

The authors thank Anonymous Referee #1 for his/her considered comments.

Reviewer's comments are provided in italics.

*Lack of explanations : The authors provide an explanation for the suppressed variability of the western side of the jet stream (though I personally think that one key aspect is missing - see comment below). However, the more complicated part of the story, explaining the jet characteristics over the eastern ocean basin, is not discussed at the same level of detail. I think this is a shame and I encourage the authors to do more analysis to improve that part of the story.*

We agree with this reviewer that it is important to disentangle the various possible contributors to deglacial jet changes on the eastern side of the North Atlantic (NAtl). However, this can't be done to the same level as the western jet with the existing set of ensemble runs. The potential contributors that we have considered to the eastern jet changes include:

- Stationary and transient eddy responses to ice sheet topography changes,
- Thermal effects on latitudinal surface temperature gradients in the North Atlantic (and possibly sea ice) due to ice sheet area and height (over North America and Fennoscandia), greenhouse gas concentrations and orbital forcing,
- Indirect effects associated with the pinning of the western side of the jet to a particular latitude, and
- Indirect effects associated with ocean circulation responses to the boundary condition changes.

We will add to the revised text the following conclusions that we can draw based on our existing runs.

1. The presence of elevated and extensive ice sheets provides the dominant controls on the jet characteristics on both sides of the NAtl jet. When the ice sheets are fixed to their LGM configurations in FixedGlac, little change is seen in the position or distribution of the jet on both its western and eastern sides. One notable exception to this is after 4ka BP, when the eastern side of the jet shows a reduced frequency at its preferred latitude and an expansion of its range. This timing is coincident with abrupt warming events in the FixedGlac experiments that are accompanied with abrupt retreats in Northern Hemisphere sea ice extent and warmings of NAtl sea surface temperatures.
2. The eastern side of the NAtl jet is more sensitive to the background climate state than the western side of the jet is. This is evident when examining the differences between the FullyTrans and FixedOrbGHG experiments. By present day, the western side of the jet is mostly unaffected by the orbital and GHG components being fixed to LGM values. In contrast, the eastern side of the jet is centred approximately 5° further south when orbital and greenhouse gas components are fixed to LGM.
3. The position of the western side of the jet has limited control on the position of the eastern side of the jet. This conclusion is arrived at by examining the PDTopo experiment, where the position of the western side of the jet is approximately 8° further north than in the FullyTrans experiments before 20ka BP. In these same experiments at that time, the preferred eastern position of the NAtl jet is shifted approximately 3° further north.
4. The ocean state has an effect on the position of the jet on the eastern side of the NAtl. The differences in the eastern position of the jet between FullyTrans and PDTopo from 4ka BP onward indicate that although their forcings are the same or very similar, the history of the simulation affects the position of the jet on the eastern side of the NAtl. Such a difference is not apparent on the western side of the jet.

What is not clear from the simulations presented here is the role of Eurasian ice topography and extent

(ie versus that of the NAIS) and the relative role of background temperature versus temperature gradients. Given the length and content of the current paper, these last questions will be answered in a future study.

*Lack of dedicated discussion section:* The authors have decided to jump straight from the results section to the conclusions without having a proper discussion section where your findings are put in perspective with the existing literature. This makes it hard to get a sense for how your results differ from earlier studies and how they contribute to our understanding of the atmospheric circulation during the deglaciation. The discussion section is in my mind the most important part of a paper, so its omission feels instinctively wrong and may give this paper less traction than it deserves.

We have changed the Results and Discussion section to Results and changed Conclusions to Discussion and Conclusions. In the Discussion and Conclusions, we have provided much more context for our results in light of existing literature and discussed its implications.

For example, “All of the fully-transient deglacial simulations presented here show that the NATl eddy-driven jet shifted northward from the Last Glacial Maximum to the preindustrial period, and its latitudinal variability increased. These characteristics match those derived from other studies (Li and Battisti, 2008; Lofverstrom et al., 2014; Merz et al., 2015). However, unlike those studies, neither the PlaSim simulations nor TraCE-21 show much change in jet tilt between these two periods.”

“The novelty of this present study compared to those previously mentioned is that it analyses transient changes in the jet over the entire deglaciation in multiple experiments. Additionally, instead of characterizing the jet via the Gaussian statistics of its mean and standard deviation, we present the changes with time of the jet distribution itself.”

*Page 1, line 5: Remove "we performed" and specify that PlaSim is an intermediate complexity model.* We have made the description more precise. Revised text is “This study characterises deglacial winter wind changes over the North Atlantic (NATl) in a suite of transient deglacial simulations using PlaSim, an intermediate-resolution earth system model with simplified physical parametrizations, and the TraCE-21ka simulation.”

*Page 2, line 17: Missing space between sentences*

There is a space in the latex source file. It is not being rendered in this case, due to the number of characters on the line.

*Page 3, line 12: "Low levels of the atmosphere" is ambiguous. Perhaps better to say "lower troposphere".*

Done. Revised text is “Of the two dominant features of mid-latitude atmospheric circulation patterns in the NATl, the subtropical and eddy-driven jets, the eddy-driven jet has the largest presence in the lower troposphere.”

*Page 3, line 13: Missing word. The extratropical jet stream is due to "momentum-flux convergence" by synoptic eddies.*

Done. Revised text is “The eddy-driven jet (or polar front jet or jet stream) is a narrow band of fast, westerly winds that arises from the momentum-flux convergence of atmospheric synoptic-scale eddies (e.g. extratropical cyclones with lifespans of days) (Lee and Kim, 2003; Barnes and Hartmann, 2011).”

*Page 4, line 11: Lofverstrom et al. (2016) showed that stationary waves can influence the jet*

*characteristics in the eastern North Atlantic at the LGM as well.*

Revised text is “However, the influences on the western and eastern sides of the NATl have been found to differ in atmospheric simulations: the position of the western side of the jet is more affected by ice sheet orography, and the position of the eastern side of the jet is primarily influenced by stationary and/or transient eddies (Kageyama and Valdes, 2000; Lofvestrom et al., 2016).”

*Page 4, line 23: Sentence starting with "These changes.." is incorrect. To the best of my knowledge, none of the papers cited here suggest that the subtropical and midlatitude jets entered a merged state over the N Atlantic at the LGM; see, e.g., Fig. 1 in Li and Battisti (2008) where there is a clear separation between the subtropical and eddy driven jets. Page 4, lines 26-28: None of the papers cited here investigated that explicitly.*

We see that the citation here was misleading in that it appears to attribute the identification of merged jets to those papers, rather than just the data from which we concluded the change in distribution of heat and moisture transports. We will remove the citation altogether and make it clear that these are the authors' inferences based on those papers.

Nevertheless, we would argue that the separation between the jets at LGM is not as clear in all cases as the reviewer suggests. For example, in Figure 3 of Li and Battisti (2008), there is little difference in the Atlantic zonal wind profiles of the latitude of the peak winds at 200 hPa and at the surface differing at LGM (indication of the positions of subtropical and eddy-driven jets in Eichelberger and Hartmann (2007)). In Figure 2 of Lofverstrom et al (2014), the 800hPa winds across the North Atlantic during LGM are highly zonal, and there is little evidence of any separation between the subtropical and eddy-driven jets. Finally, in Figure 4 of Merz et al (2015), there appears to be a clearer separation between the subtropical and eddy-driven jets at LGM than during Present Day, or a less merged jet state, much as in our study. Delineating whether a jet is merged or not is problematic, since it is based on the separation of the distributions of the subtropical and eddy-driven jets. How much separation can there be and still be considered merged? The only definition for a merged jet that I have encountered is in Harnick et al (2014), who define the Zonal Jet Index as the anomaly with respect to monthly or seasonal climatology of the maximum value of the zonal derivative of the latitude with peak zonal winds. They define a threshold for the jet to be merged as being a negative value in this derivative with time that exceeds one standard deviation.

Revised text is “These changes are consistent with what would be expected if the North Atlantic jet approached a more “merged” state at LGM, although not all of these studies show evidence of this. Irregardless, changes to the path of the jet are expected to result in changes to the distributions of heat and precipitation over Western Europe during this period.”

*Page 4, line 26: Missing space between sentences.*

Done. This was an artifact of LaTeX's paragraph formatting.

*Page 4, line 32: "The timing.." meaning here is not clear.*

We state in the previous sentence that the jet transition detected by Lofverstrom and Lora (2017) occurred at the separation of the Cordilleran and Laurentide ice sheets at 13.89ka BP. A transition at 13.89 ka BP would be unlikely to explain either the abrupt warming into the B-A (occurring nearly a millennium earlier), nor the abrupt cooling at the start of the YD (occurring a millennium later).

Revised text is “A jet shift at 13.89ka BP lies during the middle of the B-A,...”

*Page 5, line 5 and section 2.1: Perhaps nit-pick but this not technically correct. PUMA (the dynamical*

*core of PlaSim) is indeed a dry primitive equation model. However, the extra layer of physics on top of the dynamical core makes PlaSim more than a primitive equation model. More correct to say that it is a simplified general circulation model or, better yet, an Earth-system model of intermediate complexity (EMIC).*

Most importantly, we would like to point out that PlaSim solves the moist primitive equations, not the dry. We agree with the referee that PlaSim is more than just a primitive equation model but so is any current generation Earth System Model. Our main goal in pointing out that the foundation of the atmospheric model is based on the moist primitive equations is to illustrate that the dynamics have not been simplified beyond what is common in many Earth System Models today. Rather, the simplifications in the atmospheric model arise mainly in the parametrizations included: no treatment of volcanic or anthropogenic aerosols, only a single greenhouse gas species explicitly accounted for, etc. We intentionally avoided the term EMIC, because it has become a vague term encompassing a wide range of models with different combinations of sophisticated and simplified components.

Revised text, “PUMA is an atmospheric general circulation model whose dynamical core is based on the wet primitive equations. The primary simplifications in this component of PlaSim are found in the physical parametrizations incorporated in the model: for example, carbon dioxide is the only greenhouse gas whose radiative effects are considered and the radiative transfer scheme is much simpler (and thereby much faster) than that used in current state of the art GCMs.”

*Page 5, line 28: It was recently shown by Lofverstrom and Liakka (2018) that T42 resolution is sufficient to reasonably capture planetary waves in simulations of the LGM climate.*

This reference was added. Revised text is “Herein we use 10 vertical levels at a spectral resolution of T42 (approximately  $2.8^\circ \times 2.8^\circ$ ), which has been previously shown to be sufficiently high to resolve phenomena of interest to the eddy-driven jet (Barnes and Hartmann, 2011; Lofverstrom and Liakka, 2018) while enabling fast enough model run times to make multiple deglacial experiments feasible.”

*Page 5, line 29: The description here is not correct. The Gaussian grid is the 128 x 64 cell grid in real space that the data is outputted on ("Gaussian" refers to how the grid is generated). The primitive equation are partially solved in spectral space (wave space) and are thus transformed between grid space (on the Gaussian grid, in this case 128 x 64 grid points in lon x lat) and the spectral representation in wave space, which supports at most 42 harmonics in the zonal and meridional direction, respectively. (Hence the name T42, where the T is short for "truncation" or more specifically "triangular truncation").*

We agree with the referee. Revised text is “The dynamical atmospheric solutions are generated in spectral space, while the remaining calculations (e.g. phase changes, heat exchange with the land, sea ice or slab ocean, and any changes in those sub-components) occur in real space on a Gaussian grid with 64 latitude points and 128 longitude points. The only exception to this is LSG, which is run at  $2.5^\circ \times 5^\circ$  horizontal resolution.”

*Page 6, line 1: Not sure if I understand how the LSG models works. Is it a dynamic model that only runs in the mixed layer? If yes, how can a realistic ocean circulation be established if there is no deep ocean? Do you parameterize fluxes between the deep ocean and mixed layer? If yes, how are these fluxes calculated? What is the depth of the mixed layer? Prescribed or dynamic? Studies have shown that the mixed layer depth was substantially greater at the LGM (e.g. Sherriff-Tadano et al., 2018), which can have profound implications for the ocean heat contents and energy exchange between the*

*ocean and atmosphere.*

LSG is a three-dimensional general circulation model for the entire ocean. It solves the primitive equations for the ocean under assumptions of large spatial and time scales, which filters out relatively fast components like Kelvin waves. Given these assumptions and that LSG solves its equations implicitly, the time steps used are much longer than would be commonly used for other dynamical ocean models (in this study, approximately 4 simulation days). However, in order to allow the model to respond more quickly than this to abrupt or short-lived changes at the ocean's top surface, a mixed-layer ocean model is used as an intermediary between LSG and the rest of the model. The mixed-layer model is fixed to a 50m depth, which corresponds to the depth of the top layer of LSG. LSG itself does not have a fixed mixed-layer depth, and fluxes between the deep ocean and the mixed-layer are calculated as part of an LSG integration. The mixed-layer ocean model is made to relax gradually toward the LSG solution over LSG's timestep via an applied bottom-boundary heat flux, but it is also free to respond to changing thermal forcings at its top boundary from the atmosphere and sea ice.

Revised text is “Rather than specifying a fixed deep-ocean heat flux to the mixed layer ocean, PlaSim estimates these fluxes by executing LSG every 32 atmospheric time steps (equivalent to 4.5 days). LSG is a three-dimensional, global, ocean general circulation model that solves the primitive equations implicitly under assumptions of large spatial and temporal scales (Maier-Reimer et al., 1993). This formulation permits stable solutions on longer time steps than other components of PlaSim with the trade-off that it filters out gravity waves and barotropic Rossby waves (Maier-Reimer et al., 1993). Since the time steps of LSG are so long, a slab-ocean model is used as an intermediary between LSG and the rest of the model in order to allow the ocean to respond to abrupt or short-lived phenomena. The slab-ocean model is fixed to a 50m depth, which corresponds to the depth of the top layer of LSG. Thus, at the start of an LSG integration, fields in the top layer of LSG are initialized to those from the slab-ocean model, and heat fluxes and wind stress fields are read from the sea ice and atmosphere components, respectively. The LSG integration is performed, and a spatial map of differences between the mixed-layer temperature at the end and the start of the LSG time step are calculated. These temperature differences are used to define a map of deep-ocean heat fluxes, which are subdivided by the number slab-ocean time steps before the next LSG integration and applied as bottom boundary conditions to the slab-ocean model. Thus, under constant atmospheric conditions, the slab ocean model relaxes toward the LSG solution. Under changing atmospheric conditions, the surface component of the ocean will tend toward a mixture of the LSG solution and a thermal response to the surface forcing.”

*Page 6, line 17: Please clarify, you update the boundary conditions every simulation year, but with 10x acceleration, meaning that you effectively only run every 10 years from LGM to PI. Is that correct?*

As far as the forcings go, the referee's description is correct. However, since the model is run continuously forward in time under these accelerated conditions, the solution will not be the same as if we extracted one of every 10 years from an unaccelerated simulation. The differences are described in Appendix A2 and are most noticeable in phenomena with a decadal or longer response timescale. For example, if the ocean's mixed layer takes approximately 30 simulation years to fully adjust to a change in atmospheric boundary conditions, the forcings will have progressed 300 years in this time. Thus, the timescales of these responses will appear lengthened.

Revised text is “This acceleration was not found to alter the main conclusions of this study when tested with a single unaccelerated run, but it is expected to lengthen the apparent timescales of processes. For example, if the ocean's mixed layer takes approximately 30 simulation years to fully adjust to a change in atmospheric boundary conditions, it will appear to take 300 years from the perspective of forcing changes.”

*Page 7, line 12: "...temporal resolution of 100 years". This seems to conflict with the synchronous update of boundary conditions described above.*

As stated on page 7, lines 1-3, not all of the boundary conditions were available at annual or decadal timescales. Where they weren't available, we interpolated their values linearly in time between available bracketing time points. Thus, all of the boundary conditions were updated at the start of every simulation year.

Revised text is "These data are interpolated spatially to the model grid, with land-sea mask defined so the topography of ocean grid cells lies below the contemporaneous sea level. The data are also linearly interpolated in time in order to provide updates every simulation year (i.e. every 10 forcing years)."

*Page 7, line 5: Please clarify how this process works. You can't fit an even number of 0.5° grid cells in a T42 cell (which is around 2.8°), so there must be some partial overlapping cells. Also, what does "effective higher-resolution grid cell length" mean?*

We calculated the variance of higher-resolution grid cells within the T42 grid cells in the following manner. Writing the variance as the  $\text{SUM}(x^2) - (\text{SUM}(x))^2$  and using conservative remapping as an area-weighted sum over overlapping regions in grid cells between the two grids (for a description of conservative remapping, see Jones, 1999), we conservatively remapped both the elevation and the square of the elevation from the higher-resolution grid to T42. We then squared the remapped elevation and took the difference as in the equation above to get the variance. The number of high-resolution grid cells contributing to this variance was approximated by the ratio of the total number of grid cells in the global high-resolution grid divided by the number of T42 grid cells. The effective higher-resolution grid cell length was then defined by dividing the area of the T42 grid cell evenly over the number of high-resolution grid cells contributing to the variance and taking the square root (assuming each of these grid cells are squares).

Revised text is "For each T42 grid cell, the roughness is equal to the variance of all  $0.5^\circ \times 0.5^\circ$  ice sheet grid cells contained within it divided by an effective high-resolution grid cell length. This calculation is performed by first conservatively remapping the elevation and the square of the elevation from the higher-resolution grid to the lower-resolution grid. The variance is then the difference between the square of the remapped elevation and the remap of the squared elevation. The effective higher-resolution grid cell length is the square root of the area of the T42 grid cell divided by the number of higher-resolution grid cells per T42 grid cell (taken here to be the ratio of the total number of grid cells globally in each grid)."

*Page 8, line 18: Ivanovic et al. (2016) is double cited.*

The second citation has been removed. Revised text is "Data for  $\text{CO}_2$ ,  $\text{N}_2\text{O}$  and  $\text{CH}_4$  concentration changes over the deglaciation are consistent with the prescriptions of the PMIP4 Deglacial experiment (see Ivanovic et al. (2016) and data sources Luthi et al. (2008) Meinshausen et al. (2017), and Loulergue et al. (2008))."

*Page 8, line 22: Century should probably be millennium here (you discuss 21 ka - 20 ka and 1 ka to 1950), right?*

Since the PlaSim simulations were generated with the forcings accelerated in time by a factor of ten, a millennium of forcing changes elapsed during the first or last centuries of the simulations. Thus, we were analysing 100 years of output and comparing them against a millennium of data from unaccelerated simulations.

Revised text is “We compare the climate conditions during the first and last century of the fully-transient PlaSim simulations (corresponding to forcing years 21-20ka BP and 1ka BP to 1950AD, respectively, due to acceleration) to the results of LGM and past1000 experiments in the Climate Modelling Intercomparison Project (CMIP) 5.”

*Page 9, line 10: Sentence can be simplified; e.g.: "Also, the path of the NPac jet" -> "Also, the NPac jet"*

Done. Revised text is “Also, the NPac jet is displaced further north and is more tilted in the PlaSim past1000 simulations.”

*Page 9, line 14: I agree with this assessment and a similar conclusion was reached by Lofverstrom et al. (2016); see their discussion about sensitivity simulations with extensive sea ice in the eastern N. Atlantic (their Fig. 6).*

Done. Revised text is “We speculate that this eastern shift is connected to the much more southern extent of sea ice on the eastern side of the NATl, as was found in CAM3 simulations forced by present-day ice sheets with LGM sea surface temperatures and sea ice extent (Lofverstrom et al., 2016).”

*Page 16, line 6: Write out explicitly that you are referring to Fig. 11 here.*

Done. Revised text is “In contrast, in Figure 11 the eastern side of the jet over the eastern NATl is less focussed than the west, with the jet occupying its preferred latitude 50 to 70% of the time.”

*Page 16, line 5: Typo? ...range or its tilt -> ...range of its tilt (?)*

The sentence has been reworded to avoid confusion. Revised text is “Since these jet characteristics and the timing of their changes differ on the eastern and western sides of the NATl jet, we attribute them separately in the next section.”

*Page 16, line 15: What standard metrics? Page 16, line 17: Replace "instead" with "as well", and remove "For those interested".*

“Standard” here is intended to mean “commonly-used.” The definitions employed here for jet latitudinal position and tilt arise from Woollings et al (2010) and a combination of Woollings and Blackburn (2012) and Lofverstrom and Lora (2017), respectively. However, variants on these definitions have been used in many of the papers discussed in the Introduction.

Revised text is “Due to this sensitivity and the important differences in jet characteristics in the two regions, we argue that analyses over the western and eastern jet regions are more instructive than the more commonly-used jet latitude and tilt metrics, and would encourage other authors to present these metrics as well.”

*Page 17, line 5: Meaning here is not clear. Do you mean flat ice sheets (i.e., only accounting for the albedo effect)? Also, the ice sheet height is not the only thing influencing the circulation. As you say elsewhere, the spatial extent is also important.*

The PDTopo experiment is defined with all forcings varying in time except the ice sheet thickness. The thickness of the ice sheets are fixed to present-day values, so the land elevation remains the same as during present day at all times. Nevertheless, the ice sheet area varies from an LGM extent to present-day (i.e an infinitesimally thin ice sheet). This allows the role of the ice sheet orography to be separated from the influence of its albedo and the rest of the forcings.

We do not claim that ice sheet height is the only thing influencing the circulation. Rather, the text says, “The component of the ice sheets that appears most important to this effect is their elevation.” We support this claim by noting in the results of the PDTopo experiment (with time dependent ice area) at LGM, the primary location of the jet is not shifted equatorward and is only slightly more focussed than during present-day. Since we know that the ice sheet is the primary control for the western side of the jet being equatorward-shifted and highly focussed via the results of the FixedGlac experiment (where all other forcings vary in time, but the western side of the jet remains predominantly in the same state throughout the deglaciation), this suggests that either the ice sheet orography or the combined effect of the orography and area are creating these effects. Since our DarkGlac experiment differed very little from the full-forcing runs due to extensive snow cover, we can not differentiate between these two possibilities. However, we can say that an elevated ice sheet is required for this effect.

Revised text is “Ice sheets provide the primary control over the deglacial jet changes described in the previous section. Simulations with fixed LGM ice sheets (FixedGlac in Figures 10 and 11) reproduce neither the deglacial changes to preferred jet latitude nor the bulk of changes to its variability on both sides of the jet. This effect is most prominent for the western side of the jet, which shows almost no change over the deglaciation when the ice sheets are fixed to their LGM state. In the east, the preferred position of the NATl jet does not change under fixed LGM ice sheets, but the frequency of time the jet spends at this latitude decreases, and its range of variability increases. Only orbital and greenhouse gas forcings are changing at this time, so this may indicate a sensitivity to those forcings (perhaps mediated by the changing sea ice extent and sea surface temperatures).

Other sensitivity experiments can help decompose which attributes of the ice sheets are enacting this control on the NATl jet. The PDTopo experiment isolates the thermal forcing associated with ice sheets’ relatively high albedo from the orographic forcing due to the elevation of the ice sheet by fixing ice sheet thickness to present-day values while allowing ice sheet area to vary. Thus, LGM ice sheets are infinitesimally thin but extensive. In neither the east nor the west is the NATl jet as focussed, or as equatorward-shifted in PDTopo (Figures 10 and 11) as it is at LGM in the FullyTrans runs or throughout the FixedGlac runs. Consequently, we conclude that the ice sheet albedo alone is not the primary controlling factor on the NATl jets, and that the elevation of ice sheets is important. However, it is not clear from the present experiments whether orographic changes to the ice sheets alone are sufficient to explain the jet changes, or whether the ice sheets need to be reflective. Since the ice sheets became quickly covered with highly-reflective snow in the DarkGlac simulations, that experiment did not resolve this question. “

*Page 18, line 1: How did you arrived at this specific number (725 m)?*

We determined the elevation threshold above which the jet appeared latitudinally restricted by empirical testing. The southernmost latitude of the ice sheet in eastern North America was identified by applying a mask for regions at or above the elevation value being tested and identifying its southernmost latitude value in this region. Then, as in Figure 12, the North Atlantic jet latitude for each month was plotted against the corresponding ice sheet minimum latitude. If the jet latitude ever exceeded the ice sheet latitude in any of the FullyTrans simulations, then that elevation value was rejected as the threshold.

Revised text is “ This number was arrived at empirically and represents the lowest threshold tested that did not have instances of the western side of the NATl jet exceeding its location.”

*Page 18, line 9: Typo? "jet does not always move the the latitude of the jet."*

Fixed. Revised text is “It should be noted, the jet does not always move to the latitude of the ice sheet



margin.”

*Page 19, lines 3-10: This explanation is a bit too simplistic. I agree that the presence of the ice sheet constrains the jet latitude in the west, presumably in part because of obstruction of the flow by the topography. However, the thermal gradient at the southern ice margin can influence the flow in a similar fashion (this is not mentioned here as far as I can see) - both the change in albedo at the ice sheet margin, and the adiabatic cooling of the flow by the implied elevation difference. The modern (PI) jet is also less variable in the western ocean basin because of the strong thermal gradient at the sea-ice edge. This is clearly a different mechanism than the presence of a big ice sheet, but the effect is similar.*

We reject the hypothesis that the albedo change along the southern margin of the ice sheet plays an important role in constraining the jet that we detect over North America, because there is no such constraining effect in the PDTopo experiment (See Figure 12). The PDTopo experiment includes a time-evolving, but infinitesimally-thin ice sheet, so the albedo change along the ice sheet's southern margin varies the same way in time in the PDTopo experiments as it does in the FullyTrans runs. Thus, the ice sheet must be elevated in order for this barrier effect to occur. Our analyses can not distinguish between whether the elevated barrier operates via a dynamical effect alone or whether there is a role for the thermal effects of the ice to play.

Revised text is “Other sensitivity experiments can help decompose which attributes of the ice sheets are enacting this control on the NATl jet. The PDTopo experiment isolates the thermal forcing associated with ice sheets' relatively high albedo from the orographic forcing due to the elevation of the ice sheet by fixing ice sheet thickness to present-day values while allowing ice sheet area to vary. Thus, LGM ice sheets are infinitesimally thin but extensive. In neither the east nor the west is the NATl jet as focussed, or as equatorward-shifted in PDTopo (Figures 10 and 11) as it is at LGM in the FullyTrans runs or throughout the FixedGlac runs. Consequently, we conclude that the ice sheet albedo alone is not the primary controlling factor on the NATl jets, and that the elevation of ice sheets is important. However, it is not clear from the present experiments whether orographic changes to the ice sheets alone are sufficient to explain the jet changes, or whether the ice sheets need to be reflective. Since the ice sheets became quickly covered with highly-reflective snow in the DarkGlac simulations, that experiment did not resolve this question.”

*Page 21, line 25: Meaning here is not clear - this seems to be the definition of a shift in the jet latitude.*

We agree that the wording used does not effectively bring out our point. What we intended to argue here is that the frequency maps calculated from the Trace-21ka data do not show any change in the preferred jet tilt between 14 and 13ka BP. These results are contrary to what is suggested by the results of Lofverstrom and Lora (2017), but there are two important differences in the methodology here from what they used. Firstly, although both studies examine the TraCE-21ka data, the abrupt increase in jet tilt presented in Lofverstrom and Lora (2017) was detected at 250 hPa, whereas we analysed jet changes over 700-925hPa. Secondly, the jet tilt was defined in Lofverstrom and Lora (2017) as the difference in jet positions between 10-20°W and 70-80°W, whereas we defined the jet tilt as the difference between 0-30°W and 60-90°W. When we alter our analysis conditions to match those of Lofverstrom and Lora (2017), we see that the preferred angle of jet tilt does not change around 13.9 ka BP. Rather, the frequency of time spent at this tilt and less tilted values decreases, while the range and frequency of tilts increases for more positive values. This combination of phenomena matches the abrupt increase in mean jet tilt presented by Lofverstrom and Lora (2017).

Revised text is “Note that this value is less than that calculated in Lofverstrom and Lora (2017) from TraCE-21ka data (between 3° and 4°), but they calculated jet tilt from upper-tropospheric winds and

different longitude ranges in the western and eastern regions of the NATl jet (270 - 300°E and 330 to 360°E in this study versus 280 - 290°E and 340 to 350°E).” “This results stands in contrast to Lofverstrom and Lora (2017), who diagnosed a rapid increase in jet tilt at 13.89ka BP. The source of this discrepancy is discussed further in Section 4.” “This contrasts with previous work on TraCE-21ka that identifies an abrupt increase in tilt in this dataset that occurred at 13.89ka BP (Lofverstrom and Lora, 2017). These two TraCE-21ka results were obtained from different wind data extracted from the same dataset: lower-tropospheric winds are analysed in this study, while Lofverstrom and Lora (2017) examine upper tropospheric winds at 250hPa. There are additional differences in the range of longitudes used to specify the western and eastern regions of the NATl jet: 280 to 290°E and 340 to 350°E, respectively in Lofverstrom and Lora (2017) versus 270 to 300°E and 330 to 360°E in this study. We are able to reproduce the results obtained by Lofverstrom and Lora (2017) (except for the timing, which we date to 13.87ka BP) when we calculate the jet tilt in the same manner as they did (figures are presented in Supplemental Figure S5, alongside corresponding figures using the methodology employed in this study). “

*Page 22, line 16: What Figure is discussed here?*

Figure 12, bottom left plot. Revised text is “As in the PlaSim simulations, this change is driven by a shift on the western side of the jet, plotted in the bottom-left panel of Figure 12.”

*Page 22, line 25: I would encourage you to think a little bit more about this and try to give a mechanistic explanation for this phenomena. Doesn't have to be a full explanation, but at least something that adds a little bit more to the story.*

We will expand on our discussion as discussed at the start of this document.

Revised text is “In contrast, the downstream side of the jet over the eastern North Atlantic does not show the same sensitivity to the marginal position of the North American ice complex, but it is affected by the presence of elevated ice sheets. Whether this control is exerted via changes to the stationary waves (e.g. Kageyama and Valdes (2000); Lofverstrom et al. (2014)), transient eddies (e.g. Merz et al. (2015)), surface thermal gradients from sea ice and sea surface temperatures (e.g. Li and Battisti (2008)), or some other mechanism is not entirely apparent from this study. There is some evidence that sea ice and sea surface temperatures may play a role, as the range of jet latitudes increases after abrupt sea ice retreats and sea surface temperature warmings in the FixedGlac experiment, and the eastern jet distribution is centred around different latitudes at the end of the deglaciation in FullyTrans and PDTopo even though their forcings are the same at this time. “

*Figure 1: What ice sheet remained in North America through the Holocene and is 1.5 km thick?*

Figure 1 plots the peak elevation of ice sheet-covered areas in North America and Fennoscandia. There is no 1.5km thick ice sheet over North America during the Holocene, but there are regions that have an elevation in excess of 1.5km that are covered by ice: glaciers in the Rockies, for example. Due to this confusion, we have changed Figure 1 to only include ice sheet area and elevation east of the Rockies.

Revised caption is “a) Peak elevation in ice sheet-covered areas (bedrock elevation plus ice sheet thickness) and b) ice sheet area for the Laurentide ice sheet and Eurasia (FIS). ”

*Figure 4: Panels showing LGM and past1000 are mixed up (LGM is shown in middle panels). This is correct. The labels are fixed in the revised version.*

*Figure 4: The top of the LGM ice sheets (and indeed some modern topography) is higher than the 700 hPa isobar. I would advice against extrapolating the wind field in these regions and*

*instead treat it as missing data, as extrapolation can cause some weird effects when doing statistical analysis (e.g. when determining the latitude of the strongest winds in the western N Atlantic).*

The reviewer raises a good point. Since our analyses were performed on vertical averages of winds over 700-925hPa, where there is an increase in wind speed with height (Figure 5), it is not clear what pressure level should be used to create a mask of topography. To get around this problem, we recalculated the jet statistics for FullyTrans1 only looking at 850 hPa and omitting grid cells where the land surface lies above this pressure level. The results of these tests are provided in Supplemental Figure S9. The timing and characteristics of jet transitions in the western and eastern regions and for the jet tilt are unchanged from those presented in the main paper. However, when the jet is averaged over longitudes 270°E to 360°E, there are differences compared to the FullyTrans1 results in Supplemental Figure 3. These differences can be attributed to changes to the longitudinal range over which the winds are being averaged when grid cells with an elevated ice surface are masked from the analysis. Due to the differences in characteristics of the jet on its western and eastern sides, changing the weighting of these two regions with time by excluding a changing number of grid cells on the west leads to a mixture of jet characteristics in the mean jet. This issue highlights the problems with using this metric. However, since the conclusions of our study are not affected by the inclusion or exclusion of winds interpolated onto levels below the ice sheet surface, we leave our analyses as is.

Revised text is “Note that the ice sheet elevation in some grid cells exceeds the bottom pressure level of the analysis range, so we interpolated the winds to these levels to not bias the resulting average. The land surface does not pass above the 700hPa pressure level in any of the grid cells included in our analysis, so we are not introducing winds to a region where there was none. The impact of this choice was tested on the 850hPa level and found to not change the jet results (see Supplemental Figure S9) except when the jet is calculated over the entire longitudinal range. In this case, excluding grid cells from the analysis on the western side of the region effectively weights the mean jet toward characteristics of the eastern region. This issue illustrates the sensitivity of this diagnostic to the longitudinal range that is employed. Due to this sensitivity and the important differences in jet characteristics in the two regions, we argue that analyses over the western and eastern jet regions are more instructive than the more commonly-used jet latitude and tilt metrics, and would encourage other authors to present these metrics as well.”

Figure 4 caption “Where the land surface impinges on the vertical range, winds are interpolated to not bias the vertical average. Further discussion can be found in Section 4.”

*Figure 6 - 8: Use the same range on the spines on the right hand side for easier comparison (e.g., in Fig. 6: 0-80 % in top panels and 0-35 % in lower panels).*

Done.

*Figure 9: 10 successive years is a bit ambiguous because it can be done in at least two different ways: (1) a sliding mean where the input and output arrays have the same length; (2) form decadal averages where the input array is 10x longer than the output array. These methods will yield slightly different results. I doubt that the difference will be of sufficient magnitude to challenge your conclusions, but this type of information is important for reproducibility.*

Neither of these methods were used to generate the plots of Figure 9 as no averages were performed. Instead, monthly jet latitudes and tilt were collected for every month in DJF for 10 successive years. Then, the fraction of time that the jet spent in each latitude/tilt bin was calculated by summing over the number of months with a jet in the given bin and dividing by the total number of months in the sample (= 30 months/per run \* 4 runs = 120 months).

Revised text is “Frequency maps of NAtl, lower-level, jet latitudes and tilt aggregated over 10 successive winter seasons and all ensemble members of the FullyTrans experiment. Frequencies represent the percentage of months (out of a total of 120 months) that the jet was identified at a particular latitude, where each latitude bin has a width of  $2.8^\circ$  at T42.”

*Figure 9 - 11 and 13: Write out lat and lon bounds and pressure level(s) used in statistics.*  
Done.

*Figure 11: Caption appears to be wrong as you show latitude here, not difference in latitude across the N Atlantic.*

The reviewer is correct. Revised text is “Frequency maps of ensemble-average, NAtl, lower-level, eastern jet latitude in 10 successive winter seasons for FullyTrans, FixedOrbGHG, FixedGlac, and PDTopo experiments. Colours indicate the percentage of months with the difference in jet latitudes between  $330^\circ\text{E}$  to  $360^\circ\text{E}$  and  $270^\circ\text{E}$  to  $300^\circ\text{E}$  within each bin of width  $2.8^\circ$ .”

*Figure 12: Use same latitude range on vertical axis for easier comparison.*  
Done.

The authors thank Anonymous Referee #2 for his/her detailed comments.

Reviewer's comments are provided in italics.

*The Introduction is quite variable. The description of the North Atlantic jet is great, and gives a reader unfamiliar with the topic a good start. I don't understand why there's an extensive description of the mechanisms for abrupt change in the climate during the deglaciation, because much does not appear to be relevant for the subsequent analysis. For example, it's only in the Introduction that changes in the AMOC are mentioned - why include this? I suggest focussing the Intro only on information that is pertinent for the paper itself. P12 - I don't see a figure which shows the temperature over Greenland. Why are you showing the temperature over Greenland, anyway. What does it represent in this study looking at jet shifts.*

The larger context of the paper is whether jet shifts over the last deglaciation may have contributed to the abrupt climate changes of that period. As we state in the introduction, “deglacial, winter wind conditions over the North Atlantic may have played important roles in the detected abrupt climate changes through their effects on sea ice and/or the surface ocean circulations.” This is plausible, because “... altered winter sea ice extent is sufficient to reproduce the amplitude of deglacial climate changes in northwestern Europe and explain their seasonality (Renssen and Isarin, 2001).” This question is of potential importance to anyone who studies this period, whether they collect and analyse data or perform simulations. However, analyses of atmospheric phenomena under paleo timescales, and the behaviour of the jet in particular, tend to not get a lot of attention from this broader audience. Thus, we included information about the abrupt deglacial changes in the introduction and later in the results section in order to make this connection clearer and hopefully draw attention to this idea in the broader paleo community. As changes in AMOC play a central role in most hypotheses for explaining abrupt changes, we judge it necessary to include this.

Since the reviewer found these comments out of place, we have made some changes to the text to make this motivation stronger. Revised text in the introduction is “Proposed hypotheses explaining the presence of such variability during the deglaciation commonly centre around deep-water formation changes in response to freshwater anomalies in the regions where deepwater is formed (e.g. Rooth (1982); Broecker et al. (1985, 1989); Tarasov and Peltier (2005); Bradley and England (2008); Hu et al. (2010); Keigwin et al. (2018)). In simulations, abrupt reductions of the AMOC induced by hosing are successful at explaining the abruptness of cooling in the extratropical North Atlantic (NAtl), Nordic Seas, Arctic and Eurasia, the reduced precipitation in the NAtl and Europe, and the southward shift of the ITCZ (Kageyama et al., 2010, 2013). They are less successful at explaining the amplitude of temperature changes over Greenland and Europe during the last deglaciation (Clark et al., 2012), particularly when hosing amounts are constrained to realistic values (Kageyama et al., 2010).

Freshwater forcing may not be the only driver of the abrupt climate changes of the last deglaciation. Modern Earth System Models (ESMs) are now exhibiting abrupt climate changes of similar magnitude under slowly-varying or constant boundary conditions (Knorr and Lohmann, 2007; Peltier and Vettoretti, 2014; Zhang et al., 2014; Brown and Galbraith, 2016; Zhang et al., 2017; Klockmann et al., 2018), due to the bistability of the AMOC (Stommel, 1961; Broecker et al., 1985; Knorr and Lohmann, 2007; Zhang et al., 2014, 2017) and/or thermohaline instabilities involving the interactions of the ocean, sea ice and potentially atmosphere (Knorr and Lohmann, 2007; Dokken et al., 2013; Peltier and Vettoretti, 2014; Brown and Galbraith, 2016; Vettoretti and Peltier, 2016; Klockmann et al., 2018; Vettoretti and Peltier, 2018). Winter sea ice extent changes alone are sufficient to reproduce the amplitude of deglacial climate changes in northwestern Europe and explain their seasonality (Renssen and Isarin, 2001), and changes to the surface ocean heat transports can affect the

rates of deepwater formation (Lozier et al., 2010; Häkkinen et al., 2011; Muglia and Schmittner, 2015). Since low-level wind patterns over the Arctic, Greenland and NATl help constrain winter sea ice extent in this region (Venegas and Mysak, 2000) and affect surface ocean heat transports there through the application of surface wind stresses (Lozier et al., 2010; Häkkinen et al., 2011; Li and Born, 2019), these winds may play an important role in setting the conditions required for abrupt deglacial changes or be involved in the abrupt transitions themselves. However, in order to assess this potential, deglacial changes to lower-tropospheric winds must be first identified.

Of the two dominant features of mid-latitude atmospheric circulation patterns in the NATl, the subtropical and eddy-driven 5 jets, the eddy-driven jet has the largest presence in the lower troposphere, and thus the most potential to change wind stress and thereby ocean circulation. “

Revised text in section 3.2 is “The motivation of this study is to assess the potential impact of atmospheric changes in the NATl over the last deglaciation on the abrupt changes detected in Greenland ice cores, so we start by discussing climate changes over Greenland.”

Revised text in the Discussion and Conclusions is “ This paper explores the question of whether winter eddy-driven jet changes over the North Atlantic could have contributed to the abrupt climate changes detected in Greenland ice cores over the last deglaciation.”

*The Intro, as written, just stops. It lacks a clear statement of the problem that this paper addresses. It conveys much information but doesn't link it together: how does jet variability have the potential to impact the climate during the deglaciation, especially abrupt changes? How is the paper going to answer this question?*

Done. Revised text is “In summary, previous work has shown that lower-tropospheric winds over the North Atlantic have the ability to alter sea ice extent and surface ocean circulations in a manner that can reproduce abrupt climate changes detected over Greenland. Simulations have shown that these winds do change characteristics from the start to the end of the last deglaciation, although only a single study has examined how these changes may have progressed in time. Due to the manner in which boundary conditions were updated in the simulation that single study was based on and due to revised understanding of those boundary conditions, it is difficult to assess whether the timing of the wind changes that occurred are actually representative of past changes. Therefore, this study diagnoses the changes undergone by the NATl eddy-driven jet from the LGM to the preindustrial period in multiple transient deglacial experiments using boundary conditions that are updated every simulation year following the specifications of the PMIP4 (Ivanovic et al., 2016). These simulations are performed using a modified version of the Planet Simulator (PlaSim) version 16, an Earth System Model with a primitive equation atmosphere and simplified parametrizations (Fraedrich, 2012; Lunkeit et al., 2012). As such, these simulations can help elucidate whether atmospheric dynamical changes have the potential to play important roles in the abrupt climate changes of the last deglaciation and provide an important comparison against PMIP4 deglacial studies performed using more complex models.”

**Section 3.2** *What is the point in this section? At the end of this section I don't know what I am supposed to have learned. It would help to have a clear finishing paragraph to summarise this section.*

Done. Revised text is “Thus, the NATl jet exhibits changes in position and distribution that occur independently of each other in both PlaSim and TraCE-21ka simulations. Some of these changes coincide with historical climate changes. However, since these jet characteristics and the timings of their changes differ on the eastern and western sides of the NATl jet, we attribute them separately in the next section. “

*At present it [Sec 3.2] is a selection of disparate facts. If you focus on the observations which support your summary, noting any discrepancies it may help add a narrative structure.*

We have revised this section substantially, adding many more connecting sentences to improve the flow of ideas. Since other reviewer comments led us to move any discussions to a Discussion and Conclusions section, we chose not to add extra discussion in this section as the reviewer suggested.

e.g. “As discussed in Section 3.1, the low-level, NATl jet is situated further south and exhibits a narrower range of latitudinal variability in the FullyTrans runs at the start of the deglaciation compared to its end. “

“The TraCE-21ka experiment reproduces both types of jet changes detected in the PlaSim simulations, although the timings of jet shifts are not the same. “

*It would help if you were to link the discussion here [Sec 3.2] with the discussion comparing the jet in the east and west to the discussion of tilt - how do the changes at either end affect tilt? **Tilt v east/west changes** Reading the manuscript one gets a sense that the tilt of the jet and the changes in the jet in the east and west are two separate entities, which they evidently aren't. Historically, the focus has been on tilt, so it makes sense to at least look at this. However, I really like the description of how the east and west vary as this adds nuance to the very simplistic view of tilt. What's lacking the manuscript though is much of a bridge between the two. How can we interpret the previous discussions about tilt in the context of your results?*

We added explicit comparisons of jet tilt changes extracted from this study with those from previous studies. We also made more explicit interpretation of how western and eastern jet latitude changes correspond to tilt changes.

Revised text is “A shift of similar size is observed on both the western and eastern regions of the eddy-driven jet (Figure 7), so there is little change in mean tilt values between these two periods (Figure 8).”

“Ensemble statistics for the NATl jet tilt in the FullyTrans runs in Figure 9 show oscillations between the preferred jet tilt of LGM and a more zonal configuration. These changes in jet tilt reflect the very different behaviours with time of the western (270°E to 300°E) and eastern (330°E to 360°E) sides of the NATl eddy-driven jet, which are shown in Figures 10 and 11. The timing of these transitions match the first two (more gradual) shifts in the jet as a whole and are consistent with the historical timings of the OD and B-A. They also correspond to reductions in the jet tilt .” “There is a single, gradual, northward shift in the eastern region, occurring between 16 and 15ka BP. This change is a little later than the time of increasing jet tilt. “ “Without the ice sheet barrier effect, the preferred tilt in the PDTopo experiment is much smaller than in FullyTrans and does not change over the deglaciation (Supplemental Figure S7), as the western and eastern sides of the jet appear to shift together. “ “All of the fully-transient deglacial simulations presented here show that the NATl eddy-driven jet shifted northward from the Last Glacial Maximum to the preindustrial period, and its latitudinal variability increased. These characteristics match those derived from other studies (Li and Battisti, 2008; Lofverstrom et al., 2014; Merz et al., 2015). However, unlike those studies, neither the PlaSim simulations nor TraCE-21 show much change in jet tilt between these two periods. “

*I'm not sure “oscillation” is a useful term to describe periods like the Younger Dryas. Oscillation implies some set of physics that gives a distinct cycle, and it's not clear to me that any changes which occur over the last deglaciation can be described as cycles. A better term would be “variability”,*

*which encapsulates the fact that there are changes without implying any cyclical physics. You even make this point on page 2 line 28. The presence or absence of cycles is not important for the interpretation in the paper so I'd suggest the less loaded term "variability" |.*

We acknowledge the reviewer's point. Revised text is Mid-latitude atmospheric dynamics may have played an important role in these climate variations ...” “Thus, we suggest that changes to the NAtl jet may play a critical role in abrupt glacial climate changes.” “The last deglaciation encompassed a period of large-scale global warming of the Earth's surface climate, with regional patterns of millennial-timescale variability ...” “Signatures of these climate variations are present in the mid- to high-latitudes of both hemispheres...” “Such variability is also present in proxy indicators...” “Proposed hypotheses explaining the presence of such variability commonly centre around deep-ocean...” “For example, altered winter sea ice extent is sufficient to reproduce the amplitude of deglacial climate changes ...” “Thus, deglacial, winter wind conditions over the North Atlantic may have played important roles in the detected abrupt climate changes...” “None of the transient simulations presented here produce abrupt transitions between stadial and interstadial conditions at the historical time of the OD, B-A, or YD.”

*p3 l5 - “During the deglaciation, changes to the variability of low-level winds can alter gyre transports (and to a lesser degree, wind position and strength” Not sure I understand this, surely variability of the low level wind is changes in the wind position and strength?*

The sentence was rearranged to clarify our meaning. “Since low-level wind patterns over the Arctic, Greenland and NAtl help constrain winter sea ice extent in this region (Venegas and Mysak, 2000) and affect surface ocean heat transports there through the application of surface wind stresses (Lozier et al., 2010; Häkkinen et al., 2011; Li and Born, 2019), these winds may play an important role in setting the conditions required for abrupt deglacial changes or be involved in the abrupt transitions themselves.

”

*p3 l27 - jet not yet.*

Done. Revised text is “However, the eddy-driven jet is ...”

*p5 l29 - how many ensemble members are there?*

Since this section is a description of the model rather than the experiments run for this study, it doesn't seem fitting to discuss how many ensemble members were generated here. That information is provided in the introduction to this section. “The experiments discussed in this paper consist of four transient simulations of the last deglaciation generated using a modified version of PlaSim and a suite of sensitivity studies (FixedOrbGHG, FixedGlac, PDTopo and DarkGlac).” Instead, we reworded the identified sentence to focus the reader's attention on the attributes of the model. “Herein we use a spectral resolution of T42 (approximately  $2.8^\circ \times 2.8^\circ$ ), which has been previously shown to be sufficiently high to resolve phenomena of interest to the eddy-driven jet (Barnes and Hartmann, 2011; Lofverstrom and Liakka, 2018) while enabling fast enough model run times to make multiple deglacial experiments feasible.”

*p5 l30 - “Gaussian grid that is then used for diabatic calculations” not sure what diabatic calculations are.*

Diabatic calculations are those that involve the exchange of heat between fluid parcels and their



environment or phase changes. The text has been changed to clarify this. Revised text is “The dynamical atmospheric solutions are generated in spectral space, while the remaining calculations (e.g. phase changes, heat exchange with the land, sea ice or slab ocean, and any changes in those sub-components) occur in real space on a Gaussian grid with 64 latitude points and 128 longitude points.”

*p8 l22 - You don't mention anything about model spin up? How is the model initialized?*

Done. Revised text is “All deglacial simulations are initialized from the same initial conditions, which are derived from year 2567 of an equilibrated LGM spin-up started from present-day.”

*p9 l7 - I'm not sure what “peak zonal winds” means. Perhaps just say strongest winds?*

Done. Revised text is “For the LGM, northern midlatitude zonal winds from the PlaSim simulations are stronger than those from the CMIP5 multi-model ensemble. Also, the strongest winds of both the NATl and the NPac jets are shifted further east toward the the eastern margins of their respective ocean basins.”

*p9 l16 “the pattern of wind changes from the LGM to the past1000 are similar in both CMIP5 and PlaSim runs (including during JJA, not shown) even though the differences are stronger in the PlaSim transient simulations.” Saying transient simluations at the end of this sentence makes it sound like there's an extra set of simulations - “the transient simulations” - as well as the normal “runs”. This is not the case?*

There is only one set of FullyTrans deglacial simulations performed with PlaSim. Revised text is “In spite of these specific differences, the pattern of wind changes from the LGM to the past1000 are similar (but differ in magnitude) between the CMIP5 and PlaSim runs (including during JJA, not shown).”

*p10 l9 - I'm not sure how you get from “10 consecutive DJF periods” to the histogram on figure 6. 10 DJF periods surely gives 30 months, yet the frequencies on Fig 6. show 100s of months. Is this due to all the ensemble members?*

The reason the numbers of months presented in Figure 6 are much larger than expected based on 10 consecutive DJF periods is that the statistics in this Figure are based on 100 simulation years for all four ensemble members. Revised text is “Unlike Woollings et al. (2010), however, these latitudes are defined from monthly data (without low- pass filtering) over longitudes of 90°W to 0°W. Unless otherwise indicated, the monthly jet latitudes are aggregated over consecutive DJF periods to generate jet latitude frequencies.” in Figure 6 caption: “Histograms of latitudes corresponding to peak NATl zonal winds for all PlaSim ensemble members (left column) and the TraCE- 21ka data (right column) during indicated periods. Monthly jet latitude statistics are aggregated over 100 simulation years and four ensemble members for PlaSim and 1000 simulation years for the TraCE-21ka simulation.”

*p12 l6 - “tilt .. shifts slightly higher” - better as tilt becomes steeper. p12 l7 - It would be interesting to compare the spread in histograms between Trace21ka and PlaSim. You discuss spread for PlaSim on p11, why not Trace21ka too?*

Done. Revised text is “Differences between the PlaSim ensemble and the TraCE-21ka simulation primarily arise with respect to the jet tilt. The mean jet tilt increases by approximately 2°. ... However, either value of jet tilt change in the TraCE-21ka simulation is larger than that detected in the PlaSim simulations, and asymmetries in the increase in the range of jet tilt are opposite for these two datasets. Examining the eastern and western sides of the jet separately, the distributions in both regions change

more similarly from LGM to past1000 in TraCE-21ka than in the PlaSim simulations (see Supplemental Figure S2). ”

*p12 l14 - There needs to be a discussion of “abrupt”. What constitutes abrupt: changes over what timescale? When looking at jet shifts in a coarse resolution model, a movement from one grid box to the next come across as abrupt, tipping point like, but is actually just a smooth rapid change. To be abrupt suggests some set of non-linear feedbacks giving a larger response than the input would suggest. A linear response to a large change to me is not abrupt, just rapid. This is totally personal, but to avoid anyone misinterpreting what **you** mean by abrupt you need to define it.*

We agree and added the following paragraph to the Discussion and Conclusions section.

“Assessing the abruptness of NATl jet changes is problematic, because the abruptness of a phenomenon depends on its context. During the deglaciation, changes are generally considered abrupt if they occur within a couple of decades and are of sufficient amplitude to appear unusual compared to background climate variability. In this study, additional complication arises from the fact that the wind data is gridded; a latitudinal change in the position of the NATl jet will involve a discrete step from one latitude grid to another. Thus, we consider a jet change to be abrupt (given the decadal resolution of our jet diagnostics) when the jet shifts its median latitudinal position from one grid cell to the next without an intermediate period when the jet splits its time roughly equally between the two. “

*p13 l5 - What exactly are you saying in this paragraph? I don't see what the point is.*

Since those abrupt climate changes were associated with changes to surface conditions over Greenland, based on  $\delta^{18}\text{O}$  ratios in Greenland ice cores, we discuss whether we see evidence of such variability in Greenland temperatures in the PlaSim simulations. The answer is that during the historical periods of the Oldest Dryas, Bolling-Allerod and Younger Dryas, we detect changes to the jets, but they do not yield large-amplitude, abrupt climate changes over Greenland. Instead, we detect that type of variability over Greenland at other times in the simulations. Is this sufficient to rule out these jet changes as important to the OD, B-A or YD? This depends on whether PlaSim represents all of the (presently unknown) feedback processes important to these events effectively enough to capture any possible link between the jet changes and the rest of the climate system and the degree to which these historical events were stochastic.

Revised text is “Due to the absence of abrupt climate changes over Greenland, we conclude that the changes in the position, tilt and variability of the NATl eddy-driven jet are not sufficient on their own to generate large-amplitude, abrupt climate changes in PlaSim. It may be that feedbacks between the atmosphere, ocean, land ice and sea ice that are not captured in the simulations here are important in abrupt changes. For example, one very plausible process that is missing from PlaSim is the effect of winds on sea ice. Furthermore, this absence of simulated abrupt climate change does not rule out the possibility that the discerned atmospheric dynamical changes were important to historical abrupt climate changes through their controls on the background climate state. Thus, we characterize the atmospheric changes present in the accelerated transient simulations and leave further assessments of their implications for future work. “

*p14 - Transition seems to be used to describe two different things here. From line 8 there are the three events called transitions then on l10 transition is used to describe the way things change. It doesn't help that on l10 it says “A second type of transition” without ever being clear what the first type of transition is. This whole paragraph l2 onwards is really difficult to understand. I'm struggling to be more helpful and think of suggestions to improve it, but a reader is really going to struggle with this.*

The reviewer is correct in that we attempt to categorize two types of changes to the NATl jet over the deglaciation (jet shifts and changes to the distribution of jet frequencies) and use the word “transition” to describe both of them. Revised text is “The two different types of deglacial changes (the latitudinal shift and the change in the shape of its distribution) occur separately over the deglaciation. In the first type of change, the median jet latitude shifts northward three times over the deglaciation in all ensemble members.” “In the second type of jet change evident in Figure 9, the frequency of time that the NATl eddy-driven jet spends at its median latitude decreases, and the range of jet latitudes increases.”

*p15 l4 - This seems to contradict p11 l5 which says that the jet tilt doesn't change much from LGM to past 1000.*

Both are true. Throughout the deglaciation, the jet tilt switches back and forth between its state at LGM and one grid cell more zonal configuration. Since the distribution of jet tilts broadens at the end of the deglaciation without introducing much overall tendency in the changes to this variable, there is little change in mean jet tilt between the start and the end of the simulation (LGM and the past1000). “A shift of similar size is observed on both the western and eastern regions of the eddy-driven jet (Figure 7), so there is little change in mean tilt values between these two periods (Figure 8).” “Ensemble statistics for the NATl jet tilt in the FullyTrans runs in Figure 9 show oscillations between the preferred jet tilt of LGM and a more zonal configuration. These changes in jet tilt reflect the very different behaviours with time of the western (270°E to 300°E) and eastern (330°E to 360°E) sides of the NATl eddy-driven jet, which are shown in Figures 10 and 11. Nevertheless, by the end of the deglaciation, the jet on both its western and eastern sides has shifted northward by a similar amount, leading to little net change in jet tilt.”

*p15 l13 - “The preferred latitude shifts northward twice within a single decade of simulation, at 19.3ka BP and 14.6ka BP. The timing of these transitions match the more gradual shifts in the jet as a whole and two occasions when the tilt is reduced. They are also consistent with the historical timing of the start of the OD and B-A.” I do not understand this pair of sentences.*

Revised text is “The preferred latitude shifts northward twice at 19.3ka BP and 14.6ka BP, and each shift is completed within a decade of simulation. The timing of these transitions match the first two (more gradual) shifts in the jet as a whole and are consistent with the historical timings of the OD and B-A.”

*p16 l14 “This separation makes it much easier to identify what changes are occurring and attribute their causes than examinations of the mean jet position over the entire range or its tilt.. ” This is an awkward sentence.*

Revised text is “Since these jet characteristics and the timings of their changes differ on the eastern and western sides of the NATl jet, we attribute them separately in the next section.”

*p17 l4 - this is an interesting point, any conjecture as to why orbit and GHG matter?*

Since the position of the jet over the eastern NATl is determined based on where transient eddies (i.e. storm tracks) form and decay, moving the location of the polar front could affect the location of the jet in this region. Orbital and greenhouse gas forcings alter the background climate conditions in different characteristic ways. Orbital changes alter the distribution of heating around the globe, particularly on sub-annual timescales. Greenhouse gas changes are known to have a disproportionate effect in polar regions. Both of these processes could move the polar front.

Revised text is “In general, it appears that the characteristics of the jet on the eastern side of the North Atlantic are sensitive to changes in the background climate state, likely through changes to the positions of the polar front (and the growth of associated eddies) and sea ice margin.”

*p18 l10 - “Yet, the jet does not always move to the latitude of the jet” Is an odd sentence.*

Revised text is “Yet, the jet does not always move to the latitude of the ice sheet margin.”

*p19 l3 - “The consequences of this restriction are that the western end of the jet is more focussed relative to the eastern side, particularly when the NAIS extends well into the midlatitudes, and that the northern range of the western side of the jet increases much more over the deglaciation than its southern range”*

*Perhaps rewrite as: “There are two consequences of this restriction. First the western end of the jet is more focussed relative to the eastern side, particularly when the NAIS extends well into the midlatitudes. Second, the northern range of the western side of the jet increases much more over the deglaciation than its southern range”*

“The western side of the jet is more focussed to a single latitude than the eastern side, particularly when the NAIS extends well into the midlatitudes. This is because the barrier is being applied to the winds in the western region of the jet, but not the eastern region.” “The distribution of the western side of the jet during most of the deglaciation is strongly skewed with the jet spending the bulk of its time at the northern boundary of its range. In contrast, the jet distribution in the eastern region is more symmetrical. As long as the ice sheet continues to impinge on where the jet would preferentially be located in the absence of the ice sheet, the wind shear along the northern edge of the jet remains very strong. Thus, eddies tend to break along this boundary and accelerate the flow there. This keeps the jet preferentially in its northernmost position. Since there is no such constraint on the jet in the eastern region, it is free to vary equally in both directions around its mean position. “

*p19 l10 - “The preferred tilt in the PDTopo experiment is near zero”. The tilt doesn't change much in this simulation and stays at its past1000 value, which you show and argue does have a tilt, 5 degrees in Fig. 8. I agree that the **change** is near zero, but not that there is no tilt.*

Revised text is “Without the ice sheet barrier effect, the preferred tilt in the PDTopo experiment is much smaller than in FullyTrans and does not change over the deglaciation (Supplemental Figure S7), as the western and eastern sides of the jet appear to shift together.”

*p19 l15 - “In contrast, the shift in latitudes occurs earlier on the eastern side of the jet, and no further change to the preferred range of jet latitudes occurs following this.” This sentence exemplifies why, I think, this paper is so confusing. What is important in this sentence is “the eastern side of the jet”: this is what is being compared to the preceding sentence. Yet the way that this sentence is structured puts this midway through the sentence, slightly buried. Thus it takes very careful reading to parse the sentence. If you wrote it as: “In contrast, on the eastern side of the jet the shift in latitudes occurs earlier...” it would be much more obvious what's going. It may be that this reviewer is a bit stupid, but with the long sentences that you use any help that a reader can get would be good. I'd have a look through the paper for more instances of this inverting of sentences. Given the quality of the English in this review you may, however, choose to ignore the stylistic recommendations of this reviewer.*

Thank-you to the reviewer for pointing out sentences that (s)he finds difficult to parse. We tried to shorten the sentences and make the language clearer as we edited the manuscript. For the example provided, the revised text is “In the eastern region, the shift in latitudes occurs earlier than in

FullyTrans, but the jet never reaches as northern a position as it does in FullyTrans.”

*p22 11 - This section of the conclusions relates to the weakest part of the main text, much of what is in this part of the conclusions was not clear from the preceding sections.*

We have substantially revised the results section and hope that it is much clearer now.

*p22 110 colon inappropriate here.*

Revised text is “These shifts are each accomplished within a decade of simulation (century of forcing), and their timings are consistent between the accelerated simulations, an unaccelerated run, and an accelerated transient simulation starting from a warmer initial state. “

*p22 121 - it would be clearer to say “through two phenomena: first, .... second ....” the two descriptions are so long you need to make it clear where one stops and the other starts.*

This sentence was removed in more recent edits of the manuscript.

*p23 17 - “Conversely, the sensitivity of the jet position on the eastern side of the North Atlantic to the background climate state implies that it would be difficult to estimate historical changes to the jet in this region from model simulations, since estimates would vary between models and between simulations with different boundary conditions.” Need to explain this more. Surely, because the orbit and GHG are better constrained than ice sheets, this response will be better simulated?*

While the reviewer is correct in that our knowledge of deglacial changes in orbital forcing and greenhouse gases is less uncertain than our knowledge of past ice sheet configuration, his/her conclusion is mistaken. Climate responses to orbital and greenhouse gas forcings are complex and involve a multitude of feedbacks between different climate components and depend on subgrid parametrizations for phenomena like clouds. The combined effect of all of these processes makes predicting climate responses challenging and model-dependent. In contrast, ice sheet margins acting as a physical barrier to the winds is a very simple process that does not depend as strongly on the most uncertain components of climate models.

Revised text is “As such, it would be difficult to estimate historical changes to the jet in this region from model simulations, since the pattern of thermal responses to changes in boundary conditions is sensitive to model parametrizations for processes like cloud physics, and feedbacks between the atmosphere, ocean and sea ice. Thus, the effect of changing boundary conditions likely varies between models and even between simulations using the same model but different initial boundary condition states.”

*p23 112 - I disagree. The assumption here is that the surface temperature response is linear with respect to the jet latitude: as jet latitude increases so will temperature in direct proportion. But, if there are non-linear feedbacks it could be that when the jet reaches a certain latitude abrupt changes in temperature are possible. For example, imagine the jet is well south of the sea ice margin but gradually moves north due to a slow retreat of the ice sheet. At some point the jet will be over the sea ice margin and a different set of feedbacks become possible. Thus you can get abrupt changes in temperature from a smoothly varying jet/ice sheet.*

The reviewer raises a good point. Revised text is “It is unlikely that relevant changes in the ice sheet margin occur on timescales of decades, so it appears that changes to the upstream end of the North Atlantic jet are more likely to play an enabling role than a causal role for abrupt climate changes. Yet, we can not entirely rule out the possibility that gradual jet changes can trigger abrupt climate changes.

The non-linearity of the coupled climate system implies that gradual changes do not necessarily lead to gradual responses, particularly if there are thresholds (e.g. sea ice edge) beyond which feedbacks change. “

*Figure 1(a) - There's an enormous remnant ice sheet over NAm: 1.7km at 0ka. What is this?*

Figure 1 plots the peak elevation of ice sheet-covered areas in North America and Fennoscandia. There is no 1.5km thick ice sheet over North America during the Holocene, but there are regions that have an elevation in excess of 1.5km that are covered by ice: glaciers in the Rockies, for example.

Revised caption is “a) Peak elevation in ice sheet-covered areas (bedrock elevation plus ice sheet thickness) and b) ice sheet area for North America (NAIS) and Eurasia (FIS).” Revised text is “In Figure 1a, there appears to be an elevated remnant of the NAIS that continues to present day, which corresponds to small glaciers located in the Rocky Mountains.”

*Figure 5 - Its hard to judge in this figure how the amplitude of the jet changes. If you highlight one isotach, 20m/s, in both the contours and colours it would make it simpler to see how the structure of the jet differs.*

From our perspective, highlighting a colour and adding a highlighted line isotach for LGM would likely both reduce and add confusion.

# Towards understanding potential atmospheric contributions to abrupt climate changes: Characterizing changes to the North Atlantic eddy-driven jet over the last deglaciation

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**Abstract.** Abrupt climate shifts of large amplitude were common features of the Earth's climate as it transitioned into and out of the last full glacial state approximately twenty thousand years ago, but their causes are not yet established. Mid-latitude atmospheric dynamics may have played an important role in these ~~oscillations~~ [climate variations](#) through their effects on heat and precipitation distributions, sea ice extent, and wind-driven ocean circulation patterns. This study characterises deglacial winter wind changes over the North Atlantic (NAtl) in a suite of transient deglacial simulations ~~we performed using the PlaSim~~ [using PlaSim, an intermediate-resolution earth system model](#), ~~as well as in~~ [with simplified physical parametrizations](#), and the TraCE-21ka simulation. We detect multiple instances of NAtl jet transitions that occur within 10 simulation years and a sensitivity of the jet to background climate conditions. Thus, we suggest that changes to the NAtl jet may play a critical role in abrupt glacial climate ~~oscillations~~ [changes](#).

We identify two types of simulated wind changes over the last deglaciation. Firstly, the latitude of the NAtl eddy-driven jet shifts northward over the deglaciation in a sequence of distinct steps. Secondly, the variability of the NAtl jet gradually shifts from a Last Glacial Maximum (LGM) state with a strongly preferred jet latitude and a restricted latitudinal range to one with no single preferred latitude and a range that is at least 11° broader. [These changes can significantly affect ocean circulation](#). Changes to the position of the NAtl jet alter the location of the wind forcing driving oceanic surface gyres and the limits of sea ice extent, whereas a shift to a more variable jet reduces the effectiveness of the wind forcing at driving surface ocean transports.

The processes controlling these two types of changes differ on the upstream and downstream ends of the NAtl eddy-driven jet. On the upstream side over eastern North America, the elevated ice sheet margin acts as a physical barrier to the winds in both the PlaSim simulations and the TraCE-21ka experiment. This constrains both the position and the latitudinal variability of the jet at LGM, so the jet shifts in sync with ice sheet margin changes. In contrast, the downstream side over the eastern NAtl is more sensitive to the thermal state of the background climate. Our results suggest that ~~knowing~~ the position of [ice of above a critical threshold \(in our case 725 m\) proximal to](#) the south-eastern margin of the North American ice complex strongly constrains the deglacial position of the jet over eastern North America and the western North Atlantic as well as its variability.

# 1 Introduction

The last deglaciation encompassed a period of large-scale global warming of the Earth's surface climate, with regional patterns of millennial-timescale ~~oscillations detected in oxygen isotopes in Greenland ice and surface ocean temperatures variability~~ (Blunier et al., 1998; Shakun and Carlson, 2010; Clark et al., 2012). The Oldest Dryas (OD, 19-14.7ka BP, which includes Heinrich Stadial 1, 17.5-14.7ka BP), the Bølling-Allerød (B-A, 14.7-12.8ka BP), and the Younger Dryas (YD, 12.8-11.7ka BP) ~~describe denote~~ consecutive periods of stadial and interstadial conditions with rapid adjustments between them (Hammer et al., 1986; Grachev and Severinghaus, 2005; Clark et al., 2012). Signatures of these ~~oscillations climate variations~~ are present in the mid- to high-latitudes of both hemispheres with increasing amplitude toward the poles, although the ~~sign tends signs tend~~ to be anti-phased between the two hemispheres and of lower amplitude in the south (Shakun and Carlson, 2010). Such ~~oscillations are variability is~~ also present in proxy indicators for variables other than temperature. Ocean circulation proxies indicate a deepening of the Atlantic Meridional Overturning Circulation (AMOC) and a northward shift in the northern boundary of the subtropical gyre with shifts from stadial to interstadial conditions in northern high latitudes (and vice versa) (e.g. ~~Gherardi et al. (2009); Clark et al. (2012); Repschläger et al. (2015)~~ Gherardi et al. (2009); Benway et al. (2010); Clark et al. (2012); Repschläger et al. (2015)). Abrupt shifts have also been detected in reconstructed lake levels and speleothem data in the subtropics and Indian and African monsoon regions, suggesting latitudinal shifts of the InterTropical Convergence Zone (ITCZ) (e.g. ~~Jacob et al. (2007) and Mohtadi et al. (2016)~~ Jacob et al. (2007); Mohtadi et al. (2016)).

Proposed hypotheses explaining the presence of such ~~oscillations variability during the deglaciation~~ commonly centre around ~~deep-ocean circulation deepwater formation~~ changes in response to ~~salinity freshwater~~ anomalies in the regions ~~of deepwater formation. Different freshwater sources have been proposed to generate an abrupt reduction in the AMOC: changes in regional discharge from North American ice sheets (Rooth, 1982; Broecker et al., 1989; Tarasov and Peltier, 2005; Keigwin et al., 2018); increased freshwater export from the Arctic in response to the opening of the Bering Strait (Hu et al., 2010); and export of thick sea ice from the Arctic basin (Bradley and England, 2008). In climate model simulations, slowing down the AMOC using freshwater sources can provide an effective way of generating abrupt~~ where deepwater is formed (e.g. Rooth (1982); Broecker et al. (1985, 1989); Clark et al. (2012)). ~~In simulations, abrupt reductions of the AMOC induced by hosing are successful at explaining the abruptness of cooling in the extratropical North Atlantic (NAtl), Nordic Seas, Arctic and Eurasia, as well as reducing the reduced precipitation in the NAtl, European and African and Indian monsoon regions (Kageyama et al., 2010, 2013). Southward shifts and Europe, and the southward shift of the ITCZ in the Atlantic basin have also been detected in response to simulated AMOC reductions (Kageyama et al., 2010, 2013). However, reducing freshwater fluxes is less effective at generating abrupt warmings such as were observed at the start of the B-A and the end of the YD (Kageyama et al., 2010). If AMOC changes occur at least in part from hysteresis under the gradually changing background conditions of the last deglaciation or through internal variability of the climate, rather than solely freshwater surges, then abrupt changes in either direction are possible (Knorr and Lohmann, 2007; Kageyama et al., 2010). Nevertheless, AMOC changes alone may be insufficient to explain all aspects (Kageyama et al., 2010, 2013). They are less successful at explaining the amplitude of temperature changes over Greenland and Europe during the last deglaciation (Clark et al., 2012), particularly when hosing amounts are constrained to realistic values (Kageyama et al., 2010).~~



~~Freshwater forcing may not be the only driver of the abrupt changes during climate changes of the last deglaciation, as corresponding warming in the South Atlantic and Southern oceans do not always accompany simulated AMOC reductions (Kageyama et al., 2013) and. Modern Earth System Models (ESMs) are now exhibiting abrupt climate changes of similar~~  
5 ~~magnitude under slowly-varying or constant boundary conditions (Knorr and Lohmann, 2007; Peltier and Vettoretti, 2014; Zhang et al., 2014) due to the bistability of the AMOC (Stommel, 1961; Broecker et al., 1985; Knorr and Lohmann, 2007; Zhang et al., 2014, 2017) and/or thermohaline instabilities involving the interactions of the amplitude of corresponding simulated signals over Greenland and Europe are smaller than reconstructed (Clark et al., 2012).~~

~~Alternative explanations for the abrupt transitions of the last deglaciation include thermohaline circulation responses as a~~  
10 ~~single aspect of more complex mechanisms (Seager and Battisti, 2007), or that changes in wind fields played the central role (Wunsch, 2006). For example, altered winter ocean, sea ice and potentially atmosphere (Knorr and Lohmann, 2007; Dokken et al., 2013; Peltier et al., 2013) are~~  
~~Winter sea ice extent is changes in model simulations alone are sufficient to reproduce the amplitude of deglacial climate oscillations deglacial January temperature changes in northwestern Europe and explain their seasonality (Renssen and Isarin, 2001).~~  
~~Winter sea ice cover today is constrained by (Renssen and Isarin, 2001), and changes to the surface ocean heat transports~~  
15 ~~can affect the rates of deepwater formation (Lozier et al., 2010; Häkkinen et al., 2011; Muglia and Schmittner, 2015). Since low-level wind patterns over the Arctic and Greenland (Venegas and Mysak, 2000) and, Greenland and NATl help constrain winter sea ice extent in this region (Venegas and Mysak, 2000) and affect surface ocean heat transports in the NATl (themselves affected by wind forcing over the NATl) (Lozier et al., 2010; Häkkinen et al., 2011; Li and Born).~~  
~~During the deglaciation, changes to the variability of low-level winds can alter gyre transports (and to a lesser degree, wind position and strength), as~~  
20 ~~highly variable winds are less effective at transporting surface water via Sverdrup transport than steady winds (Li and Born). A stronger and more eastwardly extensive subpolar gyre restricts the transport of warm, salty water northward from the subtropical gyre, which also affects rates of deepwater formation (Häkkinen et al., 2011; Muglia and Schmittner, 2015). Thus, deglacial, winter wind conditions over the North Atlantic may have played important roles in the detected abrupt climate oscillations through their effects on sea ice and/or the surface ocean circulations. there through the application of surface wind~~  
~~stresses (Lozier et al., 2010; Häkkinen et al., 2011; Li and Born, 2019), these winds may play an important role in setting the conditions required for abrupt deglacial changes or be involved in the abrupt transitions themselves. However, in order to assess this potential, deglacial changes to lower-tropospheric winds must be first identified.~~

Of the two dominant features of mid-latitude atmospheric circulation patterns in the NATl, the subtropical and eddy-driven jets, the eddy-driven jet has the largest presence ~~at low levels of the atmosphere in the lower troposphere, and thus the most~~  
30 ~~potential to change wind stress and thereby ocean circulation.~~ The eddy-driven jet (or polar front jet or jet stream) is a narrow band of fast, westerly winds that arises from the ~~momentum-flux~~ convergence of atmospheric synoptic-scale eddies (e.g. extratropical cyclones with lifespans of days) (Lee and Kim, 2003; Barnes and Hartmann, 2011). These baroclinic eddies are primarily created by the strong temperature gradients along the boundary between polar and tropical air masses and/or the wind shear on the flank of the subtropical jet (Lee and Kim, 2003; Justino et al., 2005). Since these two phenomena occur at different latitudes, the position of the eddy-driven jet depends on their relative strengths (Lee and Kim, 2003):

- under a weak subtropical jet as in the NATl today, the eddy-driven jet tends to be distinct from the subtropical jet and located in the mid-latitudes;
- under a strong subtropical jet as in the North Pacific (NPac) today, the eddy-driven jet tends to lie along the poleward flank of the subtropical jet in a "merged" state.

Additional eddy sources that localize the eddy-driven jet in longitude as well as latitude include the baroclinicity of land-sea boundaries or other surface temperature gradients, and the breaking of Rossby waves (see Box 1 of Cohen et al. (2014) for an overview of the phenomena affecting and affected by the eddy-driven jet). Due to the greater temperature contrasts between equator and pole or land and sea during a hemisphere's winter, the eddy-driven jet is stronger and more localized during winter.

~~Summer changes to the winds and climate during the deglaciation are of primary importance to the rates and locations of ice sheet melt and retreat. However, these conditions make it more likely that the eddy-driven jet is strongest in the winter and is therefore more likely to impact the rest of the atmosphere/ocean system during that season.~~ winter. As such, we restrict our attention in this study to the northern winter, or DJF. However, summer changes to the winds and climate during the deglaciation are of greater importance to the rates and locations of ice sheet melt and retreat, so we will address those changes in a following study.

Since the eddy-driven jet's position depends on the characteristics of the eddy field, any changes to locations or rates of eddy production and decay will change the jet. However, the jet itself is a source of eddies in the form of midlatitude cyclones, or storm tracks. Thus, variations in the jet's position over time arise from a complex process of feedback interactions between changes to the eddies generated by the background climate, and changes to the eddies arising from the jet's response (Cohen et al., 2014). The type of variability depends on the latitudinal position of the jet. Eddy-driven jets located closer to the equator (and the subtropical jet) or the pole tend to vary in strength (pulse) due to dynamical limits provided by background wind conditions in these regions, while jets in the central midlatitudes tend to meander latitudinally (Barnes and Hartmann, 2011). Depending on the type of variability, the patterns of heat and moisture transported by the jet will be either concentrated to a narrow band of latitudes around the jet's mean position or spread over a large area.

Under LGM boundary conditions, with ice sheet cover extending to the mid-latitudes over North America (NAmer) and over Fennoscandia (Dyke, 2004; Hughes et al., 2016), both the position of the ITCZ (and presumably the subtropical jet) (Arbuszewski et al., 2013) and the regions of baroclinicity are different from present-day. The topographic and thermal barriers presented by the ice sheet complex over NAmer, in particular, alter the stationary wave field, the pattern of transient eddy production and decay, and the locations of baroclinic zones around the NH (Rind, 1987; Cook and Held, 1988; Roe and Lindzen, 2001a, b; Justino et al., 2005; Li and Battisti, 2008; Lofverstrom et al., 2014; Merz et al., 2015). These effects have their strongest manifestation just downstream of the North American Ice Sheet complex (NAIS), in the NATl. However, the influences on the western and eastern sides of the NATl have been found to differ in atmospheric simulations, ~~whereby:~~ the position of the western side of the jet is more affected by orography-ice sheet orography, and the position of the eastern side of the jet is primarily influenced by transient eddies (Kageyama and Valdes, 2000)-stationary and/or transient eddies (Kageyama and Valdes, 2000; Lofvestrom et al., 2016). While the routing of storm tracks and the jet's contribution to pole-

ward atmospheric heat transport may be most affected by the behaviour of the jet over the eastern NATl, the position of the western side of the jet over eastern NAm is of particular importance to the wind-driven ocean circulation through Sverdrup transport (Li and Born) (Li and Born, 2019). Given the above and that there is no reason to expect equal and synchronous changes in eastern and western NATl jet positions over deglaciation, both positions should be diagnosed. Following the convention in recent literature, we also use the jet's mean latitudinal position and its east-west difference in latitudinal position (differencing regions marked by black boxes in Figure 4), or its tilt, as additional metrics.

NATl eddy-driven jet characteristics in LGM simulations for multiple models from the Paleoclimate Modelling Intercomparison Project (PMIP) 3 show little consistency, except that the jets are all stronger and less variable than in corresponding preindustrial simulations (P. Hezel, personal communication). However, in simulations based on the NCAR family of models (CCSM3, CCSM4 and their components), the NATl eddy-driven jet at LGM follows a less tilted path and is stronger and less latitudinally-variable than at present (Li and Battisti, 2008; Lofverstrom et al., 2014; Merz et al., 2015). These changes are consistent with what would be expected if the NATl eddy-driven jet entering the aforementioned entered a more "merged" state at LGM, which corresponds to a reduction in the transport of heat to although not all of these studies show evidence of this. Irregardless, changes to the path of the jet are expected to result in changes to the distributions of heat and precipitation over the British Isles and Fennoscandia (Li and Battisti, 2008; Lofverstrom et al., 2014; Merz et al., 2015). Western Europe during this period.

Sometime during the last deglaciation, the pattern and variability of simulated midlatitude winds must change, especially in response to the ice sheet topography changes (Cook and Held, 1988; Rind, 1987; Justino et al., 2005; Li and Battisti, 2008; Merz et al., 2015). However, there is little information as to whether these changes occurred at the time of the climate oscillations abrupt climate transitions. In the TraCE-21ka deglacial simulation Liu et al. (2009); He (2011); Liu et al. (2012) (Liu et al., 2009) the NATl jet exhibits two characteristic states: a strong, stable, zonal glacial jet and a weaker, latitudinally-variable, tilted interglacial jet (Lofverstrom and Lora, 2017). The transition from the one jet state to the other is abrupt and coincident with the separation of the Cordilleran and Laurentide ice sheets at 13.89 ka BP (Lofverstrom and Lora, 2017). This timing would place the abrupt change A jet shift at 13.89ka BP lies during the middle of the B-A, which would rule out its playing an important, proximal role in triggering abrupt climate oscillations transitions during the last deglaciation. However, their study employed only a single simulation forced by the ICE-5G it is difficult to assess the representativeness of the timing of changes associated with ice sheets in the TraCE-21ka experiment, since that simulation only enacted ice sheet and corresponding meltwater changes via step functions applied at irregular intervals (He, 2011). Additionally, the ice sheet reconstruction used, ICE-5G, which over-predicts the height of the Keewatin dome with respect to more recent reconstructions (Tarasov et al., 2012; Peltier et al., 2015) and is inconsistent with present-day uplift data (Tarasov and Peltier, 2004). This study-

In summary, previous work has shown that lower-tropospheric winds over the North Atlantic have the ability to alter sea ice extent and surface ocean circulations in a manner that can reproduce abrupt climate changes detected over Greenland. Simulations have shown that these winds do change characteristics from the start to the end of the last deglaciation, although only a single study has examined how these changes may have progressed in time. Due to the manner in which boundary conditions were updated in the simulation that single study was based on and due to revised understanding of those boundary

5 conditions, it is difficult to assess whether the timing of the wind changes that occurred are actually representative of past changes. Therefore, this study diagnoses the changes undergone by the NATl eddy-driven jet from the LGM to the preindustrial period in multiple transient deglacial experiments using ~~a newer ice sheet reconstruction without prescribed meltwater fluxes~~boundary conditions that are updated every simulation year following the specifications of the PMIP4 (Ivanovic et al., 2016). These simulations are performed using a modified version of the Planet Simulator (PlaSim) version 16, ~~a simplified an~~ Earth System Model with a primitive equation atmosphere (~~Lunkeit et al., 2012~~), ~~and transient boundary conditions following the specifications of the PMIP4 (Ivanovic et al., 2016) and simplified parametrizations (Fraedrich, 2012; Lunkeit et al., 2012)~~. As such, these simulations can ~~provide an important comparison against PMIP4 deglacial studies performed using more complex models and~~ help elucidate whether atmospheric dynamical changes have the potential to play important roles in the abrupt climate changes of the last deglaciation ~~and provide an important comparison against PMIP4 deglacial studies performed~~  
10 using more complex models.

## 2 Methods

The experiments discussed in this paper consist of four transient simulations of the last deglaciation generated using a modified version of PlaSim, and a suite of sensitivity studies (FixedOrbGHG, FixedGlac, PDTopo and DarkGlac). ~~A subset of the same boundary conditions and initial conditions are applied in all of the fully transient experiments~~All deglacial simulations are initialized from the same initial conditions, which are ~~described in Table 1~~derived from year 2567 of an equilibrated LGM spin-up started from present-day. Ensemble members differ by the radiation parameter set used, all of which were identified as  
5 optimized configurations for reproducing radiative fields during the preindustrial period. Further details of the tuning procedure are available in Supplemental Section S1.0.1. A subset of the same boundary conditions are applied in all of the fully transient experiments, which are described in Table 1.

The goals of the sensitivity experiments are to isolate the contributions of ice sheet height, ice sheet albedo, and orbital and GHG forcings to the jet changes we detect, by fixing one forcing at a time and running otherwise identical simulations over  
10 the entire deglaciation. Each sensitivity experiment was repeated for all tuning configurations employed in the fully-transient experiments. Note that the results of the DarkGlac (artificially low ice albedo) experiments were not significantly different than the fully-transient runs due to the reflectivity of snow on top of the dark ice, so their results are not discussed.

Characteristics of PlaSim are described in Section 2.1, and the boundary conditions are described in Section 2.2. Finally, the model's performance at simulating LGM climate with these boundary conditions is described in Section 2.2.5. ~~Finally, the~~  
15 ~~boundary conditions are described in Section 2.2.~~

### 2.1 Planet Simulator

PlaSim consists of the Portable University Model of the Atmosphere (PUMA) wet primitive equation atmosphere model, the Simulator for Biospheric Aspects (SIMBA) dynamic vegetation model, a zero-layer thermodynamic sea ice model, a slab-ocean model and the Large-Scale Geostrophic (LSG) ocean model ~~PUMA solves the~~ (Fraedrich, 2012; Lunkeit et al., 2012). PUMA

**Table 1.** Characteristics of numerical simulations presented in this study. The time-varying forcings are described in section 2.2, and are either transient (T) or fixed (F). Topography includes ice sheet topographic variations as well as corresponding changes to surface roughness and land mask. GHG represents greenhouse changes enacted through effective CO<sub>2</sub> concentrations.

Name	Timespan		Time-varying Forcings			
	Start (BP)	End (BP)	Topography	Land ice albedo	GHG	Orbital
FullyTrans1-4	21000	0	T	T	T	T
FixedOrbGHG1-4	21000	0	T	T	F (LGM)	F (LGM)
FixedGlac1-4	21000	0	F (LGM)	F (LGM)	T	T
PDTopo1-4	21000	0	F (past1000)	T	T	T
DarkGlac1-4	21000	0	T	F (past1000)	T	T

20 is an atmospheric general circulation model (GCM) whose dynamical core is based on the wet primitive equations. The primary simplifications in this component of PlaSim are found in the physical parametrizations incorporated in the model: for example, carbon dioxide is the only greenhouse gas whose radiative effects are considered and the radiative transfer scheme is much simpler (and thereby much faster) than that used in current state of the art GCMs. Herein we use 10 vertical levels at a spectral resolution of T42 (approximately 2.8°x2.8°), which has been previously shown to be ~~of sufficiently high resolution~~ sufficiently  
25 high to resolve phenomena of interest to the ~~the~~ eddy-driven jet (Barnes and Hartmann, 2011) (Barnes and Hartmann, 2011; Lofverstrom and  
enabling fast enough model run times to ~~enable an ensemble of deglacial experiments~~ make multiple deglacial experiments  
feasible. The dynamical atmospheric solutions are ~~interpolated to~~ generated in spectral space, while the remaining calculations  
(e.g. phase changes, heat exchange with the land, sea ice or slab ocean, and any changes in those sub-components) occur in  
real space on a Gaussian grid ~~that is then used for diabatic calculations, including all other sub-components except for LSG.~~  
30 ~~Thus, for with~~ 64 latitude points and 128 longitude points. The only exception to this is LSG, which is run at 2.5°x5° horizontal  
resolution. For every atmospheric time step, the land, sea ice and slab-ocean components are called sequentially using the same  
grid and land-sea mask (a schematic is available in Supplemental Figure S1).

Rather than specifying a fixed deep-ocean heat flux to the mixed layer ocean, PlaSim estimates these fluxes by executing LSG  
every 32 atmospheric time steps (equivalent to 4.5 days). LSG is ~~run at 2.5°x5° horizontal resolution with a fixed, present-day~~  
~~land-sea mask.~~ LSG a three-dimensional, global, ocean general circulation model that solves the primitive equations implicitly  
~~for all oceanic layers~~ under assumptions of large spatial and temporal scales (Maier-Reimer et al., 1993). This formulation  
permits stable solutions on longer time steps than other components of PlaSim with the trade-off that it filters out gravity waves  
and barotropic Rossby waves (Maier-Reimer et al., 1993). ~~The~~ Since the time steps of LSG are so long, a slab-ocean model is  
5 used as an intermediary between LSG and the rest of the model in order to allow the ocean to respond to abrupt or short-lived  
phenomena. The slab-ocean model is fixed to a 50m depth, which corresponds to the depth of the top layer of LSG. Thus, at

the start of an LSG integration, fields in the top layer of LSG are initialized to those from the slab-ocean model, and heat fluxes and wind stress fields are read from the sea ice and atmosphere components, respectively. The LSG integration is performed, and a spatial map of differences between the mixed-layer temperature ( $T_{mix}$ ) at the end and the start of the LSG time step are calculated. These temperature differences are used to define a map of deep-ocean heat fluxes ~~for the~~, which are subdivided by the number slab-ocean time steps before the next LSG integration and applied as bottom boundary conditions to the slab-ocean model. Thus, under constant atmospheric conditions, the slab ocean model relaxes toward the LSG solution. Under changing atmospheric conditions, the surface component of the ocean will tend toward a mixture of the LSG solution and a thermal response to the surface forcing.

For the experiments performed in this study, the PlaSim model was modified to allow time-varying boundary conditions. Changing boundary conditions include land-sea mask (implemented for all model components except LSG, whose land-sea mask remains at present-day conditions throughout), topography, ice mask, orographic component of surface roughness, orbital configuration and greenhouse gas concentration. Note that although the land mask was altered consistently with changing ice sheet mass, no corresponding salinity anomalies were introduced to the oceans. However, surface runoff routing was recalculated every time the ice sheet configuration changed.

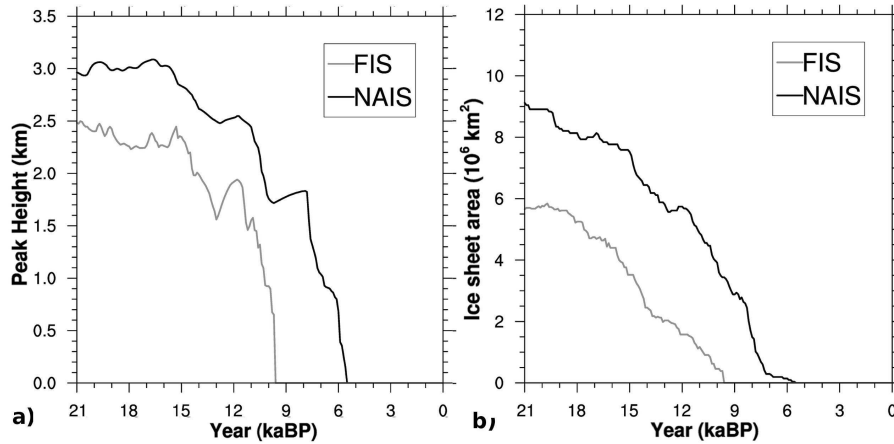
Further details about PlaSim are available in Supplemental Section S1.

## 2.2 Boundary Conditions

PlaSim boundary conditions are updated every simulation year. ~~For~~ However, for all of the transient simulations presented, the forcings are accelerated by a factor of ten. This acceleration was not found to alter the main conclusions of this study when tested ~~with-against~~ a single unaccelerated run, but it is expected to lengthen the apparent timescales of processes. For example, if the ocean's mixed layer takes approximately 30 simulation years to fully adjust to a change in atmospheric boundary conditions, it will appear to take 300 years from the perspective of forcing changes. More particulars about the differences between the accelerated and unaccelerated runs are presented in Appendix section A2. Where the time between boundary condition updates is shorter than the temporal resolution available for a boundary condition dataset, the boundary conditions are linearly interpolated in time. For ice sheet and land-sea masks, the interpolated values are then rounded to zero or one with a cutoff of 0.5.

### 2.2.1 Land-sea mask, land topography, land-ice mask

Changes in land-sea mask, land topography and land-ice mask are derived from the GLAC1-D deglacial chronology generated with the three-dimensional glacial systems model (GSM) that includes a thermomechanically-coupled ice sheet model, visco-elastic bedrock response, and various other components (cf Tarasov et al., 2012; Briggs et al., 2013, and references therein). The North American (Tarasov et al., 2012) and Eurasian components (Tarasov et al., 2014) are obtained from large ensemble Bayesian inversions against large sets of geophysical and geological observations. The Antarctic component (Briggs et al., 2014) is a best scoring run (against data constraints) from a large ensemble and the Greenland component (Tarasov and Peltier, 2003) is an older hand-tuned model. These four components have then been post-processed to create a gravitationally self-



**Figure 1.** a) Peak elevation in ice sheet-covered areas (bedrock elevation plus ice sheet height-thickness) and b) ice sheet area for the Laurentide component of the North America-American Ice Sheet complex (NAIS) and Eurasia (FIS).

consistent global deglaciation chronology with a temporal resolution of 100 years. These data are interpolated spatially to the model grid, with land-sea mask defined so the topography of ocean grid cells lies below the contemporaneous sea level. The data are also linearly interpolated in time in order to provide updates every simulation year (i.e. every 10 forcing years).

Time series of ice sheet areas and peak heights-elevations for North America (east of the Rockies) and Fennoscandia are plotted in Figure 1. In both the North American ice sheet complex (NAIS) and Fennoscandian ice sheet complex (FIS), ice sheet margins begin retreating before peak heights change noticeably. The ice sheet areas decrease approximately linearly, with pauses for both the NAIS and the FIS during the Younger Dryas (approximately 13 to 12ka BP). In contrast, the rate of peak height decrease accelerates with time. Thus, the bulk of peak height changes occur from 12ka BP to 9ka-6ka BP. The FIS completely disappears by 9 ka, while a significant Labrador ice dome is present at 8 ka (and largely dissipates by 7-6 ka).

### 2.2.2 Surface roughness

The component of surface roughness due to orography is calculated from the topography data described above via a similar method to what was used for the default present-day roughness provided with the model (Tibaldi and Geleyn, 1981). For each T42 grid cell, the roughness is equal to the variance of all  $0.5^\circ \times 0.5^\circ$  ice sheet grid cells contained within it are identified. The variance of the topography of these higher-resolution grid cells are calculated and divided by an effective higher-resolution grid cell length per the T42 grid cell. This effective length is. This calculation is performed by first conservatively remapping the elevation and the square of the elevation from the higher-resolution grid to the lower-resolution grid. The variance is then the difference between the square of the remapped elevation and the remap of the squared elevation. The effective higher-resolution grid cell length is the length of a side of a square whose area is calculated by dividing the square root of the area of the T42 model grid cell evenly over grid cell divided by the number of high-resolution grid cells within it higher-resolution grid cells per T42 grid cell (taken here to be the ratio of the total number of grid cells globally in each grid).

### 2.2.3 Orbital configuration

Orbital parameters are calculated internally within the model given an orbital forcing year. The equations follow Berger (1978), and the orbital year is updated every simulation year.

### 2.2.4 Greenhouse gas concentration

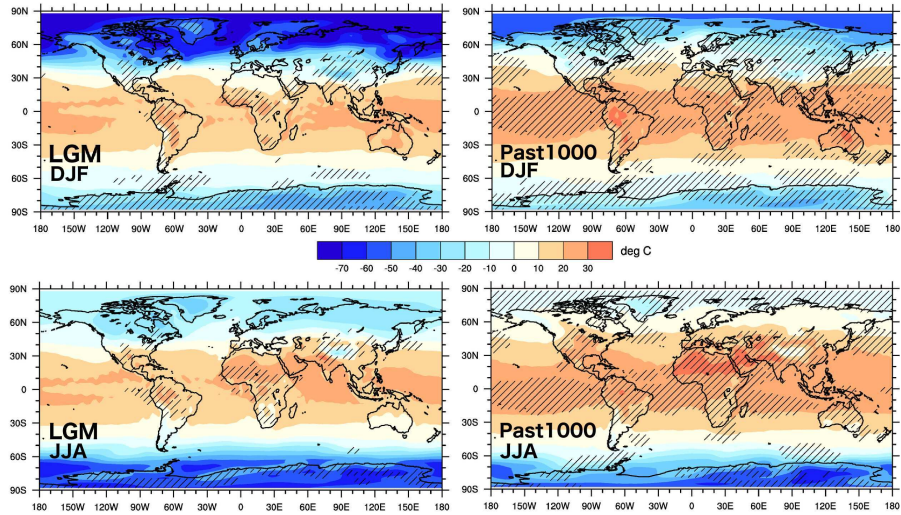
- 15 The only greenhouse gas explicitly handled in PlaSim is carbon dioxide (CO<sub>2</sub>). In this study, other trace gases are accounted for by defining an effective CO<sub>2</sub> concentration value that yields radiative changes equivalent to the combination of CO<sub>2</sub>, nitrous oxide (N<sub>2</sub>O) and methane (CH<sub>4</sub>). Effective CO<sub>2</sub> concentrations were defined with respect to reference CO<sub>2</sub> concentrations at year 22.3ka BP using the equations in Ramaswamy et al. (2001). This reference year was chosen, because both N<sub>2</sub>O and CH<sub>4</sub> values were at a relative minimum at that time, and this year precedes the period of interest for our study. Data for CO<sub>2</sub>, N<sub>2</sub>O
- 20 and CH<sub>4</sub> concentration changes over the deglaciation are consistent with the prescriptions of the PMIP4 Deglacial experiment [except for CO<sub>2</sub>, which uses an older dataset](#) (see Ivanovic et al. (2016) and data sources Luthi et al. (2008) Meinshausen et al. (2017), ~~Ivanovic et al. (2016)~~, and Loulergue et al. (2008)). Effective CO<sub>2</sub> concentration values are updated every simulation year, and are linearly interpolated in time between available data points as needed.

### 2.2.5 Model Evaluation

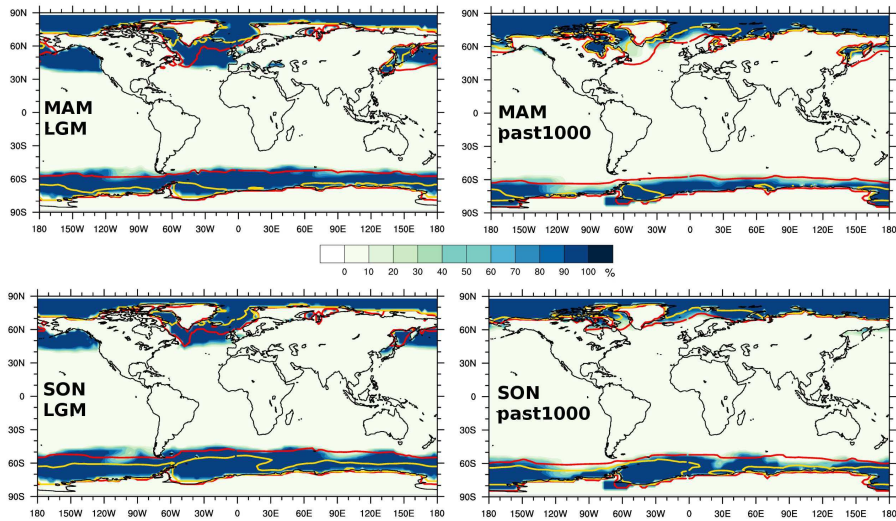
- 25 We compare the climate conditions during the first and last century of the fully-transient PlaSim simulations ([corresponding to forcing years 21-20ka BP and 1ka BP to ~~1950AD, respectively~~1950CE, respectively, due to acceleration](#)) to the results of LGM and past1000 experiments in the Climate Modelling Intercomparison Project (CMIP) 5. Only CMIP5 simulations that include experiments using the same model configuration for both LGM and past1000 are included here, as tabulated in Supplementary Table S1.
- 30 In Figures 2 and 3, near-surface temperatures (T2m) and sea ice concentrations are plotted for ensemble averages of the first and last centuries of the fully-transient PlaSim simulations. Hatching in Figure 2 indicates where the PlaSim ensemble average T2m lie within the range spanned by the CMIP5 multi-model ensemble members (interpolated to the same resolution). Red and gold lines in Figure 3 identify CMIP5 multi-model ensemble maximum and minimum sea ice extents during the same season, respectively. The surface climate is colder and sea ice more extensive during LGM in the PlaSim simulations than the CMIP5 multi-model ensemble members for both DJF and JJA. This is particularly true in the northern high latitudes, where temperatures over the Arctic Ocean lie below all CMIP5 ensemble members and sea ice is anomalously extensive in the NPac and on the eastern side of the NAtl. In contrast, Antarctic temperatures lie within the range of CMIP5 models, and Southern Ocean sea ice is close to the CMIP5 maximum.

- Most of these disagreements are resolved by the past1000, when PlaSim-predicted temperatures and sea ice concentrations
- 5 lie within the CMIP5 range in most regions. However, temperatures remain anomalously cold over the Arctic during DJF and over oceans in the midlatitudes in both hemispheres and seasons, and sea ice extent exceeds the CMIP5 maximum in the Southern Ocean during JJA. These differences are discussed in more detail in Appendix section A1.



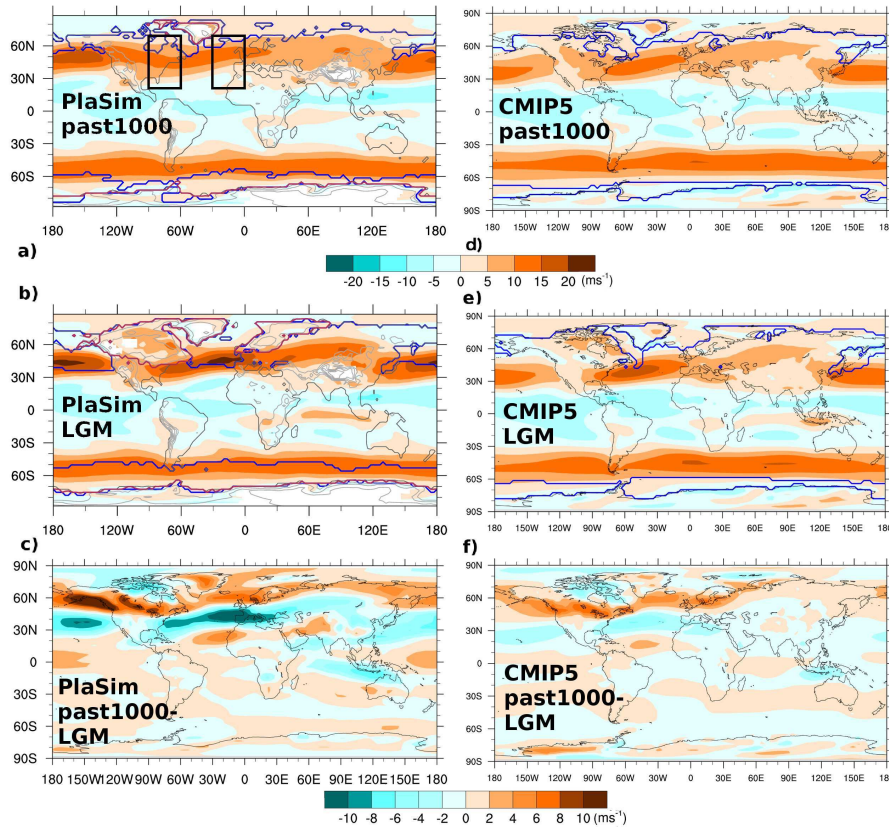


**Figure 2.** 2m temperatures averaged over all PlaSim ensemble members for indicated seasons and periods. Hatching indicates where the PlaSim ensemble average values lie within the range of CMIP5 models.



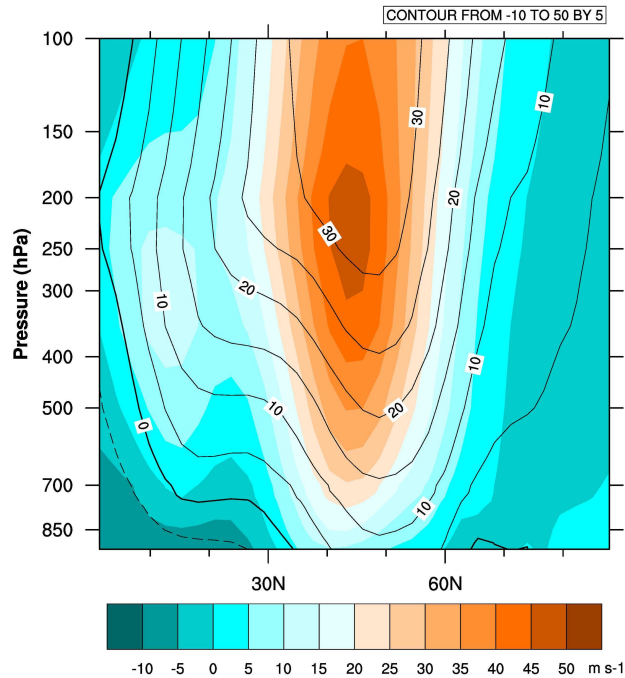
**Figure 3.** Maps of sea ice concentration averaged over all PlaSim ensemble members for indicated seasons and periods. The CMIP5 multi-model maximum extents denoted by the 15% concentration line are plotted for corresponding seasons and experiments in the red lines. The CMIP5 multi-model minimum extents are plotted in the gold lines.

Lower-level zonal winds from both PlaSim and CMIP5 averages are plotted in Figure 4 for DJF with the sea ice margin outlined in blue. Zonal winds during the past1000 in the PlaSim simulations lie within the range covered by the CMIP5 multi-model ensemble except over North America and central Eurasia, where winds are stronger in PlaSim. Also, the ~~path-of-the~~



**Figure 4.** Zonal winds averaged over 700 to 925hPa and averaged over all PlaSim ensemble members or CMIP5 multi-model ensemble members for DJF and indicated periods. [Where the land surface impinges on the vertical range, winds are interpolated to not bias the vertical average. Further discussion can be found in Section 4.](#) Differences between climatologies for these two periods are in the bottom row. Blue lines mark the outline of the 15% concentration line for sea ice, and purple lines mark the land ice mask in PlaSim simulations. Black boxes outline the regions over which the western and eastern components of the NATl jet are evaluated.

NPac jet is displaced further north and is more tilted in the PlaSim past1000 simulations. [During For](#) the LGM, [peak-northern midlatitude](#) zonal winds from [the](#) PlaSim simulations are stronger than [those from](#) the CMIP5 multi-model ensemble [in-northern midlatitudes, and the peak winds of-](#). Also, the [strongest winds of both the NATl and the NPac](#) jets are shifted further east toward the eastern margins of [the-northern-their respective](#) ocean basins. We speculate that this eastern shift is connected to the much more southern extent of sea ice on the eastern side of the NATl, [as was found in CAM3 simulations forced by present-day ice sheets with LGM sea surface temperatures and sea ice extent \(Lofvestrom et al., 2016\)](#). In spite of these specific differences, the pattern of wind changes from the LGM to the past1000 are similar [in-both-\(but differ in magnitude\) between the](#) CMIP5 and PlaSim runs (including during JJA, not shown) [even though the differences are stronger in the PlaSim transient simulations.](#)



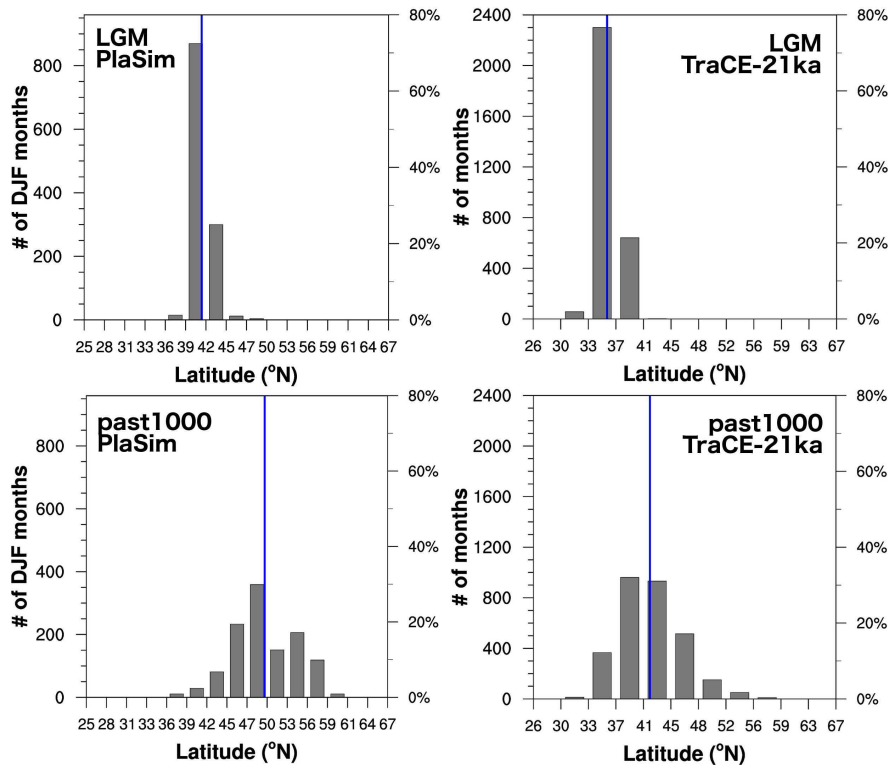
**Figure 5.** Ensemble average of zonal wind profiles for the NATl for LGM in coloured contours and past1000 in contour lines.

### 3 Results and Discussion

#### 3.1 Differences between the LGM and past1000 Climates

We begin by comparing in more detail the characteristics of the NATl eddy-driven jets during LGM and past1000. ~~The peak winds of the subtropical and eddy-driven jets derived from DJF zonal wind profiles in Figure 5 occur at similar levels in the upper troposphere during both periods. In contrast, only the eddy-driven jet continues to have a strong influence on winds in the lower troposphere. Therefore, as in~~ As in Woollings et al. (2010), eddy-driven jet latitudes are defined for the remainder of this analysis to be the location of maximum zonal winds averaged over the NATl basin within 15°N to 75°N and over atmospheric levels 700hPa to 925hPa. Unlike Woollings et al. (2010), however, these latitudes are defined from monthly data (without low-pass filtering) over longitudes of 90°W to 0°W ~~and~~. Unless otherwise indicated, the monthly jet latitudes are aggregated over 10 consecutive DJF periods to generate jet latitude frequencies. NATl eddy-driven jet tilt is defined to be the difference between ~~the jet latitudes calculated in the same manner from zonal winds averaged over 90°W to 60°W and 30°W to 0°W, denoted the western and eastern regions of the jet, respectively, and outlined by black boxes in Figure 4.~~

The NATl eddy-driven jet ~~in these simulations~~ is stronger, narrower, and shifted equatorward at LGM compared to past1000 ~~according to the profiles of in these simulations according to~~ low-level ~~winds~~ wind profiles in Figure 5 and histograms for the jet latitudes in Figure 6. The mean jet latitude shifts from 41°N to 50°N (with a grid cell length of 2.8°) from LGM to

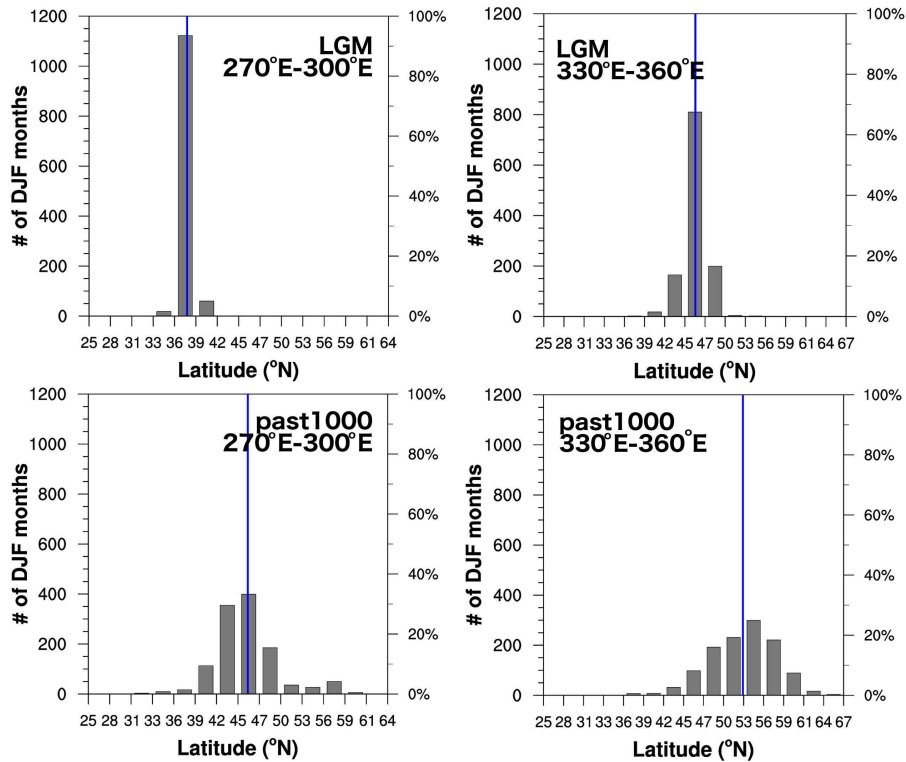


**Figure 6.** Histograms of latitudes corresponding to peak NATl zonal winds for all PlaSim ensemble members (left column) and the TraCE-21ka data (right column) during indicated periods. [Monthly jet latitude statistics are aggregated over 100 simulation years and four ensemble members for PlaSim and 1000 simulation years for the TraCE-21ka simulation.](#) Vertical blue lines indicate mean jet latitudes for the time period.

10 the past1000 ~~in the PlaSim simulations~~. A shift of ~~the same similar~~ size is observed on both the ~~upstream and downstream~~ western and eastern regions of the eddy-driven jet (Figure 7)-, ~~so there is little change in mean tilt values between these two periods (Figure 8).~~ This result stands in contrast with results from Li and Battisti (2008) , and Lofverstrom et al. (2014) , ~~where at LGM the NATl eddy-driven jet is less tilted than during the preindustrial or present period. This issue will be discussed in more detail in Section 4.~~

5 ~~Although the range of jet latitudes broadens from the LGM to the past1000, the increase is asymmetrical.~~ The lowest latitude occupied by the jet remains ~~mostly~~ unchanged between these two periods, while the highest latitude occupied by the jet increases by 11°. This ~~reflects both an increased range of NATl~~ ~~asymmetry is consistent with the subtropical jet providing a dynamical limit on the southernmost position of the~~ eddy-driven jet ~~latitudinal variations as well as an asymmetric change to the shape of the jet latitudinal distribution. Whereas the jet latitudinal distribution is weakly bimodal that cause equatorward-propagating waves to break (Barnes and Hartmann, 2011) . The wave breaking accelerates the westerly flow~~ locally, which strengthens the eddy-driven jet in its southern position at LGM and creates a weakly bimodal jet distribution

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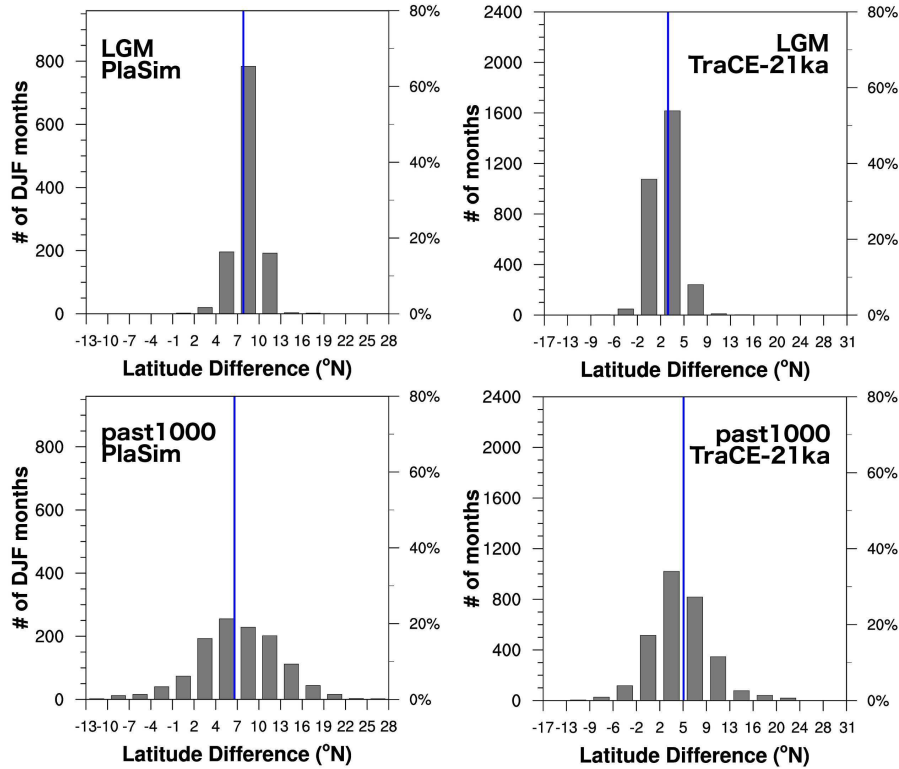


**Figure 7.** Histograms of latitudes corresponding to peak NATl zonal winds for all PlaSim ensemble members over the western and eastern regions of the jet during indicated periods. Vertical blue lines indicate mean jet latitudes for the time period.

at past1000 when ~~calculated over the entire geographic range of the NATl jet (as in Barnes and Hartmann (2011) and similar to the central and northern mean jet latitude shifts north (similar to Barnes and Hartmann (2011) and the southern and central positions of Woollings et al. (2010)), it is unimodal at LGM.~~ Such asymmetry is apparent on both sides of the jet, although there is a larger northward increase in the jet latitude range on the western side than on the eastern end. Thus, the range of jet tilts (downstream minus upstream latitude) increases from LGM to past1000 slightly more in the negative direction.

In contrast, the mean tilt values in Figure 8 change little from LGM to past1000. Instead, the most prominent difference in the jet tilt between LGM and past1000 is in its distribution: at past1000, the fraction of time that the jets spends in its preferred jet tilt position is smaller and its range of values is larger. This difference reflects a shift away from a single, preferred jet latitude on both the eastern and western sides of the eddy-driven jet, and an increase in the range of both.

The Changes in the NATl eddy-driven jet ~~changes~~ from LGM to past1000 in the PlaSim simulations are compared against changes in the only publicly-available fully-transient, coupled deglacial simulation (TraCE-21ka, Liu et al. (2009); He (2011); Liu et al. (2012)) in the right columns of Figures 6 and 8. Jet histograms for TraCE-21ka are calculated in the same way as for the PlaSim simulations, except that the data are binned according to the lower resolution of this simulation (T31, equivalent to 3.7° of latitude). Although the mean jet positions ~~and jet distributions over years 1000ka BP to 1950 AD are different~~ differ



**Figure 8.** Histograms of jet tilt for the PlaSim ensemble (left column) and TraCE-21ka fully-transient simulation (right column) over indicated periods. Vertical blue lines mark the mean jet tilt for each period.

between the two datasets, the changes from the LGM to the past1000 are quite similar between TraCE-21ka and the PlaSim ensemble. In TraCE-21ka, the mean jet latitude shifts poleward by approximately  $6^\circ$ , which is (less than a grid cell smaller than the change in the PlaSim ensemble. The). Also, the minimum jet latitude remains unchanged, and the maximum jet latitude expands-increases by  $18^\circ$ . The mean-tilt for the jet shifts slightly higher in

Differences between the PlaSim ensemble and the TraCE-21ka simulation primarily arise with respect to the jet tilt. The mean jet tilt increases by approximately  $2^\circ$ . Note that this value is less than that calculated in Lofverstrom and Lora (2017) from TraCE-21ka data (between  $3^\circ$  and  $4^\circ$ ), but they calculated jet tilt from upper-tropospheric winds and different longitude ranges in the western and eastern regions of the NATl jet ( $270\text{-}300^\circ\text{E}$  and  $330\text{-}360^\circ\text{E}$  in this study versus  $280\text{-}290^\circ\text{E}$  and  $340\text{-}350^\circ\text{E}$ ). However, either value of jet tilt change in the TraCE-21ka dataset-by-the-past1000, but the most common-tilt-value-remains unchanged-from-the-LGM.-

The distributions-of-jet-latitude-are-not-Gaussian-in-either-simulation is larger than that detected in the PlaSim simulations, and asymmetries in the increase in the range of jet tilt are opposite for these two datasets. Examining the eastern and western sides of the jet separately, the distributions in both regions change more similarly from LGM to past1000 in TraCE-21ka than in the PlaSim simulations or-the-TracE-21ka-simulation, so-assessing-changes-to-these-jetcharacteristics-over-the-deglaciation-via

their means and standard deviations can lead to misleading interpretations of the changes that are occurring. Such differences in interpretations can have important implications for heat and moisture transports to the northern NATl and north-western Europe. Thus, we characterize changes to (see Supplemental Figure S2). Also, there is no evidence of jet bimodality in any of the regions for the TraCE-21ka experiment, which may be due to the jet's being located further south.

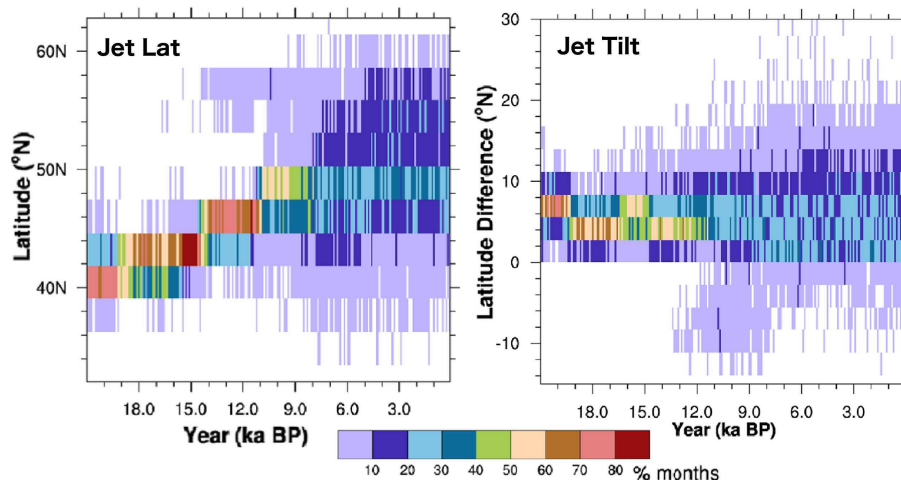
Having shown that there are changes in both the jet location and its distribution from the LGM to the distributions of jet attributes as we analyse the simulations over the deglaciation, past1000 in the PlaSim simulations, and that these changes are similar to those occurring in the TraCE-21ka experiment, we now analyse how these changes arise in time.

### 20 3.2 Transitioning from LGM to past1000

The motivation of this study is to assess the potential impact of atmospheric changes in the NATl on the abrupt deglacial changes detected in Greenland ice cores, so we start by discussing climate changes over Greenland. None of the transient simulations presented here produce abrupt ~~oseillations transitions~~ between stadial and interstadial conditions ~~at the time over Greenland at the historical times~~ of the OD, B-A, ~~and or~~ YD. Instead, the accelerated runs all show a single abrupt increase in Greenland temperatures (~~not shown~~) that occurs at different times for each simulation between 12ka BP and 5ka BP. This appears to be a manifestation of internal variability of the model, as the timings of the changes do not coincide between ensemble members and an identically-forced simulation without acceleration exhibits five such abrupt changes over the course of the deglaciation. ~~The characteristics of~~ Further details about this phenomenon will be discussed in another paper.

~~The accelerated transient simulations do show changes~~ Due to the absence of abrupt climate changes over Greenland, we ~~conclude that the changes~~ in the position, tilt and variability of the NATl eddy-driven jet ~~, but these changes do not coincide with the~~ are not sufficient on their own to generate large-amplitude ~~climate oseillations~~. Nevertheless, this absence does not rule out the possibility that jet changes may have played an important role in historical ~~, abrupt climate changes via in PlaSim~~. It may be that feedbacks between the atmosphere, ocean, land ice and sea ice that are not captured in the simulations here ~~are important in abrupt changes~~. For example, one very plausible process that is missing from PlaSim is the effect of winds ~~on sea ice~~. Furthermore, this absence of simulated abrupt climate change does not rule out the possibility that the discerned atmospheric dynamical changes were important to historical abrupt climate changes through their controls on the background climate state. Thus, we characterize the atmospheric changes present in the accelerated transient simulations and leave further assessments of their implications for future work.

~~The following results~~ Deglacial changes to NATl jet distributions are presented via frequency plots that use colour to illustrate the percentage of months in ten successive winter seasons (DJF) that the jet occupies a given latitude band or tilt plotted as a function of latitude and time. Ten years of winters are chosen as a balance between providing sufficient statistics (30 months) to be able to characterise the distribution of jet characteristics and a desire for high temporal resolution to assess the abruptness of changes. Only ensemble statistics are presented, as deglacial changes over time occurred similarly in all ensemble members. Frequency plots for jet latitude and tilt changes over the deglaciation for each ensemble member individually can be found in Supplemental Figures ~~S2 and S3~~ ~~and S4~~.



**Figure 9.** Frequency maps of NATl ~~lower-level, mean~~ jet latitudes and tilt ~~in-averaged over 700hPa to 925hPa and aggregated over 10 successive winter seasons accumulated over and~~ all ensemble members of the FullyTrans experiment. ~~Colours indicate~~ Winds are averaged over 270°E to 360°E when calculating jet latitude, and tilt is defined as the difference in latitudes calculated over 330°E to 360°E and 270°E to 300°E. Frequencies represent the percentage of months ~~with peak zonal winds within~~ (out of a total of 120 months) that the jet was identified at a particular latitude, where each latitude bin ~~of~~ has a width of 2.8° at T42.

The ~~As discussed in Section 3.1, the~~ low-level, NATl jet ~~exhibits a narrow~~ is situated further south and exhibits a narrower range of latitudinal variability in the FullyTrans runs at the start of the deglaciation ~~in-compared to its end~~. In Figure 9, ~~with the peak winds occurring~~ peak winds occur at the same latitude for more than ~~half~~ two-thirds of the months. ~~However, the latitude at which the jet is preferentially situated~~ from 21ka BP to approximately 19ka BP, whereas the jet is only situated at its preferred latitude less than 40% of the time from 8ka BP onward. The two different types of deglacial jet changes (the latitudinal shift and the change in the shape of its distribution) occur separately over the deglaciation. In the first type of change, the median jet latitude shifts northward three times over the deglaciation in all ensemble members. The shifts occur around 19ka BP, 14ka BP and ~~11ka~~ at 11.0ka BP in all simulations, but the abruptness is not the same for all shifts. The first transition is ~~a gradual one, with a gradual reduction in the frequency of time that the jet spends at the lower latitude at the same time as~~ a gradual increase in the frequency spent at the next grid cell clearly gradual, as the jet spends nearly a century of simulation (a millennium of forcing) with its time nearly equally split between two grid cells before shifting to spending most of its time at the more northern latitude. In contrast, the ~~second and third transitions occur~~ third transition occurs within a decade of simulation (a century of forcing) and shows little evidence of such mixed states.

A ~~In the~~ second type of transition is evident in the FullyTrans results in jet change evident in Figure 9, whereby the frequency of time that the NATl eddy-driven jet spends at its preferred median latitude decreases, and the range of jet latitudes increases. This reduction in frequency ~~occurs gradually over a few centuries of simulation, and begins after 11ka BP and is completed by 8ka BP,~~ but its timing differs between ensemble members (see Supplemental Figure S3). Note that the development of an



isolated northern branch of mean jet latitudes sometime between 15 and 14ka BP in Figure 9 is an artifact due to a computed contribution from a split jet stream over North America. This issue is discussed in more detail in Section 3.3 and Supplemental Section S2.

Ensemble statistics for the NATl jet tilt in the FullyTrans runs in Figure 9 show oscillations between the preferred jet tilt of LGM and a more zonal configuration. ~~These switches occur just prior to 19ka BP, sometime between 17 and 16ka BP, and between 15 to 14 ka BP. The first transition occurs within one decade of simulation, while the other two transitions are much more gradual. Finally, the jet shifts away from a preferred tilt position between 12ka BP and 11ka BP, while the range of jet tilt values increases later.~~

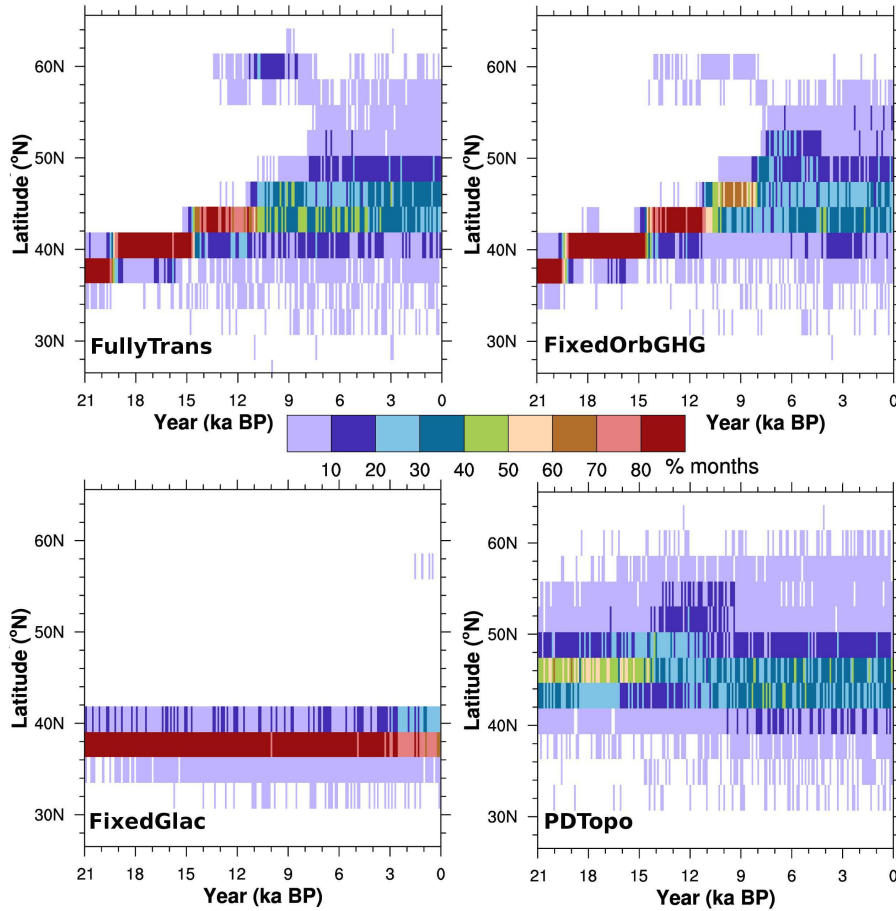
~~Frequency maps of NATl, lower-level, western jet latitudes in 10 successive winter seasons accumulated over all ensemble members of the FullyTrans, FixedOrbGHG, FixedGlac and PDTopo experiments. Colours indicate the percentage of months with peak zonal winds within each latitude bin of width 2.8° at T42.~~

~~Frequency maps of ensemble-average, NATl, lower-level, eastern jet latitude in 10 successive winter seasons for FullyTrans, FixedOrbGHG, FixedGlac, and PDTopo experiments. Colours indicate the percentage of months with the difference in jet latitudes between 330°E to 360°E and 270°E to 300°E within each bin of width 2.8°.~~

~~The These changes in jet tilt reflect the very different behaviours with time of the upstream (western, western (270°E to 300°E) and downstream (eastern, eastern (330°E to 360°E) sides of the NATl eddy-driven jet, which are outlined by black boxes in Figure 4. Ensemble average changes in jet latitude in the western and eastern regions of the NATl eddy-driven jet are shown in Figures 10 and 11 shown in Figures 10 and 11. Nevertheless, by the end of the deglaciation, the jet on both its western and eastern sides has shifted northward by a similar amount, leading to little net change in jet tilt.~~

The western side of the jet over NAmer is very focussed and narrowly-distributed, with more than 80% of the winter months spent at the same latitude for most of the deglaciation. The preferred latitude shifts northward twice ~~within a single decade of simulation,~~ at 19.3ka BP and 14.6ka BP, and each shift is completed within a decade of simulation. The timing of these transitions match the more gradual first two (more gradual) shifts in the jet as a whole and two occasions when the tilt is reduced. They are also are consistent with the historical timing of the start of the timings of the OD and B-A. They also correspond to reductions in the jet tilt. The transition away from a preferred jet latitude occurs more abruptly than for the jet as a whole at 10.910.8ka BP. The steady, focussed nature of the western side of the jet under glacial conditions increases its importance for Sverdrup transport in the surface ocean, and conversely, as it becomes more latitudinally-variable, its effectiveness in generating a net transport in the surface ocean reduces (Li and Born). Thus, both the shifting of the focussed, western jet northward and its move to a more broadly-distributed state have important implications for the wind-driven ocean circulation of the NATl.

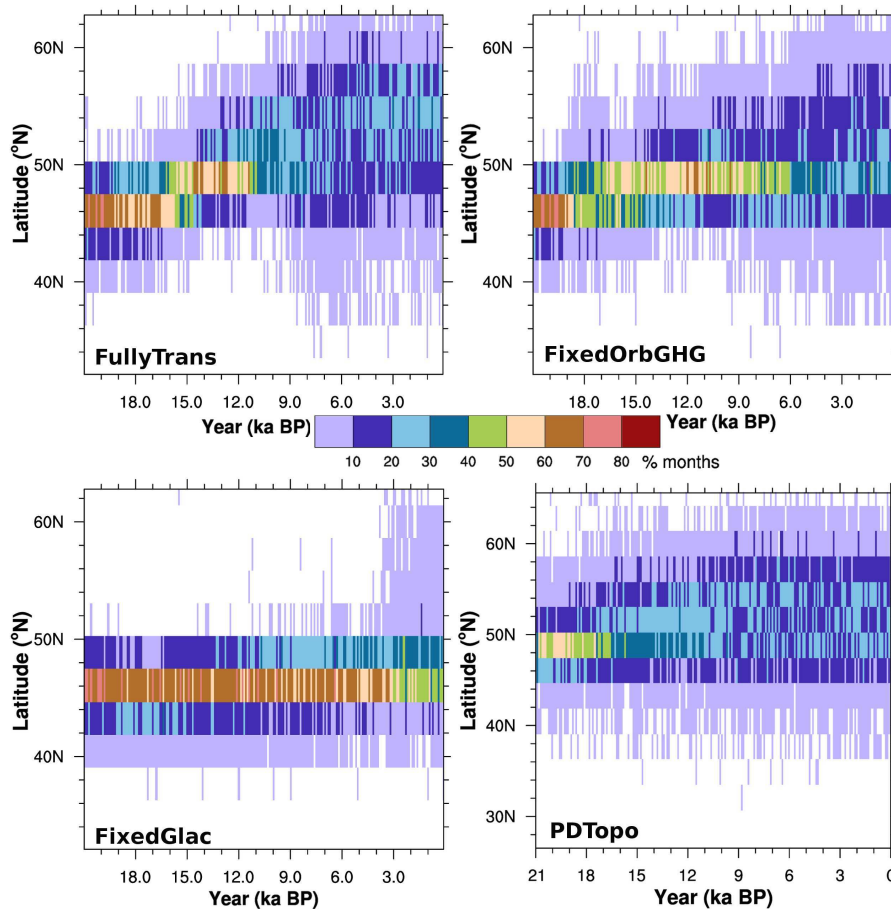
In contrast, in Figure 11 the eastern side of the jet over the eastern NATl is less focussed than the west, with the jet occupying its preferred latitude 50 to 6070% of the time. There is a single, gradual, northward shift in the eastern region, occurring more gradually than on the west, between 16 and 15ka BP. This change is a little later than the time of increasing jet tilt. The eastern side of the jet moves away from any ~~preferred latitude between 12ka BP and 11ka BP~~ single, preferred latitude after 11.4ka BP, near the historical end of the YD and start of the Holocene.



**Figure 10.** Frequency maps of NATl, western jet latitudes based on winds over 700hPa to 925hPa and 270°E to 300°E in 10 successive winter seasons accumulated over all ensemble members of the FullyTrans, FixedOrbGHG, FixedGlac and PDTopo experiments. Colours indicate the percentage of months with peak zonal winds within each latitude bin of width 2.8° at T42.

### 3.3 **Attributing causes of simulated jet transitions**

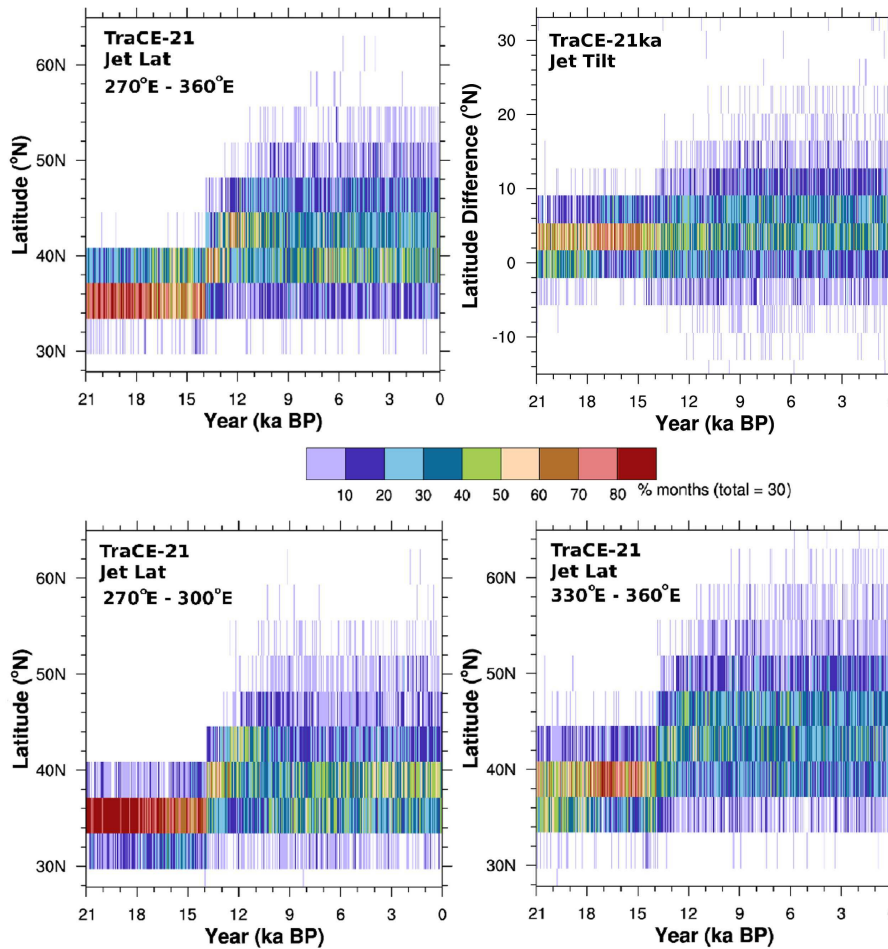
In order to attribute the deglacial jet changes to boundary condition changes, we turn to the sensitivity experiments. Since the sources and characteristics of the variations ~~The TraCE-21ka experiment reproduces both types of jet changes detected in the PlaSim simulations, although the timings of jet shifts are not the same. At LGM, the jet is highly focussed with a narrow range of values, and its primary latitude shifts northward two times over the deglaciation (Figure 12). Unlike the PlaSim simulations, the first northward jet shift occurs within one decade of simulation at 13.87 ka BP, which coincides with a change in the ice sheet boundary conditions and freshwater forcing provided to the model (He, 2011). As in the PlaSim simulations, this change is driven by a shift~~ on the western and eastern sides side of the jet differ, we present the results of the sensitivity experiments separately for these two regions in Figures 10 and 11. This separation makes it much easier to identify what changes are



**Figure 11.** Frequency maps of ensemble-average, NATl jet latitudes based on winds over 700hPa to 925hPa and 330°E to 360°E in 10 successive winter seasons for FullyTrans, FixedOrbGHG, FixedGlac, and PDTopo experiments. Colours indicate the percentage of months with the difference in jet latitudes between 330°E to 360°E and 270°E to 300°E within each bin of width 2.8°.

~~occurring and attribute their causes than examinations of the mean jet position over the entire range or its tilt, where the influences on the western and eastern sides are mixed. As such, we argue that analyses over these separate regions are more instructive than the standard position and tilt metrics, and would encourage other authors to present these metrics instead. For those interested, sensitivity~~ plotted in the bottom-left panel of Figure 12. The second shift is much more gradual and occurs from 13 to 12.5ka BP. This second transition appears to be an artifact of more gradual and asynchronous changes in the western and eastern sides of the jet.

The transition away from the NATl jet occupying a single latitude more than 50% of the time in TraCE-21ka occurs more gradually and begins a little earlier than in the PlaSim simulations. This transition is complete by approximately 11ka BP and the range of jet values continues to increase until 6ka BP.



**Figure 12.** Frequency maps for the NATl jet derived from the TraCE-21ka deglacial experiment over 700hPa to 925hPa for jet latitudes evaluated over longitudes 270°E to 360°, as well as the upstream (270°E-300°E) and downstream (330°E-360°E) regions and their difference (i.e. jet tilt).

10 The NATl jet tilt in Figure 12 calculated from the TraCE-21ka experiment exhibits no change over the deglaciation. This result stands in contrast to Lofverstrom and Lora (2017), who diagnosed a rapid increase in jet tilt at 13.89ka BP. The source of this discrepancy is discussed further in Section 4.

15 Thus, the NATl jet exhibits changes in position and distribution that occur independently of each other in both PlaSim and TraCE-21ka simulations. Some of these changes coincide with historical climate changes. Since these jet characteristics and the timings of their changes differ on the eastern and western sides of the NATl jet, we attribute them separately in the next section.

### 3.3 Attributing causes of simulated jet transitions

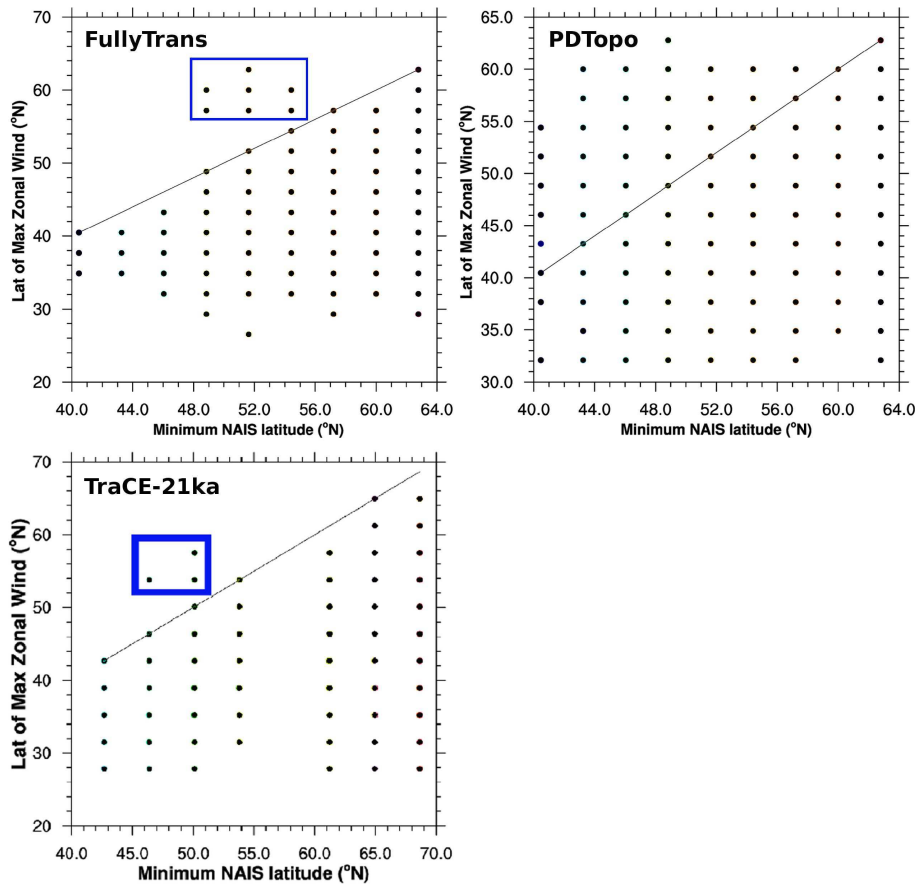
In order to attribute the deglacial jet changes to boundary condition changes, we turn to the sensitivity experiments, plotted in Figures 10 and 11 for the western and eastern regions, respectively. Sensitivity results for the mean jet position and tilt are presented in Supplemental Figures S5 and S6 and S7.

Ice sheets provide the primary controls over the deglacial jet changes described in the previous section. Simulations with fixed LGM ice sheets (FixedGlac in Figures 10 and 11) reproduce neither the deglacial changes to mean-preferred jet latitude nor the bulk of changes to its variability on the western and eastern both sides of the jet. This effect is most prominent for the western side of the jet, which shows very little almost no change over the deglaciation when the ice sheets are fixed. In contrast, while the eastern jet favoured position to their LGM state. In the east, the preferred position of the NATl jet does not change under fixed LGM ice sheets, its variability does increase in response to the but the frequency of time the jet spends at this latitude decreases, and its range of variability increases. Only orbital and greenhouse gas changes. The component forcings are changing at this time, so this may indicate a sensitivity to those forcings (perhaps mediated by the changing sea ice extent and sea surface temperatures).

Other sensitivity experiments can help decompose which attributes of the ice sheets that appears most important to this effect is their elevation, as simulations with infinitesimally thin but extensive ice sheets (PDTopo) are unable to reproduce the narrow, are enacting this control on the NATl jet. The PDTopo experiment isolates the thermal forcing associated with ice sheets' relatively high albedo from the orographic forcing due to the elevation of the ice sheet by fixing ice sheet thickness to present-day values while allowing ice sheet area to vary. Thus, LGM ice sheets are infinitesimally thin but extensive. In neither the east nor the west is the NATl jet as focussed, or as equatorward-shifted jet seen in PDTopo (Figures 10 and 11) as it is at LGM in the FullyTrans runs or throughout the FixedGlac runs. Further experiments are required to discern the importance of orography in particular. Consequently, we conclude that the ice sheet albedo alone is not the primary controlling factor on the NATl jets, and that the elevation of ice sheets is important. However, it is not clear from the present experiments whether orographic changes to the ice sheets alone are sufficient to explain the jet changes, or whether the ice sheets need to be reflective. Since the ice sheets became quickly covered with highly-reflective snow in the DarkGlac simulations, that experiment did not resolve this question.

Additional experiments are required to unequivocally isolate the regions of the ice sheets to the jet characteristics whose orography is affecting the NATl jet. Yet, a relationship can be identified between the latitude of the western side of the jet and the minimum latitude of the south-eastern margin of the NAIS in scatter plots based on the FullyTrans and TraCE-21ka experiments (Figure 13).

The western side of the jet either reaches or lies south of the 725m contour along of the south-eastern NAIS margin at all times in the FullyTrans simulations and south of the 1000m contour in the TraCE-21ka experiment. The only exception to this is when the wind branch along the north-eastern slope of the NAIS is identified by the algorithm as having the fastest winds (points located within the blue box boxes in Figure 13). This number was arrived at empirically and represents the lowest tested threshold that did not have instances of the western side of the NATl jet exceeding its location.



**Figure 13.** Scatter plots for monthly NATl jet latitudes from 700hPa to 925hPa on the western side of the Atlantic (270°E - 300°E) versus the minimum latitude of the NAIS east of 260°E (whose contour is defined by 725m for PlaSim simulations and 1000m for TraCE-21ka) for all FullyTrans and PDTopo ensemble members and TraCE-21ka. Note the PlaSim latitudes are calculated on the T42 grid, and the TraCE-21ka latitudes are calculated on the T31 grid. Blue boxes identify points associated with the northern jet latitude branch.

It should be noted the jet does not always move to the latitude of the ice sheet margin. This may be due to other controls on the western side of the jet restricting its movement, or more likely, that the barrier effect depends on the pressure level at which it is applied (which is not fixed to a given elevation over the deglaciation) rather than absolute elevation. There is no such clear relationship with the latitude of the eastern side of the jet (not shown), nor with the latitude of the western side of the jet when the ice sheet is infinitesimally thin in PDTopo. Thus, it appears that the elevated southern margin of the NAIS acts as a physical barrier to the eddies and restricts the positioning of the jet on its northern side. Additional evidence for this is found in the fact that two other simulations generated using PlaSim under different background conditions (i.e. starting from a warmer state and without acceleration, described in Appendices A1 and A2) show western jet shifts at the same time as the FullyTrans simulations. Yet, the jet does not always move to (right side of Figure 13). Since the albedo of the south-eastern

margin of the NAIS is insufficient on its own to restrict the latitude of the jet. This may be due to other controls on the western side of the jet restricting its movement, or more likely, that the barrier effect of the elevation depends on the pressure level at which it is applied (and the vertical profile of pressure will change over the deglaciation), it appears that the margin must be elevated to restrict the jet. Whether this barrier effect is enacted via dynamical processes alone or is amplified by the thermal gradient associated with the ice sheet's albedo and lapse rate is not distinguishable from the experiments here.

Scatter plots for monthly NATl jet latitudes on the western side of the Atlantic (270°E–300°E) versus the minimum latitude of the 725m contour line of the NAIS east of 260°E for all FullyTrans and PDTopo ensemble members. Note these latitudes are calculated on the T42 grid. The blue box identifies points associated with the northern jet latitude branch.

The consequences of this restriction are that the western end of the ice sheet's acting as a barrier to the winds in the western region of the NATl jet explains many of the deglacial changes discussed earlier.

– The western side of the jet is more focussed relative to a single latitude than the eastern side, particularly when the NAIS extends well into the midlatitudes, and that the northern range of the western side. This is because the barrier is being applied to the winds in the western region of the jet, increases much more over the deglaciation than its southern range. No ice sheet provides such a restriction to the eastern, but not the eastern region.

– The preferred latitude of the western side of the jet shifts northward in a step-wise fashion. The ice sheet mask and topography are specified on the model grid, so the jet in this region is never as focussed as in the west and is more symmetrical in its distribution. The absence of this barrier effect is able to move northward into a grid cell as soon as the ice sheet retreats from it. Without the ice sheet barrier effect, the preferred tilt in the PDTopo experiment in Figure 10 is characterized by a more northern position for the preferred jet latitude in the early part of the deglaciation, a lower frequency of time spent at the preferred position, and a broader distribution of values. The preferred tilt in the PDTopo experiment is near zero, as the positions of the western and eastern sides is much smaller than in FullyTrans and does not change over the deglaciation (Supplemental Figure S7), as the western and eastern sides of the jet appear to shift together.

– The distribution of the western side of the jet during most of the deglaciation is strongly skewed with the jet spending the bulk of its time at the northern boundary of its range. In contrast, the jet distribution in the eastern region is more symmetrical. As long as the ice sheet continues to impinge on where the jet would preferentially be located in the absence of the ice sheet, the wind shear along the northern edge of the jet appear to coincide and shift together, remains very strong. Thus, eddies tend to break along this boundary and accelerate the flow there. This further keeps the jet preferentially in its northernmost position. Since there is no such constraint on the jet in the eastern region, it is free to vary equally in both directions around its mean position.

Ice sheet orography Although ice sheet orography appears most important to NATl jet changes, it does not provide the only controls on the jet. Fixing the radiative forcings to their LGM values (FixedOrbGHG in Figures 10 and 11) delays the transition away from a strongly preferred jet latitude on both sides of the NATl eddy-driven jet, but particularly in the east. The timing

of the ~~original-first~~ two western jet latitude shifts are unaffected by changes to the radiative forcings ~~,-although since these are primarily driven by ice sheet changes. However,~~ an additional shift occurs after 11ka BP ~~in the western region of the NATl jet~~ when the radiative forcings are fixed ~~.-In contrast to their LGM values, and the jet shifts away from a single, preferred jet location later than before at 8ka BP. In the eastern region,~~ the shift in latitudes occurs earlier ~~on the eastern side of the jet,-~~ and no further change to the preferred range of ~~than in FullyTrans, but the jet latitudes occurs following this. Additionally,~~ the changing radiative forcings in FixedGlae increases the total latitudinal range on the eastern side of the jet and reduces the frequency of the preferred jet location after 4ka BP. Thus, ~~never reaches as northern a position as it does in FullyTrans. Thus,~~ orbital configuration and greenhouse gases appear to be key for the transition of the jet away from a single preferred latitude to a broader, less peaked distribution, particularly in the eastern region of the NATl jet.

25 Overall, the results presented here indicate that changes to the western side of the jet appear to be predominantly controlled by changes ~~to the position of the southern in the position ice above a critical threshold (725 m in our case) proximal to the south-eastern~~ NAIS margin, while ~~changes to~~ the position of the eastern side of the jet are sensitive to the thermal background conditions of the climate ~~-(which the ice sheets also affect).~~

### 3.4 TraCE-21ka

30 It is unclear the extent to which the results presented so far are model specific. As a test of their generality, we compare these results against those calculated similarly from the TraCE-21ka experiment, which are plotted in Figure 12.-

Frequency maps for the NATl jet derived from the TraCE-21ka deglacial experiment for jet latitudes evaluated over longitudes 270°E to 360°, as well as the upstream (270°E-300°E) and downstream (330°E-360°E) regions. Additionally, a scatter plot is presented of NATl jet latitudes from the upstream end versus NAIS latitude evaluated as the minimum latitude of the 1000m elevation contour between 260°E to 315°E. A blue box outlines points where winds along the northern slope of the NAIS are stronger than those along its southern margin.

5 The NATl-

## 4 Discussion and Conclusions

This paper explores the question of whether winter eddy-driven jet ~~in the changes over the North Atlantic could have contributed to the abrupt climate changes detected in Greenland ice cores over the last deglaciation. Lower-tropospheric winds are most likely to contribute to abrupt, large-scale climate changes either by directly triggering changes in surface ocean circulation patterns and/or sea ice extent (and thereby deepwater formation rates), or by altering the state of these components in a way that makes them unstable to perturbations from another source. Thus, we have assessed the timing and abruptness of changes to the latitudinal position and variability of the North Atlantic (NATl) eddy-driven jet in a small ensemble of transient deglacial simulations using the PlaSim model and the~~ TraCE-21ka experiment reproduces many of the phenomena observed in the PlaSim simulations, but the details of timing and order differ. At LGM, the jet is highly focussed with a narrow range of values. Its primary latitude shifts northward two times over the deglaciation, and its range increases and preference for a particular



latitude decreases. Unlike the PlaSim simulations, simulation. Since none of the PlaSim simulations exhibit large-scale, abrupt climate changes at the time of changes in these properties of the NATl jet, our results provide no support for a direct role for jet changes in triggering historical abrupt climate changes. It is unclear the extent to which model limitations (such as purely thermodynamic sea ice) and run acceleration are contributing to this negative result. However, as we do detect at times abrupt changes in these properties of the jet over the deglaciation, we can not discount the possibility that the first transition occurs abruptly at 13.87 ka BP, which coincides with a change in the ice sheet boundary conditions provided to the model. The second transition is much more gradual and occurs at approximately 13ka BP. The first transition is associated with a change on the western side of the jet, whereas the second transition appears to be an artifact of more gradual and asynchronous changes in the western and eastern sides of the jet. The transition away from the jet occupying any latitude more than 50% of the time occurs earlier than in the PlaSim simulations, by 11ka BP, and the range of jet values increases from then until 6ka BP. set the stage for such events to occur.

The scatter plot in Figure 12 shows that the western side of the NATl eddy-driven jet does not move north of the 1000m elevation level of the NAIS in eastern NAmer. As with the PlaSim simulations, Assessing the abruptness of NATl jet changes is problematic, because the abruptness of a phenomenon depends on its context. During the deglaciation, changes are generally considered abrupt if they occur within a couple of decades and are of sufficient amplitude to appear unusual compared to background climate variability. In this study, additional complication arises from the fact that the wind data is gridded; a latitudinal change in the only exceptions to this are months when the winds south of the ice sheet are weaker than those north of the ice sheet. The ice sheet height threshold required here is higher than that in the PlaSim simulations, whose threshold is closer to 725m. Given the differences in horizontal and vertical resolution between these two models and that the barrier is likely enacted via a pressure threshold rather than an elevation, such a threshold difference is not unexpected. However, the fact that both models exhibit a strong relationship between winds over eastern NAmer and the regional minimum icesheet latitude indicates that changes to the position of the jet in this region can be somewhat predictable. From these results, we hypothesize that different ice sheet reconstructions represented at different resolutions will lead to different timings and numbers of jet shifts, but that the jet over the western side of the NATl will tend to follow the advance and retreat of the southern margin of the NAIS until the margin is sufficiently far north to not interfere with the jet's preferred position. If this hypothesis is correct and this mechanism is as important in reality as it is in models, then the uncertainty in our understanding of the historical position of the jet over eastern NAmer during this period is dominated by the uncertainty in our knowledge of the southernmost position of regional 1000 m (or so) high ice. NATl jet will involve a discrete step from one latitude grid to another. Thus, we consider a jet change to be abrupt (given the decadal resolution of our jet diagnostics) when the jet shifts a dominant median latitudinal position from one grid cell to the next.

Lofverstrom and Lora (2017) diagnose that the eastern side of the NATl jet in the All of the fully-transient deglacial simulations presented here show that the NATl eddy-driven jet shifted northward from the Last Glacial Maximum to the preindustrial period, and its latitudinal variability increased. These characteristics match those derived from other studies (Li and Battisti, 2008; Lofverstrom et al. However, unlike those studies, neither the PlaSim simulations nor TraCE-21 show much change in jet tilt between these two periods. This contrasts with previous work on TraCE-21ka experiment exhibits a rapid northward shift at 13.89ka BP, which

they attribute to the separation of the Laurentide and Cordilleran ice domes within the NAIS. This leads to that identifies an abrupt increase in jet tilt. There is no such increase in tilt detected in the PlaSim simulations, which may be partly explained by a difference in the longitudes over which the tilt is calculated in this study compared to theirs. Instead, we detect a change in the frequency of time that the jet spends in its preferred location: the eastern jet shifts from spending 40-60% of its time near 40° tilt in this dataset that occurred at 13.89ka BP (Lofverstrom and Lora, 2017). These two TraCE-21ka results were obtained from different wind data extracted from the same dataset: lower-tropospheric winds are analysed in this study, while Lofverstrom and Lora (2017) examine upper tropospheric winds at 250hPa. There are additional differences in the range of longitudes used to specify the western and eastern regions of the NATl jet: 280 to 290°N at E and 340 to 350°E, respectively in Lofverstrom and Lora (2017) versus 270 to 300°E and 330 to 360°E in this study. We are able to reproduce the results obtained by Lofverstrom and Lora (2017) (except for the timing, which we date to 13.87ka BP to spending 30-40% of its time there and 40-60% of its time two grid positions north of there. This change would look like an abrupt northward shift in the mean NATl jet position in this region. ka BP) when we calculate the jet tilt in the same manner as they did (figures are presented in Supplemental Figure S5, alongside corresponding figures using the methodology employed in this study). Since Li and Battisti (2008) and Lofverstrom et al. (2014) also derive their tilt results from upper-tropospheric winds, it is not clear how much their results are in conflict with those presented here (Merz et al. (2015) analyse lower-tropospheric winds, but do not discuss tilt changes).

We have diagnosed winter eddy-driven jet changes in the North Atlantic over the last deglaciation along with some of their controls through the use of a small ensemble of transient simulations using the PlaSim model and the TraCE-21ka simulation. Our main context is the potential for these The novelty of this present study compared to those previously mentioned is that it analyses transient changes in the jet to contribute to the abrupt climate changes detected in Greenland ice cores and elsewhere. The expected means by which the jet could contribute to abrupt deglacial climate changes is through the influence of winds on surface ocean circulation patterns (and thereby deepwater formation) and on wintertime sea ice extent. Surface ocean circulation patterns are expected to be particularly sensitive to changes in the variability of low-level winds in the North Atlantic and both components are sensitive to changes in the mean latitudinal position of these winds. We have shown that both of these types of changes occur independently in our simulations. We detect multiple transitions in the mean latitude of the North Atlantic eddy-driven jet over the last deglaciation as well as a more gradual change in its variability. entire deglaciation in multiple experiments. Additionally, instead of characterizing the jet via the Gaussian statistics of its mean and standard deviation, we present the changes with time of the jet distribution itself.

During the last deglaciation, the North Atlantic eddy-driven jet in the PlaSim simulations makes three distinct steps in latitude at The deglacial NATl jet changes arise in the PlaSim simulations via three well-separated northward shifts in latitudinal position (at 19ka BP, 14ka BP and at 11ka BP 11.0ka BP) followed by a gradual transition away from a latitudinally-constrained regime of variability that is complete by 8ka BP in all simulations. The TraCE-21ka experiment exhibits two shifts in the preferred position of the jet (at 13.87ka BP and 13ka BP) contemporaneous with the start of a gradual increase in latitudinal variability.

Interpreting the detected jet changes is complicated by the fact that the NATl jet calculated over longitudes 270°E to 360°E mixes characteristics of the upstream and downstream regions, which we find differ in both timing, abruptness and dependence

on background model conditions. The first two of ~~these shifts~~ the mean jet shifts detected in the PlaSim simulations are driven by changes in the position of peak winds on the upwind region of the eddy-driven jet over eastern North America. ~~Only a single shift in peak winds between 16~~ These shifts are each accomplished within a decade of simulation (century of forcing), and 14ka BP is evident in the downstream region of the eddy-driven jet over the eastern side of the North Atlantic. Thus, the tilt of the jet, diagnosed as the difference in the jet position between these two regions, oscillates between values of approximately 8° and 5° according to the asynchronicity of their shifts. The timings of the latitudinal shifts in the western region of the jet ~~their timings~~ are consistent between ~~the accelerated simulations, an unaccelerated run, and an accelerated transient simulation starting from a warmer initial state. The abruptness of the diagnosed shifts are likely an artifact of the spatial discretization of the model grid, but the two shifts on the western side of the jet both occur within a decade of simulation (a century of forcing).~~ In contrast, the ~~Only in the TraCE-21ka experiment are the timings of these shifts different. In contrast, only a single shift in peak winds between 16 and 14ka BP is evident in the downstream region of the eddy-driven jet over the eastern side of the NATl. The shift on the eastern side of the jet occurs over 200 simulation years (two millennia of forcing), and its timing differs between runs with and without acceleration~~ and, in the warmer transient simulation, and in the TraCE-21ka experiment.

~~The TraCE-21ka experiment also exhibits shifts in the preferred position of the jet, particularly on~~ The different characteristics of changes in the upstream and downstream regions of the North Atlantic jet correspond to different mechanisms of change. While previous work shows that the western side of the jet ~~The shifts in the western jet occur at 13.87ka BP and 13ka BP, with the first transition occurring within a single year of a change in the ice sheet boundary condition and with the introduction of anomalous freshwater into the Nordic Seas and St. Lawrence River. The second transition is more gradual, is more strongly affected by ice sheet orography and the eastern side by stationary and/or transient eddies (Kageyama and Valdes, 2000; Lofvestrom et al., 2005)~~ we identify a more specific relationship between the North American ice sheet complex and the western side of the jet. In both the PlaSim and TraCE-21ka experiments, low-level winds over eastern North America are highly-focussed to the latitude of the ice sheet margin and vary only south of this margin. It is the orography of the south-eastern margin of the North American Ice Sheet complex that appears to play the most important role in this effect, as simulations with spatially extensive but infinitesimally thin ice sheets do not reproduce this effect. However, whether the thermal gradients associated with the elevated ice sheet surface contribute to this effect in a subsidiary way is not clear from this study.

~~The variability of the North Atlantic eddy-driven jet changes from a latitudinally-constrained regime to one with a high degree of latitudinal variability over~~ From these results, we hypothesize that different ice sheet reconstructions represented at different resolutions will lead to different timings and numbers of jet shifts over eastern North America. This was indeed the case in this study, as the timing and number of northward jet shifts in the PlaSim simulations (T42 resolution with GLAC1-D updated every simulation year) and TraCE-21ka (T31 with ICE-5G updated approximately every 500-1000 years) differed. If this hypothesis is correct and this mechanism is as important in reality as it is in models, then the uncertainty in our understanding of the deglaciation in both datasets. This transition is difficult to date, since it occurs gradually. It is identified through two phenomena: the historical position of the jet over eastern Namer during this period is dominated by the uncertainty in our knowledge of the southernmost position of the regional 1000m (or so) high ice.

15 In contrast, the downstream side of the jet over the eastern North Atlantic does not show the same sensitivity to the marginal  
position of the North American ice complex, but it is still affected by the presence of elevated ice sheets. Whether this control  
is exerted via changes to the stationary waves (e.g. Kageyama and Valdes (2000); Lofverstrom et al. (2014) ), transient eddies  
(e.g. Merz et al. (2015) ), surface thermal gradients from sea ice and sea surface temperatures (e.g. Li and Battisti (2008) ), or  
20 some other mechanism is not entirely apparent from this study. There is some evidence that sea ice and sea surface temperatures  
may play a role, as the range of positions occupied by the jet expands over time, latitudes increases after abrupt sea ice retreats  
and sea surface temperature warmings in the FixedGlac experiment, and the frequency that the jet occupies its most likely  
position decreases. The first change occurs in all runs between 11 and 10 ka BP, but only after 8ka BP on the jet's western  
side. The second change is less distinct and is complete (highest likelihood at any latitude less than 50%) by 8ka BP. eastern  
25 jet distribution is centred around different latitudes at the end of the deglaciation in FullyTrans and PDTopo even though their  
forcings are the same at this time.

~~Due to the differences in characteristics of the jet on its western side over eastern North America and its eastern side over~~  
~~the eastern North Atlantic, we attribute the jet changes in these two regions separately.~~ Orbital and greenhouse gas forcings  
contribute to the spreading of the distribution of jet latitudes away from its peak value in both regions of the jet. However, this  
effect is most prominent in the eastern North Atlantic, where these forcings also affect the jet's latitudinal position after the  
30 deglaciation.

~~The orography of the ice sheets plays a dominant role over jet changes in both regions; the preferred jet position remains~~  
~~fixed to its value at LGM in both regions in the sensitivity experiment with constant LGM ice topography. For low-level winds~~  
~~over eastern North America, it is the orography of the south-eastern margin that appears to play the most important role, as it~~  
~~acts as a physical barrier for winds in that region in both the PlaSim simulations and~~ In general, it appears that the characteristics  
35 of the jet on the eastern side of the North Atlantic are sensitive to changes in the TraCE-21ka experiment background climate  
state, likely through changes to the positions of the polar front (and the growth of associated eddies) and sea ice margin.

As such, it would be difficult to estimate historical changes to the jet in this region from model simulations, since the pattern  
of thermal responses to changes in boundary conditions is sensitive to model parametrizations for processes like cloud physics,  
and feedbacks between the atmosphere, ocean and sea ice. Thus, the western side of effect of changing boundary conditions  
5 likely varies between models and even between simulations using the same model but different initial boundary condition  
states.

One advantage of the design of the PlaSim simulations compared to TraCE-21ka for studies such as this one is that ice sheet  
characteristics were updated every simulation year in the PlaSim runs. Enacting these boundary condition changes gradually  
provided better estimates of the timing of jet changes and made attributing these changes easier. The TraCE-21ka experiment  
10 updated ice sheet and meltwater prescriptions every few hundred to a few thousand simulation years and held them fixed in  
between (He, 2011) . This likely contributed to the lack of change in the jet is found to be highly-focussed to the latitude of  
the ice sheet margin and varying only south of the margin until the ice sheet retreats north of the jet 's preferred position. In  
contrast, the downstream side of the jet over the eastern North Atlantic does not show the same sensitivity to marginal position  
of the North American ice complex and responds to other characteristics of the elevated ice sheet instead. Precisely which

15 ~~characteristics are most important to~~ North America in TraCE-21ka until 13.87 ka BP, when its ice sheet area and topography  
were adjusted from 15ka BP specifications to 14ka BP values. At the same time, Northern Hemisphere freshwater routing was  
shifted from the Mackenzie River to the ~~jet in this eastern region is not apparent from this study~~ Nordic Seas and St. Lawrence  
River, and Weddell Sea hosing was turned off. Lofverstrom and Lora (2017) attributed the increase in jet tilt at this time to  
the opening of the Cordilleran and Laurentide ice sheets, but there were many other factors that may have contributed to this  
20 change as well.

Note that the ice sheet elevation in some grid cells exceeds the bottom pressure level of the analysis range, so we ~~leave that~~  
~~for future work.~~

~~The dependence of the jet's western position on the position of the ice sheet margin suggests that deglacial jet changes in~~  
~~this region can be reconstructed from a knowledge of~~ interpolated the winds to these levels to not bias the resulting average.

25 The land surface does not pass above the 700hPa pressure level in any of the grid cells included in our analysis, so we are not  
introducing winds to a region where there was none. The impact of this choice was tested on the 850hPa level and found to  
not change the jet results (see Supplemental Figure S9) except when the jet is calculated over the entire longitudinal range.  
In this case, excluding grid cells from the analysis on the western side of the region effectively weights the mean jet toward  
characteristics of the eastern region. This issue illustrates the sensitivity of this diagnostic to the longitudinal range that is  
30 employed. Due to this sensitivity and ~~the ice sheet changes. Conversely, the sensitivity of the jet position on the eastern side~~  
~~of the North Atlantic to the background climate state implies that it would be difficult to estimate historical changes to the~~  
~~jet in this region from model simulations, since estimates would vary between models and between simulations with different~~  
~~boundary conditions.~~ important differences in jet characteristics in the two regions, we argue that analyses over the western  
and eastern jet regions are more instructive than the more commonly-used jet latitude and tilt metrics, and would encourage  
other authors to present these metrics as well.

5 ~~Finally, the simulations presented here did not exhibit abrupt changes in surface temperatures at the times they occurred in~~  
~~the historical record. However, the results~~ The results of this study provide some insight into what conditions would be required  
in order for ~~the jet changes detected here~~ jet changes to play either a causal or enabling role in abrupt deglacial climate changes.  
Due to the constraint provided by the ice sheet on the western side of the jet, abrupt jet changes in this region would most likely  
arise through one of two phenomena:

- 10
1. the ice sheet margin exhibiting an abrupt retreat or abrupt thinning, allowing the jet over the western NATl to abruptly shift northward, or
  2. other processes constraining the regional jet position for an interval of time, allowing a rapid adjustment of the jet to the ice sheet margin, the origin of which are not presently clear.

It is unlikely ~~to see that~~ relevant changes in the ice sheet margin ~~occurring~~ occur on timescales of decades, so it appears that  
15 changes to the upstream end of the North Atlantic jet are more likely to play an enabling role than a causal role for abrupt  
climate ~~oscillations. In contrast, the downstream (eastern) side of the jet exhibits the potential for non-linear behaviour through~~  
~~its sensitivity to the many different components that define the background climate state, including the sea ice extent, sea~~

~~surface temperatures, and temperature contrasts with the ice sheet and elsewhere. Better understanding the sensitivities of the downstream changes. It is also possible that gradual jet changes can trigger abrupt climate changes. The non-linearity of the coupled climate system implies that gradual changes do not necessarily lead to gradual responses, particularly if there are thresholds (e.g. sea ice edge) beyond which feedbacks change. Better understanding of possible climate system sensitivities to NATl jet changes will require testing with more sophisticated models that include dynamic sea ice.~~

## 5 Acknowledgements

*Code availability.* TEXT

25 *Data availability.* TEXT

*Code and data availability.* TEXT

*Sample availability.* TEXT

## Appendix A: Testing Experimental Design

There are two aspects to the design of this study which could possibly affect the results presented here. These include the model's high-latitude cold bias with respect to CMIP5 LGM simulations (described in Section 2.2.5), and the acceleration of the forcings by a factor of 10. The effects of each of these aspects have been assessed using additional simulations and are discussed below.

### 5 A1 Cold Arctic at LGM

As described in Section 2.2.5, the PlaSim simulations exhibit colder conditions in the polar regions during winter compared to the CMIP5 multi-model ensemble, particularly in the Northern Hemisphere. The strength of these temperature differences decreases over the deglaciation until by the last millennium the 2m temperatures generated by PlaSim lie mostly within the range of CMIP5 experiments. The location of the largest temperature differences over snow-covered regions suggests that the treatment of snow albedo may at least partly explain them.

Most high-latitude land is covered with a perennial snow cover in the LGM simulations that is metres thick. The albedo of snow in PlaSim is treated as a linear function of surface temperature with cutoff minimum and maximum values of 0.4

and 0.8, respectively. Most problematically, PlaSim’s default albedo scheme allows the snow albedo to return to fresh snow values after periods of snow melt, without the requirement of additional snowfall. This unphysical albedo scheme was tested in Koltzow (2007) using the HIRHAM model, and it was found to underestimate satellite-derived clear-sky snow albedo at temperatures above  $-6^{\circ}\text{C}$  and overestimate the albedo at temperatures below  $-8^{\circ}\text{C}$ . These characteristics are consistent with the climate differences detected in the PlaSim simulations for LGM: they are strongest over snow-covered regions during cold seasons.

To test the influence of this bias, we modified the snow albedo scheme in unforested regions in a manner analogous to Helsen et al. (2017). After a snowfall of at least 20 cm water equivalent, the snow albedo is reset to a maximum value of 0.85. With less snowfall than that, the increase in albedo is scaled linearly between its maximum value and its previous value according to the relative amount of snowfall. When there has been no snowfall, the snow begins to age via an exponential decay via a temperature-dependent time constant toward a temperature-dependent minimum albedo value. This value ranges linearly between an upper limit for firn (albedo 0.75) at temperatures below  $-5^{\circ}\text{C}$  and a lower limit for wet snow (albedo 0.55) at temperatures above the melt temperature. The time constant for this decay is defined in Equation A1, where tau is the time constant in days and T is the surface temperature in Kelvin.

$$\tau = 30 - 29.875 * \text{MIN}[1, \text{MAX}[0, ((T - 268.16)/(273.15 - 268.16))^{0.25}]] \quad (\text{A1})$$

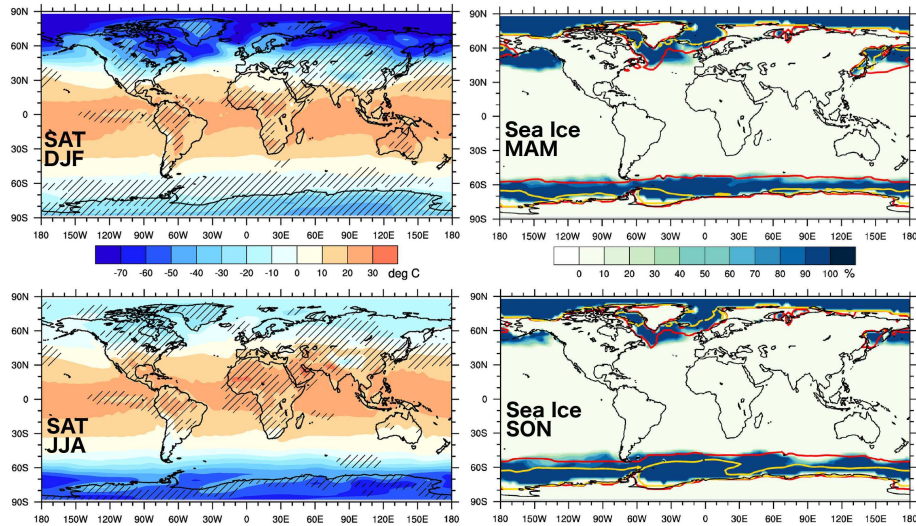
This parametrization of the time constant gives values of 3 hours for temperatures at the melting point, 4 days for  $-2^{\circ}\text{C}$  and 30 days for  $-5^{\circ}\text{C}$ .

This updated snow albedo parametrization was applied in PlaSim to snow cover over land and sea ice, and a new LGM spin-up and accelerated transient experiment were performed. Sea ice is much less extensive at LGM in the new transient simulation as seen in Figure A1 and temperature biases with respect to the CMIP5 multi-model ensemble are reduced. However, Arctic winter temperatures are still outside the range of the CMIP5 models at LGM. The remaining model differences suggest the need for additional comparisons in the tuning procedure that constrain the seasonal cycle, which would better constrain the changes in the climate under different forcing conditions.

The jet latitudes in the transient run using the new albedo parametrization are very similar to those in the original accelerated transient simulations in the upstream region of the jet. However, in the jet as a whole and in the downstream regions plotted in Figure A2, the transition to a more distributed jet without a single preferred latitude over the eastern NATl occurs much earlier, by 15ka BP instead 11ka BP. These changes are consistent with the conclusions presented here that the constraints on the upstream end of the jet are primarily caused by the position of the south-eastern margin of the NAIS, while the controls on the east are based on the thermal state of the atmosphere and sea surface temperatures. A warmer initial state with less extensive sea ice achieves a similar jet state over the eastern NATl earlier.

## A2 Simulation Acceleration

Another run was generated identical to FullyTrans1 except without acceleration to identify what influence the ten times acceleration may have had on the results presented here and to better assess the abruptness of the transitions. Frequency plots for



**Figure A1.** 2-metre temperatures and sea ice concentration at LGM in the first century of a single transient simulation employing the new snow albedo parametrization compared to CMIP5 multi-model minimum and maximum values. Hatching represents regions where climatological values lie within the range of CMIP5 models, while red lines indicate CMIP5 maximum sea ice extent and yellow lines indicate CMIP5 minimum extent.

10 the jet latitudes in all regions are shown to year 6.3ka BP in Figure A3. Jet latitude shifts in the western region of the jet occur at the same time as in the accelerated runs, and the most abrupt transition between 15ka BP and 14ka BP occurs within 80 years. Over the eastern region, the jet changes occur earlier than without acceleration. Thus, allowing the ocean to adjust to the changing climate conditions results in a change to the timing of the shifting of the jet over the eastern NATl and the shift

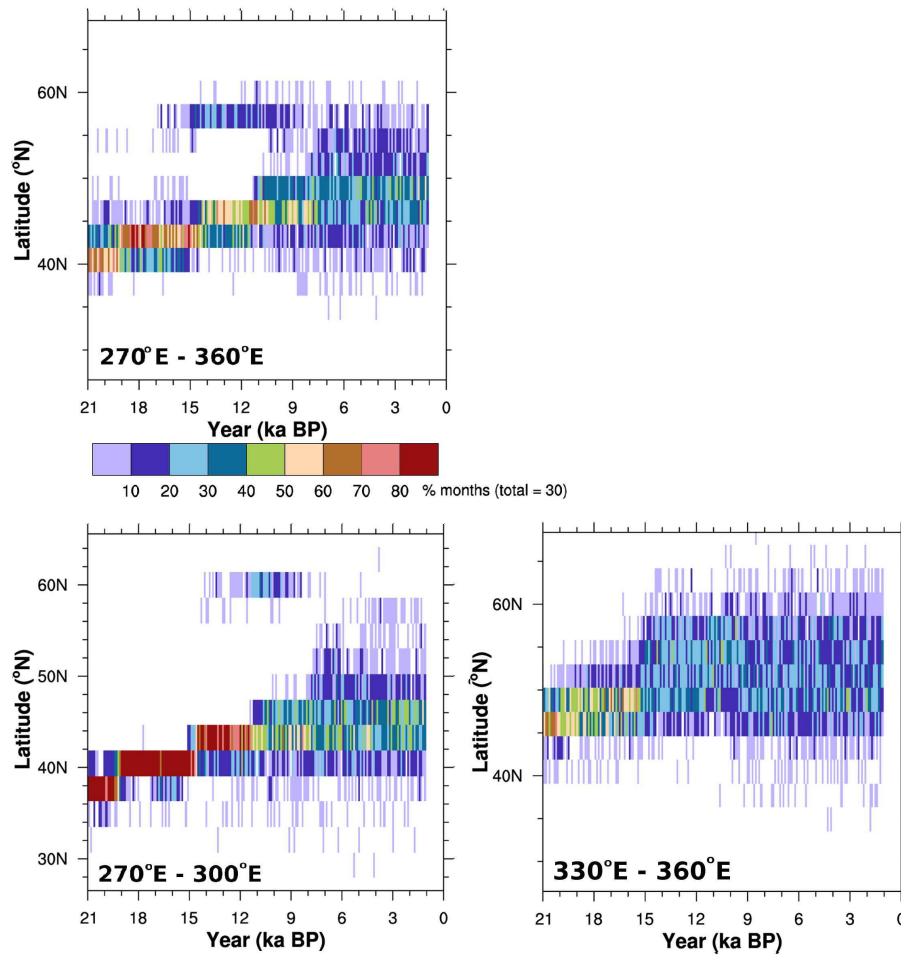
15 with episodes of abrupt warming in the run.

*Author contributions.* HJA and LT designed the experiments. HJA modified the PlaSim model code, performed the simulations and analysed the output. HJA prepared the manuscript with contributions from LT.

*Competing interests.* The authors declare that they have no conflict of interest.

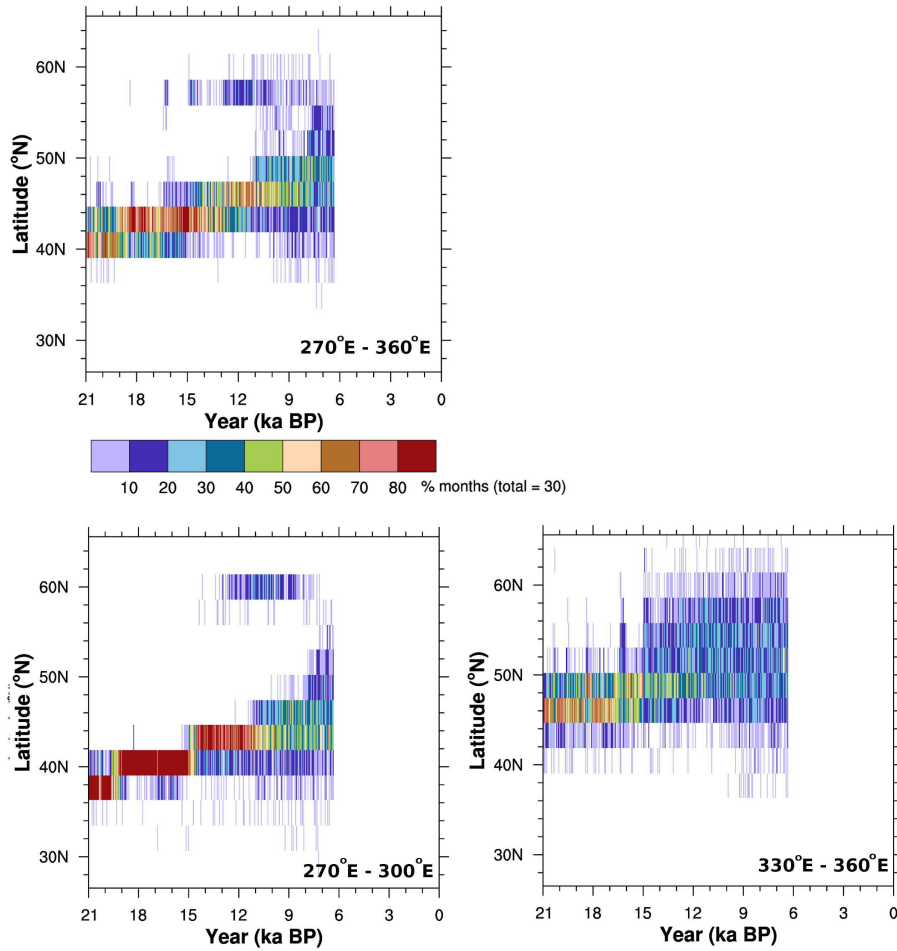
20 *Disclaimer.* TEXT





**Figure A2.** Frequency plots for North Atlantic eddy-driven jet latitudes as a function of time for the transient deglacial simulation using a revised snow albedo parametrization.

*Acknowledgements.* The authors thank Camille Li for her insightful comments and Taimaz Bahadory for his editing. Funding for HJA was provided by ArcTrain Canada and the German Federal Ministry of Education and Research (BMBF) in its Research for Sustainability initiative (FONA) through the PalMod project. All calculations were performed using HPC services from the Centre for Health Informatics and Analytics at the Memorial University of Newfoundland. TraCE-21ka was made possible by the DOE INCITE computing program, and supported by NCAR, the NSF P2C2 program, and the DOE Abrupt Change and EaSM programs.



**Figure A3.** Frequency plots for North Atlantic eddy-driven jet latitudes as a function of time for the unaccelerated transient deglacial simulation.

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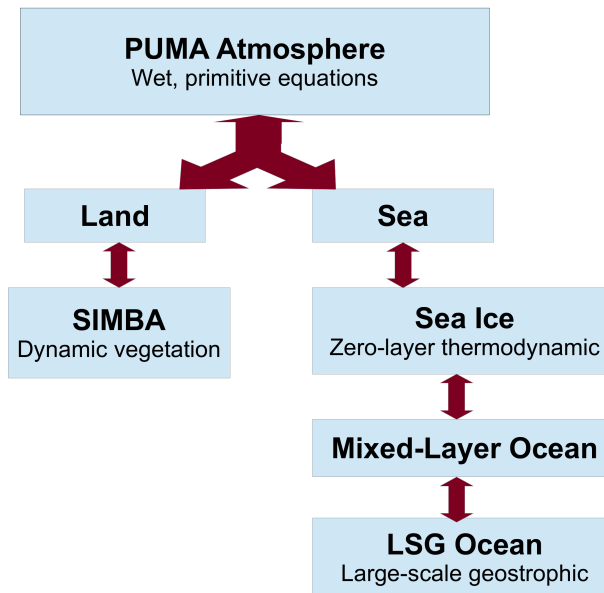
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**Figure S1.** Conceptual schematic of how different model sub-components interact in PlaSim version 16.

## S1 Detailed Description of PlaSim

PlaSim's atmosphere component, PUMA, controls the execution of this model by exchanging surface data with both the land surface and sea components and facilitating the exchange of fields between them. The sea component attenuates incoming radiation through any sea ice thickness and passes the resulting heat fluxes and wind stresses to a mixed-layer ocean model of thickness 50m. The mixed-layer ocean model adjusts mixed-layer temperatures ( $T_{mix}$ ) in response to incoming heat fluxes and returns  $T_{mix}$  to the sea ice component as a lower boundary. Where the ocean is covered with sea ice or where  $T_{mix}$  is lower than the freezing temperature,  $T_{mix}$  is changed to the freezing/melting temperature and the consequent heat fluxes are used to increase or reduce sea ice thickness as appropriate. Note that the sea ice model only evaluates thermodynamic changes and does not advect the ice with ocean currents or wind forcing.

The land component determines land surface temperatures in 5 soil layers, based on local energy balance (Lunkeit et al., 2012). Hydrology and runoff are evaluated through the use of a single reservoir or bucket-depth. This bucket depth depends on the vegetation type in the grid cell. Excess water is lost from the cell via runoff and is advected to ocean grid cells following topographic slopes calculated on the model grid. Runoff amounts are returned to the atmosphere, which passes the information through the sea ice and mixed-layer components to [LSGthe LSG ocean model](#). Additionally, PlaSim includes a dynamic vegetation model, SIMBA, which estimates vegetative changes from surface atmospheric conditions, precipitation and evaporation, incoming short-wave radiation and carbon dioxide concentrations (Lunkeit et al., 2012). These vegetative changes, in turn, affect the atmosphere through changes to the surface albedo, roughness, temperature and humidity. No vegetation calculation is performed in glaciated regions, which are prescribed.

Note that due to the mixed-layer ocean and LSG being on different grids, ocean variables are interpolated when passed between these two components. Heat fluxes are thus adjusted by adding a correction factor to all ocean grid cells that offsets differences in the area-weighted global average values from both grids. This allows for the land-sea masks to differ between the slab-ocean model and LSG without creating a substantial model drift.



## S1.0.1 Model Modifications

Boundary condition changes were implemented as follows. At the start of every simulation year, the topography, land-sea mask, ice mask and surface roughness datasets are read in or interpolated from source data. The number of sea grid points are calculated and the soil temperature of the top layer is initialized to the surface air temperature at the previous time step. This allows cells that transition from ocean to land to have defined surface temperatures. From these data, runoff patterns and velocities, albedo, and other surface parameters are calculated. Where land grid cells become ocean, sea surface temperatures and sea ice are initialized to interpolations from the nearest LSG grid cells. Then, the model performs its integration.

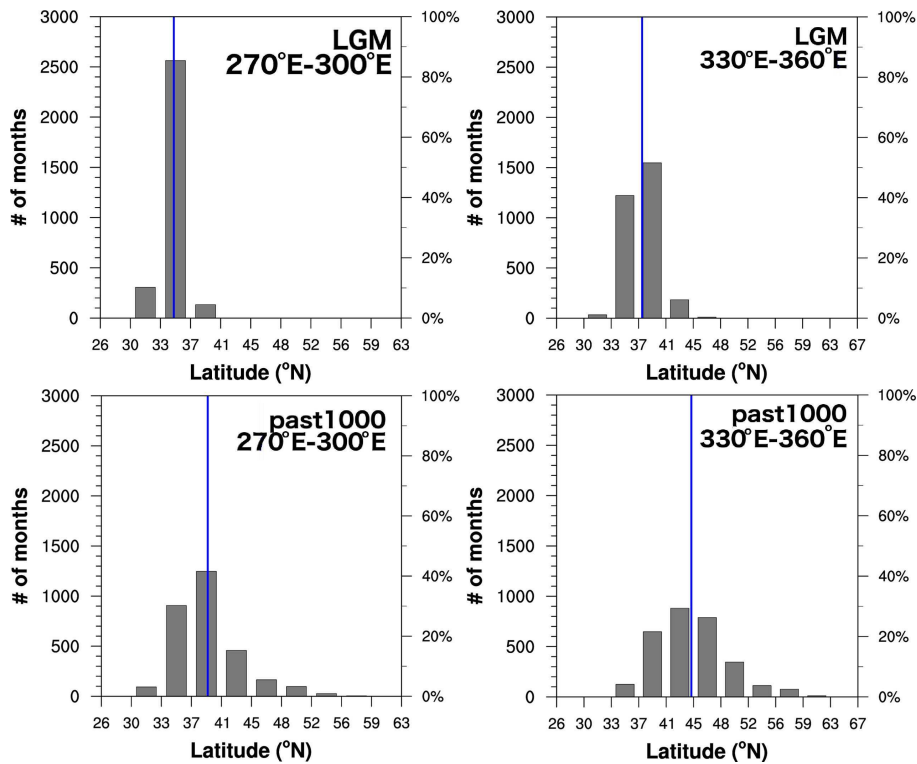
Additional changes included modifying LSG to run with PlaSim at T42 and activating the diurnal cycle. These two changes necessitated retuning the model. PlaSim was tuned to preindustrial conditions by modifying four different radiation parameters, all of which are bounded by values of zero and one. A set of 30 initial random selections for these parameters were constructed, and preindustrial atmosphere general circulation model simulations (year 1850) of 10-years' duration were performed using each set. Sea ice and sea-surface temperatures were prescribed to adhere to AMIP II values averaged over years 1870 to 1899 (Taylor et al., 2000). Global-average, net top-of-atmosphere (TOA) fluxes were calculated, as well as surface sensible and latent heat and shortwave and longwave fluxes. These radiation fields were compared against fluxes from CMIP5 models presented in Table 2 of Wild et al. (2015). Those values correspond to present day fluxes, so they were adjusted to estimate preindustrial values by shifting them according to flux differences between both time periods extracted from PlaSim AGCM simulations. For every run, each flux value was compared to the corresponding reference value, and if it lay within  $\pm 2\text{W/m}^2$  (or  $\pm 1\text{W/m}^2$  for TOA net flux and  $\pm 3\text{W/m}^2$  for surface latent heat), then that metric value was deemed within tolerance. Those parameter sets that yielded the largest unique set of flux terms within the specified thresholds were identified as Pareto-optimal (Fonseca and Fleming, 1995) and retained. Then, a new set of random parameters were selected in the vicinity of each of these optimal sets to refine the selections. As a result, four different tuning configurations were identified, and they form the basis of the four-member ensemble of transient simulations performed here.

~~Coupled Model Interecomparison Project 5 simulations included in the the multi-model ensemble plots presented in this study. Institute ID Model Name-~~

## 25 S2 Split jet occurrences

Both the PlaSim simulations and TraCE-21ka exhibit months when the location of the jet is identified to be situated further north than the southern margin of the NAIS. In Figures S3, S4 and 11, these instances are clearly separated from the rest of the distribution, although the timing of their first occurring differs between ensemble members. The number of instances are fewer in the TraCE-21ka experiment and are less separated from the rest of the distribution in Figure 12. In the jet latitudes ~~calculated~~ diagnosed over  $90^\circ\text{W}$  to  $0^\circ\text{W}$ , these anomalous cases first arise between years 15ka BP and 14ka BP. In contrast, the instances of negative jet tilt and anomalous northern jet positions on the western side of the jet first arise between 14ka BP and 13 ka BP. ~~The delay between these occurrences when evaluated over the full longitudinal range versus only over the western region is due to these events being composed of three different types~~ first anomalous cases arise out of limitations to the algorithm used to identify the NATl eddy-driven jet latitude. The later cases reflect temporary changes in the structure of winds over eastern NAmer. Three types of anomalous winds make up these instances altogether, which are described below.

The first type of anomalous jet is ~~only the only one that occurs from 15ka BP to 14ka BP, and it is only~~ detected when the jet is ~~calculated~~ diagnosed over its entire range, but not when ~~evaluated~~ diagnosed only over the west. ~~In Figure S6, the strongest winds are found on the eastern side of the NATl at the same latitude as a branch of zonal winds on the north-eastern side~~ Identifying a northern position for the jet of this type represents an error in the detection algorithm due to the latitudinal position of the winds over the eastern NATl aligning with the latitude of winds along the northern slope of the NAIS. ~~This represents an anomalously northward-positioned jet~~ Zonally averaging thereby yields a maximum at that latitude, although the bulk of the winds are routed south of the ice sheet. In Figure S6, zonal wind anomalies over eastern NAmer are weak. ~~Instead, this type exhibits anomalously northern-situated winds~~ over the eastern NATl compared to other months during the same century of simulation. ~~The zonal average over these two wind centres is larger than at other latitudes, even though the winds in the branch of the jet south of the ice sheet are stronger than those on the northern face. ~~This~~ This explains why this~~



label-years label-years NCAR-CCSM4 r1i1p1-085001-185012 r1i1p1-180001-190012 NASA-GISS-GISS-E2-R r1i1p1-23-0850-1850  
 r1i1p1-150-3000-3099 NASA-GISS-GISS-E2-R r1i1p1-126-0850-1850 r1i1p1-151-3000-3099 MIROC-MIROC-ESM r1i1p1-085001-184912  
 r1i1p1-460001-469912 MPI-M-MPI-ESM-P r1i1p1-085001-184912 r1i1p1-185001-194912 MPI-M-MPI-ESM-P r1i1p2-185001-194912  
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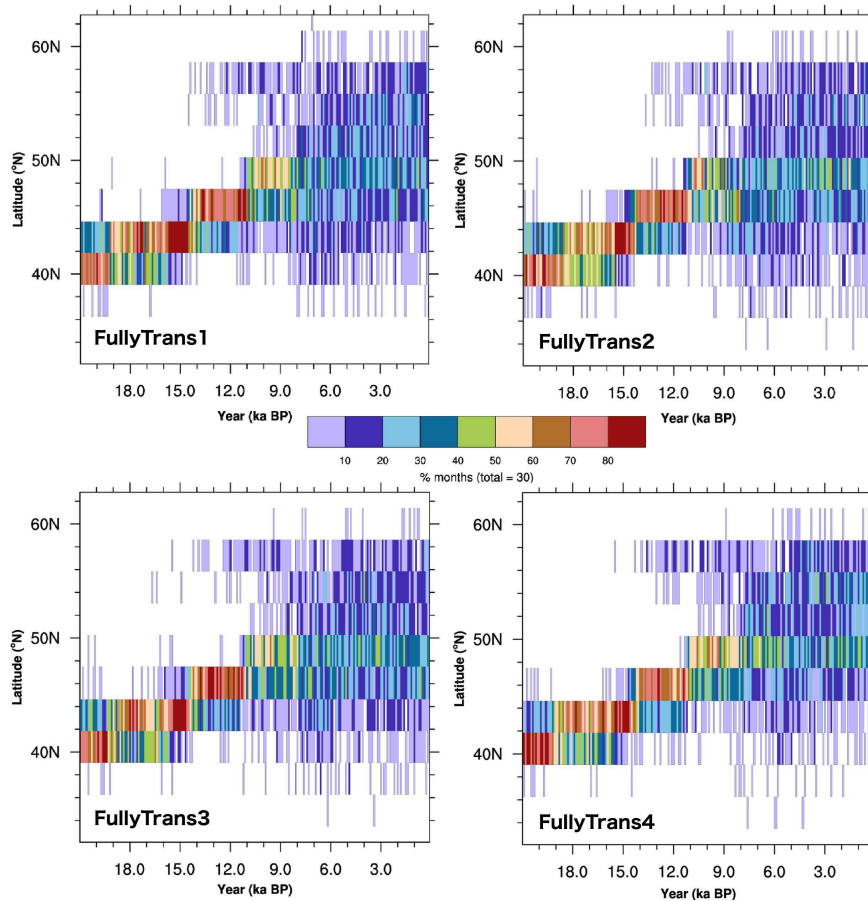
**Figure S2.** Histograms of latitudes corresponding to peak NATl zonal winds for the TraCE-21ka experiment over the western and eastern regions of the jet during indicated periods. Vertical blue lines indicate mean jet latitudes for the time period.

type of jet anomaly is the only one that occurs from 15ka BP to 14ka BP, explaining the lack of does not exhibit a corresponding signal arising in the jet tilt or western jet the jet detected only over eastern NAmer.

The second type of anomalous jet occurs when the winds along the northern face of the NAIS are stronger than usual and the winds become stronger than those along the southern face of the NAIS are weaker than usual margin of the ice sheet. This is the result of a northward shift in the zonal winds around the entire hemisphere, although its effects are strongest over eastern NAmer and the NATl. The northern position of the jet for this type is detected when averaged over the entire range and over eastern NAmer. It does not correspond with negative tilts, however.

The third type of anomalous jet is similar to the second type, except that the northward shifting of the jet is isolated to NAmer. In contrast, the winds over the eastern NATl have their peak values further south than climatology. This case leads to the most pronounced negative values of jet tilt.

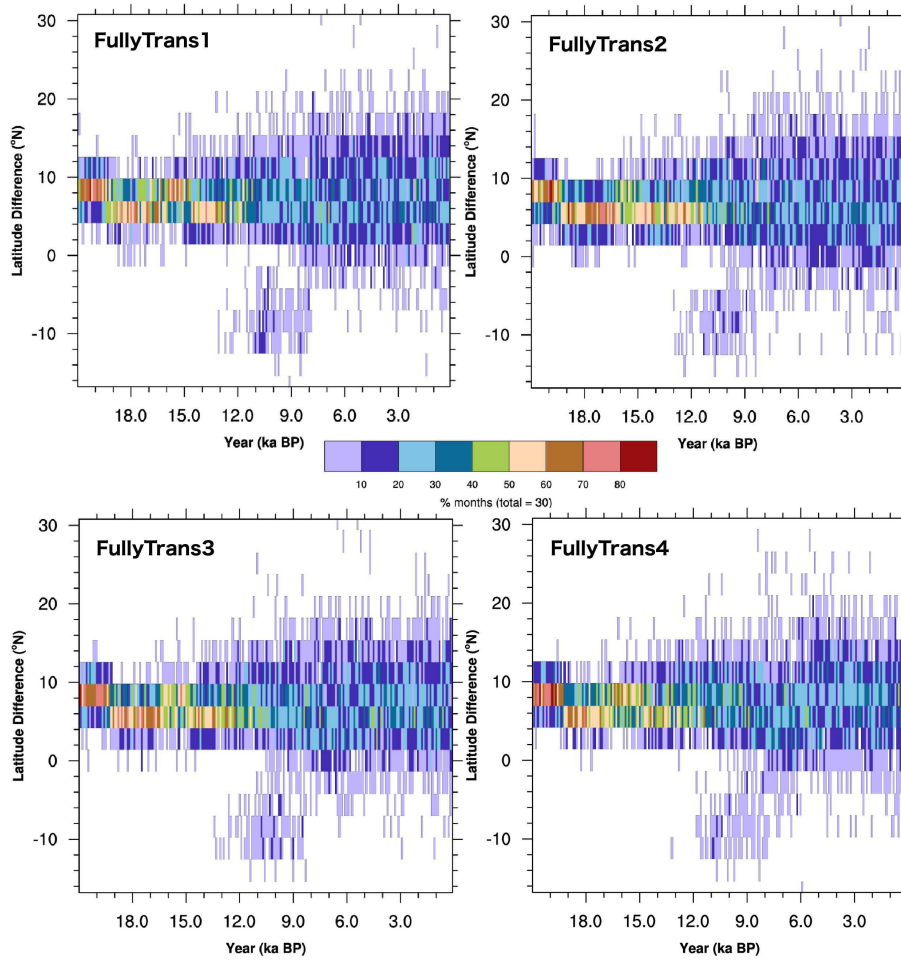
As the NAIS retreats, the northern branch of winds merges with the predominant winds passing south of the ice sheet, and the cases of northward-positioned jets become indistinguishable from the rest of the distribution.



**Figure S3.** Frequency maps of zonal mean of NATl lower-level jet latitudes in 10 successive winter seasons for all fully transient ensemble members. Colours indicate the number of months with peak zonal winds within each latitude bin, which correspond to latitude ranges in PlaSim at T42.

## References

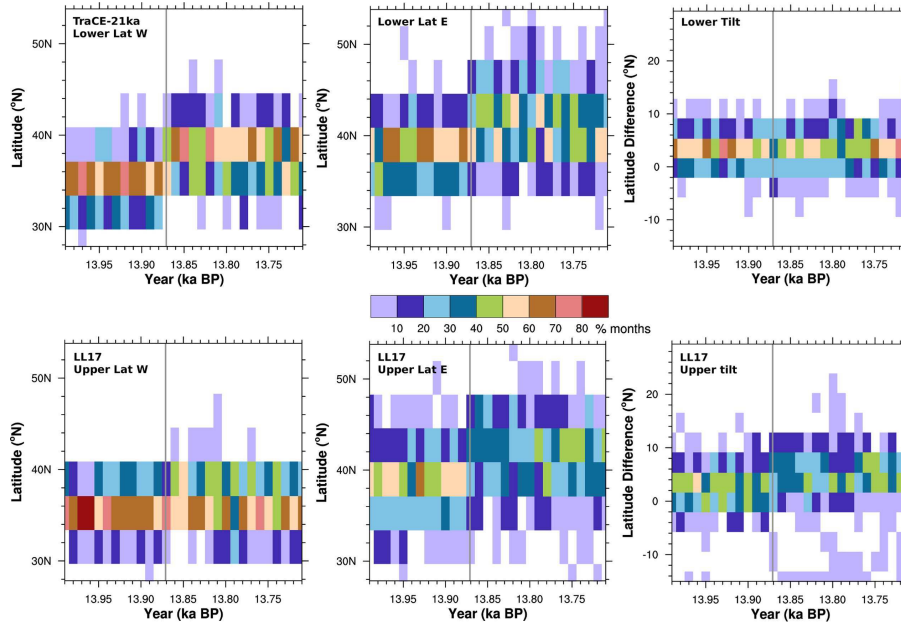
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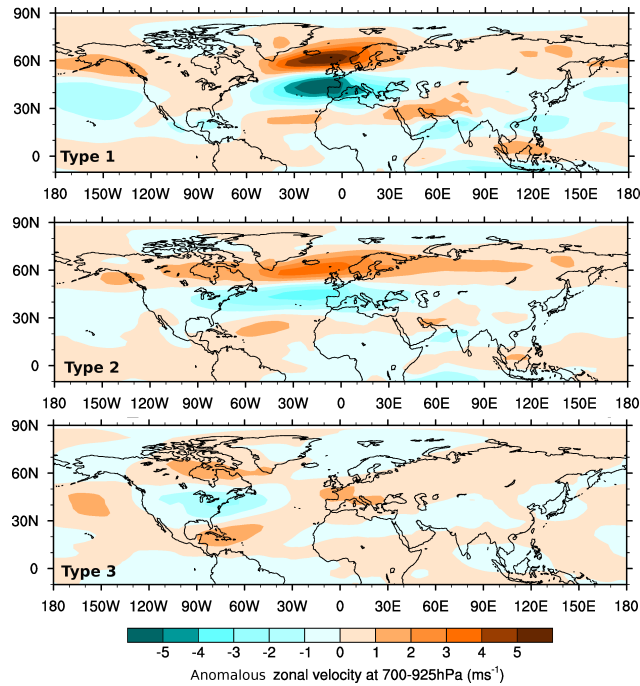
**Figure S4.** Frequency maps of NATl lower-level jet tilt in 10 successive winter seasons for FullyTrans1, FullyTrans2, FullyTrans3, and FullyTrans4. Colours indicate the number of months with the difference in jet latitudes between 330°E to 360°E and 270°E to 300°E within each bin of width 2.8°.

**Table S1.** [Coupled Model Intercomparison Project 5 simulations included in the the multi-model ensemble plots presented in this study.](#)

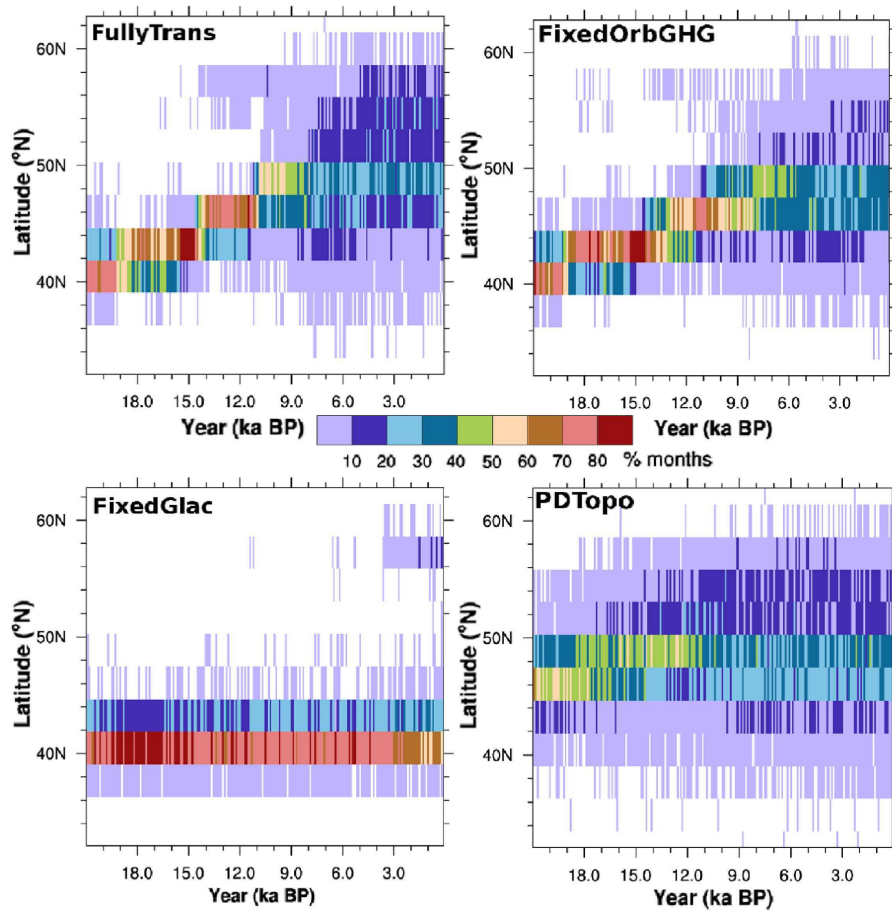
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		label	years	label	years
NCAR	CCSM4	rlilp1	085001-185012	rlilp1	180001-190012
NASA GISS	GISS-E2-R	rlilp123	0850-1850	rlilp150	3000-3099
NASA GISS	GISS-E2-R	rlilp126	0850-1850	rlilp151	3000-3099
MIROC	MIROC-ESM	rlilp1	085001-184912	rlilp1	460001-469912
MPI-M	MPI-ESM-P	rlilp1	085001-184912	rlilp1	185001-194912
MPI-M	MPI-ESM-P			rlilp2	185001-194912
MRI	MRI-CGCM3	rlilp1	0850-1850	rlilp1	250101-260012



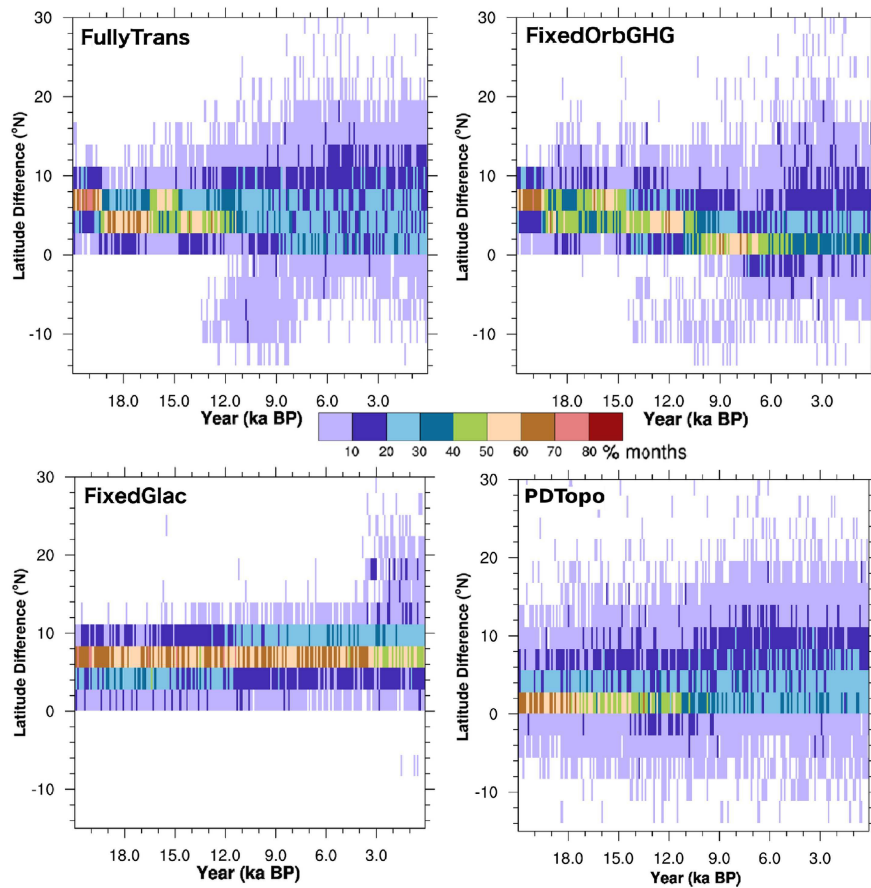
**Figure S5.** Frequency maps for jet tilt in the western and eastern regions, and jet tilt around the time of the main transition (13.871ka BP) in the TraCE-21ka experiment. The top row are calculated similarly to the rest of this study, over levels 700hPa to 925hPa, with western and eastern regions defined as 270°E to 300°E and 330°E to 360°E, respectively. Statistics in the bottom row are calculated following Lofverstrom and Lora (2017), at 250hPa with western and eastern regions defined as 280°E to 290°E and 340°E to 350°E, respectively. The vertical grey lines mark year 13.871ka BP.



**Figure S6.** Composite plots of zonal ~~winds~~ wind anomalies over levels 700hPa to 925hPa during months when the NATl eddy-driven jet ~~exhibits anomalous behaviour with respect to~~ is detected at a more northern position and separate from the rest of the distribution. The months are organized according to their type, which are described in the text.

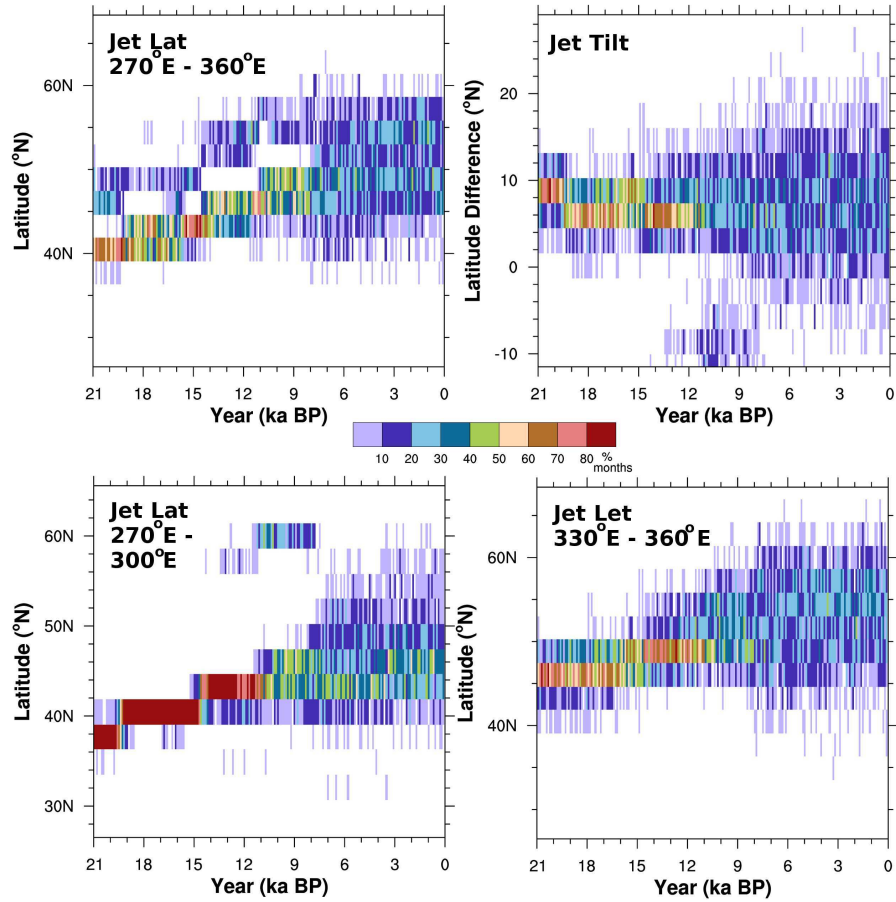


**Figure S7.** Frequency maps of NATl lower-level jet latitudes calculated from 270°E to 360°E in 10 successive winter seasons accumulated over all ensemble members of the FullyTrans, FixedOrbGHG, FixedGlac and PDTopo experiments. Colours indicate the percentage of months with peak zonal winds within each latitude bin of width 2.8° at T42.



**Figure S8.** Frequency maps of NATI lower-level jet tilt in 10 successive winter seasons accumulated over all ensemble members of the FullyTrans, FixedOrbGHG, FixedGlac and PDTopo experiments. Colours indicate the percentage of months with peak zonal winds within each latitude bin of width  $2.8^\circ$  at T42.





**Figure S9.** Frequency maps of NATl lower-level jet latitude (averaged over three different regions) and tilt in 10 successive winter seasons from the FullyTransI simulation. Winds are extracted at 850hPa, and grid cells where the surface lies above this pressure level are not included in the analysis. Colours indicate the percentage of months with peak zonal winds within each latitude bin of width 2.8° at T42.