Author response to interactive comment on
"Role of CO_2 and Southern Ocean winds in glacial abrupt climate change"
by R. Banderas, J. Álvarez-Solas and M. Montoya

Anonymous Referee #1

The authors thank the referee for the time devoted to review the manuscript and for his/her useful and constructive comments. All the points cited by the referee were carefully considered and the article has substantially benefited from the changes proposed. Each point arisen by the referee has been highlighted in blue and precedes the corresponding response of the authors. Changes in the manuscript have been highlighted here in italics below each point.

This paper describes a modelling experiment with CLIMBER-3α, a model of intermediate complexity in order to investigate processes, which might be responsible for an abrupt stadial/interstadial transition during so-called Dansgaard/Oeschger (D/O) events during glacial times. The model strategy is based on hypotheses (e.g. wind stress in Southern Ocean causes AMOC resumption) published elsewhere, thus this paper focuses if one or two of such hypothesis, in detail CO2 increase and/or wind stress increase in the Southern Ocean, might indeed be responsible for a stadial/interstadial transition and connected with that a bipolar temperature pattern, typically found in reconstructions.

1. One major issue, however, is the question if the chosen model really shows a bipolar temperature pattern during stadial/interstadial transitions. So far Fig 1c shown surface air temperature (SAT) in the Nordic sea (an abrupt resumption). This needs to be extended by southern hemispheric SAT simulations. Ideally, both Antarctic SAT (showing rather gradual changes, slow warming during stadial northern phase and then a switch to gradual cooling synchronous to the temperature switch in the north as seen in ice cores) and South Atlantic SAT or SST or shown. The second should according to the theory of the bipolar seesaw show similar abrupt changes as in the North, but of opposite sign as documented in proxy records (Barker et al., 2009).

   The Antarctic SAT evolution has been included in Fig. 1e. The simulated Antarctic SAT indeed resembles the bipolar seesaw behaviour within the CO_2-only and CO_2-plus-wind forcing experiments. However, this result should be taken with caution since the gradual Antarctic warming is essentially caused by the radiative effect exerted by increasing atmospheric CO_2 levels and not by the effect of a previous weakening of the AMOC. Nevertheless, the final state is characterised by high AMOC and northern SATs and cold southern SATs in response to the AMOC reactivation and the subsequent redistribution of heat. These results suggest that our model is properly reproducing the bipolar seesaw. Simulating several D/O cycles would help to confirm this. Although undoubtedly interesting, this is beyond the scope of this study. A new panel showing Antarctic SATs has been added in Figure 1 and the former discussion has been taken into account in section 3 (*Stadial to interstadial transition*):

   > *Note the SAT evolution over Antarctica exhibits a behaviour which resembles the bipolar seesaw (Fig. 1e). The simulated gradual warming over Antarctica precedes the abrupt temperature increase in the North Atlantic. Nordic and Antarctic SATs reach peak warming roughly at the same time. The system subsequently switches into the interstadial state in centennial timescales at the expense of a more gradual cooling of the Southern Ocean. Note that the initial warming in Antarctica here is exclusively caused by the increase in atmospheric CO_2 rather than by a previous AMOC weakening. Yet, the final state is characterised by high AMOC and northern SAT values, and cold southern SATs, as expected according to the bipolar seesaw. In the latter case the Antarctic cooling is indeed the response to the redistribution of heat by the reactivation of the AMOC.*

   Concerning the wind-only forcing scenario, the bipolar seesaw effect is less evident in the transition state than in the other two simulations. However, again, the final state clearly evidences the Antarctic cooling associated with the strong AMOC and high northern temperatures. This has been taken into account in section 3 (*Stadial to interstadial transition*):

   > *Note in this case, in the transient stage, the bipolar seesaw effect is less evident than in the CO_2-only forcing scenario. However, the final state clearly evidences the cold Antarctica state associated with the strong AMOC and high northern temperatures.*

   Concerning South Atlantic SSTs, our model qualitatively reproduces the results of Barker et al. (2009). South Atlantic SSTs show an opposite behaviour to their northern counterpart. Moreover, the abruptness of the Southern Ocean cooling is similar to that observed in the North Atlantic coinciding with the AMOC reactivation, and somewhat larger than in Antarctica. However, as mentioned before these results must be taken with caution and should be reassessed in the future. That is the reason why we finally decided not to include it in the manuscript (Fig. R1).

Finally, to investigate the two-dimensional spatial pattern of the bipolar seesaw we have analysed the anomalies of the final interstadial state (yr 2600, several centuries after the AMOC reactivation) with respect to the transition stage. In the final state the strong AMOC leads to high temperatures in the North Atlantic and cooling in the Southern Ocean in all three simulations (Fig. R2).

Connected with that it is also necessary to discuss in more detail, that the "abrupt" SAT warming in the model in the North is still a lot slower than in the ice core records. Steffensen et al. (2008) showed that in Greenland some changes occurred within a few years, but the overall interpretation is that all chemical proxies change within 50 yr during the stadial/interstadial transition into the Bolling/Allerod, while the CLIMBER model here needs about 200 yrs.

We recognise that the timescale with which the model simulates the transition between the stadial and the interstadial state is not as fast as indicated by proxy records. In our three experiments an abrupt SAT increase in the North Atlantic of about 4 K in less than a decade takes place followed by a more gradual temperature increase greater than 10 K within 200 yrs. The first abrupt warming appears to be related to the onset of convection in the Nordic Seas. The subsequent more gradual warming is caused by the AMOC recovery and associated northward heat transport intensification. The existence of two phases of warming in the North Atlantic, with only the first one corresponding to an abrupt change but with a smaller magnitude than D/O events, is now explicitly stated in the manuscript. In addition, a brief discussion of model difficulties to reproduce abrupt climate changes has been included:

Abstract:

> *An initial abrupt surface air temperature (SAT) increase over the North Atlantic by 4 K in less than a decade, followed by a more gradual warming greater than 10 K on centennial timescales, is simulated in response to increasing atmospheric CO_2 levels and/or enhancing southern westerlies. The simulated peak warming shows a similar pattern and amplitude over Greenland as registered in ice-core records of Dansgaard-Oeschger (D/O) events.*

Section 3 (Stadial to interstadial transition):

> *Under CO_2-only forcing conditions, an abrupt surface air temperature (SAT) increase of up to 4 K in less than a decade occurs in the Nordic Seas once CO_2 reaches a level of ca. 215 ppmv (Fig. 1c).*

Section 3 (Stadial to interstadial transition):

> *Within the wind-only forcing scenario, an abrupt SAT increase by 4 K in less than a decade is also found in the North Atlantic about 1650 years after switching on the forcing.*

Conclusions:

> *We have investigated the climatic response to increasing atmospheric CO_2 levels and Southern Ocean winds when the glacial climate state is close to a threshold. Both are found to lead to an initial abrupt SAT increase on decadal timescales over the Nordic Seas followed by further warming on centennial timescales, resembling the large and rapid warmings associated with D/O events occurred during the last glacial period. The initial simulated abrupt warming is caused by reduced seasonal sea-ice southward export in the North Atlantic within all forcing scenarios.*
>
> *Although the abrupt warming simulated in the North Atlantic resembles those reported for D/O events, the comparison against the paleorecord is not fully satisfactory. The simulated rapid warming in the Nordic Seas in our case takes place in two steps: a sudden increase by 4 K in less than a decade, followed by more gradual warming greater than 10 K on centennial timescales, rather the warming by more than 10 K in only a few years found in proxy records (Steffensen et al., 2008). The difficulty to simulate climate changes as abrupt as those registered in the paleorecord is a common feature to many models, and the possible reasons are yet unclear. Recent studies point out the necessity to improve the ability of state-of-the-art models to simulate abrupt climate changes within the context of threshold values. This highlights the necessity to explore new research lines of past forcing factors which may help to understand the ensuing climate response (Valdes, 2011; Stocker and Marchal, 2000).*

2. Throughout the text it needs to be clear, what changes in the westerlies are proposed and investigated. Your experiment is a change in the WIND STRESS, but it is also mentioned that the westerlies might move north or south. In the final discussion (page 3498-33499) you also give as chain of argument: Southern westerlies move north, thus less upwelling, thus less CO_2, in order to connect how CO_2 and wind might be connected. Please be aware, that this westerly wind hypothesis brought up by Toggweiler et al. (2006) (also for explaining glacial/interglacial CO2) was so far NOT reproduced by model, both Menviel et al. (2008) and Tschumi et al. (2008) do NOT find the proposed effect of westerly winds on CO2. This might need some discussion. I understand that Lee et al. (2011), cited in the paper, finds some CO_2 changes caused by Southern westerlies change, so this discrepancy might need to get some discussion.

   Here, changes in the westerlies are computed by linearly increasing the zonal ocean wind-stress over the latitudinal band of Drake Passage (actually, south of 30°S). The position of the westerlies is indeed not modified in our experiments. This was already explained in the experimental setup. We recognise the two different issues of strengthening and shifting of westerlies were not clearly distinguished in the Conclusions and we have attempted to clarify this:

   > *Reconstructions suggest that during deglaciation, as well as throughout the last glacial period, CO_2 rises were primarily caused by the increase in deep upwelling in the Southern Ocean (Anderson et al., 2009). Models furthermore indicate that wind and CO_2 increases could themselves be the response to a previous North Atlantic cooling leading to a southward shift of the ITCZ and/or strengthening of the westerlies over the Southern Ocean (Chiang and Bitz, 2005; Lee et al., 2011; Timmermann et al., 2007). The oceanic explanation is that during stadial conditions, northward oceanic heat transport is strongly diminished in response to a weak overturning. As a consequence, the Southern Hemisphere warms at expense of the Northern Hemisphere through the bipolar seesaw effect. The temperature asymmetry is thereby reduced and the ITCZ and the westerlies shift to the south and/or possibly strengthen. In this situation Southern Ocean westerlies are better aligned with the Antarctic Circumpolar Current (ACC). Within these conditions, atmospheric CO_2 levels increase in response to an oceanic upwelling intensification (Denton et al., 2010; Toggweiler and Lea, 2010). Alternatively, atmospheric models also indicate cooling in the North Atlantic (as would follow from a decrease in NADW formation and AMOC strength) leads to a southward shift of the ITCZ and Southern Ocean winds intensification, with a marginal southward shift, via atmospheric teleconnections [...]*
   >
   > *According to our results, higher atmospheric CO_2 concentration and enhanced westerlies act to promote NADW formation over the Nordic Seas region through vital sea-ice variations which eventually enhance the meridional density gradient. Thus, the AMOC is intensified and thereby its associated northward oceanic heat transport. At this point, in the light of the above studies, the ITCZ would shift northward again and Southern westerlies progressively weaken, decreasing upwelling and atmospheric CO_2.*

   Regarding the results of Menviel et al. (2008) and Tschumi et al. (2008) we find no substantial disagreement with the work of Lee et al. (2011). As discussed below, one reason for the different pCO_2 amplitude relative to the former was the incorporation of the "downstream effect", where marine biology was able to respond to changes in nutrient redistribution that accompanies changes to the westerlies. This issue is discussed now in the Conclusions to avoid confusion:

   > *Alternatively, atmospheric models also indicate cooling in the North Atlantic (as would follow from a decrease in NADW formation and AMOC strength) leads to a southward shift of the ITCZ and Southern Ocean winds intensification, with a marginal southward shift, via atmospheric teleconnections leading to a rise in atmospheric CO_2 by 20-60 ppmv, consistent with proxy records (Lee et al., 2011). The upper limit is obtained when taking into account exclusively the physical process of increased outgassing of CO_2 due to enhanced upwelling; the lower limit includes as well the biological response to the increased upwelling. This results in an increase in surface nutrients which fuels biological productivity, thereby damping the atmospheric CO_2 rise and accounting for the smaller increase found previously by Menviel et al. (2008) and Tschumi et al. (2008).*

3. Also throughout the text: When you argue about changes in the Arctic sea ice front, please make always clear if this is about its position in annual mean, or only summer or only winter. My understanding of the text so far was, that summer position of the sea ice front might be relevant, but maybe not.

   The referee is right. The northward shift in the Arctic sea-ice position takes place during the summer transition stage. This point has been clarified in section 3 (*Stadial to interstadial transition*):

Although rising temperatures due to increased CO_2 levels result in local widespread freshening, a northward shift of the northern summer polar front takes place north of the Fennoscandian coast (Fig. 5a).

[...]

To summarise, increased CO_2 levels translate into a modest radiative forcing of about 0.35 W m^{-2} which leads to warming in the Nordic Seas by about 1 K (Fig. 1c) and, thereby, impacts the sea-ice distribution in this region, especially its southernmost margins, by leading to a northward retreat of the summer polar front.

[...]

Within the wind-only forcing scenario, an abrupt SAT increase by 4 K in less than a decade is also found in the North Atlantic about 1650 years after switching on the forcing [...] As a result, North Atlantic waters become warmer in response to a slightly more vigorous AMOC. Increased North Atlantic SATs related to enhanced northward heat transport driven by the AMOC result in melting of the Nordic sea-ice cover. The summer sea-ice polar front retreats to the north, which translates into reduced freshwater fluxes and thereby increased surface salinity in critical convective areas in the North Atlantic.

4. abstract line 5: "implications of NADW" on what?

   Here we meant the implication of North Atlantic deep water (NADW) formation reorganisations in glacial abrupt climate change. This sentence has been rephrased in the abstract:

   Although the implication of North Atlantic deep water (NADW) formation reorganisations in glacial abrupt climate change seems robust nowadays, the final cause of these reorganisations remains unclear.

5. page 3490, line 25: Greenland warming during D/O events: Dansgaard et al. (1993) shows only the water isotopes, but I think does not calculate how much warming that might be, maybe consider Lang et al. (1999) for warming.

   We agree on this point and have included a reference to Lang et al. (1999) in the Introduction:

   These are considered to be the most abrupt, i.e., large and rapid, climate changes of the past 110 kyr, repeatedly manifested as warming in Greenland by more than 10 K on decadal timescales (e.g., Lang et al., 1999) with widespread global climatic effects (Voelker and Workshop Participants, 2002).

6. Introduction: I think this should be expanded on more details of the bipolar seesaw, e.g. more gradual temperature changes in Antarctica, but similar rapid but opposite changes in the South Atlantic. Also, the similarity or differences to Lee et al. (2011), cited p 3491, last lines needs to be clarified even further. Taken all together, my understanding is, that a) North Atlantic cooling might change Southern westerlies (after Lee et al. (2011)), leading to b) a resumption of NADW (after this study), and in consequences c) a rapid warming in the North (this study as well). If that might be amplified by CO_2 might be a matter of debate (cycle climate models give different answers, Lee et al. (2011) finds a CO_2 response, Menviel et al. (2008) and Tschumi et al. (2008) did not, although the focus of the later two was on glacial/interglacial timescales). So, does this mean, the initial driver might be in the North Atlantic and everything else is a feedback loop reversing the initial temperature anomaly in the North? What would then be a cause for the cooling in the North?

   We have followed the referee's suggestion and described in more detail the basic aspects of the bipolar seesaw effect in the Introduction:

   This is supported by the close agreement between results of climate simulations involving variations in NADW formation and the Atlantic meridional overturning circulation (AMOC), and the evidence from paleoclimate reconstructions. Models are in this way able to reproduce the so-called bipolar seesaw behaviour between Greenland and Antarctica (Blunier and Brook, 2001; EPICA-Project, 2006). The idea is that an intensification of the AMOC translates into an increase in northward heat transport at the expense of the southernmost latitudes; conversely, a weakening of the AMOC reduces northward heat transport, thereby warming the south (Crowley, 1992; Stocker, 1998). The different timescale between northern and southern latitudes can be explained by the fact that the Southern Ocean acts as a heat reservoir which dampens and integrates in time the more rapid North Atlantic signal (Stocker and Johnsen, 2003).

We have tried to distinguish between the oceanic mechanism invoking the bipolar seesaw and the atmospheric teleconnections described by Lee et al. (2011). This is taken into account in the Introduction:

> *Recent model studies suggest that a southward shift of the intertropical convergence zone (ITCZ) and Southern winds intensification can also take place via atmospheric teleconnections, that is, without involving the bipolar seesaw, in response to a cooling in the North Atlantic and leading to a rise in atmospheric CO_2 by 20-60 ppmv, consistent with proxy records (Lee et al., 2011).*

We note that the apparent discrepancy between Lee et al. (2011) and Menviel et al. (2008) and Tschumi et al. (2008) has already been addressed in the second point. Thus, we think the CO_2 increase in response to a northern cooling is a robust result.

The chain of argument given by the referee is indeed what we defend in the paper. This has now explicitly been mentioned in the Introduction and in the Conclusions:

Introduction:

> *These results indicate several mechanisms by which a decrease in the AMOC strength leading to northern cooling, would have translated into a southward shift and/or intensification of Southern Ocean westerlies, which through enhanced deep upwelling would have contributed to increase the atmospheric CO_2 concentration.*

Conclusions:

> *According to our results, higher atmospheric CO_2 concentration and enhanced westerlies act to promote NADW formation over the Nordic Seas region through vital sea-ice variations. Thus, the AMOC is intensified and thereby its associated northward oceanic heat transport. At this point, in the light of the above studies, the ITCZ would shift northward again and Southern westerlies progressively weaken, decreasing upwelling and atmospheric CO_2. This constitutes a negative feedback that favours the return into stadial conditions through an AMOC weakening, which would lead to enhanced westerlies and higher atmospheric CO_2 concentration.*

Regarding the question as to what constitutes the ultimate driver of stadial-interstadial transitions, our view is that these are part of an internal oscillation. In this context it is hard to elucidate where the starting point is and its initial causes. This suggestion was already done in the final paragraph of the Conclusions:

> *As a conclusion this suggests that D/O events could be part of an internal oscillation which involves changes in CO_2, surface winds and AMOC on millennial timescales.*

Finally, the cooling in the North would be ultimately driven by a previous AMOC slow down which could be triggered through variations in background climate conditions (e.g., Arzel and England, 2012). These interesting points will be thoroughly addressed in future studies.

7. Experimental setup: I am wondering what would happen, if you would follow in your simulations not only a stadial/interstadial transition, but also the reverse. My understanding of the bipolar seesaw is, that at the same time when the North sees the rapid temperature rise, Antarctica switches from gradual warming to gradual cooling. This would imply you change your forcing once you reach interstadial northern temperature. This might be an interesting final experiment. Will the model return (with which time delay?) to stadial conditions?

   We totally agree with the reviewer. Simulating the full cycle is actually planned to be our next target. To that end we could reverse the forcing starting from interstadial conditions. However, we think the present study should focus exclusively on the possibility of triggering abrupt climate change through the mechanism described. The full cycle should be the scope of future work.

8. Fig 3: Units are unclear to me. Fig 3b should be relative temperature anomalies in the range -1.3 to +1.3? Is SST in the stadial regime expressed in deg C or K, thus does +1.3 mean a rise in SST by 130 percent (then in deg C or K)??? Similar difficulties for the other subfigures of Fig 3.

   Figs. 3b and c show the temperature and salinity contributions to density changes based on the use of a linear equation of state for density. To make this more clear we have rephrased caption in Fig. 3:

Surface density anomalies at the transition stage relative to the stadial regime for the CO_2-only experiment and contribution to the latter by b) temperature and c) salinity in kg m^{-3} assuming a linear equation of state. The black box in panel a) indicates the region where the surface freshwater flux balance was calculated.

9. Fig 4a: For what experiment are the timeseries?

   Timeseries shown in Fig. 4 correspond to the CO_2-only experiment. We have corrected the caption in Fig. 4 to mention it explicitly:

   a) Surface anomalies with respect to the stadial state of density (black), together with salinity (red) and temperature (blue) contributions to density changes in kg m^{-3} over the Nordic Seas area (67.5N - 75N, 4W - 7.5E; black box in Figure 3a) assuming a linear equation of state for density for the CO_2-only experiment; b) density evolution in kg m^{-3} over the same region at the surface (0-87.5 m; black line) and depth (2800 m; red line). The red shaded bar indicates the transition stage for the CO_2-only experiment.

10. Fig 6b: What about northward heat transport in the CO2+wind experiment?

    We have modified Fig. 6 to include the northward heat transport in the CO_2-plus-wind experiment at the transition stage. The northward heat transport in this case is larger than for the CO_2-only experiment but lower than for the wind-only simulation because of lower wind-stress factor for which the transition to the interstadial state is achieved.

Finally, we would like to mention that we have received a comment by Dr. Gregor Knorr suggesting some clarifications. Knorr and Lohmann (2007) does not restrict slowly varying background climate changes to the Southern Ocean. In the deglacial scenarios of Knorr and Lohmann (2007) they applied gradual background climate changes from glacial to interglacial conditions at a global scale, e.g. including global temperature changes (therein CO_2) and wind stress changes. The Introduction has been modified to properly take into account this previous study.

Enhanced surface freshwater fluxes (Weaver et al., 2003) and slowly varying background climate conditions in the Southern Ocean (Knorr and Lohmann, 2003) have been shown to be able to trigger an AMOC intensification leading to an abrupt warming in the North Atlantic. The same result was found when applying gradual background climate changes from glacial to interglacial climate conditions on a global scale, including temperature and wind-stress (Knorr and Lohmann, 2007). [...] *Taken together, these results led Knorr and Lohmann (2007) to suggest CO_2 increases could have contributed to rapid AMOC intensification after Heinrich events, corresponding with the largest DO events.*

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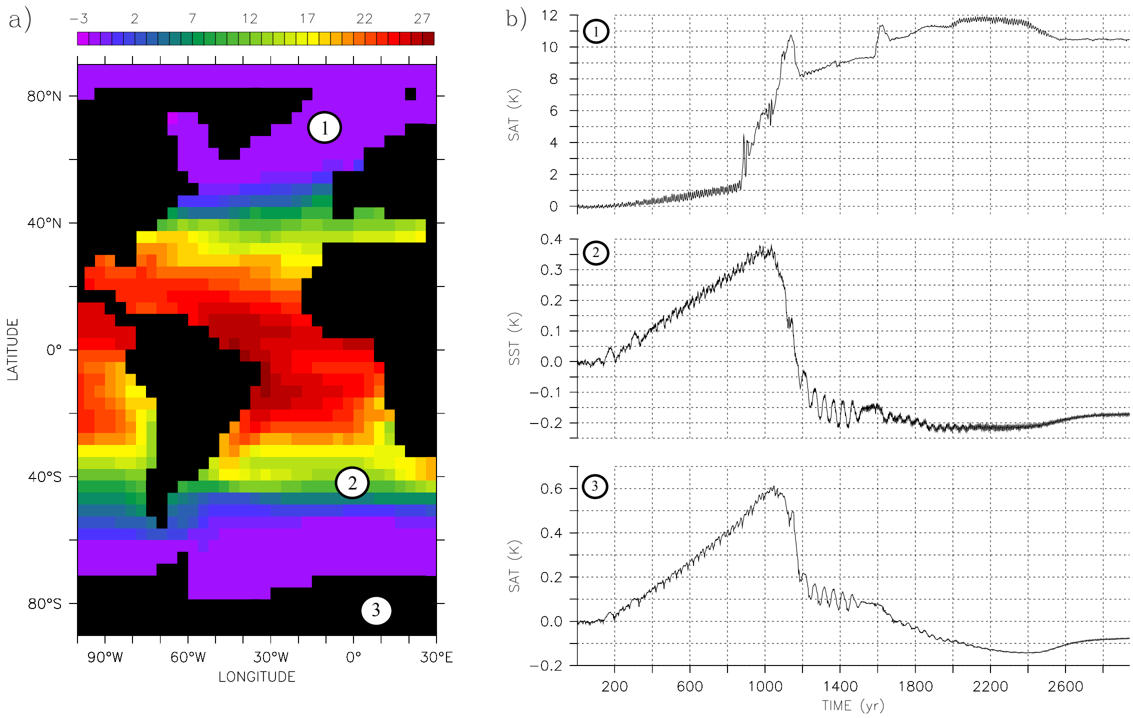

Fig. R. 1: a) Map showing stadial SSTs and the locations where SAT and SST anomalies shown in panel b were calculated; b) anomalies with respect to the stadial state of North Atlantic SAT (67.5°N 11°W, in the Nordic Seas, site 1), south Atlantic SST (41°S 4°W, site 2) and Antarctic SAT (86.2°S 11°E, site 3) in K, for the CO_2-only experiment. This figure illustrates the somewhat more abrupt evolution of South Atlantic SSTs compared to Antarctic SATs.

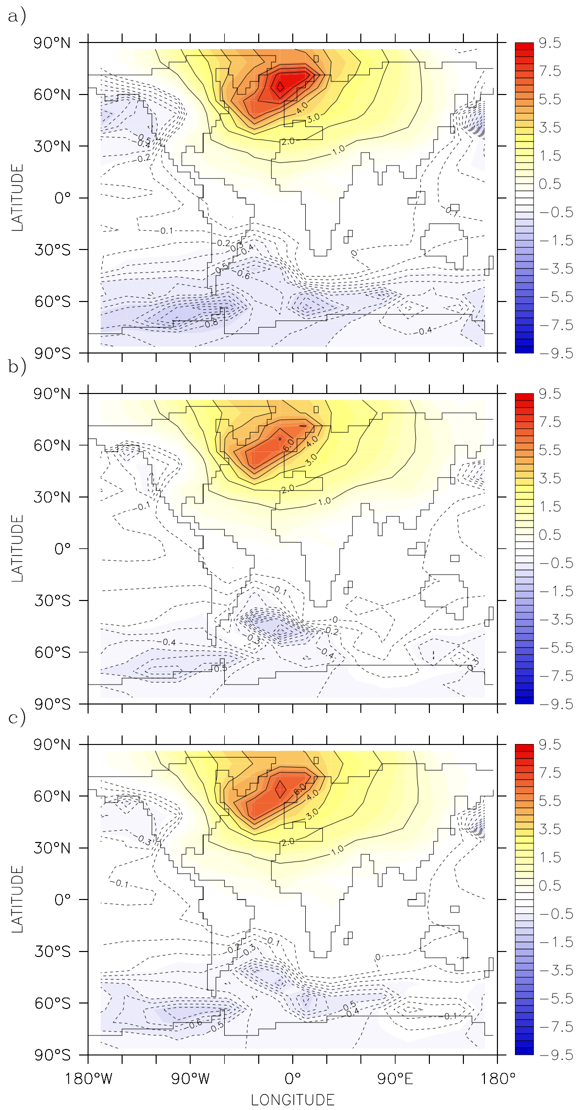

Fig. R. 2: SAT anomalies between the final interstadial and the transition state in K for: a) the CO_2-only experiment; b) the wind-only simulation and c) the CO_2-plus-wind scenario. This figure illustrates the bipolar seesaw in all the experiments with warming in the North Atlantic and cooling in southern latitudes.

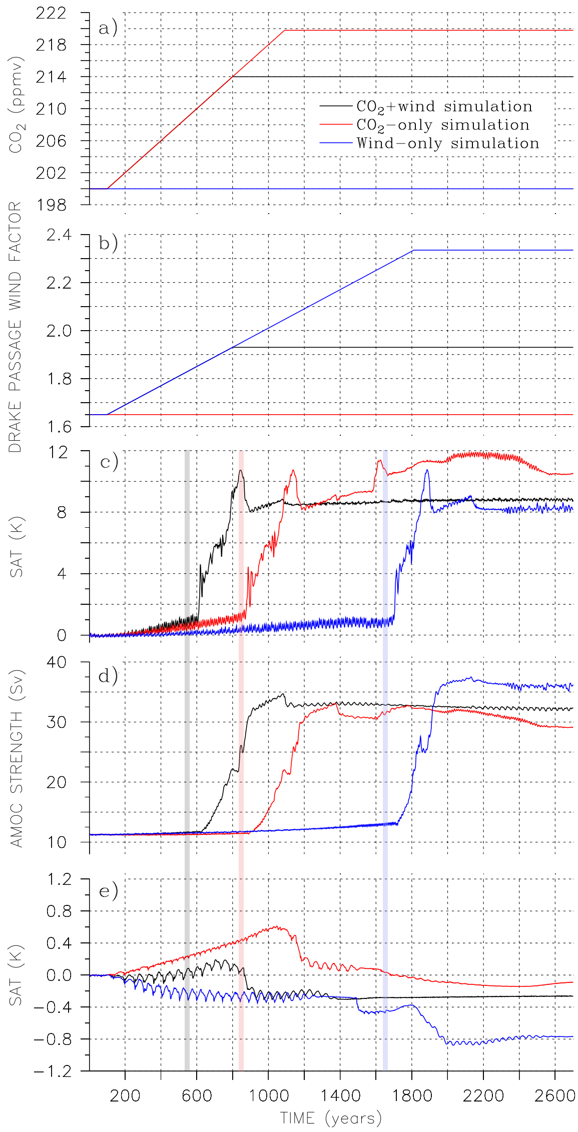

Fig. 1: Timeseries of forcings and relevant climatic variables: a) CO_2 forcing in ppmv; b) wind amplification factor over the Drake Passage (no units); c) anomalies of North Atlantic SAT (67.5°N 11°W, in the Nordic Seas) with respect to the stadial state in K; d) AMOC strength in Sv; e) anomalies of Antarctic SAT (86.2°S 11°E) with respect to the stadial state in K. Black, red and blue lines show the simulation combining CO_2 and wind forcings, the CO_2-only experiment, and the wind-only forced run, respectively. Black, red and blue shaded bars indicate the transition stages for the simulation combining CO_2 and wind forcings, the CO_2-only experiment and the wind-only forced run, respectively.

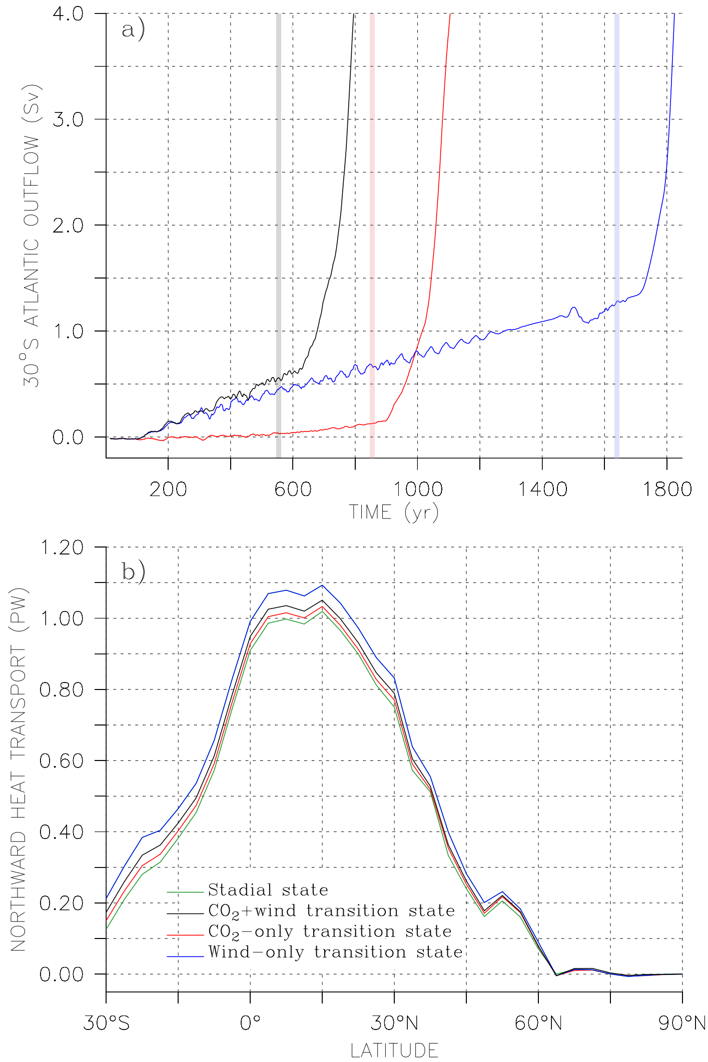

Fig. 6: a) Evolution of AMOC outflow at 30°S in Sv for the CO_2-plus-wind simulation (black), CO_2-only (red) and wind-only (blue) forced experiments; b) northward oceanic heat transport (0 -1000 m depth) in PW for the stadial state (green) and transition stages for the CO_2-plus-wind (black), CO_2-only (red) and wind-only (blue) forced experiments. Black, red and blue shaded bars indicate the transition stage for the simulation combining CO_2 and wind forcings, the CO_2-only run and the wind-only experiment, respectively.