Reply to reviewer CC1

We are grateful for the reviewers' insightful and constructive comments and have addressed all issues as described below. The original reviewer questions and comments are colored in blue.

Line 83: Are google hits a good measure, since they will vary over time.

Reply:
We acknowledge the issue of results varying with time and we accept the criticism and omit the complete sentence and Google scholar is not mentioned any more in the article.

Line 124: I realise that you do this later, but maybe the references for the different model components should be here as well or instead of later?

Reply: We now have included references already here.

New text:
“EC-Earth3 comprises model components for various physical domains and system components describing atmosphere, ocean, sea ice, land surface, dynamic vegetation, atmospheric composition, ocean biogeochemistry and the Greenland ice sheet. The component models are described in section 3. The atmosphere and land domains are covered by ECMWF’s IFS cycle 36r4 (based on IFS system 4, https://www.ecmwf.int/sites/default/files/elibrary/2011/11209-new-ecmwf-seasonal-forecast-system-system-4.pdf), which is supplemented with a coupling interface to allow boundary data exchange with other components (ocean, dynamic vegetation, aerosols and atmospheric chemistry, etc). The NEMO3.6 (Madec 2008, Madec et al., 2015) and LIM3 (Vancoppenolle et al., 2009; Rousset et al, 2015) models are the ocean and sea-ice components, respectively. Biogeochemical processes in the ocean are simulated by the PISCES model (Aumont et al. 2015). Both LIM3 and PISCES are code-wise integrated in NEMO. Dynamical vegetation, land use and terrestrial biogeochemistry are provided by LPJ-GUESS (Smith et al., 2014, Lindeskog et al., 2013). Aerosols and chemical processes in the atmosphere are described by TM5. The ice sheet model PISM (Bueler and Brown, 2009, and Winkelmann et al., 2011, The PISM Team, 2019) is optionally utilized to model the Greenland ice sheet.”

Line 179: Do different configurations of the model have different E-P imbalances, and hence is this flux corrector changed? Also how do future projections work, might having this corrector affect how the future change in runoff is simulated?

Reply:
The compensating flux by the corrector is calculated separately for different resolutions, since different resolutions give different results. The effects are described both here and in the section “Low resolution configuration”. Correctors are derived for observed climate and applied throughout future scenario periods without change. Sensitivity experiments concerning the effects on future runoff have not been carried out. Sea level variables in ESMs such as EC-Earth are generally not used directly for estimates of expected future

sea level rise. These are rather derived indirectly from different types of model and observations.

We add additional text:"The compensating flux by the corrector is calculated separately for different resolutions, since different resolutions give different results. The effects are also described in the section "Low resolution configuration". Correctors are derived for observed climate and applied throughout future scenario periods without change. Sensitivity experiments concerning the effects on future runoff have so far not been carried out."

L219: can you state which timestep is used in the final model (perhaps refer to the table)

Reply:
We added new timestep information to the text, and table 2 has been extended:
"In final model configurations timesteps ranging from 900s (high resolution) to 3600 s (low resolution) have been used; see table 2."

L239: I think this sentence would be clearer if rewritten, e.g.: The goal was to maintain the same atmospheric tuning as much as possible, and only modify the ocean and sea-ice parameters…

Reply:
The text has been modified accordingly.

Modified text:
"The goal was to maintain the same atmospheric tuning as much as possible, and only modify the ocean and sea-ice parameters"

L386: Do I understand that this is not a dynamic ice sheet (i.e. it cannot grow or shrink). It may be worth noting this just for clarity, or if I misunderstand then clarifying what the ice sheet can do.

Reply:
PISM is a dynamic ice sheet model. It handles the ice sheet dynamical and thermodynamical processes, including ice flow, subglacial hydrology, bed deformation, as well as the basal ice melt. The text has been updated accordingly

New added text:
"GrIS handles the ice sheet dynamical and thermodynamical processes, including ice flow, subglacial hydrology, bed deformation, as well as the basal ice melt."

L516: was the closure of Bechtold included in the model (it is implied but not said).

Reply:
Yes, the Bechtold et al. 2014 closure is implemented in the model.

We modified the sentence to "A closure described by Bechtold et al. (2014) **improving** the diurnal cycle of convection **has been implemented** in EC-Earth3.

L516: for what reason was the Rayleigh friction included - the other changes have reasons why they were included.

Reply:
We modified the text:
"...Rayleigh friction was activated in EC-Earth IFS for all resolutions to avoid unphysically large wind speeds at higher resolution.

L566: it might be useful to briefly mention what processes are missed by the MACv2-SP scheme, such as natural aerosol variability.

Reply:
We added text:
"As EC-Earth3 uses MACv2-SP in combination with a pre-industrial aerosol climatology, natural aerosol variability is only accounted for via the prescribed seasonal cycle of the climatology. Furthermore, MACv2-SP only captures the seasonal cycle and long-term changes in the optical properties and derived CDNC impact factor of anthropogenic aerosols. Diurnal variability in aerosol amounts or properties is not explicitly described. Day-to-day variability is only included to the extent captured by the seasonal cycles of the pre-industrial climatology and MACv2-SP. Of the interannual variability in the amount and properties of anthropogenic aerosols, only the long-term changes in plume strengths, which are assumed to covary with the 11-year averaged emissions of SOx plus NH3 in the associated countries, are accounted for. Changes in the spectral distribution of the optical properties, the single-scattering albedo and asymmetry factor of anthropogenic aerosols due to long-term changes in their size distribution and composition are ignored by MACv2-SP."

L1025: Can you say any more about the Southern Ocean warm bias? For a 1 degree model this seems quite large.

Reply:
The text has been updated with more information:
"Most coupled climate models suffer from a warm southern ocean (SO) bias (Hyder et al 2018).
In EC-Earth3 configurations, the warm bias is found in all seasons. Large parts of the bias have been attributed to biases in short wave cloud radiative effects. Modifications in the cloud scheme and the representation of supercooled liquid water made in more recent versions of IFS, including cycle 45r1 (Forbes and Ahlgrimm, 2014; Forbes et al., 2016), together with the introduction of the new ecRad radiation scheme in cycle 43r3 (Hogan et al., 2017) have been shown to substantially reduce these biases."

We also added new references:

Hyder, P., Edwards, J.M., Allan, R.P., Hewitt, H.T., Bracegirdle, T.J., Gregory, J.M., Wood, R.A., Meijers, A.J., Mulcahy, J., Field, P., Furtado, K., Bodas-Salcedo, A., Williams, K. D., Copsey,D., Josey, S. A., Liu, C., Roberts, C.D., Sanchez, C., Ridley, J., Thorpe, L., Hardiman, S. C., Mayer, M., Berry, D. I., ansd Belcher, S. E.: Critical Southern Ocean

climate model biases traced to atmospheric model cloud errors, Nat. Commun., 9, 3625, https://doi.org/10.1038/s41467-018-05634-2, 2018.

Forbes, R. M., and Ahlgrimm, M.: On the representation of high-latitude boundary layer mixed-phase cloud in the ECMWF global model, Mon. Wea. Rev., 142, 3425–3445, https://doi.org/10.1175/MWR-D-13-00325.1, 2014.

Forbes, R., Geer, A., Lonitz, K., and Ahlgrimm, M.: Reducing systematic error in cold-air outbreaks, ECMWF Newsletter No. 146, 17–22, 2016.

Hogan, R., Ahlgrimm, M., Balsamo, G., Beljaars, A., Berrisford, P., Bozzo, A., Di Giuseppe, F., Forbes, R. M., Haiden, T., Lang, S., Mayer, M., Polichtchouk, I., Sandu, I., Vitart, F., and Wedi, N.: Radiation in numerical weather prediction, ECMWF Technical Memorandum No. 816, 49 pp., https://doi.org/10.21957/2bd5dkj8x, 2017.

L1142. You note that the AMOC strength is close to observations, but why is there no mention of the northward heat transport, which is as or more important for the climate state. Some mention of how this compares to observations would be welcome.

Reply:
We now mention the northward heat transport.

Added text:
"The ocean heat transport (Figure 16) is related to the AMO. North of 20o N it shows values slightly lower than observation estimates from Trenberth et al. (2019), that covers the period from 2000-2014."

We also added a new figure illustrating the northward heat transport (new Figure 16) and a new reference:

Trenberth, K. E., Zhang, Y., Fasullo, J. T., & Cheng, L. (2019). Observation-Based Estimates of Global and Basin Ocean Meridional Heat Transport Time Series, Journal of Climate, 32(14), 4567-4583. Retrieved May 20, 2021, from https://journals.ametsoc.org/view/journals/clim/32/14/jcli-d-18-0872.1.xml

L1196: You make no mention of the large range in power of the different ensemble members. For example, does the member with the strongest ENSO power have any other climatological differences, is such as range understandable?

Reply:
We added background information to the text.

The range among the different members spectra is considerable. Climatologically, most ensemble members show only small differences over the tropics when compared with the whole ensemble mean. Although the members with the most energetic ENSO share some

climatological features (cold Arctic and Labrador seas) compared to the ensemble mean, the reason why they have developed a more energetic ENSO remains unclear.

L1213: Are there any hypotheses for the reason for the improvement in the ENSO-NAO that could inform other models?

Reply:
We added a hypothesis to the text:

“Previous research has linked La Niña/El Niño events to the positive/negative NAO patterns (Fereday at al. 2020). Although this link is relatively weak due to the fact that internal atmospheric variability is large in the North Atlantic European (NAE) region (Brönnimann, 2007), it depends on ENSO strength (Jiménez-Esteve & Domeisen, 2019; Toniazzo & Scaife, 2006). Therefore a more energetic ENSO (more comparable in scale with observations) such as in the current EC-Earth3 could impact on the intensity and sign of NAO.”

We also added references:

Brönnimann, S. (2007). Impact of El Niño–Southern Oscillation on European climate. Reviews of Geophysics, 45, RG3003. https://doi.org/10.1029/2006RG000199

Fereday, D., Maidens, A., Arribas, A., Scaife, A., & Knight, J. (2012). Seasonal forecasts of Northern Hemisphere winter 2009/10. Environmental Research Letters, 7(3), 034031.

Jiménez-Esteve, B., & Domeisen, D. (2019). Nonlinearity in the North Pacific atmospheric response to a linear ENSO forcing. Geophysical Research Letters, 46, 2271– 2281.

Toniazzo, T., & Scaife, A. (2006). The effect of non-linearity on winter ENSO teleconnections over Europe. Geophysical Research Letters, 33, L24704. https://doi.org/10.1029/2006GL027881

Table 2: It is implied that the timestep in the ocean and atmosphere are the same, could this be stated explicitly.

Reply:
Table 2 is now updated with more time step information.

	Resolution atmosphere	Resolution ocean	Timestep
Standard resolution	T255L91 (~80 km)	ORCA1L75 (1 deg)	2700 s (atm) 2700 s (oce) 2700 s (coupling)
Low resolution EC-Earth3-LR and EC-Earth3-Veg-LR	T159L62 (~125 km)	ORCA1L75 (1 deg)	3600 s (atm) 2700 s (oce) 10800 s (coupling)
High resolution (EC-Earth3P-HR and EC-Earth3-HR))	T511L91 (~40 km)	ORCA025L75 (0.25deg)	900 s (atm) 900 (oce) 2700 s (coupling)

Table 2: Commonly used resolutions for CMIP6. The suffixes LR and HR are added to the name of the model configuration where applicable (e.g. EC-Earth3-Veg-LR)

Table 3: The variable “Sensitivity of non solar heat flux” may need more explanation.

Reply:
We now explain the variable in the text:

“The “Sensitivity of non solar heat flux” refers to the sensitivity with respect to sea ice surface temperature. The variable is used by the sea ice model to distribute the non-solar heat fluxes over different ice categories.”

Table 12: I’m not sure what is meant by “Mem.B. is the division between the theoretical memory of a memory and the real one”.

Reply: “Mem. B.” means Memory Bloat. It represents the division between the size (bytes) of the total number of prognostics variables used in the code and calculated manually from the code of the application (which is called theoretical memory) and the memory consumed and instrumented (using top command for example) during the execution of the application (which is called real).

We added the term “Memory Bloat” to the caption.

Table 13: I’m slightly concerned that the web links used in the table here will not be persistent years hence, references to the datasets themselves used may be better (or in addition).

Reply:
We use complete references for the CMIP forcing whenever possible. Unfortunately not all of those exist as of today. We are afraid we need to stick with at least 2 web links.
One of the links was replaced by three references:

Hurtt, G. C., Chini, L., Sahajpal, R., Frolking, S., Bodirsky, B. L., Calvin, K., Doelman, J. C., Fisk, J., Fujimori, S., Klein Goldewijk, K., Hasegawa, T., Havlik, P., Heinimann, A., Humpenöder, F., Jungclaus, J., Kaplan, J. O., Kennedy, J., Krisztin, T., Lawrence, D., Lawrence, P., Ma, L., Mertz, O., Pongratz, J., Popp, A., Poulter, B., Riahi, K., Shevliakova, E., Stehfest, E., Thornton, P., Tubiello, F. N., van Vuuren, D. P., and Zhang, X.: Harmonization of global land use change and management for the period 850–2100 (LUH2) for CMIP6, Geosci. Model Dev., 13, 5425–5464, https://doi.org/10.5194/gmd-13-5425-2020, 2020

Hurtt, G. C., Chini, L., Sahajpal, R., Frolking, S., Bodirsky, B. L., Calvin, K., Doelman, J., Fisk, J., Fujimori, S., Goldewijk, K. K., Hasegawa, T., Havlik, P., Heinimann, A., Humpenöder, F., Jungclaus, J., Kaplan, J., Krisztin, T., Lawrence, D., Lawrence, P., Mertz, O., Pongratz, J., Popp, A., Riahi, K., Shevliakova, E., Stehfest, E., Thornton, P., van Vuuren, D., Zhang, X. (2019). Harmonization of Global Land Use Change and Management for the Period 850-2015. Version 20190529. Earth System Grid Federation. https://doi.org/10.22033/ESGF/input4MIPs.10454

Hurtt, G. C., Chini, L., Sahajpal, R., Frolking, S., Bodirsky, B. L., Calvin, K., Doelman, J., Fisk, J., Fujimori, S., Goldewijk, K. K., Hasegawa, T., Havlik, P., Heinimann, A., Humpenöder, F., Jungclaus, J., Kaplan, J., Krisztin, T., Lawrence, D., Lawrence, P., Mertz, O., Pongratz, J., Popp, A., Riahi, K., Shevliakova, E., Stehfest, E., Thornton, P., van Vuuren, D., Zhang, X. (2019). Harmonization of Global Land Use Change and Management for the Period 2015-2300. Version 20190529. Earth System Grid Federation. https://doi.org/10.22033/ESGF/input4MIPs.10468

Fig. 2c: I hope the quality of this will improve, the black dots are difficult to see.

Reply:
We have replaced the figure with improved dot density.

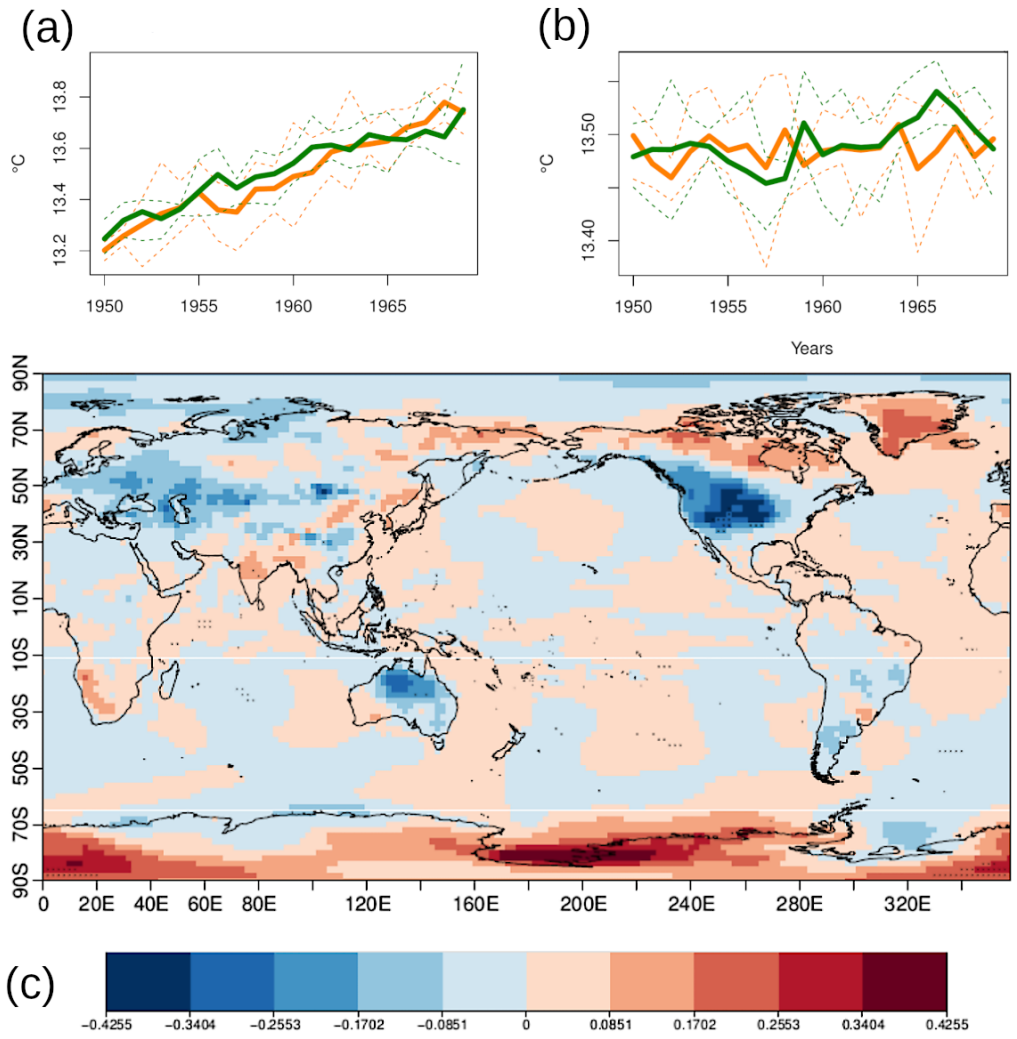

Fig. 4: would be nice to have this split into land and ocean to better understand.

Reply:
The figure has been split up in three parts: global, land-only and ocean-only. The caption has been adjusted, and the text has been modified with a few words.

“The bias in the EC-Earth3 global mean TAS is mainly due to a warmer ocean and especially due to a strong warm bias in the Southern Ocean as we will show below.”

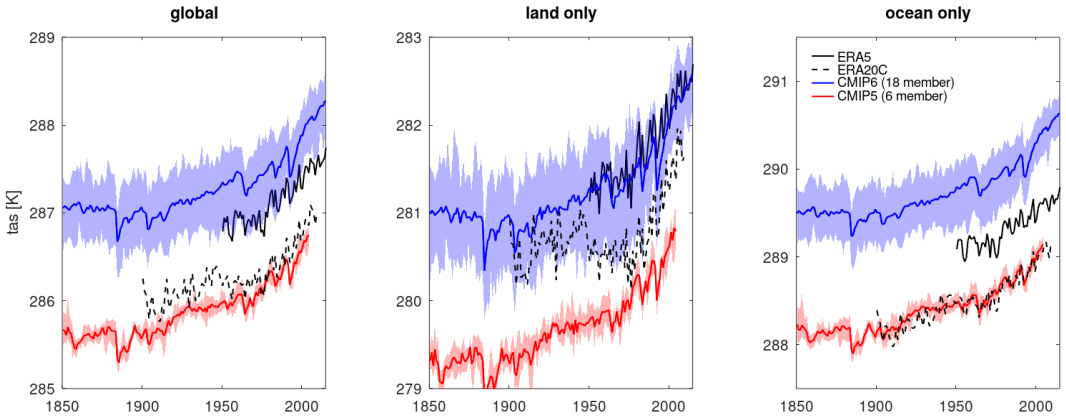

Figure 4: Global annual mean TAS in K from the EC-Earth2.3 (red, for CMIP5) and EC-Earth3 (blue, for CMIP6) ensembles, for (a) global mean, (b) land only and (c) ocean only. Ensemble means are shown as thick lines and the ensemble spread is shown as a shaded area. Global annual mean TAS from the ERA5 (black, solid) and ERA20C (black, dashed) re-analyses are shown for comparison.

Fig. 6: The bias in pr might be more instructive than just the full field – as you have done for the other variables.

Reply:
Figure 6b has been replaced by an anomaly figure

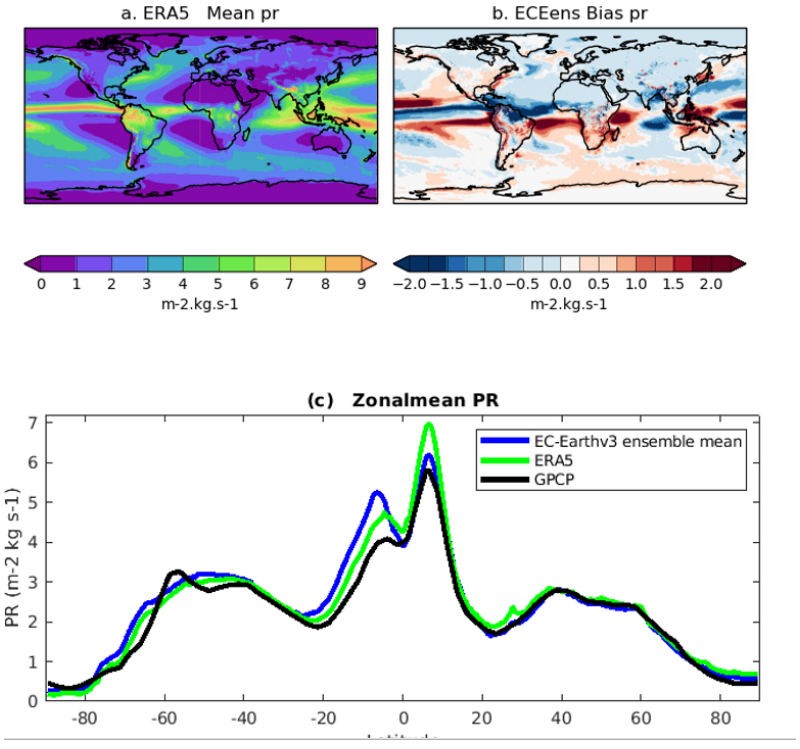

Figure 6: Mean precipitation for the period 1980-2010 for ERA5 (a), precipitation anomaly with respect to ERA5 for EC-Earth3veg (b) and zonal mean precipitation for ERA5 (c) (green), GPCPv2,2 (black) and EC-Earth3veg ensemble mean (blue).

Fig. 10: In Fig. 10b have EC-Earth#19 on it?

Figure 10 has been replaced

Fig. 11: I assume the quality of this figure will improve in the final version.

Reply: The dot density has been increased

Fig. 15: I confess I don't find this figure very instructive as it is, as a rather bland mean with no orography shown, in z-space. I think it would be much more useful if you showed (either or both) of the overturning in density space, and/or some measure of where the variance between ensemble members occurs.

We re-plotted Figure 15 in the revised version by adding the bathymetry.

In addition, we show an additional figure (15.b) to illustrate the location of variance between ensemble members. showing the standard deviation of AMOC between the members (after being averaged over 1980-2010 for each member). This figure shows how the members are spread out over the mean and where the variance occurs.

We added text:

"The variation between members occurs mainly at depth of 1000-2000 m and between 0-40oN and has a pattern and magnitude similar to the AMOC multidecadal variability (Figure 2 in Boulton et al. 2014)."

Fig. 17: big range

The big range of spread between the ensemble members is discussed in the revised version, see reply on ENSO questions above.

Technical corrections
Line 82: Need an open bracket (e.g. Koenigk
is now corrected
Line 219: testwise – is this a typo?
is now corrected
L241: I think sought may be better than searched.
is now corrected
L264: I think you mean "... interactive vegetation (using LPJ-GUESS)..."
is now corrected
L311: Repeat of the title of the next section
is now corrected
L455: typo "and. Is"
is now corrected

L1197: “impact on”
is now corrected
L1352: “though n”
is now corrected
Table 6: 4.2e-5 → 4.2E-5 for consistency.
is now corrected
Table 11: the formatting of the table is slightly off for each row.
is now corrected
Fig. 18 caption: Regression of Nino3.4 SST index onto…
is now corrected