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Climate of the Past Discussions

Interactive comment on "The Middle Miocene climate as modelled in an atmosphere-ocean-biosphere model" *by* M. Krapp and J. H. Jungclaus

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Response to Review #1

We thank Nicholas Herold for his constructive and helpful suggestions on the manuscript. In the following we refer individually to each of his comments

Krapp and Jungclaus describe simulations of middle Miocene climate conducted using a coupled ocean-atmosphere model. Such models have until recently been rare in deep time paleoclimate research, particularly for the Miocene, and are a fundamental addition to the area. The experiment design is sound. The subject of the paper is *certainly within the scope of Climate of the Past and I believe this can be a very useful contribution, however, I feel the text needs significant revision. It seems to skim over some of the important/interesting details in the model output. Particularly, differences are described between the simulations but with little breakdown of the model diagnostics to find out (if possible) why, or without discussion of what the ramifications of such changes may be (for proxy interpretation or for maintaining lower temperature gradients for example). More in-depth analysis is required and the conciseness of the text needs improving.*

answer: (General answer) To achieve a more thorough picture of the warming mechanisms for the Middle Miocene we re-structured the manuscript and added new aspects regarding the model diagnostics. We do no longer differentiate between the topographic impact and the role of CO2 in order to avoid repetition. Instead, the results of the former Results section are now treated in four (independent) sections. In the first, we describe the mean climate of each Miocene setup and their differences. A comparison to previous studies in terms of the sensitivity to a doubling of CO2 is also given and we apply the EBM diagnostics in this section. From here, we lead over to the next section where a more detailed analysis of the atmospheric and oceanic heat transport is given. We make use of heat transport decomposition into mean meridional and eddy transports and we show how the large-scale circulation patterns alter the heat transports. We add a subsection about the Bjerknes compensation as a possible explanation for the relatively small changes of the total poleward heat transport that in turn hinder a flatter temperature gradient. Because our study is the first study that includes full ocean dynamics we decide to treat the ocean circulation in a separate section to highlight this new advancement. We present arguments why the AMOC can is as strong as today and why it collapses under high CO2. We add a paragraph to the comparison section where we evaluate the proxy-model agreement. In the new version we also revised the discussion to account for organisational changes of the paper.

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The goal of this study is to see if a meridional temperature gradient closer to proxy records can be achieved using a dynamic ocean model (as opposed to previous studies) and to see how topography/bathymetry and CO2 contribute to Miocene warmth. However some results, such as winter storminess, while interesting are not linked by the text in any obvious way to poleward heat transport. Thus more in-depth analysis is needed or the associated figure could be excluded without subtracting significantly from the paper.

answer: We improve on the link between midlatitude storm tracks and heat transport changes, because it shows the balance between atmospheric and ocean heat transport, especially in the MIOC720 setup. We included a new section about the heat transports and revised the figures for the heat transport and the heat transport changes. They now describe the individual transports by ocean and atmosphere and their decompositions in terms of mean meridional and eddy heat transports (Fig. 1 replaces Fig. 10 in the discussion paper).

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The response from the ocean is really interesting and here a lot more could be said. Namely, the near-modern AMOC at 360 ppmv and its collapse at 720 ppmv, and the consequent reduction in poleward heat transport, need analysis. The authors include plots of the zonal and meridional volume transports, which are very useful, but do not explore why this collapse occurs, and perhaps more importantly why the AMOC is at near modern strength at 360 and 480 ppmv despite the Panama gateway. Of course, this has something to do with the increased salinity in the Atlantic as implied. Looking at the surface winds I imagine surface flow through Panama is westward. If it's believed that Tethys outflow is involved (e.g. Schnitker, 1980) then this should be examined. Looking into this seems useful in the context of examining mechanisms responsible for lowering the equator-pole temperature gradient.
It can be difficult to decide which aspects of the output to focus on from such models. As the authors state, the addition of a dynamic ocean is what is novel here, so it would

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be nice to see what insights can be gained from this. While future sensitivity studies or analysis may be conducted regarding bathymetric changes, I think it is still appropriate to examine the results to the extent that the main climatic changes can be understood.

answer: In the new section about the large-scale ocean circulation we included a detailed analysis of the mechanisms that lead to a strong and stable AMOC comparable to present day: 1) Because the sill depth of the Caribbean plateau is shallower than the deep western boundary current, deepwater returns into the South Atlantic as today (Fig. 2, this figure has just been added for this discussion.). That North Atlantic deepwater formation occurred prior to the closure of the Panama Seaway has also been shown in a sensitivity study for different sill depths of the gateway (Nisancioglu et al., 2003). 2) The salinity contrast between Pacific and Atlantic is determined by the freshwater balance between Atlantic and Pacific Ocean (e.g. Zaucker and Broecker, 1992). During the Middle Miocene, moisture transport across the the Andes was easier due to their lower elevation. The increased westward moisture transport into the Pacific dominates the inflow of Pacific water in the upper ocean (Fig. 3 has been added to the revised manuscript). We improved the analysis of the T-S diagram and added a plot for the relative freshwater flux into the Atlantic basin (Fig. 4 has been added to the T-S diagram in Fig. 8 of the discussion paper). The mechanism that lead to a collapse of the AMOC in the MIOC720 setup is a relatively fresh North Atlantic. Its surface is less dense compared to the other experiments and the density difference between the North Atlantic and the South Atlantic is smaller, leading to a weaker meridional overturning circulation (Schewe and Levermann, 2010). Freshwater from large runoff into the Baltic and North Sea in the east, and runoff at the north-eastern American coast spread into the North Atlantic, making the surface ocean fresher and more buoyant (Figure 5, this figure has just been added for this discussion).

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Specific Comments

- The abstract needs revising. The 4–8% net increase in poleward heat transport isn't

actually even discussed in the body of the text.

answer: We withdraw this statement and instead refer to the relative changes in terms of Bjerknes compensation instead.

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The conclusion that a CO2 higher than present is needed to qualitatively support Miocene proxy temperatures isn't new. Instead, it would be good, again, if insights could be gleaned from these results in order to add to our understanding of Miocene climate.

answer: That CO2 warms the global climate is not new. Instead, we want to emphasise the role of higher CO2 in a fully coupled model study that adds additional support to the findings of You et al. (2009). We added to the discussion that the high latitude feedbacks, namely vegetation and ice-albedo, are too weak to seriously flatten the temperature gradient.

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- The Tripati et al. (2009) reference is not for temperature, they reconstruct CO2, look in there for references to the 3–6 deg. warming. In any case, I don't think global mean temperature should be compared to this warming since this is based on bottom water temperatures and high southern latitude SSTs.

answer: We withdraw the overall statement of the 3–6 K global warming. Instead, in the light of the model-proxy comparison, we highlight regional differences for land temperature, surface ocean, and deep ocean, and cite appropriate references.

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- While it is true that "The large forest cover and the northward extension of forest is in line with vegetation reconstructions (Wolfe, 1985)." This is stated several times as though it were surprising that a high CO2 would lead to an overall increase in forest cover. This is again stated in the conclusion; "Assuming higher atmospheric CO2 lev-

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els, we are also able to reproduce the densely wooded Middle Miocene." While this is true it is very qualitatively proven (and again, not surprising) and doesn't seem to warrant mentioning in the conclusions, or at least not without more rigorous examination.

answer: Our idea is to use the dynamic vegetation as test to identify the Miocene setup that provides the best environmental conditions for maximum tree cover while reducing the desert fraction. We show that forest cover is largest in MIOC480 and MIOC72 and, therefore, conclude that a denser vegetation needs at least higher than present-day CO2.

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- It would be useful to cite Butzin et al. (2011), as well as Micheels et al. (2011) who also use a coupled model. While the latter is for the late Miocene it could provide a useful comparison. I also believe the authors compare their results to the same or similar dataset as Micheels et al.(?) What age range do the data that are used for comparison span?

answer: We use a dataset from 2010 ranging from 16.4 - 11.2 million years ago (Torsten Utescher, personal communication). We add a point to the discussion where we compare to the findings of Micheels et al.. We refer to Butzin et al. in the introduction where we describe the setup of Henrot et al..

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- Please add a sentence or two describing the vegetation model, particularly how many vegetation types it simulates. As a side note, could the soil properties in the biosphere model not have been globally averaged to provide a 'level playing field' for all grid points? This may or may not be more accurate but would help with places like the Sahara.

answer: We add a description of the PFTs used in JSBACH and how the dynamic vegetation is calculated. These are tropical broadleaf evergreen, tropical broadleaf deciduous, extra-tropical evergreen, extra-tropical deciduous, raingreen shrubs, decid-

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uous shrubs, C3 grass, and C4 grass. JSBACH calculates the leaf area index, evapotranspiration, and vegetation cover for each PFT in terms of net primary production, natural-, and disturbance-driven mortality.

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- Page 6, lines 9–19: Henrot et al. (2010) use initial conditions from an OGCM with altered bathymetry, thus their predicted SSTs reflect these changes to some extent. I think it is worth mentioning this as it shows an evolution in complexity from studies like You et al. (2009) and Herold et al. (2010); with your study being the next step.

answer: We emphasise the advancement in Middle Miocene climate modelling in the introduction.

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- A sentence on the metric used for determining model equilibrium is needed.

answer: We added a sentence about the model equilibrium. We assume equilibrium because the maximum drift in deep ocean temperatures below 2000 m is 0.2 mK/year in CTRL, -0.1 mK/year in MIOC360, -1.5 mK/year in MIOC480, and 0.9 mK/year in MIOC720.

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- Comparing absolute values between different models isn't so useful (e.g. page 9, line 24 and page 6, line 24), You et al. (2009) use a modified ocean heat flux (not based on a dynamic ocean). Better to compare model sensitivities if possible.

answer: We compare the climate sensitivity (temperature increase for a doubling of CO2) of our coupled model to earlier studies where possible. The sensitivity of the climate to a doubling of CO2 in our experiment is 4 K. That is higher than 2.0 K and 2.2 K in the studies by You et al. (2009) and Tong et al. (2009). For the study by Henrot et al. (2010) we calculate a climate sensitivity between 2.6 and 4.9, depending on the experiments (with or without Miocene vegetation, 200 or 280 ppm compared to

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500 ppm). While the CCSM as used in Tong et al. (2009); You et al. (2009) is known for its lower climate sensitivity, the setup of Henrot et al. (2010) shows a climate sensitivity that is comparable to our estimate. We also compare the sensitivity of precipitation to increased CO2 and find a model sensitivity of 51 mm/a at the lower side compared to the 53 to 106 mm/a by Henrot et al. (2010).

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- Page 10: include an additional sentence or two (or rephrase the last paragraph) explaining more the steps involved in attributing the temperature change between each set of two experiments (in Fig. 11) to albedo, heat flux and emissivity. Just so people don't need to go to Heinemann et al. (2009) for the process.

answer: In the EBM subsection, we added a description of how the individual contributions to the warming are obtained and add a simple example.

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- I think it would be fair to place much more emphasis on the cold bias that has almost certainly effected the low latitude marine SSTs in your model-data comparison. In fact, why not use the SSTs by Stewart et al. (2004) (which are much warmer) in your comparison or as an example of well-preserved samples?

answer: We discuss the cold bias of earlier marine temperature proxies more thoroughly. Sample RAS99-38 (10S, 39.8E) from Stewart et al. (2004) cover the time slice 12.2$\pm$0.3 million years ago (stage M9) and has a SST-range of 20.9–26.9 deg C (samples correspond to 24.7$\pm$1.9)

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- The proxy comparison needs work, model-data plots have been made but it is not stated which model performs best. Where are the majority of model-data discrepancies? Is there a reason for this?

answer: We evaluate the model-proxy data comparison for all model results. For each

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grid box we calculate the ratio between the modelled and the proxy-based temperature $T_{\text{model}}/T_{\text{proxy}}$ for both marine and terrestrial data and for the low, mid-, and high latitude locations. The closer this ratio is to one the better the agreement between model and proxy data. The distribution for all proxy locations is shown as boxplot in Figure 6 (added to Fig. 13 of the discussion paper.).

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- The conclusion reads like a summary (which is what the previous section was). Here points need to be made that draw together what has been discussed and perhaps indicate some details of what is to be done next. Also, there doesn't seem to be any statement as to how well or how poorly the model recreates the meridional temperature gradient suggested by proxies, as mentioned in the introduction. This should be stated and if temperature gradients are too high compared to proxies then perhaps some discussion of why this is so should be included (in the discussion).
- Where conclusions are consistent with previous studies, this needs to be stated. Even if certain results have not been shown for the Miocene, they have been shown for other time periods (e.g. Eocene, Pliocene).

answer: We add a discussion to the question why the meridional temperature gradient cannot be reproduced and where the discrepancies may arise from. Our conclusion is that high-latitude warming is limited by the feedbacks that are at work, namely the ice-albedo feedback, or the vegetation feedback are too weak in our setup.

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Technical Corrections
- Page 2, line 22: "wet to very wet" isn't informative, please rephrase.
- Page 3, line 10: Herold et al. (2010) did reproduce a low temperature gradient because prescribed SSTs were used.
- Page 3, line 27: Should be "Section 5".
- Page 5, line 17: Remove commas from sentence.
- Page 6, line 14: Should be "SH_700"?

- Page 9, line 6: is the "19.2" meant to be "19.8"? - Figure 5 and 6 are cited before figure 4.
- Caption for Fig. 5: Should part C be "MIOC480 compared to MIOC720"? Also the continental distribution needs to be changed for these figures. - The title "Role of topography" is misleading since you are also discussing bathymetry. Perhaps use "topography/bathymetry"?
- Line 18 Page 8: rephrase to "is not an enclosed basin"
- I don't believe sentences like Page 11, lines 8 – 9 and page 7, line 2 are necessary.
- Page 11, line 18: Rephrase to "...an enhanced hydrological cycle and stronger greenhouse effect can be attributed to higher CO2".
- Figure 13: I assume the lines at each point are error bars, perhaps try to make these lighter versions of the green, red and blue already used so that the actual data points aren't covered.
- Page 14 last line: should be "may differ". - Figure 9: The dotted boxes showing the Panama and Tethys gateways also need to be in 9b.
- Side note: Might have been interesting seeing 720-360 ppmv plots instead of 720-480 since the former is a doubling and the common yardstick.

answer: We include the technical corrections, rephrase sentences and figure captions where necessary, and update the figures accordingly. We interpolated the terrestrial data onto the atmospheric grid so less data points overlap. Because we want to highlight the differences for each increase of CO2, we do not want to include too many (redundant) plots. We, therefore, leave it to the reader to add the MIOC480-minus-MIOC360 and the MIOC720-minus-MIOC480 plots.

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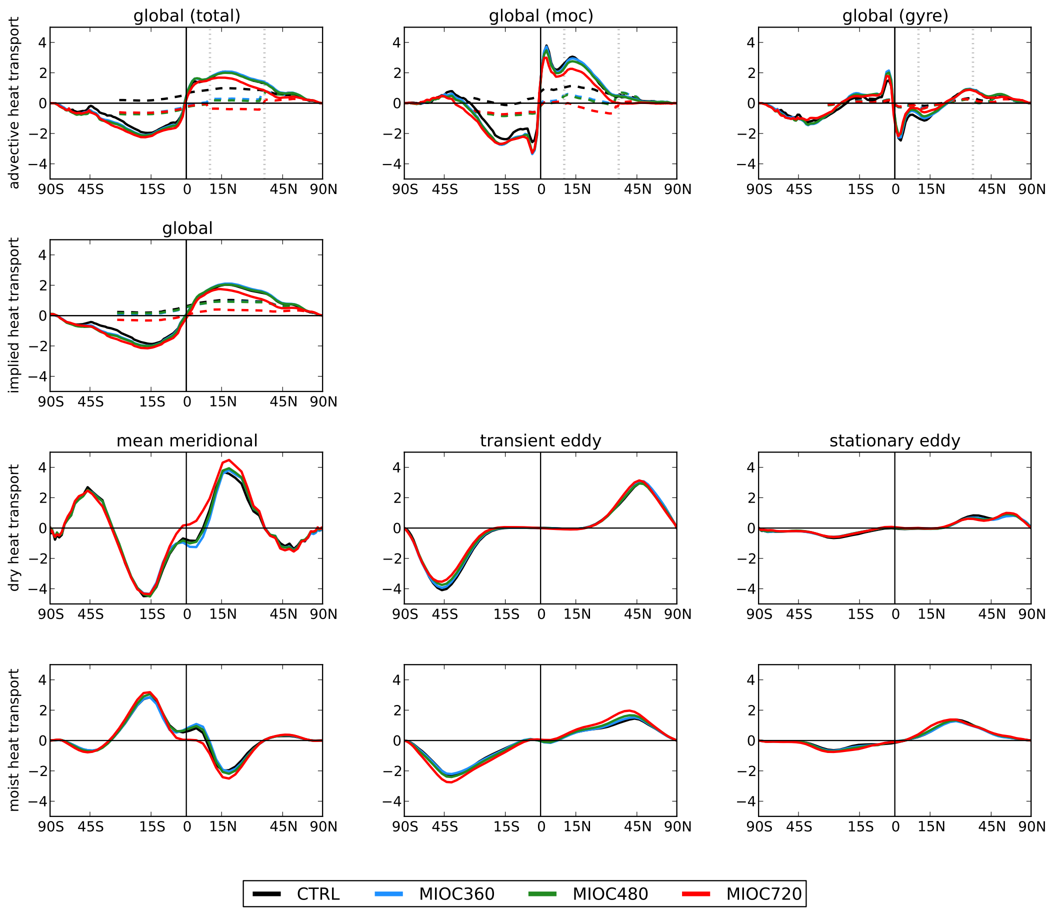

Fig. 1. Heat transport of ocean (upper two rows) and atmosphere (lower two rows) for all experiments (in PW).

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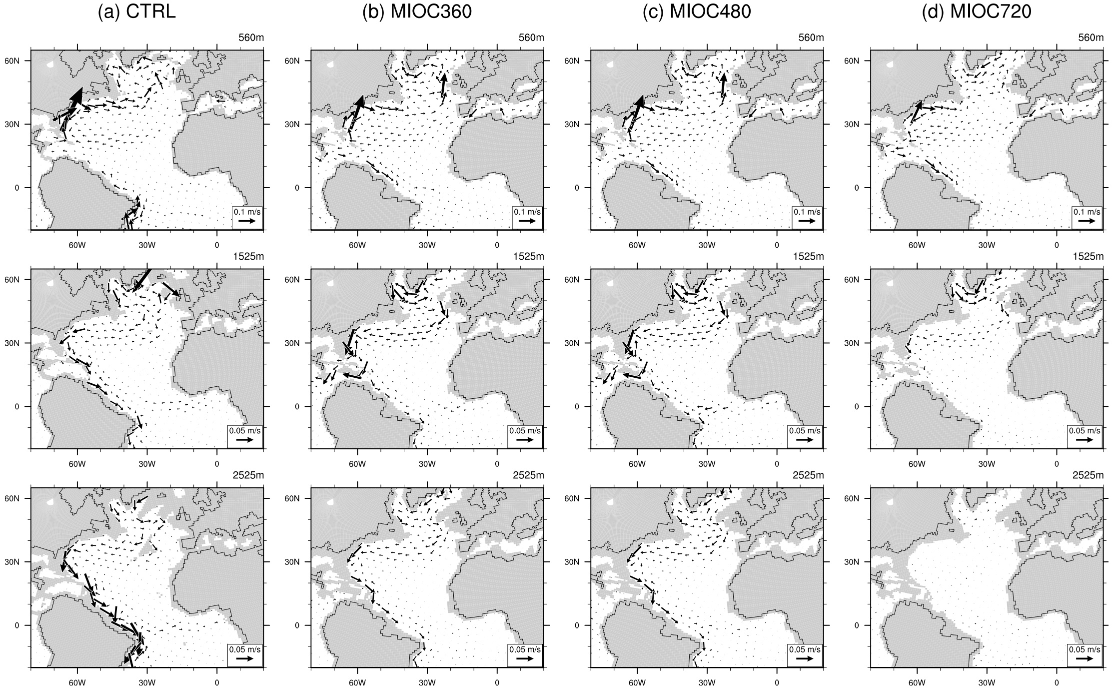

Fig. 2. Horizontal velocity field for the Atlantic Ocean at depths of 560, 1525, and 2525\,m for all experiments

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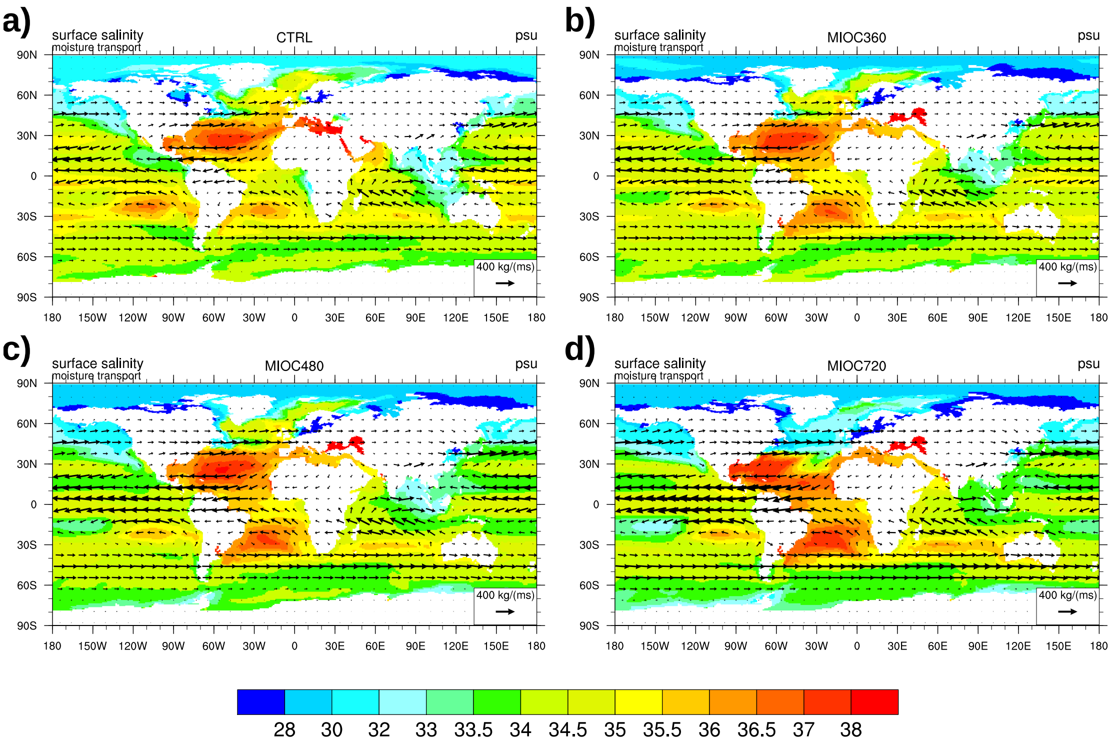

Fig. 3. Surface salinity for all experiments as contours (in psu) and overlaid the vertically integrated moisture transport.

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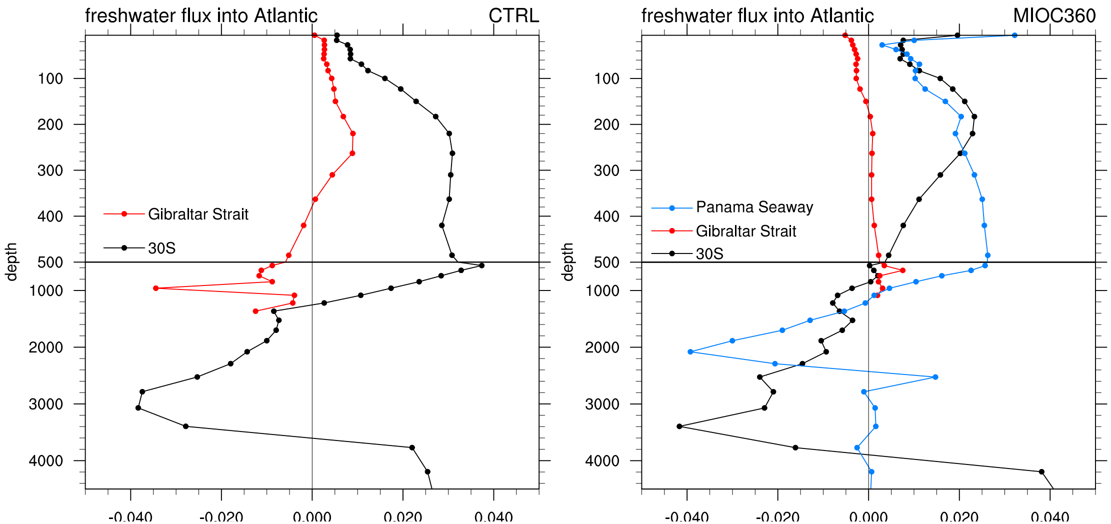

Fig. 4. The freshwater flux through the Panama Seaway (blue), Gibraltar Strait (red), and at 30S into the Atlantic Ocean relative to a salinity of 35.5\,psu.

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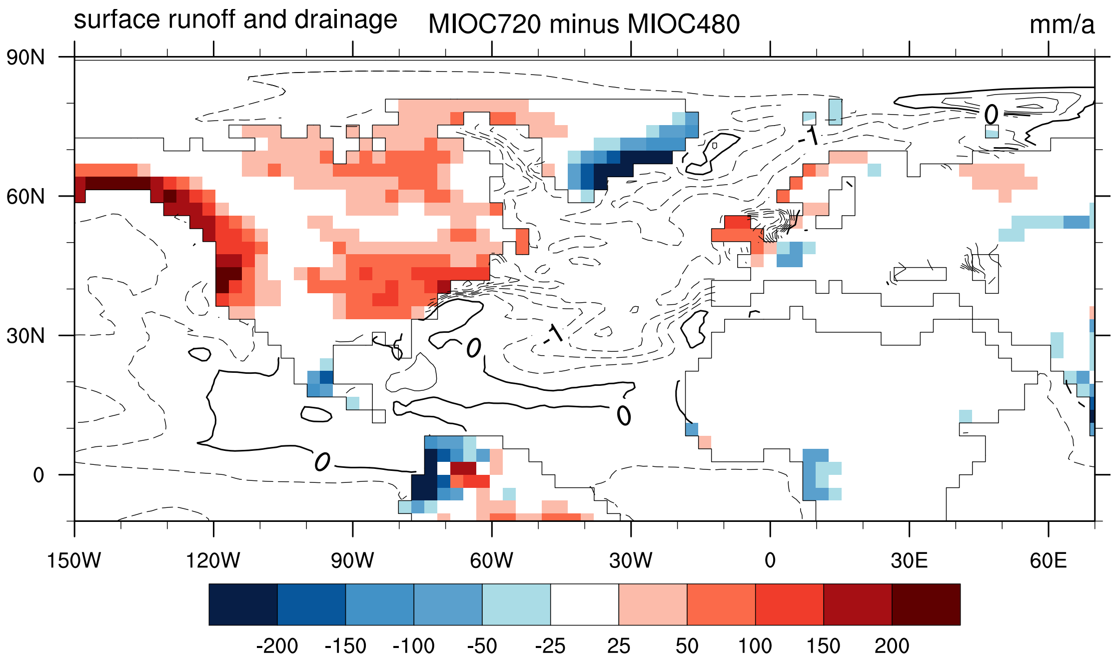

Fig. 5. MIOC720 minus MIOC480 difference of runoff/drainage into the North Atlantic (colours, in mm/a). Contour lines (0.5kg/mˆ3) are the difference of surface density

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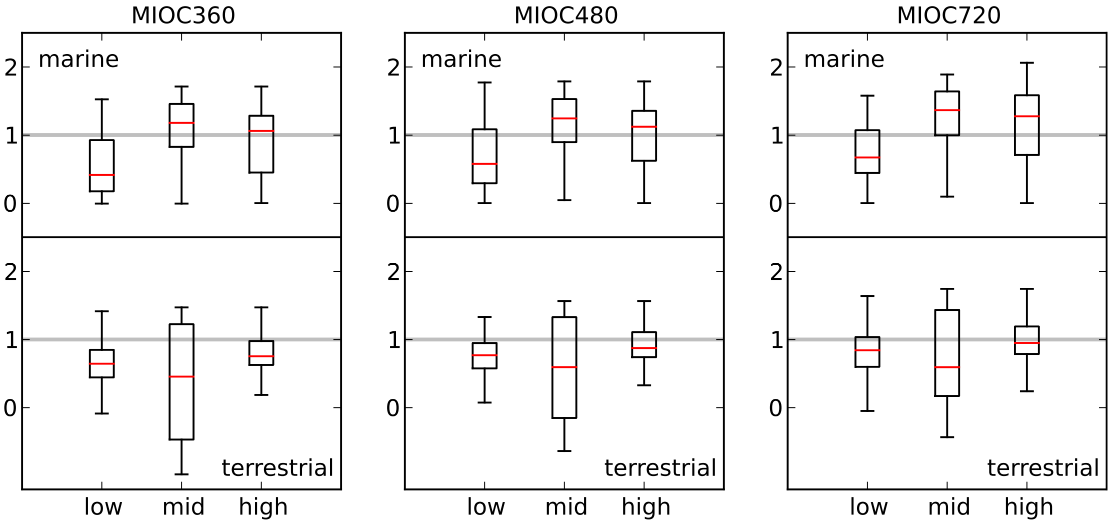

Fig. 6. Distribution of the ratios between the modelled and the proxy based temperature for terrestrial and marine data.

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