on CO_2. However, simulation results do not contain the characteristic long-term ΔT_g-CO_2 divergence found in the proxy-based reconstructions (Snyder, F2016), or in the deconvolution of LR04-$\delta^{18}O$

into land ice dynamics (K2015). This suggests that a relatively low rate of simulated land ice growth and associated cooling during times of decreasing obliquity, and not a feedback on CO_2, might be responsible for the difference between model- and proxy-based approaches.

When ΔT_g is derived mainly from proxy-based reconstructions (K2015, F2016, Snyder), our results show a strong ΔT_g-CO_2 divergence at times of obliquity decrease. An example of this is the dynamics at the end of the Eemian (see zoom-in in the inset in Fig. 1a). For comparison of the different approaches, all time series in the following are analyzed in their standardized versions (Fig. 3, Fig. S1). They confirm the earlier finding of a temperature-CO_2 divergence at times of obliquity decrease by *Hasenclever et al.* [2017], in which not global temperature change, but Antarctic temperature change derived from the EPICA Dome C (EDC) ice core [*Jouzel et al.*, 2007] has been considered. The temporal evolution of this divergence between ΔT_g and CO_2 can be observed by analyzing the multi-millennial dynamics of the ratio $\Delta T_g/\Delta R_{[CO_2]}$, which by coincidence is also defined as $S_{[CO_2]}$ (Fig. 3b). The interpretation of $S_{[CO_2]}$ as a proxy for the multi-millennial ΔT_g-CO_2-divergence represents a major improvement in the understanding of $S_{[CO_2]}$, since previously no meaningful patterns have been detected in its temporal variability [*PALAEOSENS-Project Members*, 2012]. We find that a strong $\Delta T_g - CO_2$ divergence exists in 12 out of 19 phases with decreasing obliquity (gray bands in Fig. 3) in the data from K2015. Furthermore, the ratio of land ice and CO_2 radiative forcing ($\Delta R_{[LI]}/\Delta R_{[CO_2]}$) underwent large changes during these intervals (Fig. 3c), suggesting that land ice (sea level) related changes might indeed be connected to the times of these diverging trends.

The seven phases with decreasing obliquity, but without strong $\Delta T_g - CO_2$ divergence in K2015, can furthermore be divided into periods with a stable ratio of $\Delta R_{[LI]}/\Delta R_{[CO_2]}$ (light blue bands marked A, D, G, P) and those with strong variability in $\Delta R_{[LI]}/\Delta R_{[CO_2]}$ (light red bands I, K, R). In the former periods (blue-colored) the stable ratio of land ice and CO_2 radiative forcing suggests in-phase variations of both processes, which might indicate that any potential sea level-related CO_2 outgassing from marine volcanism or other processes could be compensated by the land ice sheet albedo feedback. In the latter periods (red-colored) the ratio $\Delta T_g/\Delta R_{[CO_2]}$ is always increasing towards the end of the obliquity-half cycle, suggesting that some sea level-related process affecting CO_2 might have initiated, but not yet developed its full potential. This leads, for example, to the unusual strong $\Delta T_g - CO_2$ divergence after the end of period K at 436 kyr BP which persisted for almost a complete obliquity cycle around MIS 11. Five of these seven phases with decreasing obliquity but without a strong $\Delta T_g - CO_2$ divergence (A, D, I, K, P, but not G and R) are also characterized by very modest cooling, indicating that the net climate changes during these phases are small when compared to other phases with decreasing obliquity. These phases should, therefore, be interpreted with care since the dominant climate variations occur during other times.

Much smaller variations in the ΔT_g-CO_2 divergence are found when analyzing model-based simulations of CLIMBER and LOVECLIM than in K2015 (Fig. 3b). Furthermore, the model-based ΔT_g-CO_2 divergence observed during times of decreasing obliquity is partially in anti-phase to the proxy-based results (phases C, S), suggesting highly synchronous variations in CO_2 and simulated ΔT_g while a strong divergence to CO_2 persists

in the reconstructed ΔT_g (Fig. 3b). The two lukewarm interglacials MIS 15a, and 15e (phases N, O, 570 and 610 kyr BP, respectively, [*Past Interglacials Working Group of PAGES*, 2016]) seem to be special in this respect, since the ΔT_g-CO_2 divergence from K2015 is in anti-phase to those based on the simulation output and also to that based on EDC ΔT. Interestingly, the temperature-CO_2 divergence during the MIS 5/4 transition, around 75 kyr BP (phase B) which motivated the study of *Hasenclever et al.* [2017], is one of the largest in EDC, but rather weak in K2015. Our calculated ΔT_g-CO_2 divergence, based on ΔT_g of Snyder or F2016, contains qualitatively similar dynamics related to obliquity as that based on EDC ΔT or K2015, but differs from the model-based simulations (Fig. S1). This qualitative agreement of the divergence in proxy-based ΔT_g (K2015, F2016, Snyder, EDC) provides confidence in the global temperature record obtained in K2015. Furthermore, tests have shown that if new insights into polar amplification [*Stap et al.*, 2018] are used for an improvement of the model setup used in K2015, only small changes in ΔT_g are generated, but the general difference to the model-based simulations persists. Based on these findings, the analysis of *Hasenclever et al.* [2017] needs to be expanded: decreasing obliquity seems to be a necessary, but not a sufficient condition for the ΔT_g-CO_2 divergence. Another process related to sea level change, or in detail to $\Delta R_{[LI]}/\Delta R_{[CO_2]}$, needs to be active at the same time to explain the data.

The importance of this ΔT_g-CO_2 divergence and its connection to obliquity, for the state-dependency of our paleoclimate sensitivity estimate, becomes apparent when we split the data into times with increasing or decreasing obliquity. In the latter case the non-linearity (parameter c in the second order fit) between ΔT_g and ΔR is significantly

different in the data set of K2015 and Snyder (Fig. S5a,c), while in the CLIMBER output hardly any difference can be detected (Fig. S5b). For F2016 (Fig. S5d), which shows a non-linear relationship when all data are analyzed, the relationship is only linear in both data subsets when differentiated by their phase of obliquity. When data are split based on the ratio $\Delta T_g/\Delta R_{[CO_2]}$ in subsets with strong or weak ΔT_g-CO_2 divergence, we find an even larger difference in the non-linearity than when data are split by obliquity in K2015 (Fig. 2f), implying a more linear relationship for data with strong ΔT_g-CO_2 divergence than for data with decreasing obliquity. When using ΔT_g from the proxy-based reconstructions of Snyder and F2016, we find a non-linear relationship in the ΔT_g-$\Delta R_{[CO_2,LI]}$ scatter plot during strong ΔT_g-CO_2 divergence, while for times with more synchronous changes in ΔT_g and CO_2 (weak divergence) a linear relationship between ΔT_g and $\Delta R_{[CO_2,LI]}$ emerges (Fig. 2g,h).

3.3. Using paleoclimate sensitivity to estimate $\Delta T_{2\times CO_2}$

The ΔT_g-CO_2 divergence appears mainly during, or in connection with, periods of decreasing obliquity related to land ice growth or sea level fall. These times cover ~50% of past climates. We conclude, that for a generic climate system understanding the implementation of the processes responsible for this ΔT_g-CO_2 divergence, potentially being the solid Earth-climate feedbacks related to a sea level induced change in marine volcanism [e.g. *Lund and Asimow*, 2011; *Hasenclever et al.*, 2017], is essential.

Intervals of strong ΔT_g-CO_2 divergence should not be considered for the interpretation of paleodata in the context of future warming, e.g. by calculating the paleoclimate sensitivity S, because in the future we expect sea level to rise. Otherwise the climate system response

of a glaciation is erroneously implicated with anthropogenic warming. Here, one might rely only on the subset of ΔT_g-ΔR-data that coincide with times of weak (or no) ΔT_g-CO_2 divergence. For K2015, this restriction would lead to a different quantification of paleoclimate sensitivity following the framework of *Köhler et al.* [2017a] (Fig. 2f). In detail, $S_{[CO_2,LI]}$ can be derived from the fit to the scattered $\Delta T_g - \Delta R_{[CO_2,LI]}$ data after $S_{[CO_2,LI]} = b + c \cdot \Delta R_{[CO_2,LI]}$. The paleodata of the last 800 kyr cover mainly intervals with $\Delta R_{[CO_2,LI]} \leq 0$ W/m^2, and due to the state-dependent character of $S_{[CO_2,LI]}$ we refrain from an extrapolation of our derived fitting function to a range not coverd by the data, e.g. to $\Delta R_{[CO_2,LI]} > 0$ W/m^2. Nevertheless, climates comparable to late Pleistocene interglacials can be approximated by $\Delta R_{[CO_2,LI]} \approx 0$ W/m^2. $S_{[CO_2,LI]}$ for those interglacials would be $\sim$ 20% smaller when excluding intervals of ΔT_g-CO_2 divergence in comparsion to calculations based on all available data, $S_{[CO_2,LI]} = 1.6$ K/(W/m^2) instead of 2.0 K/(W/m^2). If based on ΔT_g of Snyder (Fig. 2g) or F2016 (Fig. 2h) these subsets of data with weak (or no) ΔT_g-CO_2 divergence are defined by a linear relationship between ΔT_g and $\Delta R_{[CO_2,LI]}$ and a constant $S_{[CO_2,LI]}$ of 0.82 and 0.88 K/(W/m^2), respectively. To estimate equilibrium warming caused by 2×CO_2 ($\Delta T_{2\times CO_2}$, the classical Charney equilibrium climate sensitivity (ECS) [*Charney et al.*, 1979; *Knutti et al.*, 2017]) from our $S_{[CO_2,LI]}$ we need to correct for missing slow processes (radiative forcing of CH_4 and N_2O; albedo changes caused by vegetation and aerosols). In a previous study [*PALAEOSENS-Project Members*, 2012] the ratio between $S_{[GHG,LI,VG,AE]}/S_{[CO_2,LI]}$ for the last 800 kyr has been determined as 0.64 ± 0.07 (1σ). Note, that this correction for the slow processes ignores any state-dependency that might be associated with them. Together with the average radiative

forcing for a doubling of CO_2 of 3.71 W/m^2 ($\pm$10% (1σ)) [*Myhre et al.*, 1998] our $S_{[CO_2,LI]}$ for late Pleistocene interglacials translates into a $\Delta T_{2\times CO_2}$ or ECS of 1.9 ± 0.3 K (Snyder), 2.1 ± 0.3 K (F2016) and 3.8 ± 0.6 K (K2015). Alternative calculations, based on the data split by obliquity (Fig. S5), would lead to slightly larger numbers of ECS (2.3 ± 0.3 K (Snyder), 2.3 ± 0.3 K (F2016) and 4.4 ± 0.7 K (K2015)), however we consider these to be less reliable following our analysis in the previous subsection. This compares well with other approaches [*Knutti et al.*, 2017], including the narrow "likely" (66% confidence interval) range of 2.2–3.4 K recently obtained from an emerging contraint from global temperature variability and CMIP5 [*Cox et al.*, 2018], and the 95% confidence range of 2.0-4.3 K from a large model ensemble, which has been constrained by observational and geological evidences [*Goodwin et al.*, 2018].

4. Conclusions

In conclusion, we find an inconsistency in the state-dependency of paleoclimate sensitivity calculated from model simulations and proxy-reconstructions, when explicitly considering radiative forcing of CO_2 change and land ice albedo change, or $S_{[CO_2,LI]}$. This may be related to the fact that fast climate feedbacks in EMICs are too linear. Furthermore, EMICs may underestimate the strength of some slow climate feedbacks. As it has been shown that solid Earth-climate feedbacks can play an important role for CO_2 dynamics during glacial cycles [e.g. *Huybers and Langmuir*, 2009; *Lund and Asimow*, 2011; *Hasenclever et al.*, 2017], these feedbacks should be incorporated in models used to simulate CO_2 concentration [e.g. *Ganopolski and Brovkin*, 2017]. Furthermore, one also needs to fully understand why current model simulations contain none of the temperature-CO_2

divergence observed during intervals of decreasing obliquity whithin proxy-based reconstructions. Our study suggests that one possible reason for this discrepancy is that the CLIMBER model underestimates the rate of land ice growth during periods of decreasing obliquity, and consequently simulates less cooling induced by land ice. It should be emphasized that the magnitude of the expected CO_2 changes connected with these solid Earth feedbacks are small when compared with anthropogenic CO_2 changes. Therefore, these missing model feedbacks in CLIMBER do not affect its ability to simulate future temperature increase caused by a rise in CO_2. Our results have important consequences for future efforts to quantify paleoclimate sensitivity from proxy-based analyses. We suggest that studies should focus on intervals without decreasing obliquity or sea level, since the detected divergence of global temperature and CO_2 during these intervals could otherwise overprint the system response.

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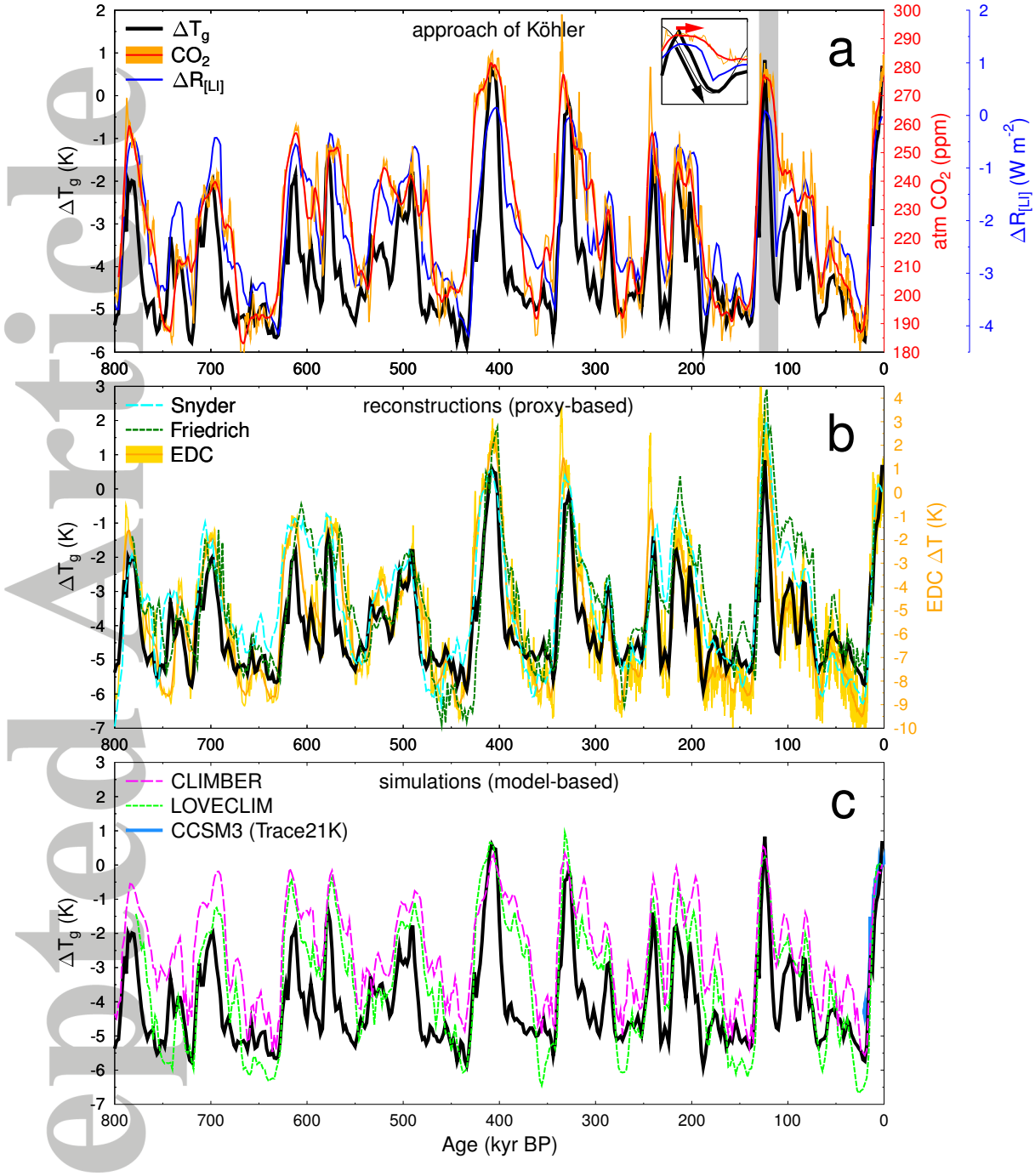

Figure 1. Paleodata of the last 800 kyr. (a) Data used in the approach of Köhler (K2015) with global mean temperature change ΔT_g, land ice-based radiative forcing change $\Delta R_{[LI]}$ and atmospheric CO_2 [*Bereiter et al.*, 2015]. Inset shows an enlarged view on the divergence of ΔT_g and CO_2 at the end of the Eemian (130-110 kyr BP, gray band), including as thin black line changes in obliquity [*Laskar et al.*, 2004]. Comparing different temperature time series with K2015-ΔT_g (black bold line); (b) proxy-based reconstructions of ΔT_g (Synder, Friedrich (F2016)) and EPICA Dome C (EDC) ΔT; (c) model-based simulations (CLIMBER, LOVECLIM) including CCSM3 for the last 21 kyr. Ice core data (EDC ΔT, CO_2) are plotted on the most recent age model AICC2012 [*Bazin et al.*, 2013; *Veres et al.*, 2013] and shown as original high resolution data (thin) and 8-kyr running means (bold).

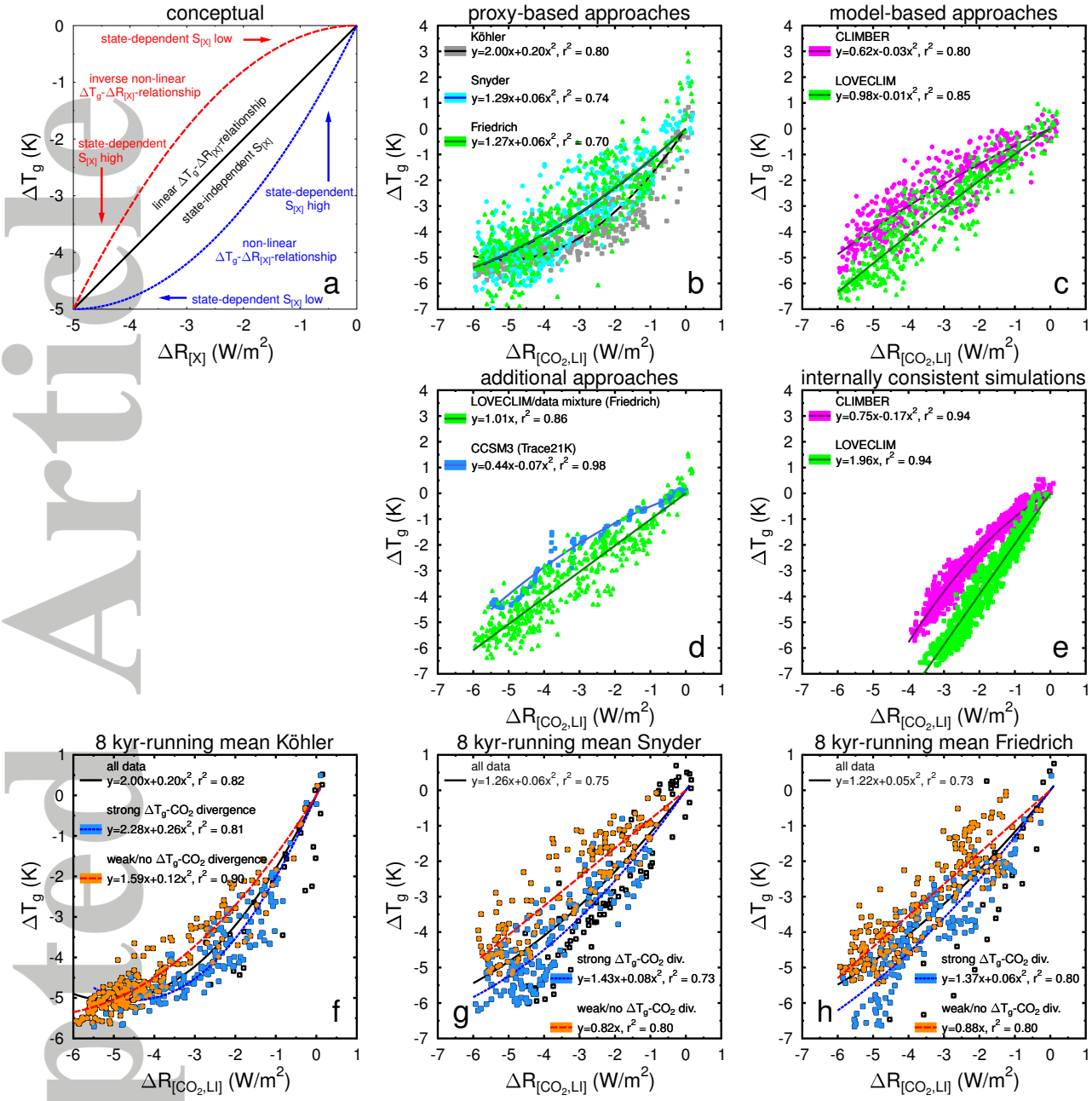

Figure 2. Scatter-plots of temperature change ΔT_g over radiative forcing change $\Delta R_{[X]}$. (a) Conceptual understanding of different relationships between ΔT_g and $\Delta R_{[X]}$ and the resulting state-(in)dependency of $S_{[X]}$. (b) data-based reconstructions of ΔT_g (Köhler, Snyder, Friedrich); (c) model simulation results of ΔT_g (CLIMBER, LOVECLIM); (d) alternative approaches (Friedrich's model/data mixture for ΔT_g, 21 kyr transient simulations with CCSM); (e) internally consist model-setups of CLIMBER and LOVECLIM; (f–h) multi-millennial component (8-kyr running mean) of the proxy-based approaches (f: Köhler; g: Snyder; h: Friedrich) split in time windows with strong or weak divergence of ΔT_g and CO_2. Data are split by the zero line in the standardized ratio $\Delta T_g/\Delta R_{[CO_2]}$ shown in Fig. 3b. White squares are data points which are filtered out in the standardizing of the data, and therefore neiter considered in strong or weak divergence part, but which contribute to the fit through all data. In most plots the same $\Delta R_{[CO_2.LI]}$ from K2015 is plotted, while in (d) CCSM3 is based on $\Delta R_{[LI]}$ from ICE-5G; in (e) we show $\Delta R_{[CO_2.LI]}$ as used in CLIMBER and LOVECLIM.

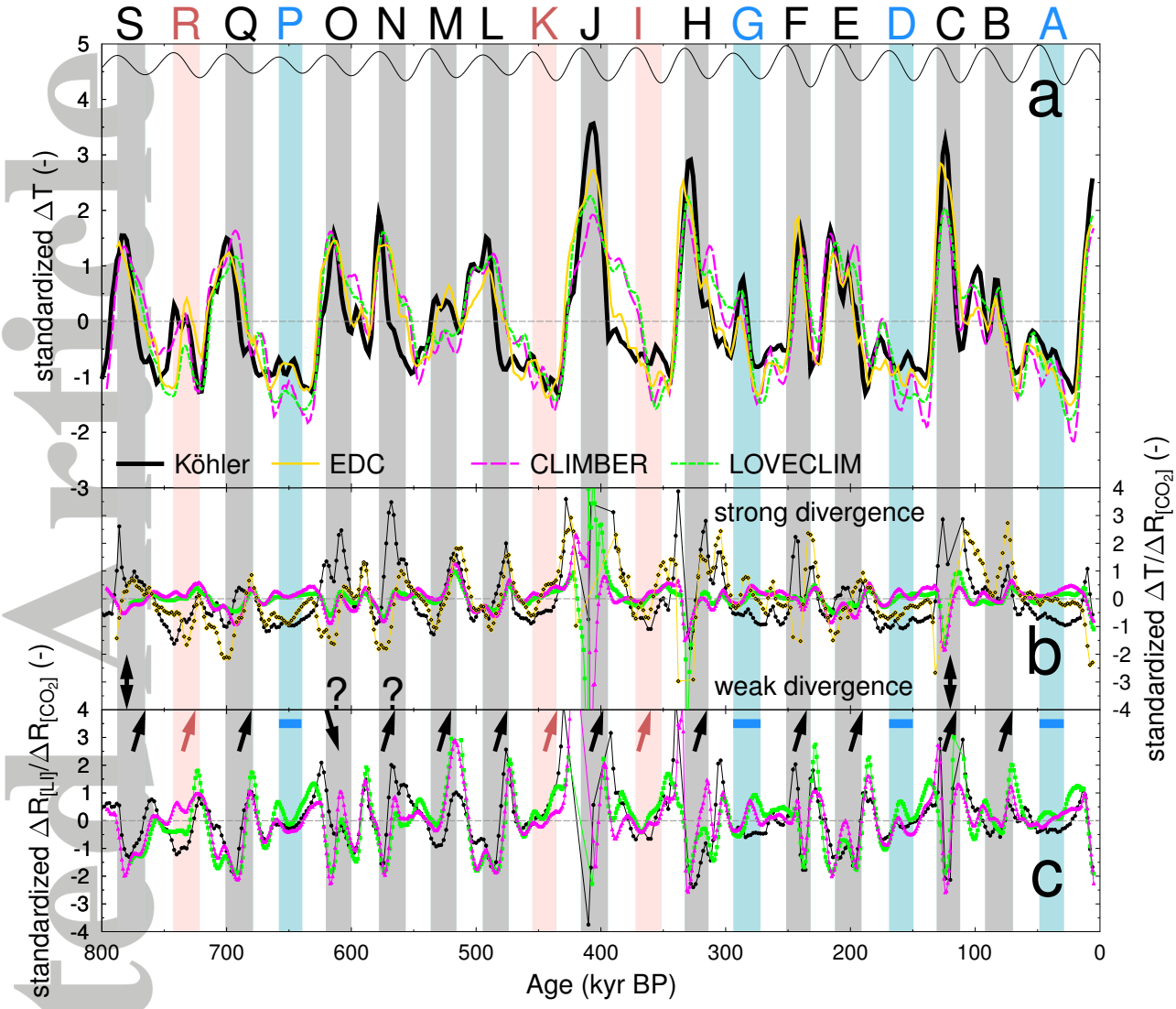

Figure 3. Multi-millennial (all data as 8-kyr running mean) ΔT-CO_2 divergence and relative contributions of radiative forcing of land ice albedo and CO_2 for ΔT in different setups. (a) ΔT (local ΔT for EDC and ΔT_g elsewhere); (b) the divergence of ΔT and CO_2 described by $\Delta T/\Delta R_{[CO_2]}$; (c) $\Delta R_{[LI]}/\Delta R_{[CO_2]}$: relative land ice (sea level) contribution with respect to CO_2. The data sets Köhler and EDC differ only by their ΔT. From the model simulations (CLIMBER, LOVECLIM) we analyzed the internally used radiative forcing. All data sets have been standardized and outliers in the ratios have been filtered out. Obliquity [*Laskar et al.*, 2004] is sketched on top of sub-panel a (thin black line), with shadings and labels (A–S) indicating times of decreasing obliquity. Color-code is given by the details of the Köhler data-set: gray: strong $\Delta T_g - CO_2$ divergence including large variations in relative sea level contribution; light red: no or weak $\Delta T_g - CO_2$ divergence and large variations in relative sea level contribution; light blue: no or weak $\Delta T_g - CO_2$ divergence and stable relative sea level contribution. Vertical two-headed arrows in the $\Delta T_g - CO_2$ divergence panel indicate the anti-phase dynamics partially seen between Köhler and the CLIMBER/LOVECLIM data sets. Question marks in (b) highlight two phases (MIS 15a, MIS15e) during which Köhler and EDC largely disagree.