Response to comments from Stuart Robinson (Referee #1)

I enjoyed reading this well-written paper that uses an Earth System model to explore the sensitivity of ocean circulation to long-term changes in Cretaceous palaeogeography by comparing simulations of Cenomanian and Maastrichtian conditions. This is an important and active area of research, as geochemical proxy records for Late Cretaceous ocean circulation (such as those from neodymium isotopes), although useful in documenting stratigraphic changes in local water mass chemistry, have proven harder to interpret unambiguously in terms of water mass sources and flow path. In this context modelling exercises are highly complementary and informative. I am certain this paper is appropriate for Climates of the Past.

Thank you for this comment.

My only significant issue with this paper is the treatment of CO2 levels and the comparison of the models with climate proxy records (Section 2.4).
The baseline simulations have CO2 set at 1120 ppm (4 times pre-industrial atmospheric levels, PAL), which is an entirely appropriate starting assumption for much of the Cretaceous, but as acknowledged (lines 981-993), was, in the latest Cretaceous, likely lower than in the mid-Cretaceous. It is surprising that no sensitivity analysis to CO2 levels has been included (especially as the same group has just published limited aspects of the model results, but including 2x and 4x simulations, in Haynes et al in press in Geology; https://doi.org/10.1130/G47197.1). The Haynes proxy and model results need to be included in the paper throughout, especially if they allow a consideration of how the sensitivity of the simulations to CO2 change.

Thank you for raising this question. We originally decided against including a sensitivity simulation to CO_2 in order to focus solely on the impact of paleogeography on Late Cretaceous ocean circulation. However, we agree that including a lower CO_2 Maastrichtian simulation allows the study to be more comprehensive. We have therefore revised the manuscript to add the 2x CO_2 simulation described in Haynes et al. (2020). Interestingly, the model shows limited sensitivity to CO_2 in terms of ocean circulation in that the pathways of intermediate and deep circulation are not noticeably modified. However, as described in Haynes et al. (2020), the lower CO_2 simulation does show a slightly more vigorous circulation. This low sensitivity of the Cretaceous ocean circulation to CO_2 is consistent with the results of Donnadieu et al. (2016) and the simulations of Farnsworth et al. (2019) with small exceptions (but see our response to next comment).

New sections devoted to the analysis and discussion of the lower CO_2 simulation can be found in the revised manuscript (sections 4.3.5, 5.1.2, 5.2.4).

Finally, the new Pacific datasets reported by Haynes et al. (2020) were already used in the original version of the manuscript. Please refer to Tables S3 and S4 (previously Tables S2 and S3) and Fig. 13.

The results at 4xPAL show substantial differences in the pattern of ocean circulation to those reported by Donnadieu et al (2016). It is suggested (lines 740 onwards) that this might be due to the more complex nature of CCSM and the role of continental run off in these different models. However, other model simulations (not discussed in the paper) have suggested that CO2 plus palaeogeographic change may be significant effects on ocean circulation at various times. in particular, Farnsworth et al (2019) in GRL highlight that in their Maastrichtian simulation using HadCM3 ocean circulation is extremely sensitive to CO2, with a switch between South Pacific deep-water production at 4xPAL to South Atlantic deep-water production at 2xPAL. It would be good if the authors could include some discussion of the results of Farnsworth et al. (2019) and their thoughts on the significance of the Farnsworth result.

We focused the comparison to previous model simulations to that of Donnadieu et al. (2016) because this study is the only one providing a detailed analysis of the reorganizations of deep ocean fluxes in the Late Cretaceous. Farnsworth et al. (2019) indeed report a strong sensitivity to CO_2 in their Maastrichtian simulation (with a shift in deep-water formation regions), but this strong sensitivity only occurs twice across all the simulations performed by Farnsworth et al. (2019) whereas the ocean circulation in all the other simulations is relatively insensitive to CO_2.

Whether this sensitivity is due to the specific Maastrichtian (~ 68.2 Ma, as per Lunt et al. 2016) and Selandian (~ 60.6 Ma) paleogeographies or to something else is unclear because Farnsworth et al. (2019) do not enter details as to what causes this response in the HadCM3BL-M2.1aD earth system model. What is even more intriguing is that if specific details of the Maastrichtian and Selandian paleogeographies are responsible for this model behavior then why is the Danian (~ 63.9 Ma) not producing the same behavior given that this stage occurs between the Maastrichtian and the Selandian? One possible answer might be provided by the model setup of the simulations of Lunt et al. (2016), of which the simulations in Farnsworth et al. (2019) are extensions. Table 1 of Lunt et al. (2016) shows that different smoothing had to be applied to the Maastrichtian, Danian and Selandian simulations to ensure model stability. For instance, the Maastrichtian simulation has a flat polar Southern Ocean, whereas the Danian and Selandian have not. In the absence of a specific analysis about the role of CO_2 on ocean circulation in the Maastrichtian simulations of Farnsworth et al. (2019), we can only speculate that these changes might be partly caused by the variable high-latitude smoothing applied.

We have added the following discussion about Farnsworth et al. (2019) results (in section 5.1.2 of the revised manuscript):

"Ocean circulation is mostly insensitive to reducing the atmospheric CO_2 concentrations in our Maastrichtian configuration. The intermediate and deep water mass pathways are identical although the intensity of the water fluxes across major oceanic gateways is slightly enhanced in the 2x CO_2 simulation (Haynes et al., 2020). This insensitivity of Late Cretaceous ocean circulation to CO_2 levels is consistent with the results of Donnadieu et al. (2016), which shows that Late Cretaceous simulations performed at 2x, 4x and 8x CO_2 PAL predict similar areas of deep-water formation. In contrast, Farnsworth et al. (2019) recently reported that reducing atmospheric CO_2 levels from 4x to 2x in a Maastrichtian configuration in the HadCM3BL-M2.1aD earth system model led to a shift in deep-water formation area from the South Pacific Ocean to the South Atlantic and Indian Oceans. This high sensitivity to CO_2 only occurs in the Maastrichtian simulation among all the 12 Cretaceous simulations (one per Cretaceous stage) performed by Farnsworth et al., and occurs again only once (in the Selandian stage, ~ 60.6 Ma) among all their 7 Paleogene simulations. In the other simulations, both the 2x and 4x CO_2 simulations predict similar areas of deep-water formation. The temporal proximity of the Maastrichtian and Selandian stages led Farnsworth et al. (2019) to suggest that the time period close to the Cretaceous/Paleogene boundary might be particularly sensitive to atmospheric CO_2 but it is not clear in this case why their simulation of the Danian stage (~ 63.9 Ma) does not exhibit a similar behavior. As Farnsworth et al. (2019) do not provide a detailed analysis of ocean circulation changes in the Maastrichtian and Selandian stages relative to the others, we can only speculate that these changes might be partly caused by high-latitude smoothing, which is performed on the simulations to ensure model stability and which varies between stages (Lunt et al., 2016; Farnsworth et al., 2019)."

In addition, we provide a discussion on the role of CO_2 on ocean circulation from a wider perspective (also in section 5.1.2 of the revised manuscript):

"More generally, the impact of atmospheric CO_2 levels on ocean circulation has been shown to significantly vary in past greenhouse climate modeling work (Poulsen et al., 2001; Lunt et al., 2010; Poulsen and Zhou, 2013; Donnadieu et al., 2016; Hutchinson et al., 2018; Farnsworth et al., 2019; Zhu et al., 2020). The causes for this large spread in results may be diverse and are difficult to isolate but we hypothesize that the model climate sensitivity to CO_2 and the range of atmospheric CO_2 levels investigated could explain such variability. Winguth et al. (2010) report results of Paleocene-Eocene Thermal Maximum (PETM) simulations using the CCSM3 fully-coupled model (with the CAM3 atmospheric model) and show that ocean circulation and deep-water formation areas remain similar regardless of CO_2, although the intensity of overturning decreases with increasing CO_2. More recently, Zhu et al. (2020) report results of PETM simulations performed at 1x, 3x, 6x and 9x CO_2 PAL using the CESM1.2 ESM (with the CAM5 atmospheric model) and document a shift in deep and intermediate water formation areas between 1x and 3x CO_2 and complete cessation of deep-water formation at 6x and 9x CO_2. The climate sensitivity of CESM1.2 has been shown to be greater than that of CCSM3, and, contrary to CCSM3, to increase with background CO_2 levels (Zhu et al., 2019). Earth System Models with high climate sensitivity to CO_2 may demonstrate a higher sensitivity of ocean circulation to CO_2 because the climate state in which the radiative forcing of CO_2 leads to a warming sufficient to stop deep-water formation can be expected to occur for smaller changes in atmospheric CO_2 levels."

Section 2.4 compares proxy temperature records with the simulations and finds (line 981) a disagreement, which the authors relate to the constant CO2 value used. Given this major assumption in the simulations presented, I think that much of the oxygen isotope discussion in section 2.4 is either irrelevant or should be prefaced by the caveat that CO2 does not vary in the simulations and, therefore, the temperatures (and temporal evolution of temperature) in the model simulations is unlikely to match the proxy records. The conclusion to this section (lines 1014-1016) raises the question of whether Section 2.4 is necessary.

The aim of this section was to compare proxy temperature records with the change in temperature between the Cenomanian and Maastrichtian to investigate whether part of the proxy temperature change could be explained by paleogeography-driven changes in ocean circulation and whether the temperature change driven by gateways change could help provide additional constraints on the configuration of the gateways.
We fully agree that many discrepancies were expected, as the CO_2 did not vary in the simulations and because the temperature changes driven by deepening of gateways was smaller than the Cenomanian-Maastrichtian change.
Because we now include the lower CO_2 Maastrichtian simulation, we have also revised this section (section 5.2.4 of the revised manuscript). In short, the comparison between proxy temperature records and model results including the lower CO_2 Maastrichtian simulation shows better consistency. This is especially true for benthic records, whereas planktic records generally show larger amplitude of change, suggesting that regional deviations from the mean -1 ‰ seawater $\delta^{18}O$ may have played a significant role (e.g., Zhou et al. 2008, Zhu et al. 2020).

Minor issues/suggestions:
Use of past and present tense – in a number of places (e.g. line 149, 153), the present tense is used to describe events in the geological past.

Done.

Line 80-82: Odd structure to this sentence - consider rephrasing as: "This conjecture is corroborated by studies of the temporal trends and spatial variations in neodymium (Nd) isotopes... a quasi-conservative tracer of waters masses..."

Thank you for the suggestion. It has been rephrased.

Line 83: insert commas before, and after, "in particular"

Done.

Line 84-85; papers led by Robinson should be included in this list as they were amongst the first to show the long-term shift in Nd between the mid and latest Cretaceous.

The Robinson papers should indeed not have been overlooked from this list. They have been added.

Line 86 onwards – I think it may also be worth mentioning here that another area of uncertainty is *regarding palaeowater depth – some sites are rather poorly constrained and thus the possibility exists that different water masses are being sampled but considered as broadly of the same depth.*

We fully agree and we thank you for the suggestion. The paleodepth issue is one of the reasons that led us to categorize water transports along a vertical axis. We have rephrased the sentence as:
"However, there is no consensus on the specific modes and evolution of ocean circulation across the Late Cretaceous as interpretation is complicated by the lack of Late Cretaceous ε_{Nd} records in key places and times, by the possibility of modification of ε_{Nd} values along flow paths, and by uncertainties in the paleodepth of sites where ε_{Nd} values were documented."

Line 154: change to "black shale deposition"

Done.

Line 157: insert "the" before "South Atlantic"

Done.

Line 201: Insert "The" before "presence of a: : :"

Done.

Line 214-216: what is the reason for the shallower depth of the Drake Passage in the Maastrichtian versus the Cenomanian?

The paleogeographies of the two baseline Cenomanian and Maastrichtian simulations are those described in Lunt et al. (2016) and which have been given to the Lunt's group by Getech Plc. These datasets are proprietary and, while they can be used for scientific research, the underlying assumptions on particular paleodepths are not available. We used these datasets because the two baseline simulations are extensions of the Cenomanian and Maastrichtian simulations described in Tabor et al. (2016), which use the Lunt et al. (2016) paleogeographies.

Line 221: On the basis of results in Donnadieu, it is argued that the shallow depth differences in the Drake passage are not significant for global ocean circulation. However, given the differences in results overall, can the authors be certain that differences in depths <1000m will make no difference in their model framework?

We are confident that differences in depth < 1000 m in the Drake Passage in our Maastrichtian simulation would not lead to significant differences in the simulated ocean circulation. Indeed, the intermediate ocean circulation (500 – 1500 m) at the global scale is similar in the different Maastrichtian experiments (baseline + sensitivity) and we also note that the South Atlantic and South Indian/Tethys Ocean intermediate circulation is similar in the Cenomanian and the Maastrichtian baseline experiments, although the Cenomanian simulation has a deeper (800 m) Drake Passage. The similarity is the result of the persistence of deep convection in the South Pacific in the Cenomanian and in the various Maastrichtian experiments.
We acknowledge, though, that a ~ 1000 m deep Drake Passage could locally alter circulation patterns in the South Atlantic and/or eastern South Pacific Ocean, and as such, could make a difference in the interpretation of geochemical data. However, the influx of radiogenic Pacific waters into the South Atlantic is less consistent with ε_{Nd} trends and such a deep Drake Passage is also less consistent with tectonic evidence.

Line 279: replace "Indian" with "Tethyan"

Done.

Line 293: comment on why Sewall is used rather than Tabor.

The dynamic vegetation model of Tabor et al. (2016) produced low vegetation density at high latitudes that did not agree well with fossil-based reconstructions. As a result, simulated high latitude land surface temperatures tended to be too cold and seasonally variable. Switching to prescribed vegetation, based on Sewall et al. (2007), helped reduce this temperature bias. Prescribed vegetation means that the distribution of plant functional types cannot change through time but plant phenology is still predicted by the model.
We have added these details in the revised version (in section 3 of the revised manuscript).

Line 330-332: Awkward sentence structure – consider rephrasing.

The sentence was changed as follows:
"Simulated changes in ocean circulation between the Cenomanian and the Maastrichtian and between the Maastrichtian and the sensitivity experiments are then compared to previous modeling studies and geochemical data."

Lines 356-357: small scale regional features of the simulations are described but the use of "South America" as the geographic descriptor is a bit too vague – please be more precise when describing where these local oceanographic features occur.

Done. We have added details in this paragraph, which now reads:
"Other low salinity coastal waters are found at equatorial latitudes in enclosed epicontinental basins on the eastern coast of West Africa (Saharan epicontinental sea) and on the northwestern coast of South America as well as in the isolated high-latitude basin located between Australia and Antarctica. In contrast, high salinity waters are found in enclosed subtropical basins, such as on the western coast of South America and on the Asian margin of the Neotethyan Ocean as well as in the Gulf of Mexico (Fig. 3B). These high salinity areas correlate with regions of high temperature, low river freshwater input and largely negative PME (Fig. 3A-D)."

Line 436: replace "to the subpolar" with "with the subpolar"

Done.

Line 437: insert "of" before "the South Atlantic"

Done.

Line 522: insert comma after "experiment" and delete "and"

Done.

Lines 760-771: This paragraph contains a lot of fundamental, introduction-level material about Nd-isotopes that might be better worked into the introduction to the paper rather than included in the discussion.

This paragraph has been moved to the introduction, as suggested.

Line 796: Robinson and Vance should be included in the citations here.

Done.

Line 819-824: I don't really see the justification for suggesting that the deep-waters exported from the Pacific in the Cenomanian were relatively low in eNd given that the values shown from the Pacific in Haynes et al (in press) suggest the south Pacific had relatively high eNd values (>-6) in the

Maastrichtian, and, if the simulations are correct, probably the Cenomanian too. Given the relatively unradiogenic values of the eastern Australian coast and Ross Sea, is it not surprising that the Pacific data have values of >-6 in the Maastrichtian, if those regions are the source of the water masses? This section seems to be at odds with aspects of Haynes et al and the actual Cenomanian values of Indian and Atlantic water masses.

Thank you for this interesting question.
In our model, deep-water formation indeed occurs in the South Pacific high latitudes (> 60°S) but Haynes et al. (2020) (hereafter H2020) South Pacific sites are located in the low latitudes (~ 5°S for Mid-Pacific Mountains site 463 and ~ 10°S for Ontong-Java Plateau Site 1186), which makes a significant difference in terms of water mass pathway.
In both the Cenomanian and Maastrichtian simulations, deep waters formed in the high-latitude South Pacific mostly flow away from the Pacific Ocean following a westward current along the Australian margin (Fig. 7 and 11). Some of these sinking waters fill the eastern Pacific sector of the Southern Ocean. The deep tropical South Pacific, as well as the deep equatorial and North Pacific, are bathed by a mixture of recirculated deep waters from the Indian/Neotethyan Ocean (Fig. 7 and 11) and of deep waters from the deep eastern part of the Pacific sector of the Southern Ocean. Figure R1 shows the water mass age at 2900 m (roughly the depth of site 1186) in the South Pacific and the red star denotes the estimated position of site 1186. Water mass ages are likely not fully equilibrated in our simulations (see discussion in section 3 of the revised manuscript) but it can be seen that the waters bathing site 1186 are much older (> several centuries) than waters that have sunk in deep-water formation areas. It is reasonable to assume that the ε_{Nd} signature of these waters may have shifted toward higher Pacific-like values. This reasoning is also true for site 463 (Fig. R2).
These results are not at odds with H2020 because the 2x CO_2 Maastrichtian simulation of H2020 shows a more intense, yet similar, ocean circulation, which allows less time for sediment/water interaction than in the less intense 4x CO_2 Maastrichtian circulation. Consequently, the faster overturning may drive a smaller shift from the unradiogenic values of the source region (Australian coast/Ross Sea) to radiogenic Pacific values, which could explain the negative excursion in ε_{Nd} at the low latitude Pacific sites.

Line 825-827: Would it be possible to test the effect of imposing barriers in the Southern Tethys (around Kerguelen, I would imagine), even if they are not very well constrained?

Yes, it would be possible to raise bathymetric barriers in the Southern Tethys but it would require a significant amount of computing resources because the CESM model is complex and relatively high-resolution. We keep this interesting idea in mind for potential future experiments.

Lines 842 onwards. The Soudry data is incorporated into the discussion of Cenomanian circulation in the Tethys, yet, on line 846, it is stated (correctly) that the Soudry data come from neritic settings so cannot be used to interpret intermediate or deepwater circulation. Thus, it seems misleading (and a bit confusing for those unfamiliar with the datasets) to discuss Soudry if the conclusion (line 847) is that the data from neritic settings cannot be used to support the simulations.

The Soudry data are consistent with our Cenomanian simulations in that the model simulates strong westward currents through the Tethyan Ocean. We agree however that these data were awkwardly used in the original manuscript. Because of their limited relevance to our interpretation, we have removed the reference to Soudry et al. (2006) and Pucéat et al. (2005). This section now reads:
"Records from the equatorial Pacific (Murphy and Thomas, 2012) shows moderately high ε_{Nd} values (> –6) from the Cenomanian onwards. In addition, modern compilations of the ε_{Nd} signature of the continental margins in the eastern Mediterranean Sea (Ayache et al., 2016) and on the northeastern coast of Africa (Jeandel et al., 2007) indicate relatively radiogenic ε_{Nd} values (> –6). Inputs of radiogenic intermediate and deep waters from the Pacific into the North Atlantic via this Neotethyan pathway, regardless of whether sediment/water exchange in the Neotethyan Ocean may have contributed to their isotopic composition, provides a possible explanation for the ε_{Nd} signature of the deep North Atlantic (Fig. 13), which has more radiogenic values than the nearby North American and

North African continents (Jeandel et al., 2007)."

Line 857: replace "and that: : :" with either "that: : :" or "but we are unable to exclude them."

The sentence was rephrased as:
"However, other events may also have contributed to raising the ε_{Nd} values of North Atlantic intermediate and deep waters."

Lines 875-881: Whilst I agree that boundary exchange could be an issue for the eNd data from Demerara Rise, the existence of very saline waters (based on the Mg/Ca and d18O data of Friedrich et al., 2008) do point to local formation of warm saline bottom waters and suggests that this feature of ocean circulation is missing in all model simulations.

This is correct and we mention that the model does not produce low-latitude intermediate or deep-water formation at Demerara Rise. However, we have modified the last part of this subsection to better emphasize the possibility that models might be unable to form low latitudes deep-water formation because of some missing processes and/or details of the local paleogeography. The new sentence reads:
"Our model results support boundary exchange as an explanation for very low Demerara Rise values but we cannot exclude the possibility that climate models are unable to reproduce low-latitude intermediate or deep-water formation at Demerara Rise because of missing processes or insufficiently detailed local paleogeography."

Line 890: The papers by Robinson support increased exchange by, and during, the Maastrichtian and should be cited here.

We have corrected this oversight.

Line 910-912: One important consideration could also be the significance of palaeowater depth differences and variable amounts of boundary exchange between sites (and through time) and the effect these factors might have on the records of eNd. Furthermore, the use of different archives of eNd, could also be a source of offsets between different datasets.

We agree and now hint at these considerations in the introductory section about Neodymium isotopes (section 5.2.1). The last two paragraphs now reads:
"All of these hypotheses explain the similarity in deep-water εNd values between the North Atlantic, South Atlantic and Indian Oceans in the Maastrichtian (Fig. 13) by greater communication between the basins (Robinson and Vance, 2012; Murphy and Thomas, 2013; Moiroud et al., 2016). Other records instead suggest that bathymetric barriers of the Rio Grande Rise (RGR) – Walvis Ridge (WR) system in the South Atlantic prevented deep north-south flow between the North Atlantic and the Southern Ocean until the Paleogene (Voigt et al., 2013; Batenburg et al., 2018) although recent work suggest that deep channels existed through the RGR-WR system in the Late Cretaceous (Moiroud et al., 2016; Pérez-Díaz and Eagles, 2017).

The opening of the Atlantic and Southern Ocean nonetheless played a major role in the convergent evolution of εNd values in the Late Cretaceous by affecting intermediate and deep flow patterns as well as the residence time of water masses and, hence, local εNd inputs such as boundary exchange."

Figures

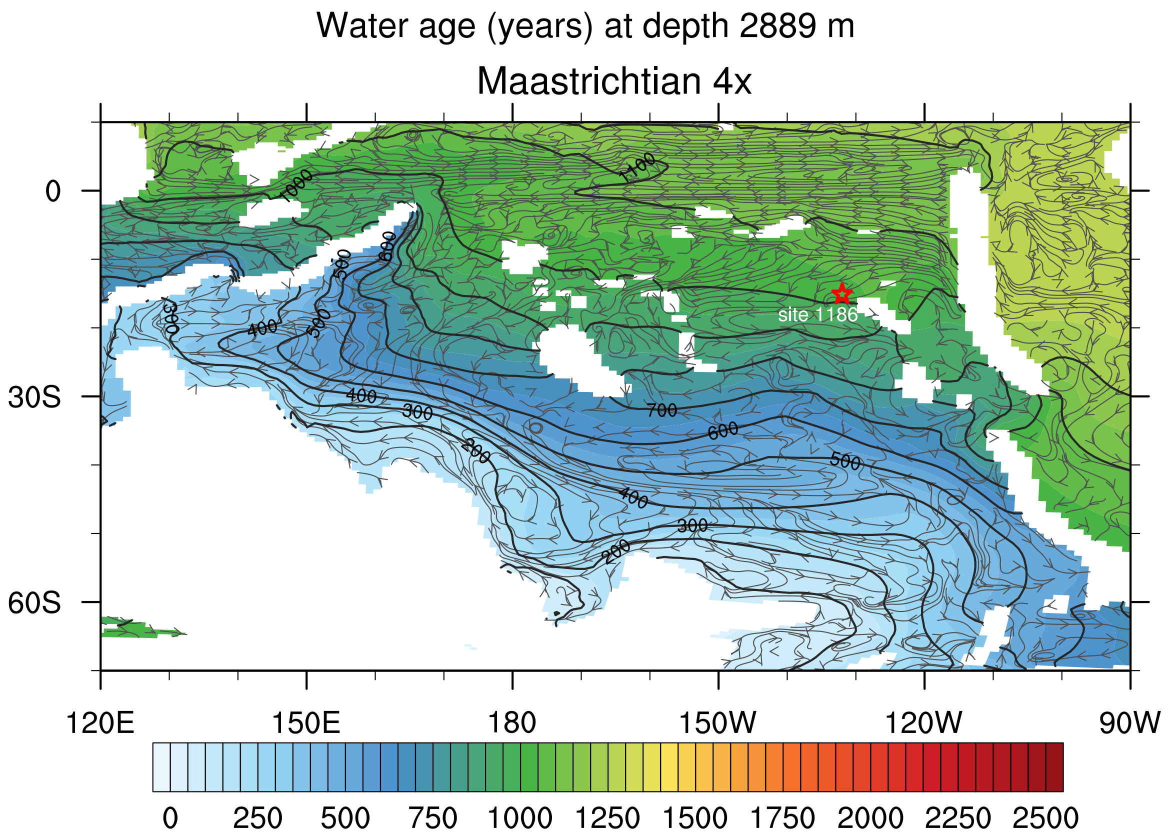

Figure R1. Maastrichtian 4x CO_2 water mass age (100 years black contours) and currents at depth 2900 m in the South Pacific. Estimated paleolocation of site 1186 is shown by the red star.

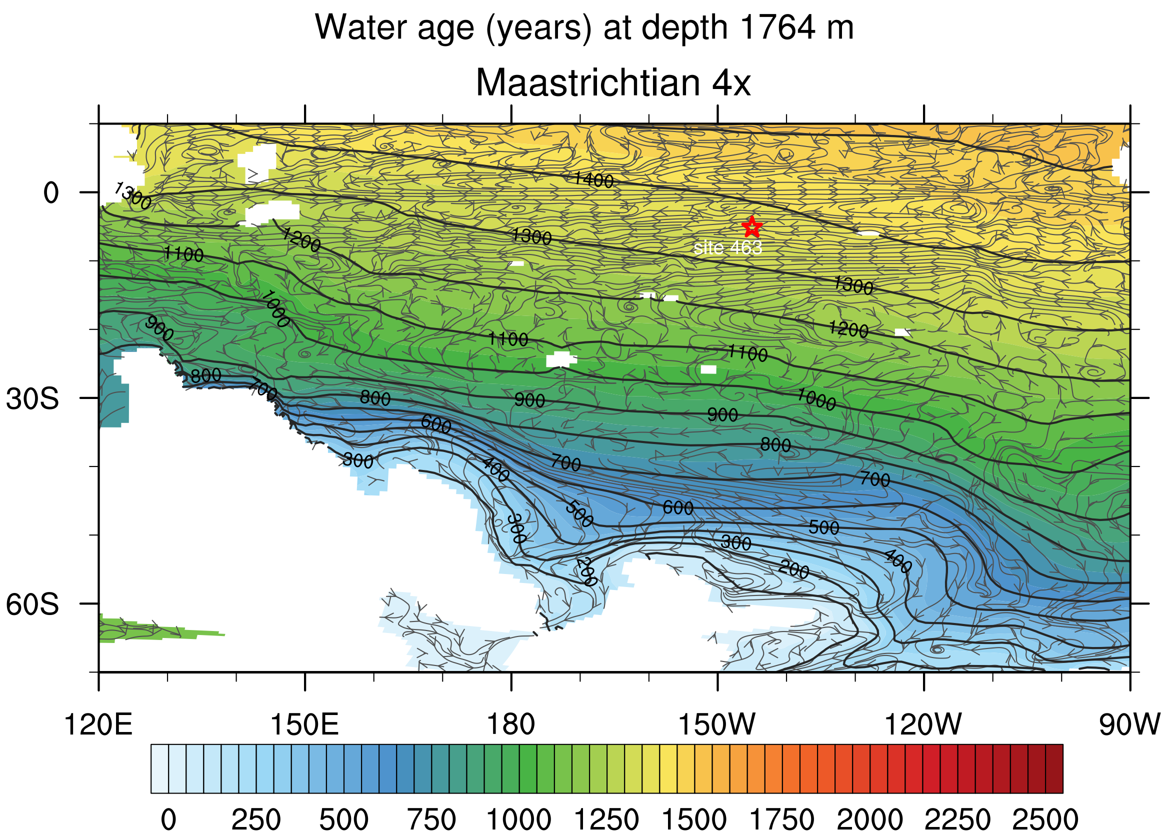

Figure R2. Maastrichtian 4x CO_2 water mass age (100 years black contours) and currents at depth 1700 m in the South Pacific. Estimated paleolocation of site 463 is shown by the red star.

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