

## ***Interactive comment on “ESMValTool v2.0 – Extended set of large-scale diagnostics for quasi-operational and comprehensive evaluation of Earth system models in CMIP” by Veronika Eyring et al.***

**Veronika Eyring et al.**

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### **Reply to Anonymous Referee #1**

We thank the reviewer for the very detailed and helpful comments. We have now revised our manuscript in light of these and the other review comments we have received. A pointwise reply is given below.

#### **General comments:**

C1

**This paper documents the latest version of the ESMValTool v2.0. The paper and the tool have lots of very good points. For example, one can reproduce IPCC Working Group 1 figures fairly easily. As an IPCC author and also a user of the IPCC, this alone makes the tool very valuable to our community. The ability to quickly assess the new CMIP6 models is equally valuable and so on. I strongly support the development of the tool.**

**That said, I found the paper very hard to read and review. The authors want to discuss each option (what they call recipes) found in the tool. In describing the recipe, it is good to show a figure or 2 to help the reader appreciate what the tool can do. Given the large number of recipes, this makes the paper very long with many figures. There is a tension between showing the figures as examples and trying to make certain scientific points/conclusion with those figures. I understand this tension well as I have also tried to produce papers like this one. Scientists want to talk about the science, not just use the figure as an example. The problem is the caveats and sometimes the complete justification for the conclusion is left out because the science is not the point. It is an example.**

**In this paper, there are conclusion sentences in the figure captions and figure caption text in the main body in many, many places. Cleaning these up would greatly help the readability of the paper. As a reader, I strongly dislike conclusions in the figure caption. This is especially true when the conclusion is not restated in the main text. The technique of giving conclusions in the caption is fine in a talk, but not in a paper. It just adds to the length.**

**Also, many figure captions are missing units and other details needed to document the figure. Sometimes these details are found in the text, but they belong**

C2

in the caption. Again, this would help the readability of the paper. I highlight some of these in my specific comment section below. As a suggestion to greatly shorten the paper, one could have the nice summary section as section 3 and move all of what is now section 3 to an appendix. I feel this would help most readers and give the authors room to add more overview type of text. If the readers need the details, they can find them in the appendix.

Another general comment is that there needs to be some documentation of the models used in the paper. Shorthand names are given in most cases. Somewhere these names have to be connected to references. Most likely another table is needed.

Finally, it needs to be made clear that most users will not run the tool themselves. The users mainly interact with a browser that displays information which has been all ready computed. This is addressed in section 4 but needs to be made clearer in the abstract, introduction and summary sections. There is a lot of misunderstanding in the community about this tool. Clearing up this aspect will help.

Thanks for valuing the development of the tool and for your detailed comments! We have followed your suggestion to move the conclusions from the figure captions to the text. We have also revisited all figure captions to include units and other details as requested in the specific comments below. We have however not moved Section 3 to an Appendix, as the structure of the paper is clear and readers who are not interested in the scientific motivation (first paragraph in each subsection) or in a particular recipe can skip this. For the majority of the readers we expect, however, that this is important information. Also from previous discussions with the community we feel it is important to scientifically justify why a certain diagnostic or recipe is included which is why we

C3

prefer keeping the description of diagnostics and the structure of Section 3 as is. The goal of the paper is to document all large-scale diagnostics and recipes that are newly included from v1 to v2 for the community in a peer-reviewed paper. This will allow those interested in a particular diagnostic or recipe to find some more background in this paper. To consider the comment on length, we have therefore not removed individual sections and have not created an Appendix, but we have streamlined the text further, following the specific comments below and by the other reviewers. Following the reviewer's suggestion, we have included another table on the CMIP5 models used in the paper and included the references to the model papers. On the last point, there are different types of users, those who only look at the results provided through the web browser, and those who use the tool for their scientific work. We have made this clearer throughout the text as suggested.

#### **Specific comments:**

##### **1. Line 57 – end-to-end provenance – This is jargon. What does this mean?**

End-to-end provenance is the history of an item of data from its creation to its present state. It includes details about the steps that were executed in order to produce the data in its current form. For the ESMValTool this means that it is kept track of which input data have been used and which processing steps have been applied to produce a given product, i.e. typically a netCDF file or a plot. This is explained in more detail in the companion paper Righi et al. (2020), which we now explicitly refer to in the text in the revised paper.

##### **2. Line 58 – ensure reproducibility – Of what? Need to mention it is reproducibility of the analysis/figures.**

Extended as suggested.

C4

**3. Line 72 – broad user community - Who do the authors have in mind? Non-specialists would struggle with most of the analysis presented in the paper.**  
User community further clarified.

**4. Line 77 – 2.1 and 4.7C for a doubling – By when? Is this transient (then a year is needed along with the time averaging period) or equilibrium?**  
Clarified.

**5. Line 105 – to achieve this – To me this sounds like the tool is the solution. It is only part of the solution. Reword.**  
Reworded.

**6. Line 131 – Reference needed for CMOR tables and definitions. I assume the CMIP6 web address is fine.**  
Reference added.

**7. Line 137 – Section 2 needs to mention that the tool helps address a major CMIP focus – to evaluate model performance by comparing models and observations. It should also mention the OBS4MIPS effort here.**  
Good point and added.

**8. Line 163-164 – The caption and the text use different words to describe what is shown: error versus deviation. Make them match. The text in the caption (lines 1022-1026) need moved to the text. An important thing to note in the caption is that the colors will change if models are added or removed. (Defining what is meant by “relative”).**  
Changed as suggested. As said above, the text in the caption has been moved to the text. The term “relative” has been further described in the caption.

C5

**9. Lines 170 – 185 – The high correlation for TAS is likely related to mountains and the land-sea mask. Is there anyway to removed these imposed boundary conditions from the analysis? For precipitation, the observations over the ocean are uncertain. Likely more uncertain than the land obs. Is it possible to weight the land more in this analysis?**

This diagnostic resembles the analysis of Gleckler et al. (2008) as also used in IPCC AR5. In their analysis, no weighting of specific regions or geographic features has been applied. Theoretically, this could be done as an extension of the portrait diagram of Gleckler et al. (2008). Since this diagram is rather intended as a summary providing an overview of the models' performance as a starting point for more detailed analyses, such weighting is (in our opinion) better suited for additional (other) diagnostics.

**10. Figure 2, lines 1035-1036 – The sentence that starts “The figure shows both” belongs in the text.**  
Sentence moved as suggested.

**11. Lines 185-201 – What variables were used to make the index? In the caption the phrase that starts “and in this case . . .” (line 1045) belongs in the text.**  
Variables clarified and sentence moved as suggested.

**12. Line 218 – 220 – Figure 4 shows . . . - This is figure caption text. In the figure caption, only the first and last sentences should remain. The middle sentences belong in the main body text. What are the units?**  
Changed as suggested.

**13. Lines 237 – 243 – Much of this text belongs in the figure caption. The sentence in the caption “Larger biases can be seen” (lines 1062 – 1064) belongs**

C6

in the text. \*\*\* Note: I stop commenting on figure caption text in the main body and main body text in the caption below this point. It occurs in most captions. \*\*\*\*

Changed as suggested.

**14. Line 253 – peculiar – What is peculiar about these regions? Change to “some”.**

Changed as suggested.

**15. Line 260 – From the caption of figure 8, I have no idea what is plotted in figure 8. What are the units? The main text again describes the figure and belongs in the caption.**

The text provides a definition and a reference for the quantile bias. The quantile bias, being a ratio, is unitless, we added this in the figure caption. We also changed the figure caption to clarify that the discussion in the caption is an example of how such a figure could be used.

**16. Line 284, figure 9 – The units for both plots are missing. It is unclear to me what is being plotted.**

Units clarified and caption improved.

**17. Line 312, figure 10 – Units? The label says percent. Percent of what? Occurrence?**

Blocking events frequency measures the percentage of blocked days in the 1979-2008 period (considering only the winter period DJF). We modified the caption of fig. 10 to specify this.

**18. Line 311 – ZIP – Is this shorthand standard? “Compressed” seems better but less precise.**

C7

Indeed *zip* is standard compression format. We added "compressed" in the text.

**19. Line 323 – severely impacts – This seems way too strong. It could impact prediction or projections. I have not seen many examples where it does. Change to “could severely impact” or reword.**

Changed as suggested.

**20. Lines 325 – 365 – I think this discussion could be greatly shortened. Just need to reference Lembo et al. 2019. I do not get much from figure 10. There is a lot of text for little gain. Even the analysis sentence in the figure caption (which belongs in the text) only states a known conclusion. Figure 14 and 15 – what are the units and shadings?**

Discussion shortened as suggested and units clarified.

**21. Line 385 – Somewhere in this discussion, the point that the observational record in many cases is too short to reliably assess the variability.**

Added.

**22. Line 419 – observed – Change to “reported”.**

Changed as suggested.

**23. Line 421 – unsuitable – This seems too strong. It depends on the questions being asked.**

Agreed, we changed the text to say “Forecast systems . . . . may have difficulties in reproducing climate variability and its long-term changes. . . .”.

**24. Line 410 – Weather regimes – One has to use these with caution. For large climate changes, they may not be useful/reliable. Caveats are needed in this section.**

C8

Yes, indeed the tool should be used with caution when applied (for example) to future scenario simulation where large climate changes are implied. We added a sentence to point this out and to explain how one could proceed in this case.

**25. Line 436 – Figure 17 – Units?**

Units clarified.

**26. Line 445 – ZIP – See comment no 18 above. I have stopped commenting on the use of ZIP.**

Changed, see also response above.

**27. Line 446 – Figure 18 – Units?**

The units are already specified close to the colorbar, it is meters [m] (written rotated along the colorbar).

**28. Line 464 – Figure 19 – Units?**

Units clarified.

**29. Line 492 – strength of northward current – This is incorrect. It is the strength of the overturning circulation – near surface and deep.**

Changed as suggested.

**30. Line 494 – Figure 22 caption – but it is not clear . . . - This is a funny statement for this paper. It could be computed using the model spread as an estimate. Also, this phrase belongs in the main body text.**

Moved to the main body of the text and sentence rephrased as suggested.

**31. Line 561 – Add “of temperature” after “Arctic amplification”.**

Changed to "... processes are Arctic atmospheric temperature warming amplification

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...".

**32. Line 570 – Figure 29 caption – A. PHC3 is used in the caption. The label is PHC. Make the labels the same. B. Eurasian Basin – Needs defined in some way. Latitude-longitude? C. Add “in Arctic” after “Eurasian Basin”. D. Atlantic water too depth – sentence belongs in text. In the caption, need to say how Atlantic water is defined.**

A. Changed as suggested.

B., C. Changed to "Eurasian Basin of the Arctic Ocean (as defined in Holloway et al., 2007)"

D. We have removed the sentence from the figure captions, following the reviewer's general suggestion above.

**33. Line 577 – Eurasian and Amerasian basins – These basins need defined in some way.**

Added "(as defined in Holloway et al., 2007)".

**34. Line 589 – 590 – linearly interpolated to climatology levels – Of what? Observations? Need reference.**

Clarified and reference added.

**35. Lines 593 – 597 – Discussion seems to suggest that velocities are interpolated and then transports are computed. If this is the case, this is calculation is wrong. The transport needs to be computed first on the native grid and then interpolated. Doing the velocity first can and will lead to incorrect transports because of issues with the dot product.**

We do not compute transports, only transects of scalar properties. Although it is clear that the confusion comes from the mention of the exchange between basins. We removed this part of the sentence and add explicitly that only temperature and salinity

C10

are considered. The new sentence reads as follows: "For each point, a vertical profile of temperature or salinity on the original model levels is interpolated."

**36. Lines 600 – 605 – Why use only T to define Atlantic water? It seems like S should be used too.**

Usually, in the literature salinity is not used when Atlantic Water of the Arctic Ocean is defined.

**37. Line 689 – Figure 33 – Relative bias (percent) needs better defined. I am not sure what it means. I also do not know what accumulated and averaged bare soil covered area mean.**

The relative bias is computed as the difference between simulated and observed land cover area divided by the observed area. It is further converted into percentage (multiplying by 100). The accumulated land cover area is the sum of the surface area covered with a specific land cover type (here bare soil) in a given hemisphere or region, while the average covered fractions gives the ratio of the accumulated area to the total area of the hemisphere or region and, again, is converted to percentage.

**38. Line 694 – LUC – Defined somewhere? I could not find it.**

This was a typo, thanks for spotting. Corrected to LCC.

**39. Line 712 – 713 – 5X5 model grid cells – Model grid cells are not 5X5. This is some interpolated grid.**

The reviewer is right that the provided figure had been produced with an algorithm applied on an interpolated grid. However, the diagnostic also provides the option to run the algorithm on the native grid. For the new version of the manuscript, we now provide the figure obtained by running the algorithm on the native grid of the MPI-ESM-LR model. This figure version exhibits very small differences compared to the previous one.

C11

**40. Line 728 – Almost only snow-free areas are visible – This makes no sense.**

We now provide more background to support this outcome: during the month of July, there is a very limited number of grid cells where the snow area fraction exceeds 0.9 (the criterion for them to be considered snow-covered). Moreover, in order to ensure that the reconstructed signal is of good quality, some more criteria need to be fulfilled for a grid cell to be included in the regression algorithm: at least 15 grid cells – either snow-free or snow-covered – need to be present in a moving window, and the sum of the considered land cover types has to equal at least 90% of the grid cell. This explains why no values are available for snow-covered areas in July for the MPI-ESM-LR model. A full description of the methodology has been included in the following paper submitted to Earth System Dynamics: Lejeune et al., Biases in the albedo sensitivity to deforestation in CMIP5 models and their impacts on the associated historical Radiative Forcing. This recently submitted paper is now referred to in the new version of the manuscript. Consistently with this new background information, we have revised the formulation for this part of the manuscript: "It can calculate albedo estimates for each of these two cases and each of the three land cover types, given that some criteria are fulfilled: the regressions are only conducted in the big boxes with a minimum number of 15 grid cells (either snow-free or snow-covered), taking only into account the grid cells where the sum of the area fractions occupied by the three considered land cover types exceeds 90%. The algorithm eventually plots global maps of the albedo changes associated with..."

**41. Lines 725 – 732 – This result seems suspect to me. It needs checked against models where land cover can change during the integration. Why is the sign of the change the same in both hemispheres given that the data are for July.**

Our algorithm provides the potential albedo change associated to a transition between

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two land cover types. In the case of Fig. 34, it is the change associated to a transition from trees to crops/grasses, which is positive in all seasons in most areas. This is in line with satellite-derived estimates of this albedo change for July, as shown by the right-hand side of Fig. 34. To make this clearer, we added the word "potential" at the beginning of the legend of Fig. 34.

**42. Line 770 – not well reproduced – This seems too strong given the large observational uncertainty.**

The text has been revised to clarify the statement: "This emergent ecosystem property, calculated, for example, as a ratio of long-term average total carbon stock to gross primary productivity, has been extensively used to evaluate ESM simulations (Todd-Brown et al., 2013, Carvalhais et al., 2014; Koven et al., 2015, Koven et al., 2017). Despite the large range of observational uncertainties and sources, ESM simulations consistently exhibit a robust correlation with the observation ensembles, but with a substantial underestimation bias."

**43. Line 777 – Figure 36 – The observational uncertainty shading band seems way too narrow. There are many estimates for observed carbon fluxes and they disagree a lot. The internal uncertainty estimates for any given observed data set is typically quite small relative to the disagreement between obs data sets. Therefore the figure and the text are quite misleading. Revise.**

The figure and the observational data used for the figure have been updated so that it is using exactly the same as the original study of Carvalhais et al., 2014. The reviewer is correct that the observational uncertainty in the submitted version of the manuscript was way too narrow. We have updated the figure. In the updated figure as well, there is a clear difference between the models and observation, and most models are outside the observation range. We have revised the text for possible uncertainties with observation-based estimates. The text has been changed to: "Most CMIP5 models (and multi-model ensemble) have a much shorter turnover time than the observation-

C13

based estimate across the whole latitudinal range. Even though different estimates of observation-based carbon fluxes and stocks can vary significantly, a recent study (Fan et al., 2020; Figure 5a) shows that the zonal distributions of observation-based estimates of turnover time is robust against the differences in observations."

**44. Line 802 – Figure 39 – Units?**

The figure has been updated. Note that this figure now uses a linear scale on the x and y axis.

**45. Line 807 – but also the spatial distribution . . . - What does this phrase mean?**

The spatial distribution is the distribution of the values of data in space (a map). To clarify, the text has been changed to "When viewed together, Figures 38 and 39 show the biases between the model and the observations in the surface layer relative to each other, both in terms of their spatially-independent distribution in fig. 38 and their spatially-dependent distribution in figure 39."

**46. Line 807 – 809 – Figure 40 – Why are there the colored lines on the right side of the figure? The main text refers to a color scale. I do not see a color scale.**

For clarity, this has been changed to: "Figure 40 shows the global average depth profile of the dissolved nitrate concentration in the CMIP5 HadGEM2-ES model and against the World Ocean Atlas dataset. The colour scale indicates the annual average, although in this specific case there is little observed inter-annual variability so the annual averages are closely overlaid. Nevertheless, this class of figure can be useful to evaluate biases between model and observations over the entire depth profile of the ocean and can also be used to identify long term changes in the vertical structure of the ocean models."

C14

**47. Line 845 – 858 – Can one access the data plotted in the figures if needed? This would be useful both to IPCC authors and anybody who needs to replot the data.**

Yes, this is possible, as every diagnostic in the ESMValTool generates one (or more) netCDF file(s) containing the data resulting from the analysis and used for plotting.

**48. Line 963 - How does the tool handle “bad data”? By bad I mean having the wrong units or the grid is wrong or the data is missing - as examples. How much of the error checking is human and how much is automated? Can other figures be generated if the input data is ok while bad data exists for some other variables?**

Checking for errors in the input data is mostly automated in the CMOR checking module of the ESMValCore preprocessor (see Righi et al., 2020 for details). This module checks for CMOR compliance of the input data and helps to identify common errors such as inconsistent units, wrong coordinates, bad missing values, etc. Errors in the actual data are however hard to detect in an automated way.

**49. Line 972 – Are the observations available? Saying they are not distributed with the tool does not address this important question.**

Due to license issues, redistribution of observational data is not allowed in most cases, but the tool provides CMORizing scripts for each observational dataset used in the recipes that is not an obs4MIPs dataset. These scripts include detailed information on how to download and process the data for usage with the tool (see Righi et al. (2020) for details).

## References

Righi, M., Andela, B., Eyring, V., Lauer, A., Predoi, V., Schlund, M., Vegas-Regidor, J., Bock, L., Brötz, B., de Mora, L., Diblen, F., Dreyer, L., Drost, N., Earnshaw, P., Hassler,

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B., Koldunov, N., Little, B., Loosveldt Tomas, S., and Zimmermann, K.: Earth System Model Evaluation Tool (ESMValTool) v2.0 – technical overview, *Geosci. Model Dev.*, 13, 1179–1199, <https://doi.org/10.5194/gmd-13-1179-2020>, 2020.

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Interactive comment on *Geosci. Model Dev. Discuss.*, <https://doi.org/10.5194/gmd-2019-291>, 2019.

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## ***Interactive comment on “ESMValTool v2.0 – Extended set of large-scale diagnostics for quasi-operational and comprehensive evaluation of Earth system models in CMIP” by Veronika Eyring et al.***

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### **Reply to Anonymous Referee #2**

We thank the reviewer for the very detailed and helpful comments. We have now revised our manuscript in light of these and the other review comments we have received. A pointwise reply is given below.

#### **General comments:**

C1

**This manuscript entails a monumental effort in attempting to facilitate the development and evaluation of climate models. Examples for analysis reproducibility, particularly output figures from IPCC chapters is commendable. A pathway to expand this to output figures in the literature is also evident. Model performance metrics, diagnostics for the evaluation of processes in different realms are presented in great detail along with the corresponding recipes. Example figures as a result of integrating community metrics is also shown in the manuscript. The flow and the content could be more consistent so the focus of ESMValTool goals and the impact in doing that is delivered as intended. Some level of brevity, citing references for details, providing more example figures from recipes, pointers to additional recipe documentation – should be made available through an external reference and/or supplementary material. Scalability and interoperability aspects can also be briefly touched upon, providing guidance to the community, making interoperability and practicality – a key to expanding the audience. There is scope for condensing and merging certain sections. Some key points to help improve readability is furnished below in specific comments. Overall, thank you for the contributions. Please see more comments below.**

Thanks for your suggestions. Please see our responses to the specific comments below how we have addressed them.

#### **Specific comments and technical corrections:**

**Page1, Ln 58 Reproducibility - Specifics and explicit wording is required here, as to what aspect is targeted.**

C2

We have rephrased accordingly.

**Page2, Ln 85 There may be more references that need to be cited while discussing data standardization for CMIP.**

**E.g. [https://pcmdi.llnl.gov/mips/cmip5/CMIP5\\_output\\_metadata\\_requirements.pdf](https://pcmdi.llnl.gov/mips/cmip5/CMIP5_output_metadata_requirements.pdf)?**

More references added.

**Page 3, Ln 92-83: The line about “full rewards of the effort. . .” should be reworded to provide more of a positive tone to the available observations and model output in standardized format. Expanding what is meant by “full rewards” will be very helpful in this line, rather than the subsequent paragraph.**

The paragraph has been reworded.

**Page2, Ln 96-97: Please cite or provide links to appropriate references w.r.t data volume estimations for CMIP. Also, what is the database that is being referred to here?**

References added and the database clarified.

**Page 2, Ln 100- I like the addition of “creativity” here.**

Thanks.

**Page 2, Ln 107- “that provides results. . .” - Substitute results with something more specific. E.g. analysis products/output?, so it better connects with Ln 108 (This is realized through..)**

Changed as suggested.

**Page 3, Ln 115- Does ESMValTool preserve the netCDF metadata (global attributes from input datasets) in output products? How is data provenance established? ( Ln 142 may answer this, please clarify)**

C3

The ESMValTool does preserve the netCDF metadata including the global attributes. These metadata are also written to the products (netCDF and plots) using W3C-PROV (Python package prov v1.5.3). Details can be found in the technical ESMValTool description paper Righi et al. (2020 that we now explicitly refer to here).

**Page 3 Ln 118- Consider stating “Figure 1 from their paper, or from Righi et al.. rather than “their Figure 1”**

Changed as suggested.

**Page 3, Ln 121- The flow from the introduction to companion papers and the present one can be better. Example- Precede the sentence “the use of the tool is demonstrated..” with “In the present paper,..”**

Changed as suggested.

**Page 3, Ln 124-125, Avoid too many conjunctions (and) here. . “Diagnostics and performance metrics and the variables and observations used”.**

Sentence rewritten for clarity.

**Page 3, Ln 129: What does “partly also with CMIP3” mean here?**

Partly refers to the fact that not all diagnostics can be run with CMIP3 data because for some diagnostics not all required variables are included in the CMIP3 data request.

**Page 3, Ln 130: Is CF-compliance and CMOR-compliance required? Please, also cite CF and CMOR references, expand acronyms. The sentence could be changed to - tool is compatible with any CF and CMOR compliant model output? Please change this as needed so users understand what is ready to be plugged in to ESMValTool, and what requires additional work.**

The ESMValTool requires that input data are following the CMOR standard. CMOR is based on the CF conventions but defines some additional metadata on top of it.

C4

For details, see Righi et al. (2020). CF and CMOR references are now added in the revised manuscript and abbreviations are defined.

**Page 3, Section 2. Ln 131-136. The data descriptions in this section are not satisfactory, especially where the manuscript reads “observation from other sources..” . obs4mip publications should be cited here. It will be nice if ty the different observation datasets used in recipes can be listed and cited thoroughly. Also, this section could be merged into the final section 6-7 on Code and Data availability.**

We now refer to Table 3 in Righi et al. (2020), which contains a list of observational data from external sources', i.e. observations that are not from obs4MIPs.

**Page 4, Ln 154-**

- **Reproducing IPCC chapter figures is impressive. Are these diagnostics-and-recipes written working directly with the IPCC authors? What is your advice to the IPCC authors to make this effort a success for CMIP6?**

Thanks! For the IPCC AR5 Chapter 9 diagnostics and recipes, they were written by the ESMValTool development team after the publication of the AR5. For AR6 Working Group I, several chapters are using the ESMValTool to produce their figures. The diagnostics and recipes are then written by the chapter scientists or the lead or contributing authors of the chapter, with support from the ESMValTool core development team. Our advice to the authors of the IPCC AR6 is to write a recipe for each chapter, so that figures can be reproduced any time. This would be a huge present to those involved in a possible AR7. It would enable a direct and prompt comparison to new model generations.

- **How are the recipe names constructed- is there a recommended naming convention?**

For recipes reproducing the analysis of a refereed publication, we use [first-C5

author] [year] [journal-abbreviation], for example "recipe\_lauer13jclim.yml". The same applies to IPCC chapters, e.g. "recipe\_flato13ipcc.yml". For other recipes there is no strict rule, but the authors are advised to give appropriate names reflecting the recipe content, e.g. "recipe\_heatwaves\_coldwaves.yml"

- **How resilient is ESMValTool to changes like the metadata conventions, DRS, etc from CMIP5 to CMIP6, or say another [inter]national assessment?**

The ESMValTool has been developed in a flexible way allowing defining the DRS structure via a configuration file. Metadata conventions are imported from the obs4mips/CMIP3/CMIP5/CMIP6 tables and can be easily extended with new tables.

**Page 4, Ln 160-161: Check and correct line,word spacing.**

Corrected.

**Page 4, Ln 164: How does one add an alternative observation dataset? One of the companion papers might be addressing this? Page 4, Ln 165: How can additional variables be added? Is it the same as the first version of the tool? Following the citation link here, I still could not get information in two hops.**

Alternative observational datasets are specified in the "recipe" (if supported by the diagnostic). Additional variables can be added by custom CMOR tables similarly to ESMValTool v1.0. In case of derived variables, Python scripts have to be provided to do the actual calculations. This has changed compared to version 1.0 in which these variable derivation scripts were written in NCL. We refer to the extensive ESMValTool documentation for more details: <https://esmvaltool.readthedocs.io/en/latest>.

**Page 5, Ln 174: Can there be a reference here to the regridding tools used? Why 4x5?**

Regridding is done by the Python Iris package, which offers different regridding

schemes. We have added a reference to the Iris user's guide at (<https://scitools.org.uk/iris/docs/latest/index.html#>). The grid resolution of 4x5 degrees has been chosen to be as consistent as possible with the equivalent diagnostic used in IPCC AR5.

### Section 3:

- **Throughout the Overview of recipes, under each sub-section, there can be more consistency. Example: For each recipe, one could ensure these are specified throughout: input (include time-frequency requirement consistently as well), output specifications, source, purpose and significance of the metrics, relevant citations to metrics calculations, summary of the recipe, a sample result. Sticking to this consistently can also condense the text.**

We have already defined a common structure how to discuss each of the recipes in each of the subsections. This is already described in the manuscript: "In each subsection, we first scientifically motivate the inclusion of the recipe by reviewing the main systematic biases in current ESMs and their importance and implications. We then give an overview of the recipes that can be used to evaluate such biases along with the diagnostics and performance metrics included, and the required variables and corresponding observations that are used in ESMValTool v2.0. For each recipe, we provide 1-2 example figures that are applied to either all or a subset of the CMIP5 models."

- **Suggest just pointing to references like how it was done for CVDP to get more information metrics.**

We already include many references in the submitted version of the manuscript. For CVDP this is more straight forward than for other recipes, as an externally developed tool exists.

C7

- **[3.3.4] Sea Ice, for instance, can be rewritten to condense text.**  
Changed as suggested and sea ice section shortened.

- **Are the recipes part of the github repositories? Where can one find them?**  
All recipes are included in the ESMValTool repository on GitHub. The directory structure of the ESMValTool is outlined in the technical description paper by Righi et al. (2020). All recipes can be found in the directory <https://github.com/ESMValGroup/ESMValTool/tree/master/esmvaltool/recipes>.

- **Though line 145 reads that the intent of the focus of the manuscript is not an assessment of CMIP5 or CMIP6 models, the construction of section 3 is not completely aligned with this. The message needs to be reiterated. If this manuscript is intended to be a documentation paper for the diagnostics and recipes used in ESMValTool, the length could be justified to an extent. Otherwise, some sections could be rewritten so focus is retained.**

The goal of the manuscript is indeed to document the diagnostics and recipes available in the ESMValTool. Assessing the CMIP models is indeed not the scope of the paper, nevertheless Section 3 presents a few examples to show how the ESMValTool output could support the scientific interpretation. We would like to stick to this structure as it turned out to be useful for users and developers, but we have followed the reviewer 1's comment to move the sentence on the results from the caption to the text which hopefully also addresses this point. We have also further shortened the paper by following specific comments from both reviewers.

- **Is this manuscript the single source for documentation for all the metrics and recipes?**

No, additional documentation will be provided in the companion papers Lauer et al. (description of diagnostics for emergent constraints and future projections from Earth system models in CMIP) and Weigel et al. (description of diagnostics for extreme events, regional model and impact evaluation and analysis of Earth

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system models in CMIP). The manuscript refers to these additional papers.

- **Page 21, Section 4.1. Automatic execution of ESMValTool at DKRZ sounds like a nice step to interface with more users. How scalable is this process? Is the idea to expand this to other nodes in ESGF? Is data replication of such huge CMIP6 volumes something that needs to be kept an eye on, leveraging distributed data access protocols or the cloud?**

The automatic execution of the ESMValTool has been tested only at DKRZ so far, but thanks to the tool's flexibility it can be easily ported to other ESGF nodes. Data replication is certainly an issue, as discussed in detail in Eyring et al. (ESSD, 2016).

#### Page 22: Ln 843-844: Section 4

- **When new plots are created, is there a step that incorporates a basic automated quality assurance conducted?**

The ESMValTool includes checks for data availability and CMOR compliance of all input datasets which provides some first basic quality control. However, at the moment the output of diagnostics (such as plots) has to be checked manually by a scientist to identify anything beyond missing or badly formatted data.

- **Is there a testing suite for each recipe?**

We have chosen not to ask scientists to implement unit tests for their recipes, because this would make the threshold to contribute diagnostics to ESMValTool too high for many scientists. ESMValCore, the part of the tool that runs the diagnostic scripts and does data quality checks, pre-processing, and records provenance, is rigorously tested with unit tests, to ensure that the tool can be used reliably. In addition to that, we are working on setting up automated tests that regularly run all recipes on a server at DKRZ, both during the development of new recipes

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as well as after incorporation into ESMValTool, to ensure that recipes are working and produce consistent output. At the moment this is still a manual process, but we hope to make progress on this in the next few months, as the hardware becomes available.

- **Ln 845: The result browser looks good. Steps to reproducing figures viewed from ESMValTool result browser should be made clearer. This is probably the place where the provenance information captured by ESMValTool will come handy?**

Yes, this is the typical target application of the provenance system, as detailed in the technical overview paper (Righi et al., 2020). The steps to produce the figures in the ESMValTool result browser are now further detailed in the revised manuscript.

- **How is the performance of running ESMValTool on CMIP data in an automated fashion, and in general from a disconnected sandbox, regardless of ESGF.**

The ESMValTool performance has little to do with the automatization. Again we refer to the technical overview for more details on the tool's performance.

- **How is the concept of data versioning incorporated within the automated generation of plots using ESMValTool in ESGF at DKRZ ? When there is bad data retracted on ESGF, and a newer version of data becomes available, what is the current implementation like at the ESMValTool-end or the result-browser to notify its users? If there is no mechanism to notify automatically or not-show-the-corresponding-plots, what is the recommendation to the users? In general, what kind of users does the ESMValTool aim to target?**

The figures on the result browser can be sorted by recipe used to produce this figure. By clicking on the figure, also all input datasets can be listed. This

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information should be enough as a starting point for reproducing a given figure for anyone familiar with running the ESMValTool. If specific dataset versions are crucial, the whole metadata provided with the plots have to be read and taken into account. By default, the ESMValTool always uses the latest version of a dataset available. The ESMValTool and the result-browser are not capable of notifying users of any changes. Recommendation to any user is therefore to check the result-browser frequently and/or get into contact with the ESMValTool team as stated on the webpage.

**Ln 857: How does the metadata w.r.t the software version get mapped to the actual source code in GitHub? With data DOIs/data citations widely prevalent for CMIP6, does ESMValTool automatically add data citations to the output figures/files? If not, please provide a pathway to achieve this. Page 24, Ln 943: Please provide an example for "preprocessor settings". Page 24, Ln 948-949. Unable to follow this line "...and tags (i.e. what is reported) ". I think these lines are not adding much value at this point.**

The exact version number of the tool used to produce a plot and written to the metadata corresponds to the release tag on GitHub, e.g. "2.0.0b6". Data citations are only added for observational data, while for model data all metadata are preserved. This typically includes the "tracking id" that can be used to exactly identify the dataset. The preprocessor settings are discussed in detail in the technical overview paper by Righi et al. (2020). We therefore do not see any use of repeating these here.

**Page 24, Ln 959. Identifying errors in the simulations early on is a key factor that is penned down as future work here. Even if there are no web-based capabilities, please address if ESMValTool can independently be installed and run by an individual user at different stages in model running. An idea or vision here to draw more inspiration and motivation for using ESMValTool can be**

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**provided.**

The ESMValTool can be installed within the user space, so each user can install and develop the tool independently.

**Ln 955, Again, enhancing quality control is a great use-case, but having ESMValTool run on published data on ESGF does not satisfy this use-case. Stand-alone, this tool seems to work towards QC. Please clarify.**

Analyzing first CMIP data published on the ESGF showed that there are still many errors in the metadata and/or the actual data. Examples of such errors include, for instance, wrong units, wrong coordinates (e.g. time) and entire fields consisting of missing values. We therefore do think that running the ESMValTool on these data can be regarded as a quality control process, admittedly on a higher level than the initial quality control done by the modeling groups.

**Section 5. Font size seems to be mixed up in the Summary section - lines till 950 and after 950 are different.**

Corrected.

**Page 25, Ln 965, Sections 6 and 7 should be condensed into one section. Addressing data citations briefly in Data availability will add more value to the CMIP and ESMValTool efforts.**

We have removed the data availability section.

**Comments on Figures:**

**Adding some of the figures to a supplementary or appendix should be considered.**

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Since we have one example figure for each of the recipes, we would like to keep them in the main manuscript. This also supports the general structure the reviewer is calling for.

**Verify that there is not much redundancy in the text in captions (e.g. Section 3, 5, Figures text). Avoid redundancy where possible.**

This has been cleaned up, see also our responses to Reviewer 1.

**I find the captions in figures helpful, especially the reference to the corresponding sections. The captions are mostly like IPCC-chapter and documentation paper style. A short caption in bold followed by the description is something that will make the figures stand out.**

Using bold font in the figure caption is unfortunately not supported by the journal standards.

**While specifying OBS in figures, please specify names of OBS in the figures.**

Changed as suggested.

**Name the variables/fields corresponding to the figures, example Figure 4,5,6 - zonal wind,air temperature,precipitation? respectively.**

Changed as suggested.

**How are the color palettes picked in general and what flexibility ESMVal-Tool allows w.r.t color palettes?**

Default color palettes are picked by the diagnostic authors. Some diagnostics allow for setting it as an option. Implementing such a feature, however, is also up to the diagnostic authors and therefore not supported by all diagnostics.

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**Expand the acronym QBO in Figure 4, although the section covers it.**

Done.

**Better labeling on the figure itself needed for Fig 15,16 especially.**

Done.

**What is “j” in r1i1j1 in several figure captions - e.g. Fig 22.**

This was typo, thanks for spotting! Changed to r1i1p1, see <https://portal.enes.org/data/enes-model-data/cmip5/datastructure>

**In Fig 20, use r1i1p1 to be consistent, not r1p1i1.**

Changed as suggested.

**Is Figure 26 a reproduction of Fig 9.14 from AR5, Chapter 9. (Including chapter helped me since there is some ambiguity looking up for Fig 9.14 from AR5).**

Yes it is reproducing Fig 9.14 from Chapter 9 of AR5. We have added "Chapter 9 of" before "AR5" for clarity.

**In Figure 30, “typo” - “ether” vs either;**

Corrected

**In Figure 34- typo: predictand, not predictant. Please use long names on the figure themselves, not the short CMOR names (example Figure 35, Y axis); Units missing in some of the figures, e.g Figure 39.**

Corrected.

**In the summary section– Given the challenges of CMIP6 (and beyond) and the scientists all over the globe working on multiple research areas, this**

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**manuscript should include something along the lines of the role and future of ESMValTool in the community as a whole and how it can be interoperable with overlapping efforts. The ability to cross-function using tools like ESMValTool and making them more inter-operable is a key challenge. The experience from developing ESMValTool in the form of these manuscripts is helpful to the community, and it can also be helpful for the expansion of metrics-and-recipes used in ESMValTool.**

Briefly expanded on this point. However, since inter-operability with other tools requires discussion and agreement with the developers of the other tools who are not authors on this paper, we cannot define this in detail here. There are also license issues to be considered. We are however very open for this collaboration and have put a lot of effort into actively seeking coordination with other tool developers in the past years. Having different and complementary tools might however well be desirable, see also Eyring et al. (2019).

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## ***Interactive comment on “ESMValTool v2.0 – Extended set of large-scale diagnostics for quasi-operational and comprehensive evaluation of Earth system models in CMIP” by Veronika Eyring et al.***

**Veronika Eyring et al.**

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### **Reply to Martine Michou**

We thank Martine Michou for the helpful comments. We have now revised our manuscript in light of these and the other review comments we have received. A pointwise reply is given below.

**The text mentions that Figures 42 and 43 consist of an adaptation of di-**  
C1

**agnostics included in the CCMValDiag tool. It is very valuable to have recipe\_eyring06jgr.yml in v2.0 of ESMValTool (it is not yet the case as of January 2020), as well as a recipe with all diagnostics of Eyring et al, JGR 2013, "Long-term ozone changes and associated climate impacts in CMIP5 simulations" that includes interesting diagnostics with regards to ozone evaluation.**

Thanks for your interest in the inclusion of the diagnostics from the Eyring et al., JGR, 2006 and 2013 papers on ozone evaluation. We agree that it would be good to have them available in ESMValTool v2. A subset of the diagnostics from Eyring et al., JGR, 2006 (e.g. Figures 42 and 43) are part of the official release of version 2 of the ESMValTool. These are described in the manuscript. Additional diagnostics from these two papers will be added as resources allow.

**Second, as of January 2020, it is not easy at all to install ESMValTool v2.0, unlike v1.0. For users without conda, that is only recommended in the install web page, the installation with the "pip install ." command, as written in the install web page does not work. Documentation should be amended, in particular for the use of more "dummy" users, if ESMValTool v2.0 is to be used by a wide community. And I think it deserves it.**

Installing the ESMValTool without using conda is not possible at the moment. The installation procedure is clearly described in the ESMValTool documentation on ReadTheDocs ([https://esmvaltool.readthedocs.io/en/latest/getting\\_started/install.html](https://esmvaltool.readthedocs.io/en/latest/getting_started/install.html)) and has been successfully applied by all users and developers so far. Specific installation issues (which might arise, for example, on some peculiar architectures) can be reported on the GitHub page of the ESMValTool and are readily addressed by the development team.



# Earth System Model Evaluation Tool (ESMValTool) v2.0 – Extended set of large-scale diagnostics for quasi-operational and comprehensive evaluation of Earth system models in CMIP

5 Veronika Eyring<sup>1,2</sup>, Lisa Bock<sup>1</sup>, Axel Lauer<sup>1</sup>, Mattia Righi<sup>1</sup>, Manuel Schlund<sup>1</sup>, Bouwe Andela<sup>3</sup>, Enrico Arnone<sup>4,5</sup>, Omar Bellprat<sup>6</sup>, Björn Brötz<sup>1</sup>, Louis-Philippe Caron<sup>6</sup>, Nuno Carvalho<sup>7,8</sup>, Irene Cionni<sup>9</sup>, Nicola Cortesi<sup>6</sup>, Bas Crezee<sup>10</sup>, Edouard L. Davin<sup>10</sup>, Paolo Davini<sup>4</sup>, Kevin Debeire<sup>1</sup>, Lee de Mora<sup>11</sup>, Clara Deser<sup>12</sup>, David Docquier<sup>13</sup>, Paul Earnshaw<sup>14</sup>, Carsten Ehbrecht<sup>15</sup>, Bettina K. Gier<sup>2,1</sup>, Nube Gonzalez-Reviriego<sup>6</sup>, Paul Goodman<sup>16</sup>, Stefan Hagemann<sup>17</sup>, Steven Hardiman<sup>14</sup>, Birgit Hassler<sup>1</sup>, Alasdair Hunter<sup>6</sup>, Christopher Kadow<sup>18</sup>, Stephan Kindermann<sup>15</sup>, Sujan Koirala<sup>7</sup>, Nikolay Koldunov<sup>19,20</sup>, Quentin Lejeune<sup>10,21</sup>, Valerio Lembo<sup>22</sup>, Tomas Lovato<sup>23</sup>, Valerio Lucarini<sup>22,24,25</sup>, François Massonnet<sup>13</sup>, Benjamin Müller<sup>26</sup>, Amarjiit Pandde<sup>16</sup>, Núria Pérez-Zanón<sup>6</sup>, Adam Phillips<sup>12</sup>, Valeriu Predoi<sup>27</sup>, Joellen Russell<sup>16</sup>, Alistair Sellar<sup>14</sup>, Federico Serva<sup>28</sup>, Tobias Staeke<sup>29</sup>, Ranjini Swaminathan<sup>30</sup>, Verónica Torralba<sup>6</sup>, Javier Vegas-Regidor<sup>6</sup>, Jost von Hardenberg<sup>4,31</sup>, Katja Weigel<sup>2,1</sup>, and Klaus Zimmermann<sup>32</sup>

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**Abstract.** The Earth System Model Evaluation Tool (ESMValTool) is a community diagnostics and performance metrics tool designed to improve comprehensive and routine evaluation of Earth System Models (ESMs) participating in the Coupled Model Intercomparison Project (CMIP). It has undergone rapid development since the first release in 2016 and is now a well-tested tool that provides end-to-end provenance tracking to ensure reproducibility. It consists of an easy-to-install, well documented Python package providing the core functionalities (ESMValCore) that performs common pre-processing operations and a diagnostic part that includes tailored diagnostics and performance metrics for specific scientific applications. Here we describe large-scale diagnostics of the second major release of the tool that supports the evaluation of ESMs participating in CMIP Phase 6 (CMIP6). ESMValTool v2.0 includes a large collection of diagnostics and performance metrics for atmospheric, oceanic, and terrestrial variables for the mean state, trends, and variability. ESMValTool v2.0 also successfully reproduces figures from the evaluation and projections chapters of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) and incorporates updates from targeted analysis packages, such as the NCAR Climate Variability Diagnostics Package for the evaluation of modes of variability the Thermodynamic Diagnostic Tool (TheDiaTo) to evaluate the energetics of the climate system, as well as parts of AutoAssess that contains a mix of top-down performance metrics. The tool has been fully integrated into the Earth System Grid Federation (ESGF) infrastructure at the Deutsches Klima Rechenzentrum (DKRZ) to provide evaluation results from CMIP6 model simulations shortly after the output is published to the CMIP archive. A result browser has been implemented that enables advanced monitoring of the evaluation results by a broad user community at much faster timescales than what was possible in CMIP5.

## 1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) concluded that the warming of the climate system is unequivocal and that the human influence on the climate system is clear (IPCC, 2013). Observed increases of greenhouse gases, warming of the atmosphere and ocean, sea ice decline, and sea level rise, in combination with climate model projections of a likely temperature increase between 2.1 and 4.7°C for a doubling of atmospheric CO<sub>2</sub> concentration from pre-industrial (1980) levels, make it an international priority to improve our understanding of the climate system and to reduce greenhouse gas emissions. This is reflected for example in the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) 21<sup>st</sup> session of the Conference of the Parties (COP21, UNFCCC (2015)).

Simulations with climate and Earth System Models (ESMs) performed by the major climate modelling centres around the world under common protocols are coordinated as part of the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP) since the early 90s (Eyring et al., 2016a; Meehl et al., 2000; Meehl et al., 2007; Taylor et al., 2012). CMIP simulations provide a fundamental source for IPCC Assessment Reports and for improving understanding of past, present and future climate change. Standardization of model output in a common format (Juckes et al., 2019) and publication of the CMIP model output on the Earth System Grid Federation (ESGF) facilitates multi-model evaluation and analysis (Balaji et al., 2018; Eyring

et al., ~~2016b~~2016a; Taylor et al., 2012). This effort is additionally supported by observations for Model Intercomparison Project (obs4MIPs, ~~Ferraro et al. (2015))~~ which provides the community with access to CMIP-like datasets (in terms of variables definitions, temporal and spatial coordinates, time frequencies and coverages) of satellite data- (~~Ferraro et al., 2015; Teixeira et al., 2014; Waliser et al., 2019~~). The availability of observations and models in the same format strongly facilitates model evaluation and analysis, ~~but the full rewards of the effort devoted to this activity were yet to be realized.~~

CMIP is now in its 6th phase (CMIP6, Eyring et al. (2016a)) and is confronted with a number of new challenges. More centres are running more versions of more models of increasing complexity. An ongoing demand to resolve more processes requires increasingly higher model resolutions. Accordingly, the data volume of 2 PB in CMIP5 is expected to grow by a factor of 10-20 for CMIP6, resulting in a ~~CMIP6~~ database of between 20 and 40 PB, depending on model resolution and the number of modelling centres ultimately contributing to the project- (~~Balaji et al., 2018~~). Archiving, documenting, subsetting, supporting, distributing, and analysing the huge CMIP6 output together with observations challenges the capacity and creativity of the largest data centres and fastest data networks. In addition, the growing dependency on CMIP products by a broad research community and by national and international climate assessments, as well as the increasing desire for operational analysis in support of mitigation and adaptation, means that ~~a system has to~~systems should be set in place that ~~allows~~allow for an efficient and comprehensive analysis of the large volume of data from models and observations.

To ~~achieve~~help achieving this, the Earth System Model Evaluation Tool (ESMValTool) is developed. A first version that was tested on CMIP5 models was released in 2016 (Eyring et al., 2016c). With the release of ESMValTool version 2.0 (v2.0), for the first time in CMIP an evaluation tool is now available that provides ~~evaluation~~ results from CMIP6 simulations as soon as the model output is published to the ESGF (~~https://cmip-esmvaltool.dkrz.de/~~)(~~https://cmip-esmvaltool.dkrz.de/~~). This is realized through text files that we refer to as recipes, each calling a certain set of diagnostics and performance metrics to reproduce analyses that have demonstrated to be of importance in ESM evaluation in previous peer-reviewed papers or assessment reports. The ESMValTool is developed as a community diagnostics and performance metrics tool that allows for routine comparison of single or multiple models, either against predecessor versions or against observations. It is developed as a community-effort currently involving more than 40 institutes with a rapidly growing developer and user community. ~~It allows for full tractability and provenance of all figures and outputs produced. Given the level of detailed evaluation diagnostics included in ESMValTool v2.0, several diagnostics are of interest only to the climate modelling community whereas others, including but not limited to those on global mean temperature or precipitation, will also be valuable for the wider scientific user community. The tool allows for full tractability and provenance of all figures and outputs produced. This includes preservation of the netCDF metadata of the input files including the global attributes. These metadata are also written to the products (netCDF and plots) using the Python package W3C-PROV. Details can be found in the ESMValTool v2.0 technical overview description paper by Righi et al. (2020).~~

The release of ESMValTool v2.0 is ~~described~~documented in four companion papers: ~~Righi et al. (2019)~~Righi et al. (2020) provide the technical overview of ESMValTool v2.0 and show a schematic representation of the *ESMValCore*, a Python package that provides the core functionalities, and the *Diagnostic Part* ~~in~~(see their Figure 1-). This paper describes recipes of the *Diagnostic Part* for the evaluation of large-scale diagnostics. Recipes for extreme events and in support of regional model evaluation are described by ~~Weigel et al. (2019)~~Weigel et al. (2020) and recipes for emergent constraints and model weighting by ~~Lauer et al. (2019)~~.

135 | ~~The~~[Lauer et al. \(2020\)](#). ~~In the present paper, the~~ use of the tool is demonstrated by showing example figures for  
each recipe for either all or a subset of CMIP5 models. Section 2 describes the type of modelling and  
observational data currently supported by ESMValTool v2.0. In Section 3 an overview of the recipes for large-  
scale diagnostics provided with the ESMValTool v2.0 release is given along with their diagnostics and  
140 | performance metrics ~~and~~[as well as](#) the variables and observations used. Section 4 describes the workflow of  
routine analysis of CMIP model output alongside the ESGF and the ESMValTool result browser. Section 5  
closes with a summary and an outlook.

## 2. Models and observations

The open-source release of ESMValTool v2.0 that accompanies this paper is intended to work with CMIP5 and  
CMIP6 model output ~~–,~~ and partly also with CMIP3 ~~(although the availability of data for the latter is~~  
145 | ~~significantly lower, resulting in a limited number of recipes and diagnostics that can be applied with such data)~~,  
but the tool is compatible with any arbitrary model output, provided that it is in CF-compliant netCDF format  
~~(CF = Climate and Forecast, <http://cfconventions.org/>)~~ and that the variables and metadata are following the  
CMOR ~~(Climate Model Output Rewriter, [https://pcmdi.github.io/cmor-site/media/pdf/cmor\\_users\\_guide.pdf](https://pcmdi.github.io/cmor-site/media/pdf/cmor_users_guide.pdf))~~  
tables and definitions ~~– (see e.g. <https://github.com/PCMDI/cmip6-cmor-tables/tree/master/Tables> for CMIP6)~~.  
150 | As in ESMValTool v1.0, for the evaluation of the models with observations, we make use of the large  
observational effort to deliver long-term, high quality observations from international efforts such as ~~observation~~  
~~for Model Intercomparison Project (obs4MIPs, [Ferraro et al. \(2015\)](#))~~ ([Ferraro et al., 2015](#); [Teixeira et al., 2014](#);  
[Waliser et al., 2019](#)) or observations from the ESA Climate Change Initiative (CCI, [Lauer et al. \(2017\)](#)). In  
addition, observations from other sources and reanalyses data are used in several diagnostics ~~– (see Table 3 in~~  
155 | ~~Righi et al. (2020))~~. The ~~technical treatment of observations~~[processing of observational data for usage](#) in  
ESMValTool v2.0 is described in ~~Righi et al. (2019)~~[Righi et al. \(2020\)](#). The observations used by individual  
recipes and diagnostics are described in Section 3 ~~– and listed in Table 1. With the broad evaluation of the CMIP~~  
~~models, the ESMValTool substantially supports one of CMIP’s main goals, which is the comparison of the~~  
~~models with observations ([Eyring et al., 2016a](#); [Eyring et al., 2019](#))~~.

## 160 | 3. Overview of recipes included in ESMValTool v2.0

In this section, all recipes for large-scale diagnostics that have been newly added in v2.0 since the first release of  
the ESMValTool in 2016 (see Table 1 in [Eyring et al. \(2016c\)](#) for an overview of namelists (now called recipes)  
included in v1.0) are described. In each subsection, we first scientifically motivate the inclusion of the recipe by  
reviewing the main systematic biases in current ESMs and their importance and implications. We then give an  
165 | overview of the recipes that can be used to evaluate such biases along with the diagnostics and performance  
metrics included, and the required variables and corresponding observations that are used in ESMValTool v2.0.  
For each recipe we provide 1-2 example figures that are applied to either all or a subset of the CMIP5 models.  
An assessment of CMIP5 or CMIP6 models is however not the focus of this paper. Rather, we attempt to  
illustrate how the recipes contained within ESMValTool v2.0 can facilitate the development and evaluation of  
170 | climate models in the targeted areas. Therefore, the results of each figure are only briefly described ~~– in each~~  
~~figure caption~~. Table 1 provides a summary of all recipes included in ESMValTool v2.0 along with a short  
description, information on the quantities and ESMValTool variable names for which the recipe is tested ~~– and the~~

~~corresponding diagnostic scripts~~, the corresponding diagnostic scripts and observations. All recipes are included in the ESMValTool repository on GitHub (see Righi et al., 2020 for details) and can be found in the directory <https://github.com/ESMValGroup/ESMValTool/tree/master/esmvaltool/recipes>.

We describe recipes separately for integrative measures of model performance (Section 3.1) and for the evaluation of processes in the atmosphere (Section 3.2), ocean and cryosphere (Section 3.3), land (Section 3.4), and biogeochemistry (Section 3.5). Recipes that reproduce chapters from the evaluation chapter of the IPCC Fifth Assessment Report (Flato et al., 2013) are described within these sections.

### 3.1 Integrative Measures of Model Performance

#### 3.1.1 Performance metrics for essential climate variables for the atmosphere, ocean, sea ice and land

Performance metrics are quantitative measures of agreement between a simulated and observed quantity. Various statistical measures can be used to quantify differences between individual models or generations of models and observations. Atmospheric performance metrics were already included in *namelist\_perfmetrics\_CMIP5.nml* of ESMValTool v1.0. This recipe has now been extended to include additional atmospheric variables as well as new variables from the ocean, sea ice and land. Similar to Figure 9.7 of Flato et al. (2013), Figure 1 shows the relative space-time root mean square error (RMSE deviation (RMSD)) for the CMIP5 historical simulations (1980-2005) against a reference observation and, where available, an alternative observational data set [*recipe\_perfmetrics\_CMIP5.yml*]. ~~Additional variables can be easily added if observations are available~~ Performance varies across CMIP5 models and variables, with some models comparing better with observations for one variable and another model performing better for a different variable. Except for global average temperatures at 200 hPa (ta\_Glob-200) where most but not all models have a systematic bias, the multi-model mean outperforms any individual model. Additional variables can be easily added if observations are available by providing a custom CMOR table and a Python script to do the calculations in case of derived variables, see further details in Section 4.1.1 of Eyring et al. (2016c). In addition to the performance metrics displayed in Figure 1, several other quantitative measures of model performance are included in some of the recipes and are described throughout the respective sections of this paper.

#### 3.1.2. Centered pattern correlations for different CMIP ensembles

Another example of a performance metric is the pattern correlation between the observed and simulated climatological annual mean spatial patterns. Following Figure 9.6 of the IPCC AR5 (Chapter 9, Flato et al. (2013)), a diagnostic for computing and plotting centered pattern correlations for different models and CMIP ensembles has been implemented (Figure 2) and added to *recipe\_flato13ipcc.yml*. ~~The variables are first regridded to a 4° x 5° longitude by latitude grid to avoid favouring a specific model resolution. Regridding is done by the Iris package which offers different regridding schemes (see <https://esmvaltool.readthedocs.io/projects/esmvalcore/en/latest/recipe/preprocessor.html#horizontal-regridding>). The figure shows both a large model spread as well as a large spread in the correlation depending on the variable, signifying that some aspects of the simulated climate agree better with observations than others.~~ ~~The variables are first regridded to a 4°x5° longitude by latitude grid to not favour specific model resolutions.~~ The centered pattern correlations, which measure the similarity of two patterns after removing the global mean, are computed against a reference observation. Should the input models be from different CMIP ensembles, they are grouped by ensemble and each ensemble is plotted side by side ~~perfor each~~ variable with a different colour. If an

alternate model is given, it is shown as a solid green circle. The axis ratio of the plot reacts dynamically to the number of variables (`n_var`) and ensembles (`n_ensemble`) after it surpasses a combined number of `n_var*n_ensemble = 16`, and the y-axis range is calculated to encompass all values. The centered pattern correlation is good to see both the spread in models within a single variable, as well as a quick overview of how well other variables and aspects of the climate on a large scale are reproduced with respect to observations. Furthermore when using several ensembles, the progress made by each ensemble on a variable basis can be seen at a quick glance.

### 3.1.3 Single model performance index

Most model performance metrics only display the skill for a specific model and a specific variable at a time, not making an overall index for a model. This works well when only a few variables or models are considered, but can result in an overload of information for a multitude of variables and models. Following Reichler and Kim (2008), a Single Model Performance Index (SMPI) has been implemented in `recipe_smpi.yml`. The SMPI (called "I2") is based on the comparison of several different climate variables (atmospheric, surface and oceanic) between climate model simulations and observations or reanalyses, and evaluates the time-mean state of climate. For I2 to be determined, the differences between the climatological mean of each model variable and observations at each of the available data grid points are calculated, and scaled to the interannual variance from the validating observations. This interannual variability is determined by performing a bootstrapping method (random selection with replacement) for the creation of a large synthetic ensemble of observational climatologies. The results are then scaled to the average error from a reference ensemble of models, and in a final step the mean over all climate variables and one model is calculated. [The plot Figure 3](#) shows the I2 values for each model (orange circles) and the multi-model mean (black circle), with the diameter of each circle representing the range of I2 values encompassed by the 5th and 95th percentiles of the bootstrap ensemble ([Figure 3](#)). [The SMPI allows for a quick estimation on which models are performing the best on average across the sampled variables \(see Table 1\) and in this case shows that the common practice of taking the multi-model mean as best overall model is valid.](#) The I2 values vary around one, with values greater than one for underperforming models, and values less than one for more accurate models. This diagnostic requires that all models have input for all of the variables considered, as this is the basis to have a [comparable I2-meaningful comparison of the resulting I2 values](#).

### 3.1.4 Auto-Assess

While highly condensed metrics are useful for comparing a large number of models, for the purpose of model development it is important to retain granularity on which aspects of model performance have changed, and why. For this reason, many modelling centres have their own suite of metrics which they use to compare candidate model versions against a predecessor. AutoAssess is such a system, developed by the UK Met Office and used in the development of [the HadGEM3 and UKESM1 models](#). The output of AutoAssess contains a mix of top-down metrics evaluating key model output variables (e.g. temperature and precipitation) and bottom-up metrics which assess the realism of model processes and emergent behaviour such as cloud variability and El Niño–Southern Oscillation (ENSO). The output of AutoAssess includes around 300 individual metrics. To facilitate interpretation of the results [they, these](#) are grouped into 11 thematic areas, ranging from the broad-scale such as

250 global tropic circulation and stratospheric mean state and variability, to the region- and process-specific, such as monsoon regions and the hydrological cycle.

It is planned that all the metrics currently in AutoAssess will be implemented in ESMValTool. At this time, a single assessment area (group of metrics) has been included as a technical demonstration: that for the stratosphere. These metrics have been implemented in a set of recipes named *recipe\_autoassess\_\*.yaml*. They include metrics of the Quasi-Biennial Oscillation (QBO) as a measure of tropical variability in the stratosphere. Zonal mean zonal wind at ~~30hPa~~ 30 hPa is used to define metrics for the period and amplitude of the QBO. Figure 4 ~~shows~~ displays the downward propagation of the QBO for a single model using zonal mean zonal wind averaged between ~~5S~~ 5°S and 5°N. Zonal wind anomalies propagate downward from the upper stratosphere. 5N. The figure shows that the period of the QBO in the chosen model is about 6 years, significantly longer than the observed period of ~2.3 years. Metrics are also defined for the tropical tropopause cold point (~~100hPa, 10S-10N~~ 100 hPa, 10°S – 10°N) temperature, and stratospheric water vapour concentrations at entry point (~~70hPa, 10S-10N~~ 70 hPa, 10°S – 10°N). The cold point temperature is an important factor determining the entry point humidity, which in turn is important for the accurate simulation of stratospheric chemistry and radiative balance (~~Hardiman et al., 2015~~) (Hardiman et al., 2015). Other metrics characterise the realism of the stratospheric easterly jet and polar night jet.

### 3.2 Diagnostics for the evaluation of processes in the atmosphere

#### 3.2.1 Multi-model mean bias for temperature and precipitation

270 Near-surface air temperature (tas) and precipitation (pr) of ESM simulations are the two variables most commonly requested by users ~~of ESM simulations~~. Often, diagnostics for tas and pr are shown for the multi-model mean of an ensemble. Both of these variables are the end result of ~~numerous interacting~~ processes in the models, making it challenging to understand and improve biases in these quantities. For example, near surface air temperature biases depend on the models' representation of radiation, convection, clouds, land characteristics, surface fluxes, as well as atmospheric circulation and turbulent transport (Flato et al., 2013), each with their own potential biases that may either augment or oppose one another.

275 The diagnostic that calculates the multi-model mean bias compared to a reference data set is part of ~~the~~ *recipe\_flato13ipcc.yaml* and reproduces Figures 9.2 and 9.4 of Flato et al. (2013). We extended the *namelist\_flato13ipcc.xml* of ESMValTool v1.0 by adding the mean root mean square error of the seasonal cycle with respect to the reference dataset. ~~Figures 5 and 6 show the CMIP5~~ The multi-model ~~average as absolute values and as biases for the annual~~ mean near-surface air temperature ~~relative to~~ agrees with ERA-Interim most within ±2°C (Figure 5). Larger biases can be seen in regions with sharp gradients in temperature, for example in areas with high topography such as the Himalaya, the sea ice edge in the North Atlantic, and over the coastal upwelling regions in the subtropical oceans. ~~and~~ Biases in the simulated multi-model mean precipitation relative compared to the Global Precipitation Climatology Project (GPCP, Adler et al. (2003)) data, ~~respectively,~~ include too low precipitation along the Equator in the western Pacific and too high precipitation amounts in the tropics south of the Equator (Figure 6). Figure 7 shows observed and simulated time series of the anomalies in annual and global mean surface temperature. The model datasets are subsampled by the HadCRUT4 observational data mask (Morice et al., 2012) and pre-processed as described by Jones et al. (2013). Overall, the models represent the annual global-mean surface temperature increase over the historical period quite well, including the more rapid warming in the second half of the 20<sup>th</sup> century and the cooling immediately following

290 | large volcanic eruptions. The figure reproduces Figure 9.8 of Flato et al. (2013) and is part of  
*recipe\_flato13ipcc.yml*.

### 3.2.2 Precipitation quantile bias

Precipitation is a dominant component of the hydrological cycle, and as such a main driver of the climate system and human development. The reliability of climate projections and water resources strategies therefore depends  
295 | on how well precipitation can be reproducesimulated by the models used for simulations. While CMIP5 models can reproduce the main patterns of mean precipitation (e.g., compared to observational data from GPCP (Adler et al., 2003)), they often show shortages and biases under particular conditions. Comparison of precipitation from CMIP5 models and observations shows a general good agreement for mean values at large scale (Kumar et al., 2013; Liu et al., 2012). Models carry  
300 | Comparison of precipitation from CMIP5 models and observations shows a general good agreement for mean values at large scale (Kumar et al., 2013; Liu et al., 2012a). Models have however a poor representation of frontal, convective, and mesoscale processes, resulting in substantial biases at regional scale (Mehran et al., 2014) at regional scale; models tend to overestimate precipitation over complex topography and underestimate it especially over arid or peuliarsome subcontinental regions as for example northern Eurasia, eastern Russia, and central Australia. Biases are typically stronger at high quantiles of  
305 | precipitation, making the study of precipitation quantile biases an effective diagnostic for addressing the quality of simulated precipitation.

The *recipe\_quantilebias.yml* implements the calculation of the quantile bias to allow for the evaluation of the precipitation biasbiases based on a user defined quantile in models as compared to a reference dataset following Mehran et al. (2014). The quantile bias (QB) is defined as the ratio of monthly precipitation amounts in each  
310 | simulation to that of the reference dataset above a specified threshold  $t$  (e.g., the 75<sup>th</sup> percentile of all the local monthly values). An example is reporteddisplayed in Figure 8, where gridded observational dataobservations from the GPCP project were adopted. A quantile bias equal to 1 indicates no bias in the simulations, whereas a value above (below) 1 corresponds to a climate-model's overestimation (underestimation) of the precipitation amount above the specified threshold  $t$ , with respect to that of the reference dataset. An overestimation over  
315 | Africa for models in the right column and an underestimation crossing central Asia from Siberia to the Arabic peninsula is visible, promptly identifying the best performances or outliers. For example, the HadGEM2-ES model here shows a smaller bias compared to the other models in this subset. The recipe allows the evaluation of the precipitation bias based on a user-defined quantile in models as compared to the reference dataset.

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### 3.2.3 Atmospheric dynamics

#### 3.2.3.1 Stratosphere-troposphere coupling

320 | ~~The current generation of climate models include the representation of stratospheric processes, as the vertical coupling with the troposphere is important for the weather and climate at the surface (Baldwin and Dunkerton, 2001). Stratosphere-resolving models are able to internally generate realistic annular modes of variability in the extratropical atmosphere (Charlton-Perez et al., 2013) which are however too persistent in the troposphere and delayed in the stratosphere compared to reanalysis (Gerber et al., 2010), leading to biases in the simulated impacts on surface conditions.~~

325 | The current generation of climate models include the representation of stratospheric processes, as the vertical coupling with the troposphere is important for the representation of weather and climate at the surface (Baldwin

and Dunkerton, 2001). Stratosphere-resolving models are able to internally generate realistic annular modes of variability in the extratropical atmosphere (Charlton-Perez et al., 2013) which are however too persistent in the troposphere and delayed in the stratosphere compared to reanalysis (Gerber et al., 2010), leading to biases in the simulated impacts on surface conditions.

The recipe `recipe_znnam.yml` can be used to evaluate the representation of the Northern Annular Mode (NAM, (Wallace, 2000)) in climate simulations, using reanalysis datasets as reference. Wallace (2000) in climate simulations, using reanalysis datasets as reference. The calculation is based on the “zonal mean algorithm” of Baldwin and Thompson (2009), and is an alternative to pressure based or height-dependent methods. This approach provides a robust description of the stratosphere-troposphere coupling on daily timescales, requiring less subjective choices and a reduced amount of input data. Starting from daily mean geopotential height on pressure levels, the leading empirical orthogonal function/Empirical Orthogonal Functions (EOFs) / principal component/components are computed from linearly detrended zonal mean daily anomalies, with the principal component representing the zonal mean NAM index. Missing values, which may occur near the surface level, are filled with a bilinear interpolation procedure. The regression of the monthly mean geopotential height onto this monthly averaged index represents the NAM pattern for each selected pressure level. The outputs of the procedure are the time series (Figure 9, left) and the histogram (not shown) of the zonal-mean NAM index, and the regression maps for selected pressure levels (Figure 9, right). The users/The well-known annular pattern, with opposite anomalies between polar and mid-latitudes, can be seen in the regression plot. The user can select the specific datasets (climate model simulation and/or reanalysis) to be evaluated, and a subset of pressure levels of interest.

### 3.2.3.2 Atmospheric blocking indices

Atmospheric blocking is a recurrent mid-latitude weather pattern identified by a large-amplitude, quasi-stationary, long-lasting, high-pressure anomaly that “blocks” the westerly flow forcing the jet stream to split or meander (Rex, 1950)(Rex, 1950). It is typically initiated by the breaking of a Rossby wave in a region at the exit of the storm track, where it amplifies the underlying stationary ridge (Tibaldi and Molteni, 1990). Blocking occurs more frequently in the Northern Hemisphere cold season, with larger frequencies observed over the Euro-Atlantic and North Pacific sectors. Its lifetime oscillates from a few days up to several weeks (Davini et al., 2012). To this day atmospheric/Atmospheric blocking still represents an open issue for the climate modelling community since state-of-the-art weather and climate models show limited skill in reproducing it (Davini and D’Andrea, 2016; Masato et al., 2013). Models are indeed characterized by large negative bias over the Euro-Atlantic sector, a region where blocking is often at the origin of extreme events, leading to cold spells in winter and heat waves in summer (Coumou and Rahmstorf, 2012; Sillmann et al., 2011).

Several objective blocking indices have been developed aimed at identifying different aspects of the phenomenon (see Barriopedro et al. (2010)Barriopedro et al. (2010) for details). The recipe `recipe_miles_block.yml` integrates diagnostics from the Mid-Latitude Evaluation System (MiLES) v0.51 (Davini, 2018) tool in order to calculate two different blocking indices based on the reversal of the meridional gradient of daily 500 hPa geopotential height. The first one is a 1-d index, namely the Tibaldi and Molteni (1990) blocking index, here adapted to work with 2.5x2.5° grids. Blocking is defined when the reversal of the meridional gradient of geopotential height at 60°N is detected, i.e. when easterly winds are found in the mid-latitudes. The second one is the atmospheric blocking index following Davini et al. (2012). It is a 2-d extension of Tibaldi and Molteni (1990) covering latitudes from 30°N up to 75°N. The recipe computes both the

370 Instantaneous Blocking frequencies and the Blocking Events frequency (which includes both spatial and 5-day-  
minimum temporal constraints). It reports also two intensity indices, ~~i.e. namely~~ the Meridional Gradient Index  
and the Blocking Intensity index, and it evaluates the wave breaking characteristic associated with blocking (~~i.e.~~  
cyclonic or anticyclonic) through the Rossby wave orientation index. A supplementary Instantaneous Blocking  
index (named “ExtraBlock”) including an extra condition to filter out low-latitude blocking events is also  
375 provided. The recipe compares ~~multiple~~multiple datasets against a reference one (default is ERA-Interim) and  
provides output (in NetCDF4 ~~compressed~~ Zip format) as well as figures for the climatology of each diagnostic.  
An example output is shown in Figure 10. ~~The MPI-ESM-MR model shows the well-known underestimation of  
atmospheric blocking – typical of many climate models – over Central Europe, where blocking frequencies are  
about the half when compared to reanalysis. Slight overestimation of low latitude blocking and North Pacific  
380 blocking can also be seen, while Greenland blocking frequencies show negligible bias.~~

### 3.2.4 Thermodynamics of the climate system

~~The climate system can be seen as a forced and dissipative non-equilibrium thermodynamic system (Lucarini et  
al., 2014), converting potential into mechanical energy, and generating entropy via a variety of irreversible  
processes. The atmospheric and oceanic circulation are caused by the inhomogeneous absorption of solar  
385 radiation, and, all in all, they act in such a way to reduce the temperature gradients across the climate system.  
~~When assessing model performances, this allows developing a comprehensive set of interrelated metrics,  
explaining climate variability over a large variety of scales and linking it to the first principles of physics. One of  
these metrics is the Top of Atmosphere (TOA) energy budget.~~ At steady-state, assuming stationarity, the long  
term ~~global~~ energy input and output should balance. Previous studies have shown that this is essentially not the  
390 case, and most of the models are affected by non-negligible energy drift (Lucarini et al., 2011; Mauritsen et al.,  
2012)). This severely impacts the prediction capability of state-of-the-art models, given that most of the energy  
imbalance is known to be taken up by oceans (~~Exarchou et al., 2015~~). This is why increasing attention is being  
devoted to the retrieval of a consistent dataset of observational-based ocean heat uptake measurements (Von  
Schuckmann et al., 2016). Nonetheless, global energy biases are also associated to (~~Exarchou et al., 2015~~).  
395 ~~Global energy biases are also associated with~~ inconsistent thermodynamic treatment of processes taking place in  
the atmosphere, as the dissipation of kinetic energy (Lucarini et al., 2011) and ~~of the water mass balance inside  
the hydrological cycle (Liepert and Previdi, 2012; Wild and Liepert, 2010)~~the water mass balance inside the  
hydrological cycle (Liepert and Previdi, 2012; Wild and Liepert, 2010). Climate models feature substantial  
400 disagreements in the peak intensity of the meridional heat transport, both in the ocean and in the atmospheric  
parts, whereas the position of the peaks of the (atmospheric) transport blocking are consistently captured  
(Lucarini and Pascale, 2014). In the atmosphere, these issues are related to inconsistencies in the models’ ability  
to reproduce the mid-latitude atmospheric variability (~~Di Biagio et al., 2014; Lucarini et al., 2007~~)(Di Biagio et  
al., 2014; Lucarini et al., 2007), and intensity of the Lorenz Energy Cycle (~~Marques et al., 2014~~)(Marques et al.,  
2011). Energy and water mass budgets, as well as the treatment of the hydrological cycle and atmospheric  
405 dynamics, all affect the material entropy production in the climate system, i.e. the entropy production related to  
irreversible processes in the system. ~~Various methods have been proposed to account for that (Ambaum, 2010;  
Fraedrich et al., 2008; Lucarini and Ragone, 2011; Romps, 2008).~~ It is possible to estimate the entropy  
production either via an indirect method, based on the radiative heat convergence in the atmosphere (the ocean  
accounts only for a minimal part of the entropy production), or via a direct method, based on the explicit~~

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410 computation of entropy production due to all irreversible processes (Goody, 2000). Ideally, the two methods are known to be equivalent, but differences (Goody, 2000). Differences in the two methods emerge when considering coarse-grained data in space and/or in time (Lucarini and Pascale, 2014). Resolving, as subgrid-scale processes have long been known to be a critical issue, when attempting to provide an accurate climate entropy budget (Gassmann and Herzog, 2015; Kleidon and Lorenz, 2004; Kunz et al., 2008). While some systematic estimates of entropy production by climate models have been produced with the indirect method (Lucarini and Pascale, 2014), an extensive comparison with the estimates resulting from the direct method is to our best knowledge still lacking, due to the limited availability of climate model outputs with the necessary temporal and spatial resolution.

415 In the current release the diagnostic tool for thermodynamics of the climate system contains a number of independent modules for: (a) energy budgets and meridional heat transports, (b) water mass and latent energy budget, (c) Lorenz Energy Cycle, (d) material entropy production with either the indirect/direct method or both. The code is set to ingest monthly mean gridded datasets for the modules (a), (b), and (d). Daily mean data are required for the computation of the Lorenz Energy Cycle (c). The intensity of the Lorenz Energy Cycle is used for computation of the material entropy production with the direct method. If (c) is not performed, a reference value for material entropy production due to kinetic energy dissipation is provided. Input variables are monthly mean radiative fluxes at TOA and at the surface, surface turbulent latent and sensible heat fluxes, surface temperature, near surface specific humidity, snowfall and total precipitation, surface pressure. The daily mean 3-dimensional fields of velocity, temperature, the two components of the near surface horizontal velocity and near surface temperature are required for the computation of the Lorenz Energy Cycle. If a land-sea mask is provided, energy and water mass budgets are also separately computed over oceans and continents. The outputs of the diagnostic modules are provided as annual mean quantities in NetCDF format. When possible (energy budgets, water mass and latent energy budgets, components of the material entropy production with the indirect method) horizontal maps for the average of annual means are provided. For the meridional heat transports, annual mean meridional sections are shown (Figure 11) (Lembo et al., 2017; Lucarini and Pascale, 2014; Trenberth et al., 2001). For the Lorenz Energy Cycle, a flux diagram (Ulbrich et al., 1991), showing all the storage, conversion, source and sink terms for every year, is provided (Figure 12) (Ulbrich and Speth, 1991), showing all the storage, conversion, source and sink terms for every year, is provided. The diagram in Figure 11 shows the baroclinic conversion of the available potential energy (APE) to kinetic energy (KE), and ultimately its dissipation through frictional heating (Lorenz, 1955; Lucarini et al., 2014). When a multi-model ensemble is provided, global metrics are related in scatter plots, where each dot is a member of the ensemble, and the multi-model mean, together with uncertainty range, is displayed. An output log file contains all the information about the time-averaged global mean values, including all components of the material entropy production budget. For the meridional heat transports, annual mean meridional sections are shown in Figure 12 (Lembo et al., 2017; Lucarini and Pascale, 2014; Trenberth et al., 2001). The model spread has roughly the same magnitude in the atmospheric and oceanic transports, but its relevance is much larger for the oceanic transports. The model spread is also crucial in the magnitude and sign of the atmospheric heat transports across the Equator, given its implications for the atmospheric general circulation. The diagnostic tool is run through the recipe `recipe_thermodyn_diagtool.yml`, where the user can also specify the options on which modules have to be run. An extensive explanation of the methods used and a discussion of results with a subset of CMIP5 datasets can be found in Lembo et al. (2019) who describe the Thermodynamic Diagnostic Tool (TheDiaTo) v1.0 should be run.

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### 3.2.5 Natural modes of climate variability and weather regimes

#### 3.2.5.1. NCAR Climate Variability Diagnostic Package

Natural modes of climate variability co-exist with externally-forced climate change, and have large impacts on climate, especially at regional and decadal scales. These modes of variability are due to processes intrinsic to the coupled climate system, and exhibit limited predictability. As such, they complicate model evaluation ~~and model inter-comparisons~~ as the observational record is often not long enough to reliably assess the variability, and confound assessments of anthropogenic influences on climate (Bengtsson and Hodges, 2019; Deser et al., 2012; Deser et al., 2014; Deser et al., 2017; Kay et al., 2015; Suárez-Gutiérrez et al., 2017). Despite their importance, systematic evaluation of these modes in Earth system models remains a challenge ~~due~~ to the wide range of phenomena to consider, the length of record needed to adequately characterize them, and uncertainties in the short observational data sets (Deser et al., 2010; Frankignoul et al., 2017; Simpson et al., 2018). While the temporal sequences of internal variability in models do not necessarily need ~~not~~ to match those in the single realization of nature, their statistical properties (e.g., time scale, autocorrelation, spectral characteristics, and spatial patterns) need to be realistically simulated for credible climate projections.

In order to assess natural modes of climate variability in models, the NCAR Climate Variability Diagnostics Package (CVDP, Phillips et al. (2014)) has been implemented into the ESMValTool. The CVDP has been developed as a standalone tool. To allow for easy updating of the CVDP once a new version is released, the structure of the CVDP is kept in its original form and a single recipe *recipe\_CVDP.yml* has been written to enable the CVDP to be run directly within ESMValTool. The CVDP facilitates evaluation of the major modes of climate variability, including ENSO (Deser et al., 2010), the Pacific Decadal Oscillation (PDO, (Deser et al., 2010; Mantua et al., 1997)), the Atlantic Multi-decadal Oscillation (AMO, Trenberth and Shea (2006)), the Atlantic Meridional Overturning Circulation (AMOC, ~~Danabasoglu et al. (2012)~~ Danabasoglu et al. (2012)), and atmospheric teleconnection patterns such as the Northern and Southern Annular Modes (NAM and SAM; (Hurrell and Deser, 2009; Thompson and Wallace, 2000)), North Atlantic Oscillation (NAO, Hurrell and Deser (2009)), and Pacific North and South American (PNA and PSA, Thompson and Wallace (2000)), patterns. For details on the actual calculation of these modes in CVDP we refer to the original CVDP package and explanations available at [http://www.cesm.ucar.edu/working\\_groups/CVC/cvdp/](http://www.cesm.ucar.edu/working_groups/CVC/cvdp/).

Depending on the climate mode analysed, the CVDP package uses the following variables: precipitation (pr), sea level pressure (psl), near-surface air temperature (tas), skin temperature (ts), snow depth (snd), sea ice concentration (siconc), and basin-average ocean meridional overturning mass stream function (msftmz). The models are evaluated against a wide range of observations and reanalysis data, for example Berkeley Earth System Temperature (BEST) for near-surface air temperature, Extended Reconstructed Sea Surface Temperature v5 (ERSSTv5) for skin temperature, and ERA-20C extended with ERA-Interim for sea level pressure. Additional observations or reanalysis can be added by the user for these variables. The ESMValTool v2.0 recipe runs on all CMIP5 models. As an example, Figure 13 shows the representation of ENSO teleconnections during the peak phase (December-February). Models produce a wide range of ENSO amplitudes and teleconnections. Note that even when based on over 100 years of record, the ENSO composites are subject to uncertainty due to sampling variability (Deser et al., 2017). Figure 14 shows the representation of the AMO as simulated by 41 CMIP5 models and observations during the historical period. The pattern of SSTA\* associated with the AMO is generally realistically simulated by models within the North Atlantic basin, although its amplitude varies. However, outside of the North Atlantic, the models show a wide range of spatial patterns and polarities of the

~~AMO. As examples, Figure 13 shows the representation of ENSO teleconnections during the peak phase (December-February) and Figure 14 the representation of the AMO as simulated by 41 CMIP5 models and observations during the historical period.~~

#### 495 3.2.5.2 Weather regimes

Weather Regimes (WRs) refer to recurrent large-scale atmospheric circulation structures that allow the characterization of complex atmospheric dynamics in a particular region (Michelangeli et al., 1995; Vautard, 1990)(Michelangeli et al., 1995; Vautard, 1990). The identification of WRs reduces the continuum of atmospheric circulation to a few recurrent and quasi-stationary (persistent) patterns. WRs have been extensively used to investigate atmospheric variability at the mid-latitudes, as they are associated with extreme weather events such as heat waves or droughts (Yiou et al., 2008)(Yiou et al., 2008). For example, there is a growing recognition of their significance especially over the Euro-Atlantic sector during the winter season, where four robust weather regimes have been identified - namely the NAO+, NAO-, Atlantic Ridge and Scandinavian Blocking (Cassou et al., 2005). These WRs can also be used as a diagnostic tool to investigate the performance of state-of-the-art climate forecast systems: difficulties in reproducing the Atlantic Ridge and the Scandinavian blocking have been often observed-reported (Dawson et al., 2012; Ferranti et al., 2015)(Dawson et al., 2012; Ferranti et al., 2015). Forecast systems which are not able to reproduce the observed spatial patterns and frequency of occurrence of WRs may be unsuitable for simulating have difficulties in reproducing climate variability and its long-term changes (Hannachi et al., 2017)(Hannachi et al., 2017). Hence, the assessment of WRs can help improve our understanding of predictability on intra-seasonal to inter-annual time scales. In addition, the use of WRs to evaluate the impact of the atmospheric circulation on essential climate variables and sectoral climatic indices is of great interest to the climate services communities (Grams et al., 2017)(Grams et al., 2017). The diagnostic can be applied to model simulations under future scenarios as well. However, caution must be applied since large changes in the average climate, due to large radiative forcing, might affect the results and lead to somehow misleading conclusions. In such cases further analysis will be needed to assess to what extent the response to climate change projects on the regimes patterns identified by the tool in the historical and future periods and to verify how future anomalies project onto the regime patterns identified in the historical period.

The recipe `recipe_modes_of_variability.yml` takes daily or monthly data from a particular region, season (or month) and period as input, and then applies k-mean clustering or hierarchical clustering either directly to the spatial data or after computing the EOFs. This recipe can be run for both a reference/observational dataset and climate projections simultaneously, and the root-mean-square error is then calculated between the mean anomalies obtained for the clusters from the reference and projection data sets. The user can specify the number of clusters to be computed. The recipe output consist of netCDF files of the time series of the cluster occurrences, the mean anomaly corresponding to each cluster at each location and the corresponding  $p$ -value, for both the observed and projected WR and the RMSE between them. The recipe also creates three plots: the observed/reference modes of variability (Figure 15), the reassigned modes of variability for the future projection (Figure 16) and a table displaying the RMSE values between reference and projected modes of variability (Figure 17). Low RMSE values along the diagonal show that the modes of variability simulated by the future projection (Figure 16) match the reference modes of variability (Figure 15). The recipe `recipe_miles_regimes.yml` integrates the diagnostics from the Mid-Latitude Evaluation System (MiLES) v0.51 tool (Davini, 2018) in order to calculate the four relevant North Atlantic weather regimes. This is done by

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analysing the ~~500hPa~~500 hPa geopotential height over the North Atlantic (~~80W 40E 30N 80W~~ – 40°E, 30°N – 87.5N 5°N). Once a 5-day smoothed daily seasonal cycle is removed, the ~~Empirical Orthogonal Functions~~EOFs which explain at least the 80% of the variance are extracted in order to reduce the phase-space dimensions. A k-means clustering using Hartigan-Wong algorithm with k=4 is then applied providing the final weather regimes identification. The recipe compares ~~multiple~~multiple datasets against a reference one (default is ERA-Interim) producing multiple figures which show the pattern of each regime and its difference against the reference dataset. Weather regimes patterns and timeseries are provided in NetCDF4 ~~compressed~~ Zip format. Considering the limited physical significance of Euro-Atlantic weather regimes in other seasons, only winter is currently supported. An example output is shown in Figure 18. The Atlantic ridge regime, which is usually badly simulated by climate models, is reproduced with the right frequency of occupancy and pattern in MPI-ESM-MR when compared to ERA-Interim reanalysis.

### 3.2.5.3 Empirical Orthogonal Functions

~~Empirical Orthogonal Function (EOF)~~EOF analysis is a powerful method to decompose spatiotemporal data using an orthogonal basis of spatial patterns. In weather sciences, EOFs have been extensively used to identify the most important modes of climate variability and their associated teleconnection patterns: for instance, the North Atlantic Oscillation (NAO, (Ambaum, 2010; Wallace and Gutzler, 1981)) and the Arctic Oscillation (AO, Thompson and Wallace (2000)) are usually defined with EOFs. Biases in the representation of the NAO or the AO have been found to be typical in many CMIP5 models (Davini ~~et al., 2012~~and Cagnazzo, 2013).

The recipe `recipe_miles_eof.yml` integrates diagnostics from the ~~Mid-Latitude Evaluation System~~—MiLES v0.51 ~~tool~~ (Davini, 2018) ~~tool~~ in order to extract the first EOFs over a user-defined domain. Three default patterns are supported, namely the “NAO” (North Atlantic Oscillation, over the ~~90W 40E 20N 85N~~90°W – 40°E, 20°N – 85°N box), the “PNA” (Pacific North America pattern, over the ~~140W 80E, 20N 85N~~140°W – 80°E, 20°N – 85°N box) and the “AO” (Arctic Oscillation, over the ~~20N 85N~~20°N – 85°N box). The computation is based on Singular-Value Decomposition (SVD) applied to the anomalies of the monthly 500 hPa geopotential height. The recipe compares multiples datasets against a reference one (default is ERA-Interim) producing multiple figures which show the linear regressions of the Principal Component (PC) of each EOF on the monthly 500hPa geopotential and its differences against the reference dataset. ~~PCs, EOF patterns, and percentage of variance explained are provided in NetCDF4 Zip format.~~By default the first four EOFs are stored and plotted. ~~An~~As an example ~~output is shown in~~, Figure 19 ~~shows that the NAO is well represented by the MPI-ESM-LR model (that is used here for illustration), although the variance explained is underestimated and the northern center of action, which is found close to Iceland in reanalysis, is westward displaced over Greenland.~~

### 3.2.5.4 Indices from differences between area averages

In addition to indices and modes of variability obtained from EOF and clustering analyses, users may wish to compute their own indices based on area-weighted averages or difference in area-weighted averages. For example, the Niño 3.4 index is defined as the sea surface temperature (SST) anomalies averaged over [170–120°W, 5°N–5°S]. Similarly, the NAO index can be defined as the standardized difference between the weighted area-average mean sea level pressure of the domain bounded by [0–80° W, 30–50° N] and [0–80° W 60–80°N].

The functions for computing indices based on area averages in `recipe_combined_indices.yml` have been adapted to allow users to compute indices for the Niño 3, Niño 3.4, Niño 4, NAO and ~~the~~ Southern Oscillation Index

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(SOI) defined region(s), with the option of selecting different variables (e.g. temperature of the ocean surface (tos, commonly named sea surface temperature) or pressure at sea level (psl, ~~commonly named~~ sea level pressure)) with the option to compute standardized variables, applying running means and select different seasons by selecting the ~~initial and final months (e.g.: defining parameter 'moninf' as 6 (12) and 'monsup' as 8 (2), for the boreal summer (winter) June July August (December January February))~~ start and end months. The output of this recipe is a netCDF file containing a time series of the computed indices and a time series of the evolution of the index for individual models and the multi-model mean (see Figure 20).

### 580 3.3 Diagnostics for the evaluation of processes in the ocean and cryosphere

#### 3.3.1 Physical ocean

The global ocean is a core component of the Earth system. A significant bias in the physical ocean can impact the performance of the entire model.

Several diagnostics exist in ESMValTool v2.0 to evaluate the broad behaviour of models of the global ocean. Figures 21 to 26 show several diagnostics of the ability of the CMIP5 models to simulate the global ocean. ~~In these figures, model datasets are selected from the historical simulations (here, ensemble member r1i1p1).~~ All available CF-compliant CMIP5 models are compared, however each figure shown in this section may include a different set of models, as not all CMIP5 models produced all the required datasets in a CF-compliant format. To minimise noise, these figures are shown with a 6-year moving window average.

The volume weighted global average temperature anomaly of the ocean is shown in Figure 21 and displays the change in the mean temperature of the ocean relative to the start of the historical simulation. The temperature anomaly is calculated against the years 1850-1900. Nearly all CMIP5 models show an increase in the mean temperature of the ocean over the historical period. This figure was produced using the recipe *recipe\_ocean\_scalar\_fields.yml*. The AMOC is an indication of the strength of the ~~Northbound current~~ overtaking circulation in the Atlantic Ocean and is shown in Figure 22. It transfers heat from tropical waters to the Northern Atlantic ocean. The AMOC has an observed strength of 17.2 Sv (~~McCarthy et al., 2015~~)(McCarthy et al., 2015). In the example shown in Figure 22, all CMIP5 models show some interannual variability in the AMOC behaviour, but the decline in the multi-model mean over the historical period is not statistically significant. Previous modelling studies (~~Cheng et al., 2013; Gregory et al., 2005~~)(Cheng et al., 2013; Gregory et al., 2005) have predicted a decline in the strength of the AMOC over the 20th century. The Drake Passage current is a measure of the strength of the Antarctic Circumpolar Current (ACC). This is the strongest current in the global ocean and runs clockwise around Antarctica. The ACC was recently measured through the Drake Passage at  $173.3 \pm 10.7$  Sv (~~Donohue et al., 2016~~). A comparison to CMIP5 models is shown in Figure 23(Donohue et al., 2016). Four of the CMIP5 models fall within this range (Figure 23). Figures 22 and 23 were produced using the recipe *recipe\_ocean\_amocs.yml*. The global total flux of CO<sub>2</sub> from the atmosphere into the ocean for several CMIP5 models is shown in Figure 24. This figure shows the absorption of atmospheric carbon by the ocean. At the start of the historic period, most of the models shown here have been spun up, meaning that the air to sea flux of CO<sub>2</sub> should be close to zero. As the CO<sub>2</sub> concentration in the atmosphere increases over the course of the historical simulation, the flux of carbon from the air into the sea also increases. The CMIP5 models shown in Figure 24 agree very closely on the behaviour of the air to sea flux of CO<sub>2</sub> over the historical period with all models showing an increase from close to zero, and rising up to approximately 2 Pg of Carbon per year (C yr<sup>-1</sup>) by the start of the 21<sup>st</sup> century. The global total integrated primary production from phytoplankton is

615 shown in Figure 25. Marine phytoplankton is responsible for  $56 \pm 7$  Pg  $C\ yr^{-1}$  of primary production ~~per year~~ (Buitenhuis et al., 2013)(Buitenhuis et al., 2013), which is of similar magnitude to that of land plants (Field et al., 1998). In all cases, we do not expect to observe a significant change in primary production over the course of the historical period. However, the differences in the magnitude of the total integrated primary production inform us about the level of activity of the marine ecosystem. All CMIP5 models in Figure 25 show little inter-annual variability in the integrated marine primary production, and there is no clear trend in the multi-model mean. Figure 24 and 25 were both produced with the recipe *recipe\_ocean\_scalar\_fields.yml*. The combination of these 620 five key time series figures allows a coarse scale evaluation of the ocean circulation and biogeochemistry. The global volume weighted temperature shows the effect of a warming ocean, while the change in the Drake ~~passage~~ Passage and the AMOC show significant global changes in circulation. The integrated primary production shows changes in marine productivity and the air sea flux of  $CO_2$  shows the absorption of anthropogenic atmospheric carbon by the ocean.

625 In addition, a diagnostic from Chapter 9 of IPCC AR5 for the ocean is added (Flato et al., 2013) which is included in *recipe\_flato13ipcc.yml*. Figure 26 shows an analysis of the SST that documents the performance of models compared to one standard observational dataset, namely the SST part of the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) (Rayner et al., 2003)(Rayner et al., 2003) dataset. The SST plays an important role in climate simulations because it is the main oceanic driver of the atmosphere. As such, a good 630 model performance for SST has long been a hallmark of accurate climate ~~predictions~~ projections. In this figure we reproduce Figure 9.14 of Flato et al. (2013). It shows both zonal mean and equatorial (~~mean~~ averaged over ~~5-degrees-South-S~~ to ~~5-degrees-North-N~~) SST. For the zonal mean it shows (a) the error compared to observations for the individual models, (c-) the multi-model mean with the standard deviation. For the equatorial average it shows (b) the individual model errors and (d) the multi-model mean of the temperatures together with 635 the observational dataset. In this way ~~we can give~~ a good overview of both the error and the absolute temperatures, ~~resolved at~~ can be provided for the individual model level. Figure 26 shows the overall good agreement of the CMIP5 models among themselves as well as compared to observations, but also highlights the global areas with largest uncertainty and biggest room for improvement. This is an important benchmark for the upcoming CMIP6 ensemble.

### 640 3.3.2 Southern ocean

The Southern ocean is central to the global climate and the global carbon cycle, and to the climate's response to increasing levels of atmospheric greenhouse gases, as it ventilates a large fraction of the global ocean volume. Roemmich et al. (2015)Roemmich et al. (2015) concluded that the Southern Ocean was responsible for 67-98% of the total oceanic heat uptake; the oceanic increase in heat accounts for 93% of the radiative imbalance at the 645 top of the atmosphere. Global coupled climate models and Earth system models, however, vary widely in their simulations of the Southern Ocean and its role in and response to anthropogenic forcing. Due to the region's complex water-mass structure and dynamics, Southern Ocean carbon and heat uptake depend on a combination of winds, eddies, mixing, buoyancy fluxes, and topography. Russell et al. (2018)Russell et al. (2018) laid out a series of diagnostic, observational-based metrics that highlight biases in critical components of the Southern 650 Hemisphere climate system, especially those related to the uptake of heat and carbon by the ocean. These components include the surface fluxes (including wind and heat and carbon), the frontal structure, the circulation and transport within the ocean, the carbon system (in the ESMs) and the sea ice simulation. Each component is

associated with one or more model diagnostics, and with relevant observational data sets that can be used for the model evaluation. [Russell et al. \(2018\)](#) noted that biases in the strength and position of the surface westerlies over the Southern Ocean were indicative of biases in several other variables. The strength, extent, and latitudinal position of the Southern Hemisphere surface westerlies are crucial to the simulation of the circulation, vertical exchange and overturning, and heat and carbon fluxes over the Southern Ocean. The net transfer of wind energy to the ocean depends critically on the strength and latitudinal structure of the winds. Equatorward-shifted winds are less aligned with the latitudes of the Drake Passage and are situated over shallower isopycnal surfaces, making them less effective at both driving the ACC and bringing dense deep water up to the surface.

Figure 27 shows the annually-averaged, zonally-averaged zonal wind stress over the Southern Ocean from a sample of the CMIP5 climate simulations and the equivalent quantity from the Climate Forecast System Reanalysis (Saha et al., 2013). While most model metrics indicate that simulations generally bracket the observed quantity, this metric indicates that ALL of the models have an equatorward bias relative to the observations, an indication of a deeper modelling issue. Although [Russell et al. \(2018\)](#) only included six of the simulations submitted as part of CMIP5, the recipe `recipe_russell18jgr.yml` will recreate all of the metrics of this study for all CMIP5 simulations. Each metric assesses a simulated variable, or a climatically-relevant quantity calculated from one or more simulated variables (e.g. heat content is calculated from the simulated ocean temperature,  $\theta_{\text{tao}}$ , while the meridional heat transport depends on both the temperature,  $\theta_{\text{tao}}$ , and the meridional velocity,  $v_o$ ) relative to the observations. The recipe focuses on factors affecting the simulated heat and carbon uptake by the Southern Ocean. Figure 28 shows the relationship between the latitudinal width of the surface westerly winds over the Southern Ocean with the net heat uptake south of  $30^{\circ}\text{S}$  – the correlation (-0.8) is significant above the 98% level.

### 3.3.3 Arctic ocean

The Arctic ocean is one of the areas of the Earth where the effects of climate change are especially visible today. Two most prominent processes are Arctic [atmospheric temperature warming](#) amplification (Serreze and Barry, 2011) and decrease of the sea ice area and thickness (see Section 3.3.2). Both receive good coverage in the literature and are already well-studied. Much less attention is paid to the interior of the Arctic Ocean itself. In order to increase our confidence in projections of the Arctic climate future proper representation of the Arctic Ocean hydrography is necessary.

The vertical structure of temperature and salinity (T and S) in the ocean model is a key diagnostic that is used for ocean model evaluation. Realistic temperature and salinity distributions mean that the models properly represent dynamic and thermodynamic processes in the ocean. Different ocean basins have different hydrological regimes so it is important to perform analysis of vertical TS distribution for different basins separately. The basic ~~diagnosti~~[diagnostics](#) in this sense ~~is~~[are the](#) mean vertical profiles of temperature and salinity over some basin averaged for a relatively long period of time. Figure 29 shows the mean (1970-2005) vertical ocean potential temperature distribution in the Eurasian Basin of the Arctic Ocean as produced with `recipe_arctic_ocean.yml`. [It shows that CMIP5 models tend to overestimate temperature in the interior of the Arctic Ocean and have too deep Atlantic water depth.](#) In addition to individual vertical profiles for every model, we also show the mean over all participating models and similar profile from climatological data (PHC3, Steele et al. (2001)). The characteristics of vertical TS distribution can change with time, and consequently the vertical TS distribution is an important

indicator of the behaviour of the coupled ocean-sea ice-atmosphere system in the North Atlantic and Arctic Oceans. One way to evaluate these changes is by using Hovmoller diagrams. ~~We have created Hovmoller diagrams for two main Arctic Ocean basins – Eurasian and Amerasian.~~We have created Hovmoller diagrams for two main Arctic Ocean basins – Eurasian and Amerasian (as defined in Holloway et al. (2007)), with T and S spatially averaged on a monthly basis for every vertical level. This diagnostic allows the temporal evolution of vertical ocean potential temperature distribution to be assessed. The T-S diagrams allow the analysis of water masses and their potential for mixing. The lines of constant density for specific ranges of temperature and salinity are shown on the background of the T-S diagram. The dots on the diagram are individual grid points from specified region at all model levels within user specified depth range. The depths are colour coded. Examples of the mean (1970-2005) T-S diagram for Eurasian Basin of the Arctic Ocean shown in Figure 30 refer to *recipe\_arctic\_ocean.yml*. ~~Most models cannot properly represent Arctic Ocean water masses and either have wrong values for temperature and salinity or miss specific water masses completely.~~

The spatial distribution of basic oceanographic variables characterises the properties and spreading of ocean water masses. For the coupled models, capturing the spatial distribution of oceanographic variables is especially important in order to correctly represent the ocean-ice-atmosphere interface. We have implemented plots with spatial maps of temperature, salinity and current speeds at original model levels. For temperature and salinity, we have also implemented spatial maps of model biases from the observed climatology with respect to PHC3 climatology. For the model biases, values from the original model levels are linearly interpolated to the climatology (PHC3) levels and then spatially interpolated from the model grid to the regular PHC3 climatology grid. Resulting fields show model performance in simulating spatial distribution of temperature and salinity. Vertical transects through arbitrary sections are important for analysis of vertical distribution of ocean water properties ~~and especially useful when exchange between different ocean basins is evaluated.~~. Therefore, diagnostics that allow for the definition of an arbitrary ocean section by providing set of points on the ocean surface are also implemented. For each point, a vertical profile of temperature or salinity on the original model levels is interpolated. All profiles are then connected to form a transect. The great-circle distance between the points is calculated and used as along-track distance. One of the main use cases for transects is to create vertical sections across ocean passages. Transects that follow the pathway of the Atlantic water according to Ilıcak et al. (2016) are also included. Atlantic water is a key water mass of the Arctic Ocean and its proper representation is one of the main challenges in Arctic Ocean modelling. A diagnostic that calculates the temperature of the Atlantic water core for every model as the maximum potential temperature between 200 and 1000-meter depth in the Eurasian Basin is included ~~in this release.~~. The depth of the Atlantic water core is calculated as the model level depth where the maximum temperature is found in Eurasian Basin (Atlantic water core temperature). In order to evaluate the spatial distribution of Atlantic water in different climate models we also provide diagnostics with maps of the spatial distribution of water temperature at the depth of Atlantic water core in *recipe\_arctic\_ocean.yml*.

### 3.3.4 Sea Ice

Sea ice is a critical component of the climate system, which considerably influences the ocean and atmosphere through different processes and feedbacks (~~Goosse et al., 2018~~)(Goosse et al., 2018). In the Arctic, sea ice has been dramatically retreating (~~Stroeve and Notz, 2018~~)(Stroeve and Notz, 2018) and thinning (~~Kwok, 2018~~)(Kwok, 2018) in the past decades. ~~In the Antarctic, there has been a small but significant increase in sea~~

ice cover from the beginning of satellite observations with large interannual variability, showing for example a sudden sea ice retreat since late 2015 (Meehl et al., 2019; Schlosser et al., 2018)). (Meredith et al., 2019). In the Antarctic, the sea ice cover has exhibited no significant change over the period of satellite observations, although this is the result of regional compensations and large interannual variability (Meredith et al., 2019). Climate models constitute a useful tool to make projections of the future changes in sea ice (Massonnet et al., 2012). However, the different climate models largely disagree on the magnitude of sea\_ice changes, even for the same forcing (Stroeve et al., 2012). One of the reasons for this disagreement is the lack of understanding and representing core(Stroeve et al., 2012). One reason could be the different treatment of thermodynamic and dynamic processes and feedbacks related to sea ice.

In order to better understand and reduce model errors, two recipes related to sea ice have been implemented into ESMValTool v2.0. The first recipe, *recipe\_seaice\_feedback.yml*, is related to the negative sea\_ice growth-thickness feedback (Massonnet et al., 2018)(Massonnet et al., 2018b). In this recipe, one process-based diagnostic named the Ice Formation Efficiency (IFE) is computed based on monthly mean sea\_ice volume estimated north of 80°N. The choice of this domain is motivated by the desire to minimize the influence of dynamic processes but also by the availability of sea ice thickness measurements. The diagnostic intends to evaluate the strength of the negative sea\_ice thickness/growth feedback, which causes late-summer negative anomalies in sea\_ice area and volume to be partially recovered during the next growing season (Notz and Bitz, 2017)(Notz and Bitz, 2017). A chief cause behind the existence of this feedback is the non-linear inverse dependence between heat conduction fluxes and sea ice thickness, which implies that thin sea ice grows faster than thick sea ice. To estimate the strength of that feedback, anomalies of the annual minimum of sea\_ice volume north of 80°N are first estimated. Then, the increase in sea\_ice volume until the next annual maximum is computed for each year. The IFE is defined as the regression of this ice volume production onto the baseline summer volume anomaly (Figure 31). The IFE was applied to the CMIP5 ensemble (Massonnet et al., 2018). It was first found that allAll CMIP5 models, without exception, simulate negative IFE over the historical period, implying that all these models display a basic mechanism of ice volume recovery when large negative anomalies occur in late summer. However, the strength of the IFE was found to be is simulated very differently by the models. (Massonnet et al., 2018a). The IFE was in fact found to be is closely associated with the background mean sea ice state of the models (defined as the annual mean sea\_ice volume north of 80°N) with stronger feedback strength ice thins. In parallel, it was found that. Also, the strength of the IFE was is directly connected to the long-term variability (persistence, year to year variability, decadal trends), providing prospects for the application of emergent constraints. However, the shortness of observational records of sea\_ice thickness and their large uncertainty precludedpreclude rigorous applications of such constraints. The analyses nevertheless allowedallow (1) to pin down that the spread in CMIP5 sea ice volume projections is inherently linked to the way they represent the strength of sea ice feedbacks, which itself is closely linked to the model mean states and so their mean state, and (2) to provide guidance for the development of future observing systems in the Arctic, by stressing the need for more reliable estimates of sea ice thickness in the central Arctic basin (Ponsoni et al., 2019).

The second recipe, *recipe\_sea\_ice\_drift.yml*, allows to quantify the relationships between Arctic sea\_ice drift speed, concentration and thickness (Docquier et al., 2017)(Docquier et al., 2017). A decrease in concentration or thickness, as observed in recent decades in the Arctic Ocean (Kwok, 2018; Stroeve and Notz, 2018)(Kwok, 2018; Stroeve and Notz, 2018), leads to reduced sea\_ice strength and internal stress, and thus larger sea\_ice drift

775 speed (~~Rampal et al., 2011~~). ~~This in turn could provide higher export of sea ice out of the Arctic Basin, resulting~~  
~~in lower sea ice concentration and further thinning.~~(~~Rampal et al., 2011~~). ~~Olason and Notz (2014)~~~~Olason and~~  
~~Notz (2014)~~ investigate the relationships between Arctic sea\_ice drift speed, concentration and thickness using  
satellite and buoy observations. They show that both seasonal and recent long-term changes in sea ice drift are  
primarily correlated to changes in sea ice concentration and thickness. Our recipe allows ~~to quantify~~~~quantifying~~  
780 these relationships in climate models. In this recipe, four process-based metrics are computed based on the multi-  
year monthly mean sea\_ice drift speed, concentration and thickness, averaged over the Central Arctic. The first  
metric is the ratio between the modelled drift-concentration slope and the observed drift-concentration slope. The  
second metric is similar to the first one, except that sea\_ice thickness is involved instead of sea\_ice  
concentration. The third metric is the normalised distance between the model and observations in the drift-  
concentration space. The fourth metric is similar to the third one, except that sea\_ice thickness is involved  
785 instead of sea\_ice concentration. Sea\_ice concentration from the European Organisation for the Exploitation of  
Meteorological Satellites Ocean and Sea Ice Satellite Application Facility (~~Lavergne et al., 2019~~), ~~sea~~  
~~(Lavergne et al., 2019)~~, sea ice thickness from the Pan-Arctic Ice-Ocean Modeling and Assimilation System  
reanalysis (PIOMAS, Zhang and Rothrock (2003)) and sea\_ice drift from the International Arctic Buoy  
Programme (IABP, ~~Tschudi et al. (2016)~~~~Tschudi et al. (2016)~~) are used as reference products to compute these  
790 metrics (Figure 32). ~~Results in this example show that the GFDL-ESM2G model can reproduce the sea ice drift~~  
~~speed - concentration/thickness relationships compared to observations, with higher drift speed with lower~~  
~~concentration/thickness, despite the too thin ice in the model, while the MPI-ESM-LR model cannot reproduce~~  
~~this result.~~

### 3.4 Diagnostics for the evaluation of land processes

#### 795 3.4.1 Land Cover

Land cover (LC) is either prescribed in the CMIP models or simulated using a Dynamic Global Vegetation  
Model (DGVM). Within the recent decade, numerous studies focused on the quantification of the impact of land  
cover change on climate (see ~~Mahmood et al. (2014)~~~~Mahmood et al. (2014)~~ and references therein for a  
comprehensive review). There is a growing body of evidence that vegetation, especially tree cover, significantly  
800 affects the terrestrial water cycle, energy balance (Alkama and Cescatti, 2016; Duveiller et al., 2018b) and  
carbon cycle (~~Achard et al., 2014~~)(~~Achard et al., 2014~~). However, understanding the impact of LC change on  
climate remains controversial and is still work in progress (Bonan, 2008; Ellison et al., 2012; Mahmood et al.,  
2014; Sheil and Murdiyarso, 2009). In order to judge the LC related ESM results, an independent assessment of  
the accuracy of the simulated spatial distributions of major land cover types is desirable to evaluate the DGVM  
805 accuracy for present climate conditions (Lauer et al., 2017).

Recently in the frame of the European Space Agency (ESA) Climate Change Initiative (CCI), a new global LC  
dataset has been published (Defourny et al., 2014; Defourny et al., 2016) that can be used to evaluate or  
prescribe vegetation distributions for climate modelling. Effects of LC uncertainty in the ESA CCI LC dataset on  
land surface fluxes and climate are described by ~~Hartley et al. (2017)~~~~Hartley et al. (2017)~~ and Georgievski and  
810 Hagemann (2018), respectively. Satellite derived LC classes cannot directly be used for the evaluation of ESM  
vegetation due to the different concepts of vegetation representation in DGVMs, which are typically based on the  
concept of plant functional types (PFTs) that are supposed to represent groups of LC with similar functional  
behaviour. Thus, an important first step is to map the ESA CCI LC classes to PFTs as described by Poulter et al.

(2015). As the PFTs in ESMs differ, the current LC diagnostic analyses only major LC types (bare soil, crops, grass, shrubs, trees), which is similar to the approach chosen by [Brovkin et al. \(2013\)](#) ~~Brovkin et al. (2013)~~ and Lauer et al. (2017). The corresponding evaluation metric was implemented into the ESMValTool in *recipe\_landcover.yml*. It evaluates areas, mean fractions and biases compared to ESA CCI LC data over [the land area of](#) four major regions (global ~~land area~~, tropics ~~(30°S–30°N)~~, northern ~~extratropical land areas north of 30°N~~, and southern ~~extratropical land areas south of 30°S~~ ~~extra-tropics~~). Currently the evaluation is using ESA CCI LC data for the epoch 2008–2012 that have been generated with the ESA CCI LC user tool at 0.5 degree resolution. Consequently, model data are interpolated to the same resolution. For the calculation of mean fractions per major region, a land area of these regions needs to be specified, ~~which and~~ is currently taken from ESA CCI land cover. Example plots of accumulated area and biases in major LC types for different models are shown in Figure 33.

### 825 3.4.2 Albedo changes associated to land cover transitions

Land Cover Changes (LCC) can modify climate by altering land surface properties such as surface albedo, surface roughness and evaporative fraction. In particular, historical deforestation ~~is believed to have since the preindustrial era~~ led to an increase in surface albedo corresponding to a global radiative forcing of  $-0.15 \pm 0.10 \text{ Wm}^{-2}$  ([Change, 2013](#)) ~~(Myhre et al., 2013)~~. There are however large uncertainties, even concerning the sign of the effect, regarding the impacts of ~~LUC/LCC~~ on near-surface temperature due to persistent model disagreement ([Davin et al., 2019/2020](#); [de Noblet-Ducoudré et al., 2012](#); [Lejeune et al., 2017](#); [Pitman et al., 2009](#)). These disagreements arise from uncertainties in 1) the interplay between radiative (albedo) and non-radiative processes (surface roughness and evaporative fraction), 2) the role of local versus large scale processes and feedbacks ([Winckler et al., 2017](#)) ~~and 3) in~~ ([Winckler et al., 2017](#), and 3) the magnitude of change in given surface properties (e.g. albedo). Concerning the latter, [Myhre et al. \(2005\)](#) ~~Myhre et al. (2005)~~ and [Kvalevåg et al. \(2010\)](#) ~~Kvalevåg et al. (2010)~~ suggest that the albedo change between natural vegetation and croplands is usually overestimated in climate simulations compared to satellite-derived observational evidence. In addition to this potential bias compared to observational data, there is a substantial spread in the ~~models' parameterized model parametrizations for the~~ albedo response to land-cover perturbations. [Boisier et al. \(2012\)](#) ~~identified that this is~~ [Boisier et al. \(2012\)](#) ~~identified that as being~~ responsible for half of the dispersion in the albedo response to LCC since preindustrial times among models participating in the LUCID project, ~~whereas~~ the remaining uncertainty ~~resulting was found to result~~ from differences in the ~~imposed Land-Cover~~ ~~prescribed land cover~~. A more systematic evaluation of model performance in simulating LUC-induced changes in albedo based on latest available observations is therefore essential in order to reduce these uncertainties.

845 A satellite-based dataset providing potential effect of a range of land cover transitions on the full surface energy balance (including albedo), at global scale, 1°-resolution, and monthly timescale ~~was recently made available~~ ([Duveiller et al., 2018b](#)) ~~is now available~~ ([Duveiller et al., 2018a](#)). The potential albedo changes associated to vegetation transitions were extracted by a statistical treatment combining the ~~recent~~ ESA CCI LC data (see 3.4.1 for references) and the mean of the white-sky and black-sky albedo values of the NASA MCD43C3 albedo product for the 2008–2012 period (see ([Schaaf et al., 2002](#)) ~~Schaaf et al. (2002)~~ for information on the retrieval algorithm). Because land cover-specific albedo values are not a standard output of climate models, in order to retrieve them a diagnostic was ~~implemented into the ESMValTool in recipe\_albedo\_landcover.yml. It follows a similar approach but applied on model outputs, i.e. determines the coefficients of multiple linear regressions~~

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855 ~~fitted~~ developed by Lejeune et al. (2020) which has been implemented into the ESMValTool v2.0 in  
860 ~~recipe~~ albedo\_landcover.yml. This approach determines the coefficients of multiple linear regressions between  
the albedo values and the tree, shrub, short vegetation (crops and grasses) and bare soil fractions of each grid cell  
within spatially moving windows encompassing ~~5x5 model grid cells, 5° x 5° model grid cells~~. These four LC  
865 ~~classes correspond to the “IGBPgen” classification in Duveiller et al. (2018a). The recipe provides the option to~~  
~~run the algorithm on an interpolated grid or on the native model grid. The latter option was used in the example~~  
~~provided in Figure 34. Solving these regressions provides the albedo values for trees, shrubs and short vegetation~~  
(crops and grasses) from which the albedo changes associated with transitions between these three ~~LC~~ land cover  
types are derived. The diagnostic is applied ~~onto~~ monthly data, and based on the value of the snow area fraction  
(snc) distinguishes between snow-free (snc<0.1) and snow-covered (snc>0.9) grid cells for each month. It can  
870 calculate albedo estimates for each of these two cases and each of the three land cover types. ~~It, given that some~~  
~~criteria are fulfilled: the regressions are only conducted in the areas with a minimum number of 15 grid cells~~  
~~(either snow-free or snow-covered), taking only into account the grid cells where the sum of the area fractions~~  
~~occupied by the three considered land cover types exceeds 90%. The algorithm~~ eventually plots global maps of  
the albedo changes associated with the corresponding LC transitions for each model in their original resolution,  
next to the satellite-derived estimates from ~~Duveiller et al. (2018a). Two versions of this observational dataset,~~  
875 ~~corresponding to two vegetation classifications, are both freely available.~~ Duveiller et al. (2018a). The diagnostic  
shows data according to the IGBPgen classification, which entails only four LC classes that can be directly  
compared to model PFTs. An example plot is shown in Figure 34 for the July albedo change associated with a  
transition from trees to short vegetation types (crops and grasses). Almost only snow-free areas are visible for  
880 this month, while grey areas indicate where the spatial coexistence of the two LC classes was not high enough  
for the regression technique to be performed, where the regression results did not pass the required quality  
checks, or grid cells which could not be categorised either as snow-free or as snow-covered (Duveiller et al.,  
2018a). In the example shown here, July albedo difference between trees and crops or grasses is about at least  
twice as high in the MPI-ESM-LR model as in the observations, strongly suggesting that the simulated summer  
albedo increase from historical land cover changes is overestimated in this model. The results reveal that the July  
albedo difference between trees and crops or grasses is about at least twice as high in the MPI-ESM-LR model as  
in the observations, strongly suggesting that the simulated summer albedo increase from historical LCC is  
overestimated in this model. (~~Duveiller et al., 2018a~~);

### 3.5 Diagnostics for the evaluation of biogeochemical processes

#### 3.5.1 Terrestrial biogeochemistry

885 With CO<sub>2</sub> being the most important anthropogenic greenhouse gas, it is vital for ESMs to have a realistic  
representation of the carbon cycle. Atmospheric concentration of CO<sub>2</sub> can be inferred from the difference  
between anthropogenic emissions and the land and ocean carbon sinks simulated by the models. These sinks are  
affected by atmospheric CO<sub>2</sub> and climate change, thus introducing feedbacks between the climate system and the  
carbon cycle (Arora et al., 2013; Friedlingstein et al., 2006). Quantification of these feedbacks to estimate the  
890 evolution of these carbon sinks and thus the atmospheric CO<sub>2</sub> concentration and the resulting climate change is  
paramount (Cox et al., 2013; Friedlingstein et al., 2014; Wenzel et al., 2014; Wenzel et al., 2016). The Anav et  
al. (2013) paper evaluated CMIP5 models in three different time scales: long-term trends, interannual variability  
and seasonal cycles for the main climatic variables controlling both the spatial and temporal characteristics of the

carbon cycle, i.e. surface land temperature (tas), precipitation over land (pr), sea surface temperature (tos), land-atmosphere (nbp) and ocean-atmosphere fluxes (fgco<sub>2</sub>), gross primary production (gpp), leaf area index (lai), and carbon content in soil and vegetation (~~esoil, evegcSoil, cVeg~~). Models are able to simulate key characteristics of the main climatic variables and their seasonal evolution, but deficiencies in the simulation of specific variables, especially in the land carbon cycle with a general overestimation of photosynthesis and leaf area index, as well as an underestimation of the primary production in the ocean, exist.

The analysis from the Anav et al. (2013) can be reproduced with *recipe\_anav13jclim.yml*. ~~Alongside porting In addition to the existing recipe~~diagnostics already implemented in ESMValTool v1.0 and ported to v2, ~~plots 0, new diagnostics~~ for the timeseries anomalies of tas, pr, ~~SSTtos~~, as well as timeseries for nbp and fgco<sub>2</sub> have been added, reproducing Figures 1, 2, 3, 5, and 13 of Anav et al. (2013), with the latter two also forming Figure 26 of Flato et al. (2013). In ESMValTool v2.0, observational estimates of gpp are included from the latest data release of the FLUXCOM project (Jung et al., 2019) which integrates FLUXNET measurements, satellite remote sensing and climate data with machine learning to provide improved global products of land-atmosphere fluxes for evaluation. The routines needed to make carbon and energy fluxes from the FLUXCOM project CMOR-compliant to facilitate process based model evaluation is also made available as part of ESMValTool v2.0. As an example of the newly added plots, Figure 35 shows the timeseries for the land-atmosphere carbon flux nbp, similar to Figure 5 of Anav et al. (2013). Shading indicates the confidence interval of the CMIP5 ensemble standard deviation, derived from assuming a  $t$ -distribution centered on the ensemble mean (inner curve), while the gray shading shows the overall range of variability of the models. As positive values correspond to a carbon uptake of the land, the plot shows a slight increase in the land carbon uptake over the whole period.

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### 3.5.2 Ecosystem Turnover Times of Carbon

The exchange of carbon between the land biosphere and atmosphere represents a key feedback mechanism that will determine the effect of global changes on the carbon cycle and vice-versa (Heimann and Reichstein, 2008). Despite significant implications, the uncertainties in simulated land carbon stocks that integrates the land-atmosphere carbon exchange are large, and, therefore, represent a major challenge for ESMs (Friedlingstein et al., 2014; Friend et al., 2014). One of the major factors leading to these uncertainties is the turnover time of carbon, the time period that a carbon atom on average spends in land ecosystems, from assimilation through photosynthesis to its release back into the atmosphere. This emergent ecosystem property, calculated, for example, as a ratio of long-term average total carbon stock to gross primary productivity, ~~is not well reproduced by most of the ESMs~~ has been extensively used to evaluate ESM simulations (Carvalhais et al., 2014; Koven et al., 2015; Koven et al., 2017; Todd-Brown et al., 2013). Despite the large range of observational uncertainties and sources, ESM simulations consistently exhibit a robust correlation with the observation ensembles, but with a substantial underestimation bias.

Carvalhais et al. (2014) evaluated the biases in ecosystem carbon turnover time in CMIP5 models, their associations with climate variables, and then quantified multimodel biases and agreements. The *recipe\_carvalhais2014nat.yml* reproduces the analysis of Carvalhais et al. (2014). It requires the simulations of total ~~ecosystem~~vegetation carbon ~~stock (or its components~~content (cVeg), total soil carbon content (cSoil), gross primary productivity, (gpp), as well as precipitation (pr), and ~~near surface air~~ temperature, (tas). As an example, an evaluation of the zonal means of turnover time in CMIP5 models is shown in Figure 36. The models follow the gradient of increasing turnover times of carbon from tropics to higher latitudes, much related to temperature

935 decreases, as observed in observations. However, for most of the latitudinal bands, with the exception of one  
model, most simulations reveal turnover times that are faster than the observations. Most CMIP5 models (and  
multi-model ensemble) have a much shorter turnover time than the observation-based estimate across the whole  
latitudinal range. ~~The spread among the models is also large and can vary by an order of magnitude. This results~~  
~~in not only~~Even though different estimates of observation-based carbon fluxes and stocks can vary significantly,  
940 ~~a recent study by Fan et al. (2020), their Figure 5a, shows that the zonal distributions of observation-based~~  
~~estimates of turnover time is robust against the differences in observations.. The spread among the models is also~~  
~~large and can vary by one order of magnitude. This results not only in~~ a large bias in turnover time, but also a  
considerable disagreement among the models. In fact, the majority of CMIP5 models simulate turnover time  
more than four times shorter than the observation-based estimate in most regions (Figure 37). A generalized  
underestimation of turnover times of carbon is apparently dominant in water limited regions. In most of these  
945 regions most models show estimates outside of the observational uncertainties (stippling). These results  
challenge the combined effects of water and temperature limitations on turnover times of carbon and suggest the  
need for improvement on the description of the water cycle in terrestrial ecosystems, globally (Figure 37).In arid  
and semi-arid regions model agreement is also low with 2 or fewer (out of 10) models within the observational  
uncertainty.  
950 In addition, the recipe also produces the full factorial model-model-observation comparison matrix that can be  
used to evaluate individual models. It further provides a quantitative measure of turnover times across different  
biomes, as well as its relationship with precipitation and temperature.

### 3.5.3 Marine biogeochemistry

955 ESMValTool v2.0 now includes a wide set of metrics to assess marine biogeochemistry performances of ESMs,  
contained in *recipe\_ocean\_bgc.yml*. This recipe allows a direct comparison of the models against observational  
data for temperature (thetao), salinity (so), oxygen (o2), nitrate (no3), phosphate (po4) and silicate (si) from  
World Ocean Atlas 2013 (WOA, Garcia et al. (2013)), CO<sub>2</sub> air-sea fluxes (fgco<sub>2</sub>) estimated by Landschuetzer et  
~~al. (2016), Chlorophyll~~Landschuetzer et al. (2016), ~~chlorophyll~~-a (chl) fields from ESACCI-OC (Volpe et al.,  
2019) and primary production expressed as carbon (intpp) produced by Oregon State University using MODIS  
960 data ~~(Behrenfeld et al., 1997).~~ (Behrenfeld and Falkowski, 1997).  
We first demonstrate the recipe using the nitrate concentration in the ~~CMIP5~~ HadGEM2-ES model in the r1i1p1  
ensemble member of the historical experiment in the years 2001-2005. However, this recipe can be expanded to  
include any other ~~CMOR-ised~~ESM with a marine biogeochemical component, or any other field with a suitable  
observational dataset. The analysis produced by the recipe is a point to point comparison of the model against the  
965 observational dataset, similar to the method described in ~~(De Mora et al., 2013).~~(De Mora et al., 2013). Figures  
38 and 39 show the results of a comparison the surface dissolved nitrate concentration in the ~~CMIP5~~-HadGEM2-  
ES model compared against the World Ocean Atlas nitrate. To produce these two figures, the surface layer is  
extracted, an average over the time dimension is produced, then the model and observational data are re-gridded  
to a common grid. Figure 38 includes four panels; the model and observations in the top two panes, then the  
970 difference and the quotient in the lower two panes. It highlights that the HadGEM2-ES model is proficient at  
reproducing the surface nitrate concentration in the Atlantic ocean, and in mid latitudes, but may struggle to  
reproduce observations at high latitudes. Figure 39 uses the same preprocessed data as Figure 38, with the model  
data plotted along the x axis and the observational data along the y-axis. A linear regression line of best fit is

shown as a black line. A dashed line indicates the 1:1 line. The results of a linear regression are shown in the top  
975 left corner of the figure, where  $\hat{\beta}_0$  is the intercept,  $\beta_1$  is the slope, R is the correlation, P is the P value, and N is  
the number of data point pairs. As both the fitted slope and the correlation coefficient are near one, the  
HadGEM2-ES simulation excelled at reproducing the observed values of the surface nitrate  
concentration. ~~Together~~ When viewed together, Figures 38 and 39 show ~~a clear indication of the presence of the~~  
biases between the model and the observations in the surface layer, ~~but also the spatial relative to each other,~~  
980 both in terms of their spatially-independent distribution of the model and observational data in Figure 38 and  
their spatially-dependent distribution in Figure 39. Figure 40 shows the global average depth profile of the  
dissolved nitrate concentration in the ~~CMIP5~~ HadGEM2-ES model and against the World Ocean Atlas dataset.  
The colour scale indicates the annual average, although in this specific case there is little observed inter-annual  
variability. ~~This so the annual averages are closely overlaid. Nevertheless, this~~ class of figure ~~is can be~~ useful to  
985 evaluate biases between model and observations over the entire depth profile of the ocean and can also be used  
to identify long term changes in the vertical structure of the ocean models. This figure shows that while the  
model and the observations both have a similar overall depth structure, the model is not able to produce the  
observed maximum nitrate concentration at approximately 1000 m depth and overestimates the nitrate  
concentration deeper in the water column. A multiple panel comparison of satellite derived observations for  
990 marine primary production against 16 CMIP5 models over the period 1995-2004 is shown in Figure 41. ~~By~~  
~~means of ESMValTool preprocessor, both~~ Both observation and ~~models~~ model data are ~~redefined over~~ regridded  
to a regular 1-degree X 1-degree horizontal grid and differences are then computed. Systematic biases characterize all  
models mainly in the equatorial Pacific and Antarctic regions, in some cases with opposite sign, and coastal  
ocean productivity is generally underestimated with major deviations in the equatorial zone.

### 995 3.5.4 Stratospheric temperature and trace species influencing stratospheric ozone chemistry

The ~~recipe\_eyring06jgr.yml is integrated in~~ has been ported in ESMValTool v2.0 from the CCMVal-Diag tool  
described by Gettelman et al. (2012) to evaluate coupled chemistry-climate model (CCM) based on a set of core  
processes relevant for stratospheric ozone concentrations, centered around four main categories (radiation,  
dynamics, transport, and stratospheric chemistry). Each process is associated with one or more model  
1000 diagnostics, and with relevant observational data sets that can be used for the model evaluation (~~Eyring et al.,~~  
~~2006; Eyring et al., 2005~~) (Eyring et al., 2006; Eyring et al., 2005).

Since most of the chemical reactions determining ozone distribution in the stratosphere depend on temperature,  
~~recipe\_eyring06jgr.yml~~ allows the comparison of modelled stratospheric temperature with observations in terms  
of climatological mean, variability and trends (Figure 42). ~~Recipe~~ High-latitude temperatures in winter and spring  
1005 are particularly important for correctly modelling polar ozone depletion induced by polar stratospheric clouds. In  
the middle stratosphere there are large variations between the analyses and most models, with no clear bias  
direction, whereas the temperature bias in the troposphere between analyses and models is somewhat smaller,  
but is negative around 200 hPa in most models. The upper stratosphere is only available for a few models, and  
while for most of the seasons shown the agreement is relatively good, the spread between analyses and models is  
1010 very large for the Antarctic polar regions in JJA. The recipe\_eyring06jgr.yml evaluates the main features of the  
atmospheric transport by examining the distribution of long-lived traces (such as methane or N<sub>2</sub>O), the vertical  
propagation of the annual cycle of water vapour (“tape recorder”) and the mean age of air. Due to its important  
role in driving stratospheric ozone depletion, especially in the polar regions, ~~the~~ this ~~recipe~~ also includes the

vertical distribution and temporal evolution of modelled chlorine ( $Cl_y$ ). It also assesses the capability of the models to simulate realistic ozone vertical distributions (Figure 43) and total ozone annual cycle. Ozone is clearly overestimated by most models, compared to the observations, in the Northern high latitudes between 50 hPa and 10 hPa, which becomes also apparent in the climatological zonal mean at 50 hPa. Southern high latitudes are slightly better represented in the models at 50 hPa with a more general spread around the observations, but at lower pressure levels an overestimation of ozone compared to the observations becomes apparent in some models.

#### 4. Routine evaluation of CMIP6 models

##### 4.1 Running the ESMValTool alongside the ESGF

~~The~~An important goal for CMIP6 was to establish a system that allows for routine model evaluation alongside the ESGF directly after the model output is published to the CMIP archive (Eyring et al., 2016a; Eyring et al., 2019; Eyring et al., 2016b). With the release of ESMValTool v2.0, this was reached through a semi-automatic ~~and automatic~~ execution of the ESMValTool at DKRZ on CMIP6 data published ~~into the~~ ESGF. This is supported by the following components: ~~A1~~ a locally hosted CMIP6 replica data pool, ~~B2~~ an automatic CMIP6 data replication process, embracing ESMValTool data needs as replication priorities, ~~and 3~~ a query mechanism to inform the ESMValTool on the availability on new data in the data pool. Based on these components both regularly scheduled ESMValTool executions as well as executions triggered by the availability of new data can be realised. ~~Initially~~At the moment, the automatic regular execution ~~was~~ implemented. The replica pool is hosted as part of the parallel Lustre HPC file system at DKRZ and associated to a dedicated data project which is supervised by a panel deciding on CMIP6 data storage priorities. However, rapid data replication from ESGF to the local replica tool remains an issue that requires further work, see also the discussion in Eyring et al. (2016b).

ESMValTool data needs are managed in a GitHub repository and automatically integrated into the ~~synda~~Synda tool (<http://prodiguer.github.io/synda/>) based CMIP6 replication pipeline at DKRZ. The content of the data pool is regularly indexed thus providing a high performance query mechanism on locally available data. This index is used to automatically update several recipes with all available CMIP6 models. If new model output has been published to the ESGF, an ESMValTool execution is triggered and new plots are created. The results produced by the ESMValTool ~~runs~~ are automatically copied to ~~the~~ result cache which is used by the result browser (see next section).

##### 4.2 ESMValTool result browser at DKRZ

~~The~~The ESMValTool result browser has been set up at <http://cmip-esmvaltool.dkrz.de/>. The ESMValTool results are visualized with the Freie University ~~evaluation~~Evaluation system (FREVA). ~~Freva~~FREVA provides an efficient and comprehensive access to the evaluation results and datasets. The application system is developed as an easy to use low-end application minimizing technical requirements for users and tool developers. Initially this website shows CMIP5 results that are already published. Newly produced results for CMIP6 are initially water-marked and are only made available without water-mark once quality control has ~~happened~~taken place and ~~possible~~related papers have been written. This strategy has been supported, encouraged, and approved by the WCRP Working Group of Coupled Modelling (WGCM). The result browser includes a search function that

allows to sort by ~~(a) ESMValTool recipes, (b) Projects, (c) projects,~~ CMIP6 ~~Realms, (d) Themes, (e) Domain, (f) Plot Type, (g) Statistics, (h) References, (i) realms, scientific themes, domain, plot type, applied statistics, references, variables, datasets~~ ~~Variables,~~ ~~(j) Models~~ (including ~~the models,~~ multi-model mean and ~~median, and~~ observations), and (k) ~~Results~~ ~~results~~. Each figure includes a ~~figure~~ caption, that is displayed alongside with the figure, and ~~also includes the corresponding~~ metadata. These metadata include the ESMValTool configuration used to ~~calculate~~ ~~perform the analysis~~ and ~~draw the plot~~ ~~the figure,~~ ~~Software, software~~ versions, ~~Date~~ ~~date~~ of production, ~~Input~~ ~~input~~ data, ~~Program's~~ ~~program~~ output, ~~Notes, and Results~~ ~~notes, and results.~~ In order to get a quick overview, a summary of the ESMValTool configuration used to create a given plot is also available. This summary includes the recipe name, variables and models used as well as the name of the diagnostic script run and the exact version of the ESMValTool (corresponds to the release tag on GitHub) used as basic information to reproduce a plot. Full provenance information providing all details on the figure creation such as version of the input files and preprocessing steps applied is stored in the metadata of the figure file itself and can be retrieved by downloading the figure and reading the Exif header of the image file.

## 1065 5. Summary and Outlook

The Earth System Model Evaluation Tool (ESMValTool) is a community diagnostics and performance metrics tool specifically targeted to facilitate and enhance comprehensive evaluation of Earth System Models (ESMs) participating in the Coupled Model Intercomparison Project (CMIP). Since the first ESMValTool release in 2016 (v1.0, Eyring et al. (2016c)), substantial technical improvements have been made by a continuously growing developer community and additional diagnostics have been added. The tool is now developed by more than 40 institutions as open source code on a Github repository (<https://github.com/ESMValGroup>).

This paper is part of a series of publications that describe the release of ESMValTool version 2.0 (v2.0). One of the main structural changes compared to v1.0 is the separation of the tool into *ESMValCore* and a *Diagnostic Part*. *ESMValCore* is an easy-to-install, well documented Python package that provides the core functionalities to perform common pre-processing operations and writes the output from models and observations to netCDF files (~~Righi et al., 2019~~) ~~(Righi et al., 2020)~~. These preprocessed output files are then read by the *Diagnostic Part* that includes tailored diagnostics and performance metrics for specific scientific applications that are called by *recipes*. These recipes reproduce sets of diagnostics or performance metrics that have demonstrated their importance in ESM evaluation in the peer-reviewed literature.

This paper describes recipes for the evaluation of large-scale diagnostics in ESMValTool v2.0. It focuses on those diagnostics that were not part of the first major release of the tool (Eyring et al., 2016c) and includes (1) integrative measures of model performance, as well as diagnostics for the evaluation of processes in (2) the atmosphere, (3) ocean and cryosphere, (4) land and (5) biogeochemistry. Recipes for extreme events and in support of regional model evaluation are described by ~~Weigel et al. (2019)~~ ~~Weigel et al. (2020)~~ and recipes for emergent constraints and model weighting by Lauer et al. (~~2019~~ ~~2020~~).

Compared to ~~v2~~ ~~ESMValTool v1.0~~, the integrative measures of model performance have been expanded with additional atmospheric variables as well as new variables from the ocean, sea\_ice and land (extending Figure 9.7 of Flato et al. (2013)). In addition, the centered pattern correlation that allows the quantification of progress between different ensembles of CMIP models for multiple variables (extending Figure 9.6 of Flato et al. (2013)) and the single model performance index proposed by Reichler and Kim (2008) that allows an overall assessment

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of model performance have been added. For the purpose of model development it is important to look at many different metrics. AutoAssess that is developed by the UK Met Office therefore includes a mix of top-down metrics evaluating key model output variables and bottom-up process-oriented metrics. AutoAssess includes 11 thematic areas which will all be implemented in ESMValTool, but ~~for~~ in v2.0 as a technical demonstration only the area for the stratosphere was implemented.

For the evaluation of processes in the atmosphere, the recipe to calculate multi-model averages (e.g., for surface temperature and precipitation) now not only includes absolute values, but also the mean root mean square error of the seasonal cycle compared to observations. The time series of the anomalies in annual and global mean surface temperature with the models being subsampled as in the observations from HadCRUT4 is also included. In addition, a recipe for the evaluation of the precipitation quantile bias has been added. For atmospheric dynamics recipes to evaluate stratosphere-troposphere coupling and atmospheric blocking indices have been included. A new diagnostic tool for the evaluation of the water, energy and entropy budgets in climate models (TheDiaTo (v1.0), ~~Lembo et al. (2019)~~Lembo et al. (2019)) has been newly implemented ~~and v2.0 was updated with a new version of,~~ while the NCAR Climate Variability Diagnostic Package (Phillips et al., 2014), ~~already available in v1.0, has been updated in ESMValTool v2.0 to its latest version.~~ In addition, several other diagnostics to evaluate modes of variability as well as weather regimes calculated by the MiLES package (Davini, 2018) have been added ~~in v2.0.~~

To evaluate the broad behaviour of models for the global ocean, several diagnostics have been newly implemented, including diagnostics to evaluate the volume weighted global average temperature anomaly, the AMOC, the Drake Passage current, the global total flux of CO<sub>2</sub> from the atmosphere into the ocean, and the global total integrated primary production from phytoplankton. A recipe to evaluate specifically the Southern ocean following ~~Russell et al. (2018)~~Russell et al. (2018) has been included and for the Arctic ocean vertical ocean distributions (e.g. temperature and salinity) for different Arctic ocean basins and a transect that follows the pathway of the Atlantic water can now be calculated. For sea-ice, a recipe related to the evaluation of the negative sea-ice growth-thickness feedback which includes the Ice Formation Efficiency (IFE) as a process-based diagnostic (~~Massonnet et al., 2018)~~ and a recipe that can quantify the relationships between Arctic sea-ice (~~Massonnet et al., 2018b)~~ and a recipe that can quantify the relationships between Arctic sea ice drift speed, concentration and thickness (~~Docquier et al., 2017)~~(Docquier et al., 2017) have been added.

For the evaluation of land processes, satellite derived land cover classes cannot directly be used for ESM vegetation evaluation because Dynamic Global Vegetation Models (DGVMs) use different concepts for vegetation representation, typically based on plant functional types (~~PFTs~~). A recipe has therefore been added that maps the ESA CCI land cover classes to ~~PFTs~~plant functional types as described by Poulter et al. (2015). It includes major land cover types (bare soil, crops, grass, shrubs, trees) similar to the evaluation study by Lauer et al. (2017). In addition, a recipe has been added that can be used to evaluate albedo changes associated to land cover transitions using the ESA CCI dataset of ~~Duveiller et al. (2018b)~~Duveiller et al. (2018a).

For the terrestrial biosphere, a recipe that allows the evaluation of the main climatic variables controlling both the spatial and temporal characteristics of the carbon cycle on three different time scales (long-term trends, interannual variability and seasonal cycles) has been added following Anav et al. (2013). These key variables include surface land temperature, precipitation over land, sea surface temperatures, land-atmosphere and ocean-atmosphere fluxes, gross primary production, leaf area index, and carbon content in soil and vegetation. To evaluate the simulated land carbon stocks that integrates the land-atmosphere carbon exchange, a recipe to

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1135 evaluate biases in ecosystem carbon turnover time, the time period that a carbon atom on average spends in land ecosystems, from assimilation through photosynthesis to its release back into the atmosphere (Carvalho et al., 2014) has been added. For marine biogeochemistry, v2.0 now includes a recipe that allows a direct comparison of the models against observational data for several variables including temperature, salinity, oxygen, nitrate, phosphate, silicate, CO<sub>2</sub> air-sea fluxes, chlorophyll-a and primary production. The point to point comparison of the model against the observational dataset is similar to ~~De Mora et al. (2013)~~De Mora et al. (2013). To evaluate stratospheric dynamics and chemistry a recipe based on a set of core processes relevant for stratospheric ozone concentrations, centered around four main categories (radiation, dynamics, transport, and stratospheric chemistry) has been added (Eyring et al., 2006). Overall these recipes together with those already included in v1.0 allow a broad characterization of the models for key variables (such as temperature and precipitation) on the large-scale, but v2.0 also includes several process-oriented diagnostics.

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1140 With this release, for the first time in CMIP it is now possible to evaluate the models as soon as the output is published to the Earth System Grid Federation (ESGF) in a quasi-operational manner. To achieve this, the ESMValTool has been fully integrated into the ESGF structure at the Deutsches Klima Rechenzentrum (DKRZ). The data from the ESGF are first copied to a local replica and the ESMValTool is then automatically executed alongside the ESGF as soon as new output arrives. An ESMValTool result browser has been set up that makes the evaluation results available to the wider community (<http://cmip-esmvaltool.dkrz.de/>).

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1150 Another major advancement of ESMValTool v2.0 is that it provides full provenance and traceability (see Section 5.2. in ~~Righi et al. (2019) for details~~);Righi et al. (2020) for details). Provenance information for example includes technical information such as global attributes of all input netCDF files, preprocessor settings, diagnostic script settings, and software version numbers but also diagnostic script name and recipe authors, funding projects, references for citation purposes, as well as tags for categorizing the result plots into various scientific topics (like chemistry, dynamics, sea-ice, etc.) realms (land, atmosphere, ocean, etc.) or statistics applied (RMSE, anomaly, trend, climatology, etc.). This not only facilitates the sorting of the results in the ESMValTool result browser but also qualifies the tool for the use in studies or assessments where provenance and traceability is particularly important. The current approach to provenance and tags (i.e. what is reported) can be adjusted to international provenance standards as they become available.

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1160 These recent ESMValTool developments and their coupling to the ESGF results can now be exploited by global and regional ESM developers as well as by the data analysis and user communities, to better understand the large CMIP ensemble and to support data exploitation. In particular with the addition of provenance, the tool can also provide a valuable source to produce figures in national and international assessment reports (such as the IPCC climate assessments) to enhance the quality control, reproducibility and traceability of the figures included.

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1165 The ESMValTool development community will further enhance the capabilities of the tool- with the goal to take – together with other activities - climate model evaluation to the next level (Eyring et al., 2019). Targeted technical enhancements will for example include the development of ~~quicklook~~quick-look capabilities that allow to monitor the simulations while they are running to help identifying errors in the simulations early on, a further extension to the application to regional models so that a consistent evaluation between global and regional models can be provided, and distributed computing functionalities. In addition, the tool will be expanded with additional process-oriented diagnostics in various projects to further enhance comprehensive evaluation and analysis of the CMIP models.

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## 6. Code and data availability

ESMValTool v2.0 is released under the Apache License, VERSION 2.0. The latest release of ESMValTool v2.0 is publicly available on Zenodo at <https://doi.org/10.5281/zenodo.3401363>. The source code of the ESMValCore package, which is installed as a dependency of the ESMValTool v2.0, is also publicly available on Zenodo at <https://doi.org/10.5281/zenodo.3387139>. ESMValTool and ESMValCore are developed on the GitHub repositories available at <https://github.com/ESMValGroup>.

## 7. ~~Data~~ availability

CMIP5 data are available freely and publicly from the Earth System Grid Federation. Observations used in the evaluation are detailed in the various sections of the manuscript- and listed in Table 1. They are not distributed with the ESMValTool, that is restricted to the code as open source software.

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*Author contribution.* VE coordinated the ESMValTool v2.0 diagnostic effort and led the writing of the paper. LB, AL, MR, and MS coordinated the diagnostic implementation in ESMValTool v2.0. CE and SK helped with the coupling of ESMValTool v2.0 and CK with the visualization of the results at the ESMValTool result browser. All other co-authors contributed individual diagnostics to this release. All authors contributed to the text.

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

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<i>recipe_autoassess_*.yml</i>	3.1.2.4	Recipe for mix of top-down metrics evaluating key model output variables and bottom-up metrics	<del>fas</del> <del>fst</del> <del>snw</del> <del>msoc</del> <del>rsns</del> <del>rlns</del> <del>rtnt</del> <del>rsnt</del> <del>swcre</del> <del>lwcre</del> <del>rsns</del> <del>rlns</del> <del>rsut</del> <del>rlut</del> <del>rsutes</del> <del>rldscs</del> <del>rlutes</del> <del>prw</del> <del>pr</del> <del>clmtiscep</del> <del>cltkiscep</del> <del>clmmtiscep</del> <del>p</del> <del>clmtkiscep</del> <del>clhmtiscep</del> <del>clhtkiscep</del> <del>ta</del> <del>ttt</del> <del>hus</del>	autoassess/autoassess_area_base.py  autoassess/plot_autoassess_metrics.py  autoassess/autoassess_radiation_rms.py	<del>rtnt</del> <del>rsnt</del> <del>swcre</del> <del>lwcre</del> <del>rsns</del> <del>rlns</del> <del>rsut</del> <del>rlut</del> <del>rsutes</del>	<a href="#">CERES-EBAF (Tier 2, Loeb et al. (2018))</a>
					<del>rlutes</del> <del>rldscs</del>	<a href="#">J RA-55 (Tier 1, Onogi et al. (2007))</a>
					<del>prw</del>	<a href="#">SSMI-MERIS (Tier 1, Schröder (2012))</a>
					<del>pr</del>	<a href="#">GPCP-SG (Tier 1, Adler et al. (2003))</a>
					<del>rtnt</del> <del>rsnt</del> <del>swcre</del> <del>lwcre</del> <del>rsns</del> <del>rlns</del> <del>rsut</del> <del>rlut</del> <del>rsutes</del>	<a href="#">CERES-EBAF (Tier 2, Loeb et al. (2018))</a>  <a href="#">CERES-SYN1deg (Tier 3, Wielicki et al. (1996))</a>
					<del>rlutes</del> <del>rldscs</del>	<a href="#">JRA-55 (Tier 1, ana4mips. )</a> <a href="#">CERES-SYN1deg (Tier 3, Wielicki et al. (1996))</a>
					<del>prw</del>	<a href="#">SSMI-MERIS Tier 1, obs4mips. )</a> <a href="#">SSMI (Tier 1, obs4mips. )</a>
					<del>clmtiscep</del> <del>cltkiscep</del> <del>clmmtiscep</del> <del>p</del> <del>clmtkiscep</del> <del>clhmtiscep</del> <del>clhtkiscep</del>	<a href="#">ISCCP (Tier 1, Rossow and Schiffer (1991))</a>

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					<u>ta</u> <u>ua</u> <u>hus</u>	<u>ERA-Interim (Tier 3, Dee et al. (2011))</u>
<b>Section 3.2: Detection of systematic biases in the physical climate: atmosphere</b>						
<u>recipe_flato13ipcc.yml</u>	3.1.2 3.2.1 3.3.1	Reproducing selected figures from IPCC AR5, chap. 9 (Flato et al., 2013) 9.2, 9.4, 9.5, 9.6, 9.8, 9.14.	<del>tas</del> <del>pr</del> <del>swcre</del> <del>lwcre</del> <del>netcre</del> <del>rlut</del> <del>tos</del>	clouds/clouds_bias.ncl clouds/clouds_ipcc.ncl ipcc_ar5/tsline.ncl ipcc_ar5/ch09_fig09_06.ncl ipcc_ar5/ch09_fig09_06_collect.ncl ipcc_ar5/ch09_fig09_14.py	<u>tas</u>	<u>ERA-Interim (Tier 3, Dee et al. (2011))</u> <u>HadCRUT4 (Tier 2, Morice et al. (2012))</u>
					<u>tos</u>	<u>HadISST (Tier 2, Rayner et al. (2003))</u>
					<u>swcre</u> <u>lwcre</u> <u>netcre</u> <u>rlut</u>	<u>CERES-EBAF (Tier 2, Loeb et al. (2018))</u>
					<u>pr</u>	<u>GPCP-SG (Tier 1, Adler et al. (2003))</u>
<u>recipe_quantilebias.yml</u>	3.2.2	Recipe for calculation of precipitation quantile bias	<del>pr</del>	quantilebias/quantilebias.R	<u>pr</u>	<u>GPCP-SG (Tier 1, Adler et al. (2003))</u>

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<i>recipe_zmnam.yml</i>	3.2.3 .1	Recipe for zonal mean Northern Annular Mode. The <del>diagnostic</del> & <del>computed</del> <del>diagnostic</del> <del>computes</del> the index and the spatial pattern to assess the simulation of the <del>strat-</del> <del>tropo</del> <del>sphere-</del> <del>troposphe</del> <del>re</del> coupling in the boreal hemisphere	#	zmnam/zmnam.py	<u>zg</u>	---
<i>recipe_miles_block.yml</i>	3.2.3 .2	Recipe for computing 1-d and 2-d atmospheric blocking indices and <del>diagnostic</del> <del>diagnostic</del> <del>s</del>	#	miles/miles_block.R	<u>zg</u>	<u>ERA-Interim (Tier 3, Dee et al. (2011))</u>
<i>recipe_thermodyn_diagtool.yml</i>	3.2.4	Recipe for the computation of various aspects associated with the thermodynamics of the climate system, such as energy and water mass budgets, meridional enthalpy transports, the Lorenz Energy Cycle and the material entropy production.		<u><a href="#">thermodyn_diagtool/thermodyn_diagnostics.py</a></u>	hfsl hfss pr ps prsn rlds rlus rlut rsds rsus rsdt rsut ts hus tas uas vas ta ua va wap	--- <del>thermodyn_diagtool/thermodyn_diagnostics.py</del>

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<i>recipe_CVDP.yml</i>	3.2.5 .1	Recipe for executing the NCAR CVDP <del>package</del> <del>package</del> in the ESMValTool framework.	<del>ps</del> <del>tas</del> <del>pr</del> <del>psl</del>	cvdp/cvdp_wrapper.py	<del>pr</del>	<del>GPCP-SG (Tier 1, Adler et al. (2003))</del>
					<del>psl</del>	<del>ERA-Interim (Tier 3, Dee et al. (2011))</del>
					<del>tas</del>	<del>Berkeley Earth (Tier 1, Rohde and Groom (2013))</del>
					<del>ts</del>	<del>ERSSTv5 (Tier 1, Huang et al. 2017)</del>
<i>recipe_modes_of_variability.yml</i>	3.2.5 .2	Recipe to compute the RMSE between the observed and modelled patterns of variability obtained through classification and their relative bias (percentage) in the frequency of occurrence and the persistence of each mode.	<del>zg</del>	magic_bsc/weather_regime.r	<del>zg</del>	<del>---</del>
<i>recipe_miles_regimes.yml</i>	3.2.5 .2	Recipe for computing Euro-Atlantic weather regimes <del>using the MILES package</del> based on k-means clustering	<del>zg</del>	miles/miles_regimes.R	<del>zg</del>	<del>ERA-Interim (Tier 3, Dee et al. (2011))</del>

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<i>recipe_miles_eof.yml</i>	3.2.5.3	Recipe for computing <del>and</del> the Northern Hemisphere EOFs	<del>zg</del>	miles/miles_eof.R	<del>zg</del>	<a href="#">ERA-Interim (Tier 3, Dee et al. (2011))</a>
<i>recipe_combined_indices.yml</i>	3.2.5.4	Recipe for computing seasonal means or running averages, combining indices from multiple models and computing area averages	<del>psl</del>	magic_bsc/combined_indices.r	<del>psl</del>	<del>---</del>
<b>Section 3.3: Detection of systematic biases in the physical climate: ocean and cryosphere</b>						
<i>recipe_ocean_scalar_fields.yml</i>	3.3.1	Recipe to reproduce time series figures of scalar quantities in the ocean.		<a href="#">ocean/diagnostic_timeseries.py</a>	gtintpp gtfgco2 amoc mfo thetaoga soga zostoga	<del>---</del> <del>ocean/diagnostic_timeseries.py</del>
<i>recipe_ocean_amoc.yml</i>	3.3.1	Recipe to reproduce time series figures of the AMOC, the Drake passage current and the stream function	<del>amoc</del> <del>mfo</del> <del>msftmyz</del>	ocean/diagnostic_timeseries.py ocean/diagnostic_transects.py	<del>amoc</del> <del>mfo</del> <del>msftmyz</del>	<del>---</del>
<i>recipe_russell18jgr.yml</i>	3.3.2	<del>Recipe to reproduce figure from Russell et al. (2018) Recipe to reproduce figure from Russell et al. (2018)</del>	<del>tauu</del> <del>tauuo</del> <del>thetao</del> <del>so</del> <del>uo</del> <del>vo</del> <del>sic</del> <del>pH</del> <del>fgco2</del>	russell18jgr/russell18jgr-polar.ncl  russell18jgr/russell18jgr-fig*.ncl	<del>tauu</del> <del>tauuo</del> <del>thetao</del> <del>so</del> <del>uo</del> <del>vo</del> <del>sic</del> <del>pH</del> <del>fgco2</del>	<del>---</del>

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<a href="#">recipe_arctic_ocean.yml</a>	3.3.3	Recipe for evaluation of ocean components of climate models in the Arctic Ocean	<del>thetao(K)</del> <del>so (0.001)</del>	arctic_ocean/arctic_ocean.py	<del>thetao(K)</del> <del>so (0.001)</del>	<a href="#">PHC (Tier 2, Steele et al. (2001))</a>
<a href="#">recipe_seaice_feedback.yml</a>	3.3.4	Recipe to evaluate the negative ice growth- <del>and ice</del> thickness feedback	<del>sst</del>	seaice_feedback/negative_seaice_feedback.py	<del>sst</del>	<a href="#">ICESat (Tier2, Kwok et al. (2009))</a>
<a href="#">recipe_sea_ice_drift.yml</a>	3.3.4	Recipe for sea ice drift <del>strength</del> evaluation	<del>sie</del> <del>sst</del> <del>sispeed</del>	seaice_drift/seaice_drift.py	<del>sie</del>	<a href="#">OSI-450-nh (Tier 2, Lavergne et al. (2019))</a>
					<del>sivol</del>	<a href="#">PIOMAS (Tier 2, Zhang and Rothrock (2003))</a>
					<del>sispeed</del>	<a href="#">IABP (Tier 2, Tschudi et al. (2016))</a>
<a href="#">recipe_Sealce.yml</a>	3.3.4	Recipe for plotting sea ice diagnostics at the Arctic and Antarctic	<del>sie</del>	seaice/SeaIce_ancyc.ncl seaice/SeaIce_tsline.ncl seaice/SeaIce_polcon.ncl seaice/SeaIce_polcon_diff.ncl	<del>sie</del>	<a href="#">HadISST (Tier 2, Rayner et al. (2003))</a>
<b>Section 3.4: Detection of systematic biases in the physical climate: land</b>						
<a href="#">recipe_landcover.yml</a>	3.4.1	Recipe for plotting the accumulated area, average fraction and bias of landcover classes in comparison to ESA_CCI_LC data for the full globe and large scale regions.		<a href="#">landcover/landcover.py</a>	baresoilFrac grassFrac treeFrac shrubFrac cropFrac	<a href="#">ESACCI-LANDCOVER (Tier 2, Defourny et al. (2016))</a> <del>landcover/landcover.py</del>
<a href="#">recipe_albedolandcover.yml</a>	3.4.2	Recipe for evaluate land cover-specific albedo values.	<del>alb</del>	landcover/albedolandcover.py	<del>alb</del>	<a href="#">Duveiller 2018 (Tier 2, (Duveiller et al., 2018a))</a>
<b>Section 3.5: Detection of biogeochemical biases</b>						

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<a href="#">recipe_anav13jclim.yml</a>	3.5.1	Recipe to reproduce most of the figures of Anav et al. (2013)	<del>tas</del> <del>pr</del> <del>tos</del> <del>abp_grid</del> <del>lai_grid</del> <del>gpp_grid</del> <del>eSoil_grid</del> <del>eVeg_grid</del> <del>fgco2_grid</del>	carbon_cycle/mvi.ncl carbon_cycle/main.ncl carbon_cycle/two_variables.ncl perfmetrics/main.ncl perfmetrics/collect.ncl	<del>tas</del> <del>pr</del>	<a href="#">CRU (Tier 3, Harris et al. (2014))</a>
					<a href="#">lai</a>	<a href="#">LAI3g (Tier 3, Zhu et al. (2013))</a>
					<a href="#">fgco2</a> <a href="#">nbp</a>	<a href="#">JMA-TRANSCOM (Tier 2, Maki et al. (2017))</a> <a href="#">GCP (Tier 2, Le Quere et al. (2018))</a>
					<a href="#">tos</a>	<a href="#">HadISST (Tier 2, Rayner et al. (2003))</a>
					<a href="#">gpp</a>	<a href="#">MTE (Tier 2, Jung et al. (2011))</a>
					<a href="#">eSoil</a>	<a href="#">HWSD (Tier 2, Wieder (2014))</a>
					<a href="#">eVeg</a>	<a href="#">NDP (Tier 2, Gibbs (2006))</a>
<a href="#">recipe_carvalhais2014nat.yml</a>	3.5.2	Recipe to evaluate the biases in ecosystem carbon turnover time.	<del>tau (non-CMOR variable, that is derived as the ratio of total ecosystem carbon stock and gross primary productivity)</del>	regrid_areaweighted.py compare_tau_modelVobs_matrix.py compare_tau_modelVobs_climatebins.py compare_zonal_tau.py compare_zonal_correlations_tauVclimate.py	<del>tau (non-CMOR variable, that is derived as the ratio of total ecosystem carbon stock and gross primary productivity)</del>	<a href="#">Carvalhais et al. (2014)</a>
<a href="#">recipe_ocean_bgc.yml</a>	3.5.3	Recipe to evaluate the marine biogeochemistry models of CMIP5. There are also some physical evaluation metrics.	<del>thetao</del> <del>so</del> <del>no3</del> <del>o2</del> <del>si</del> <del>ehh</del> <del>dlf</del> <del>talk</del> <del>intpp</del> <del>mfo</del> <del>fgco2</del>	ocean/diagnostic_timeseries.py ocean/diagnostic_profiles.py ocean/diagnostic_maps.py ocean/diagnostic_model_vs_obs.py ocean/diagnostic_transects.py <a href="#">ocean/diagnostic_maps_multi_model.py</a>	<del>thetao</del> <del>so</del> <del>no3</del> <del>o2</del> <del>si</del>	<a href="#">WOA (Tier 2, Locarnini, 2013))</a> <a href="#">WOA (Tier 2, Garcia et al. (2013))</a>

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					<a href="#">intpp</a>	<a href="#">Eppley-VGPM-MODIS (Tier 2, Behrenfeld and Falkowski, 1997)</a>
					<a href="#">chl</a>	<a href="#">ESACCI-OC (Tier 2, Volpe et al. (2019)Volpe et al., 2019)</a>
					<a href="#">fgco2</a>	<a href="#">Landschuetzer2016 (Tier 2, Landschuetzer et al. (2016))</a>
					<a href="#">dfc</a> <a href="#">talk</a> <a href="#">mfo</a>	
<a href="#">recipe_eyring06jgr.yml</a>	3.5.4	Recipe to reproduce stratospheric dynamics and chemistry figures from Eyring et al. (2006)	<del>##</del> <del>##</del> <del>vt100</del> <del>vmrh4</del> <del>vmrh2o</del> <del>mnstrage</del> <del>vmrhel</del> <del>vmrly</del> <del>vmro3</del> <del>toz</del>	<a href="#">eyring06jgr/eyring06jgr_fig*.ncl</a>	<a href="#">ja</a> <a href="#">ua</a>	<a href="#">ERA-Interim (Tier 3, Dee et al. (2011))</a>
					<a href="#">vmro3</a> <a href="#">vmrh2o</a>	<a href="#">HALOE (Tier 2, Russell et al. (1993), Grob and Russell Iii (2005))</a>
					<a href="#">toz</a>	<a href="#">NIWA-BS (Tier 3, Bodeker et al. (2005))</a>

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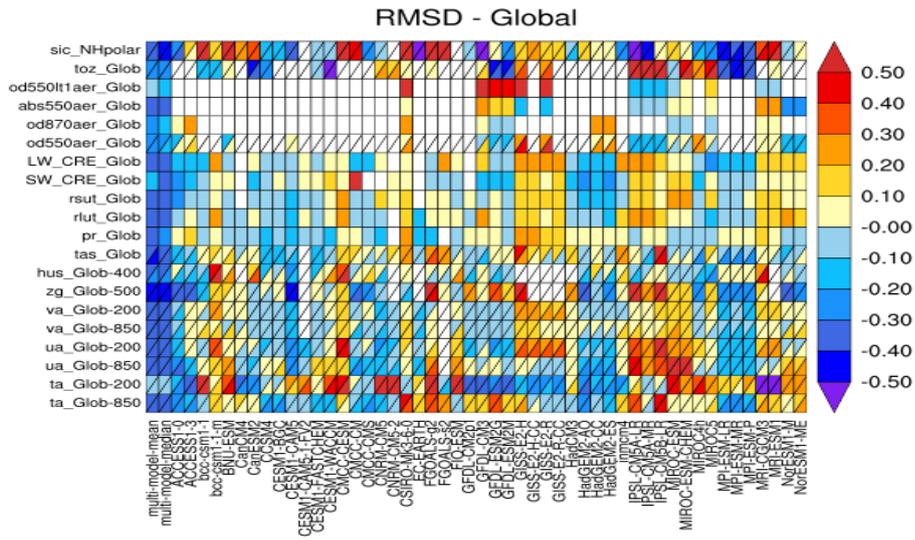
**Table 2.** Overview of CMIP5 models used in the figures shown in this paper alongside with a reference.

	<b><u>Modelling Center</u></b>	<b><u>Model</u></b>	<b><u>Reference</u></b>
1	<a href="#">Centre for Australian Weather and Climate Research, Australia</a>	<a href="#">ACCESS1-0</a>	<a href="#">Dix et al. (2013)</a>
		<a href="#">ACCESS1-3</a>	<a href="#">Dix et al. (2013)</a>
2	<a href="#">Beijing Climate Center, China Meteorological Administration, China</a>	<a href="#">BCC-CSM1.1</a>	<a href="#">Wu (2012)</a>
		<a href="#">BCC-CSM1.1-M<sup>#</sup></a>	<a href="#">Wu (2012)</a>
3	<a href="#">College of Global Change and Earth System Science, Beijing Normal University, China</a>	<a href="#">BNU-ESM</a>	
4	<a href="#">Canadian Centre for Climate Modelling and Analysis, Canada</a>	<a href="#">CanAM4</a>	<a href="#">von Salzen et al. (2013)</a>
		<a href="#">CanCM4</a>	<a href="#">von Salzen et al. (2013)</a>
		<a href="#">CanESM2</a>	<a href="#">Arora et al. (2011)</a>
5	<a href="#">National Centre for Atmospheric Research, USA</a>	<a href="#">CCSM4</a>	<a href="#">Gent et al. (2011); Meehl et al. (2012)</a>
	<a href="#">Community Earth System Model Contributors</a>	<a href="#">CESM1(BGC)</a>	<a href="#">Gent et al. (2011); Meehl et al. (2012)</a>
		<a href="#">CESM1(CAM5)</a>	<a href="#">Gent et al. (2011); Meehl et al. (2012)</a>
		<a href="#">CESM1(FASTCHEM)</a>	<a href="#">Gent et al. (2011); Meehl et al. (2012)</a>
		<a href="#">CESM1(WACCM)</a>	<a href="#">Calvo et al. (2012); Gent et al. (2011); Marsh et al. (2013)</a>
6	<a href="#">Centro Euro-Mediterraneo per I Cambiamenti Climatici, Italy</a>	<a href="#">CMCC-CM</a>	<a href="#">Fogli et al. (2009)</a>
		<a href="#">CMCC-CMS</a>	<a href="#">Fogli et al. (2009)</a>
7	<a href="#">Centre National de Recherches Meteorologiques, France</a>	<a href="#">CNRM-CM5</a>	<a href="#">Voltaire et al. (2012)</a>
		<a href="#">CNRM-CM5-2</a>	<a href="#">Voltaire et al. (2012)</a>
8	<a href="#">Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence, Australia</a>	<a href="#">CSIRO-Mk3-6-0</a>	<a href="#">Rotstayn et al. (2012)</a>
9	<a href="#">EC-EARTH consortium, Europe</a>	<a href="#">EC-EARTH<sup>#</sup></a>	<a href="#">Hazeleger et al. (2012)</a>
10	<a href="#">LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua University, China</a>	<a href="#">FGOALS-g2</a>	<a href="#">Li et al. (2013)</a>
11	<a href="#">LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, China</a>	<a href="#">FGOALS-s2</a>	<a href="#">Bao et al. (2013)</a>
12	<a href="#">The First Institute of Oceanography, SOA, China</a>	<a href="#">FIO-ESM</a>	<a href="#">Zhou et al. (2014)</a>
13	<a href="#">NOAA Geophysical Fluid Dynamics Laboratory, USA</a>	<a href="#">GFDL-CM2p1</a>	<a href="#">Qiao et al. (2004); Song et al. (2012)</a>
		<a href="#">GFDL-CM3</a>	<a href="#">Donner et al. (2011)</a>
		<a href="#">GFDL-ESM2G</a>	<a href="#">Dunne et al. (2012)</a>
		<a href="#">GFDL-ESM2M</a>	<a href="#">Dunne et al. (2012)</a>
14	<a href="#">NASA Goddard Institute for Space Studies, USA</a>	<a href="#">GISS-E2-H</a>	<a href="#">Schmidt et al. (2006)</a>
		<a href="#">GISS-E2-R</a>	<a href="#">Schmidt et al. (2006)</a>
15	<a href="#">Met Office Hadley Centre, UK</a>	<a href="#">HadCM3</a>	<a href="#">Gordon et al. (2000)</a>
		<a href="#">HadGEM2-CC</a>	<a href="#">Martin et al. (2011)</a>
		<a href="#">HadGEM2-ES</a>	<a href="#">Collins et al. (2011)</a>
16	<a href="#">National Institute of Meteorological Research, Korea Meteorological Administration, Korea</a>	<a href="#">HadGEM2-AO<sup>#</sup></a>	<a href="#">Martin et al. (2011)</a>
17	<a href="#">Russian Institute for Numerical Mathematics, Russia</a>	<a href="#">INM-CM4</a>	<a href="#">Volodin et al. (2010)</a>
18	<a href="#">Institut Pierre Simon Laplace, France</a>	<a href="#">IPSL-CM5A-LR</a>	<a href="#">Dufresne et al. (2013)</a>
		<a href="#">IPSL-CM5A-MR</a>	<a href="#">Dufresne et al. (2013)</a>
		<a href="#">IPSL-CM5B-LR</a>	<a href="#">Dufresne et al.</a>

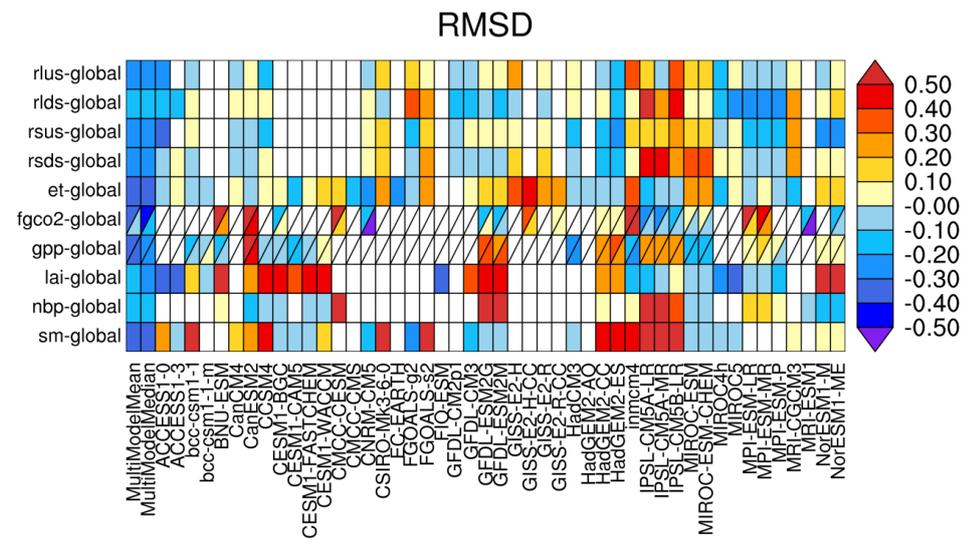
			<a href="#">(2013)</a>
<a href="#">19</a>	<a href="#">Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies, Japan</a>	<a href="#">MIROC-ESM</a>	<a href="#">Watanabe et al. (2011)</a>
		<a href="#">MIROC-ESM-CHEM</a>	<a href="#">Watanabe et al. (2011)</a>
		<a href="#">MIROC4h</a>	<a href="#">Sakamoto et al. (2012)</a>
		<a href="#">MIROC5</a>	<a href="#">Watanabe et al. (2010)</a>
<a href="#">20</a>	<a href="#">Max Planck Institute for Meteorology, Germany</a>	<a href="#">MPI-ESM-LR</a>	<a href="#">Giorgetta et al. (2013)</a>
		<a href="#">MPI-ESM-MR</a>	<a href="#">Giorgetta et al. (2013)</a>
		<a href="#">MPI-ESM-P</a>	<a href="#">Giorgetta et al. (2013)</a>
<a href="#">21</a>	<a href="#">Meteorological Research Institute, Japan</a>	<a href="#">MRI-CGCM3</a>	<a href="#">Yukimoto et al. (2012)</a>
<a href="#">22</a>	<a href="#">Norwegian Climate Centre, Norway</a>	<a href="#">NorESM1-M</a>	<a href="#">Bentsen et al. (2013); Iversen et al. (2012)</a>
		<a href="#">NorESM1-ME</a>	<a href="#">Bentsen et al. (2013); Iversen et al. (2012)</a>



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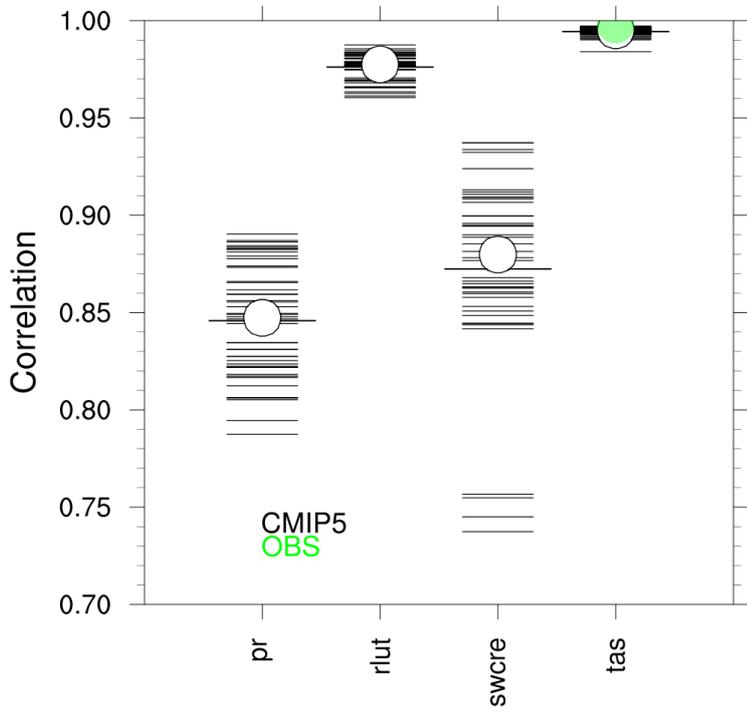
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Figure 1. Relative space-time root-mean-square deviation (RMSD) calculated from the climatological seasonal cycle of the CMIP5 simulations. The years averaged depend on the years with observational data available. A relative performance is displayed, with blue shading indicating better and red shading indicating worse performance than the median of all model results. Note that the colors would change if models are added or removed. A diagonal split of a grid square shows the relative error with respect to the reference data set (lower right triangle) and the alternative data set (upper left triangle). White boxes are used when data are not available for a given model and variable. The performance metrics are shown separately for atmosphere, ocean and sea-ice (left upper panel), and land (right). The figure shows that performance varies across CMIP5 models and variables, with some models comparing better with observations for one variable and another model performing better for a different variable. Except for global average temperatures at 200 hPa (ta\_Glob-200) where most but not all models have a systematic bias, the multi-model mean outperforms any individual model (lower panel). Extended from Figure 9.7 of Flato et al. (2013) IPCC WG I AR5 Chapter 9 (Flato et al., 2013) and produced with recipe\_perfmtrics\_CMIP5.yml, see details in Section 3.1.1.

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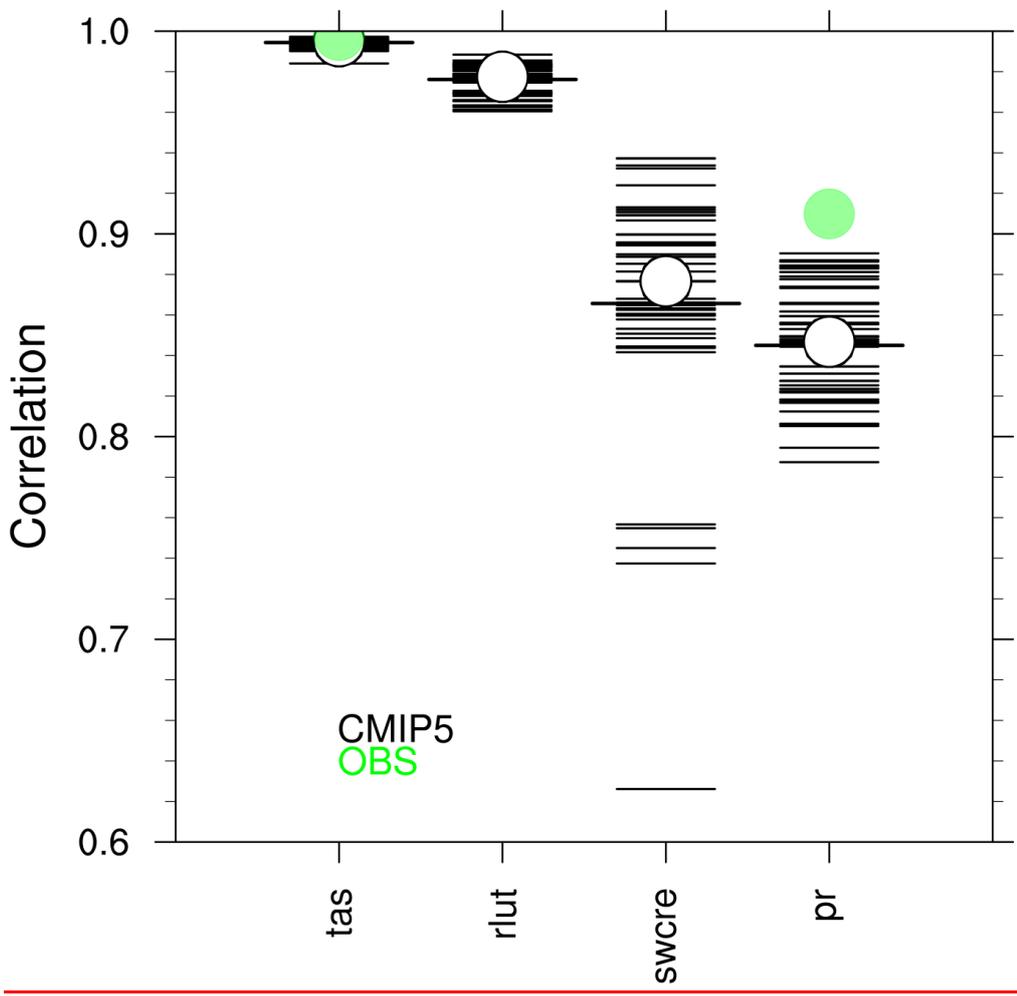


Figure 2. Centred pattern correlations for the annual mean climatology over the period 1980-1999 between models and observations. Results for individual CMIP5 models are shown (thin dashes), as well as the ensemble average (longer thick dash) and median (open circle). The correlations are computed between the models and the reference dataset. When an alternate observational dataset is present, its correlation to the reference dataset is also shown (solid green circles). ~~The models are first regridded to 4° longitude by 5° latitude to ensure the pattern correlations give a fair comparison across all model resolutions. The figure shows both a large model spread as well as a large spread in the correlation depending on the variable, signifying that some aspects of the simulated climate agree better with observations than others.~~ Similar to Figure 9.6 of [Flato et al. \(2013\) IPCC WG I AR5 Chapter 9 \(Flato et al., 2013\)](#) and produced with `recipe_flato13ipcc.yml`, see details in Section 3.1.2.

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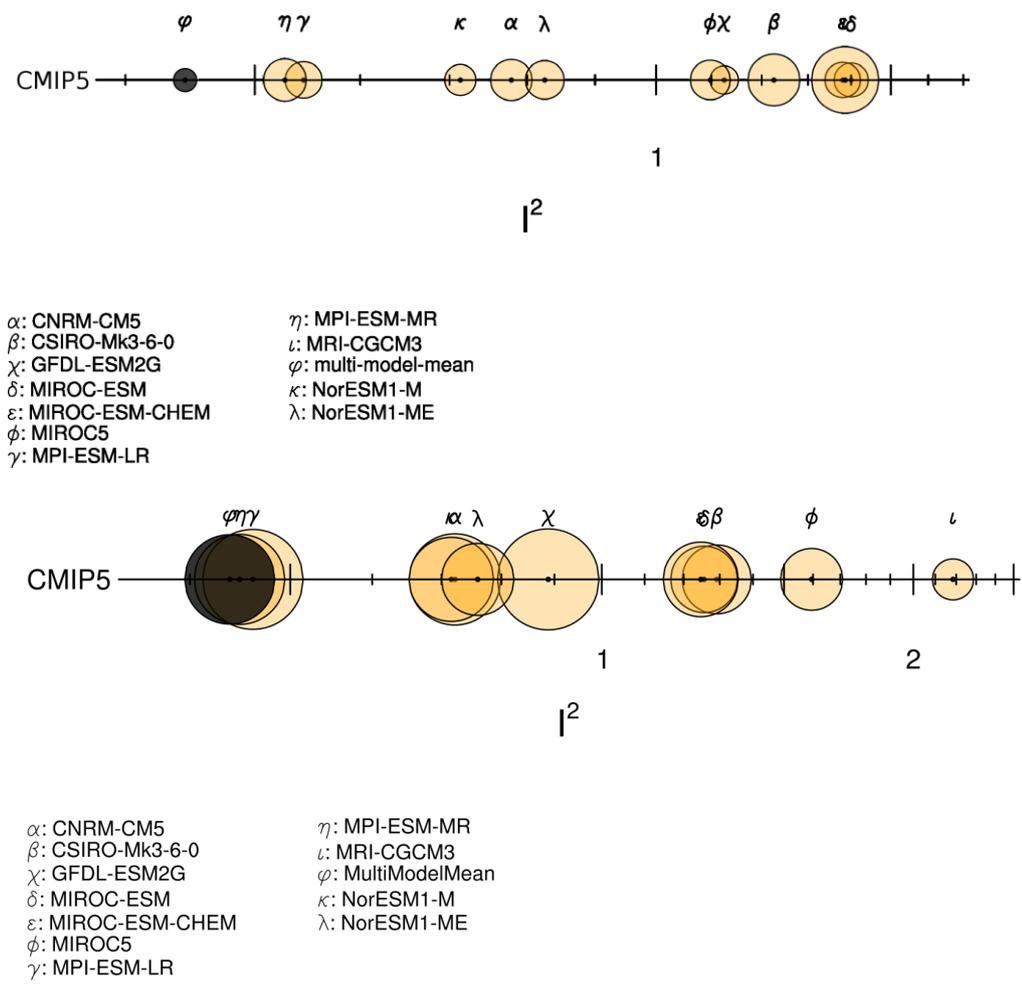


Figure 3. Single Model Performance Index  $I_2$  for individual models (orange circles). The size of each circle represents the 95% confidence interval of the bootstrap ensemble. The black circle indicates the  $I_2$  of the CMIP5 multi-model mean. The  $I_2$  values vary around one, with underperforming models having a value greater than one, while values below one represent more accurate models. **This allows for a quick estimation which models are performing the best on average across the sampled variables and in this case shows that the common practice of taking the multi-model mean as best overall model is accurate.** Similar to Reichler and Kim (2008) Figure 1 and produced with `recipe_smpi.yml`, see details in Section 3.1.3.

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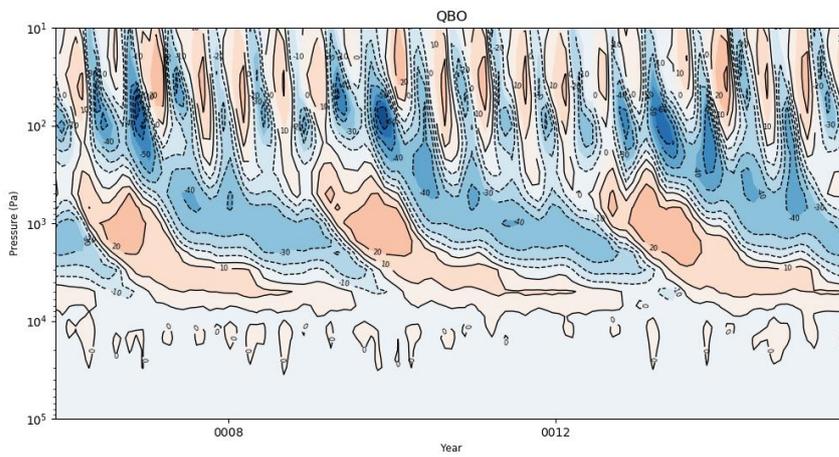
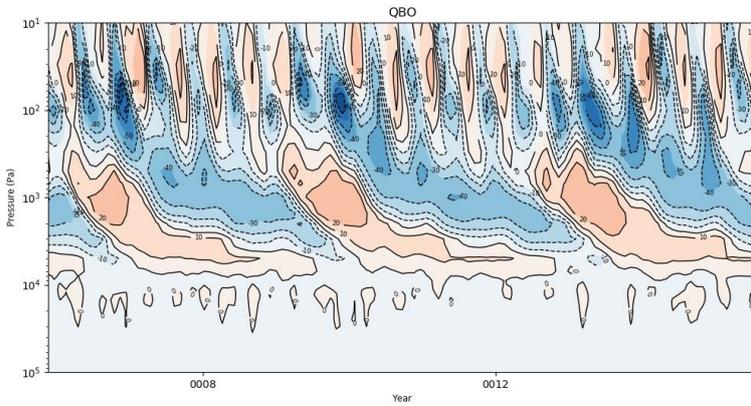
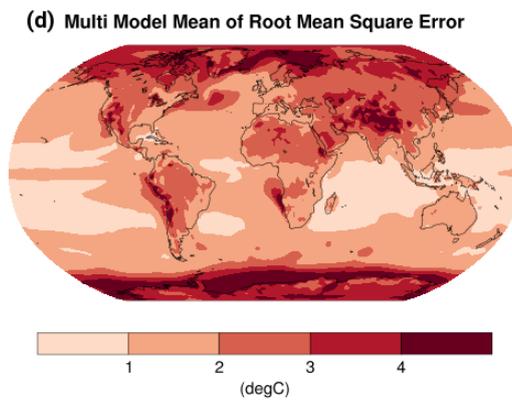
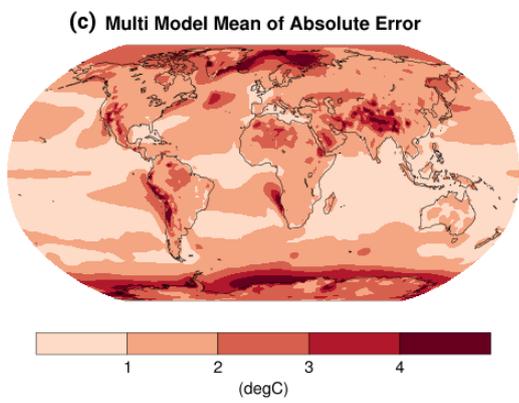
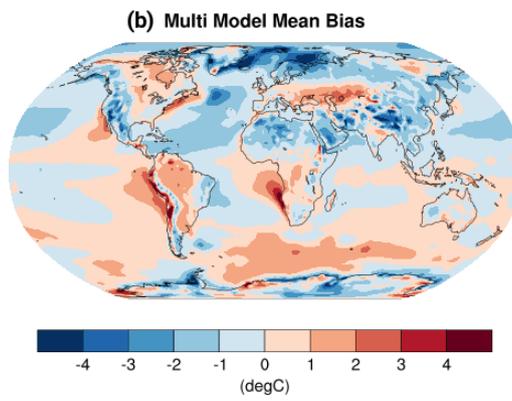
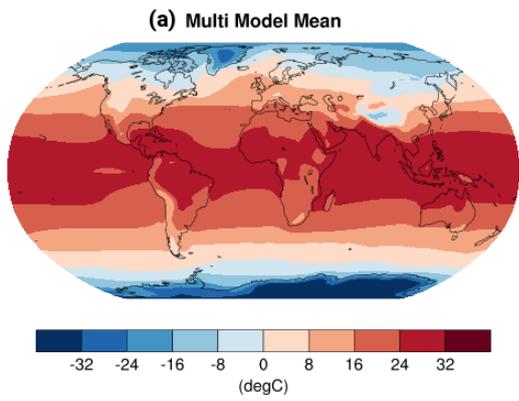


Figure 4. AutoAssess diagnostic for the Quasi-Biennial Oscillation (QBO) showing the time-height plot of zonal mean zonal wind averaged between  $55^{\circ}\text{S}$  and  $55^{\circ}\text{N}$  for UKESM1-0-LL over the period 1995-2014. Zonal wind anomalies propagate downward from the upper stratosphere. The figure shows that the period of the QBO in this model is about 6 years, significantly longer than the observed period of ~2.3 years. Produced with recipe `autoassess_*.yaml`, see details in Section 3.1.4.

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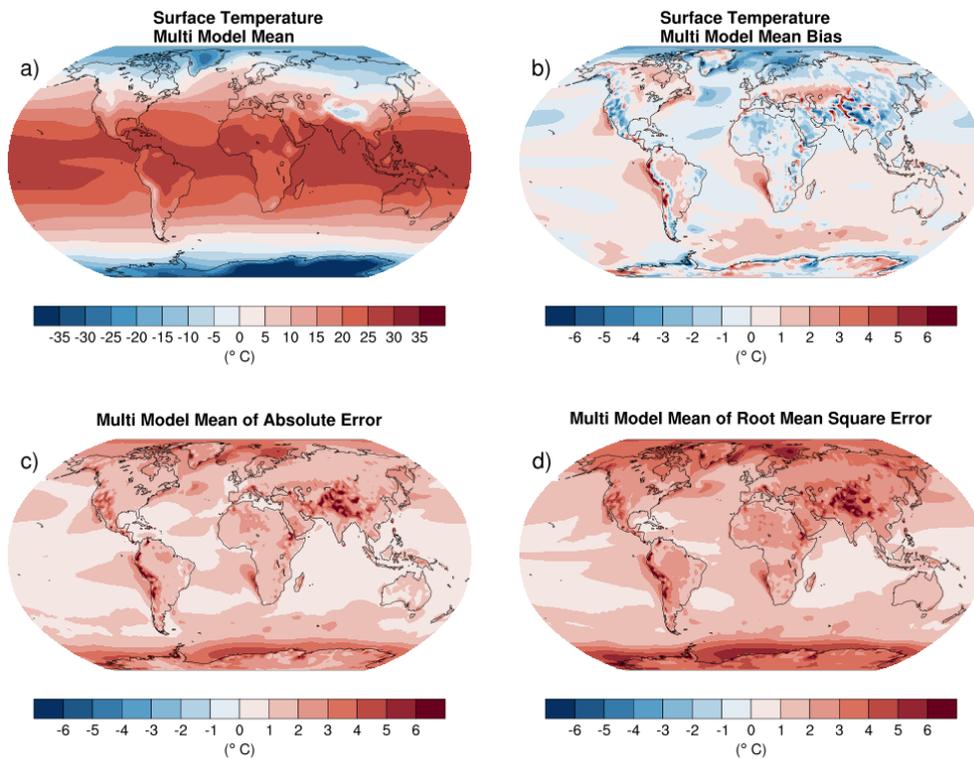


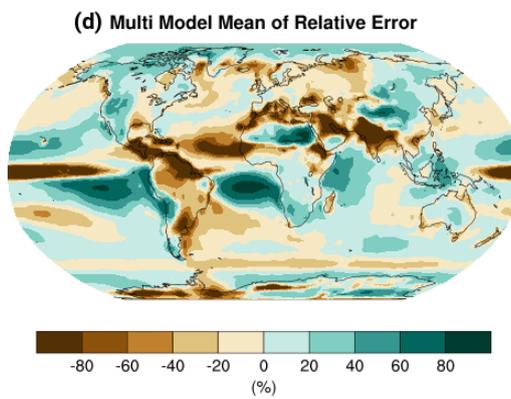
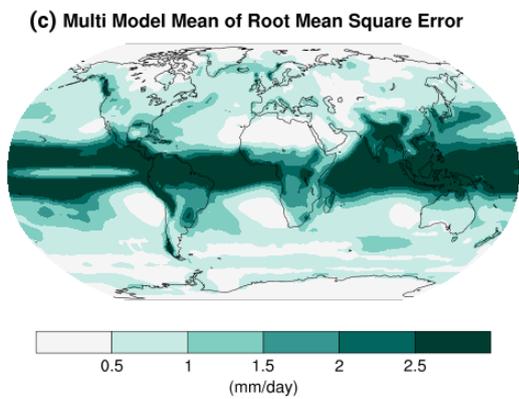
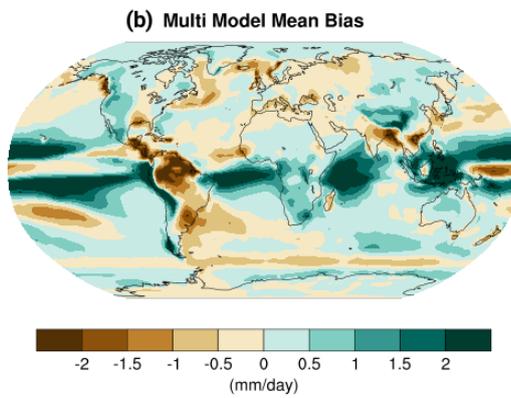
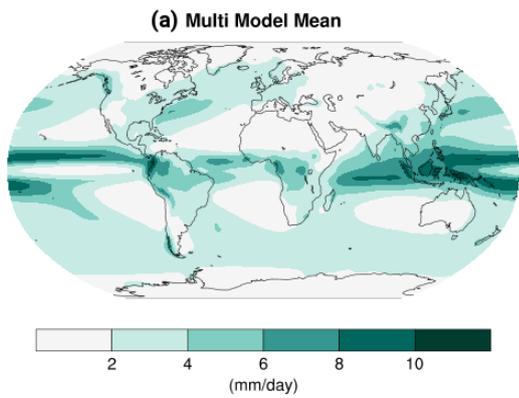
Figure 5. Annual-mean surface (2 m) air temperature ( $^{\circ}\text{C}$ ) for the period 1980-2005. (a) Multi-model (ensemble) mean constructed with one realization of all available models used in the CMIP5 historical experiment. (b) Multi-model mean bias as the difference between the CMIP5 multi-model mean and the climatology from ECMWF reanalysis of the global atmosphere and surface conditions (ERA)-Interim (Dee et al., 2011). (c) Mean absolute model error with respect to the climatology from ERA-Interim. (d) Mean root mean square error of the seasonal cycle with respect to the ERA-Interim. The multi-model mean near-surface temperature agrees with ERA-Interim mostly within  $\pm 2^{\circ}\text{C}$ . Larger biases can be seen in regions with sharp gradients in temperature, for example in areas with high topography such as the Himalaya, the sea ice edge in the North Atlantic, and over the coastal upwelling regions in the subtropical oceans. Updated from Fig. 9.2 of Flato et al. (2013) IPCC WG I AR5 Chapter 9 (Flato et al., 2013) and produced with recipe\_flato13ipcc.yml, see details in Section 3.2.1.

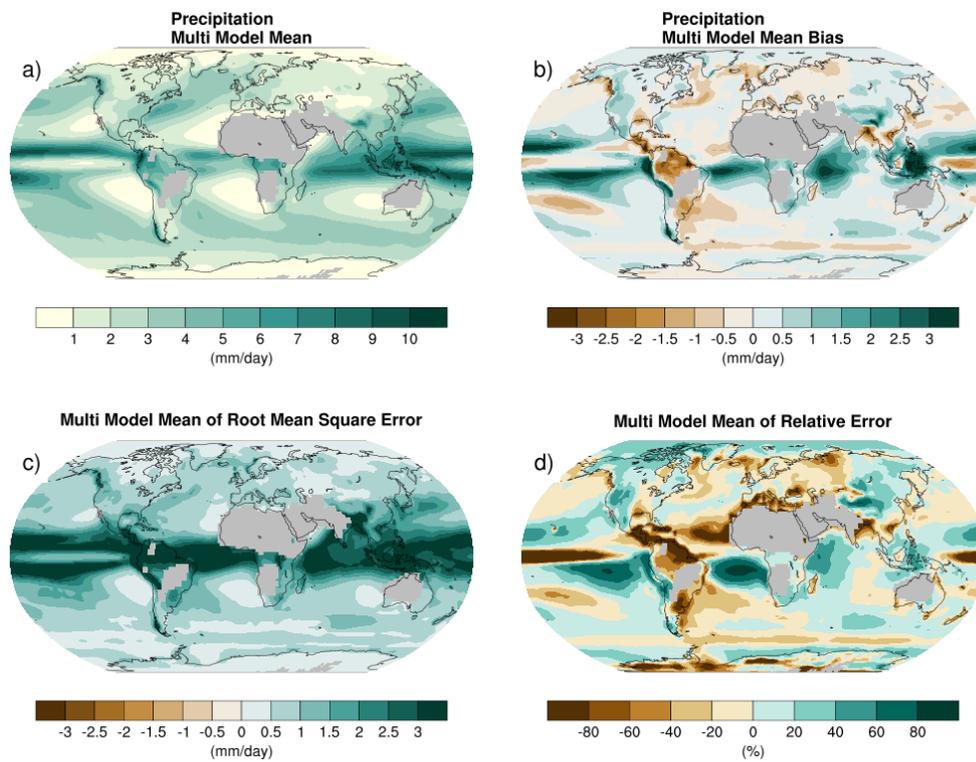
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Figure 6. Annual-mean precipitation rate ( $\text{mm day}^{-1}$ ) for the period 1980-2005. (a) Multi-model (ensemble) mean constructed with one realization of all available models used in the CMIP5 historical experiment. (b) Multi-model mean bias as the difference between the CMIP5 multi-model mean and the analyses from the Global Precipitation Climatology Project (Adler et al., 2003). (c) Mean root mean square error of the seasonal cycle with respect to observations. (d) Mean relative model error with respect to observations. Biases in the simulated multi-model mean precipitation include too low precipitation along the Equator in the western Pacific and too high precipitation amounts in the tropics south of the Equator. Updated from Fig. 9.4 of Flato et al. (2013) IPCC WG I AR5 Chapter 9 (Flato et al., 2013) and produced with `recipe_flato13ipcc.yml`, see details in Section 3.2.1.

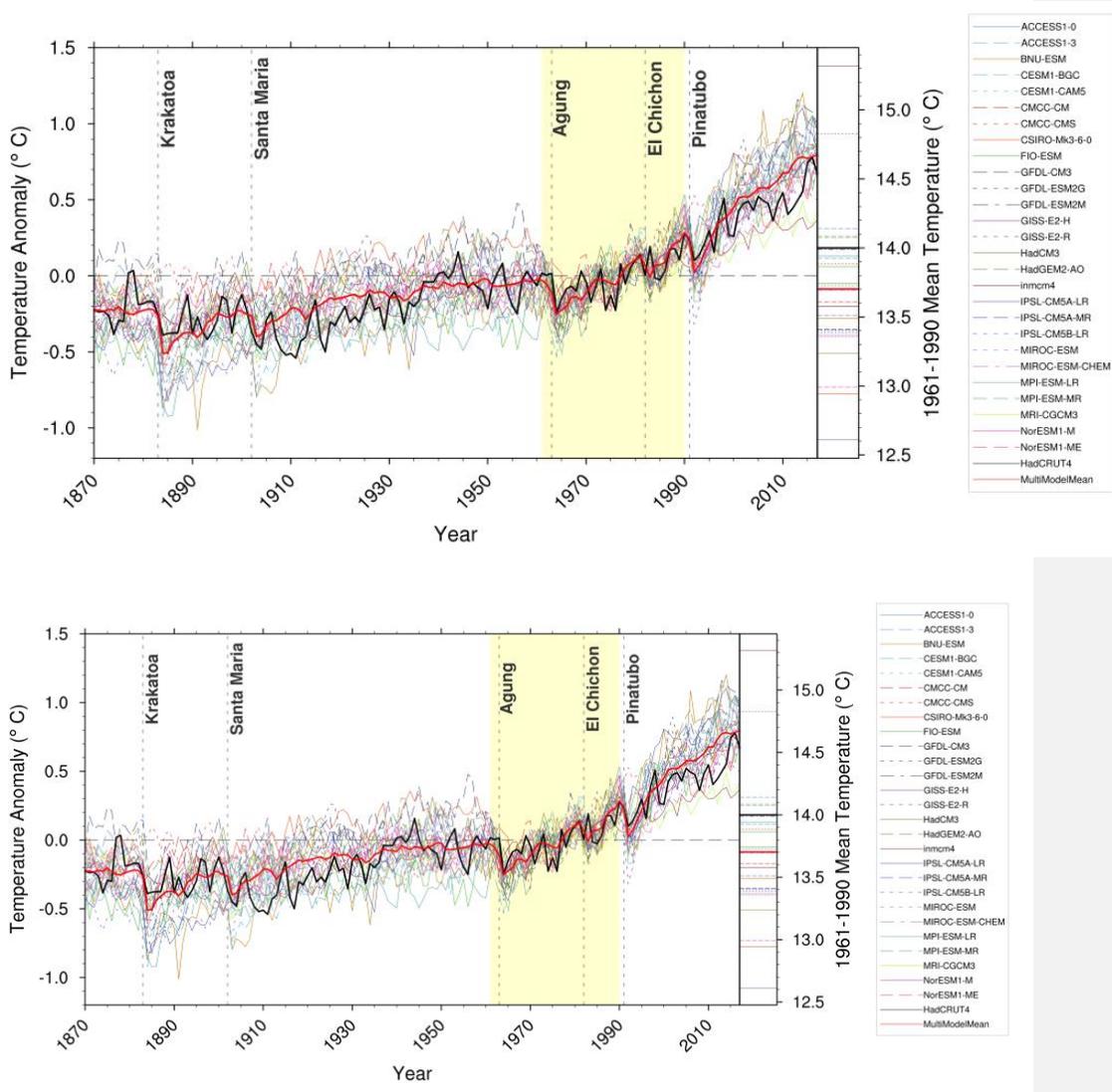
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**Figure 7. Anomalies in annual and global mean surface temperature of CMIP5 models and HadCRUT4 observations.** Yellow shading indicates the reference period (1961 -1990); vertical dashed grey lines represent times of major volcanic eruptions. The right bar shows the global mean surface temperature of the reference period. CMIP5 model data are subsampled by the HadCRUT4 observational data mask and processed like described in Jones et al. (2013). Jones et al. (2013) All simulations are historical experiments up to and including 2005 and the RCP 4.5 scenario after 2005. Overall, the models represent quite good the annual global mean surface temperature increase over the historical period including the more rapid warming in the second half of the 20<sup>th</sup> century and the cooling immediately following large volcanic eruptions. Extended from Figure 9.8 of Flato et al. (2013) Extended from Figure 9.8 of IPCC WG I AR5 Chapter 9 (Flato et al., 2013) and produced with recipe\_flato13ipcc.yml, see details in Section 3.2.1.

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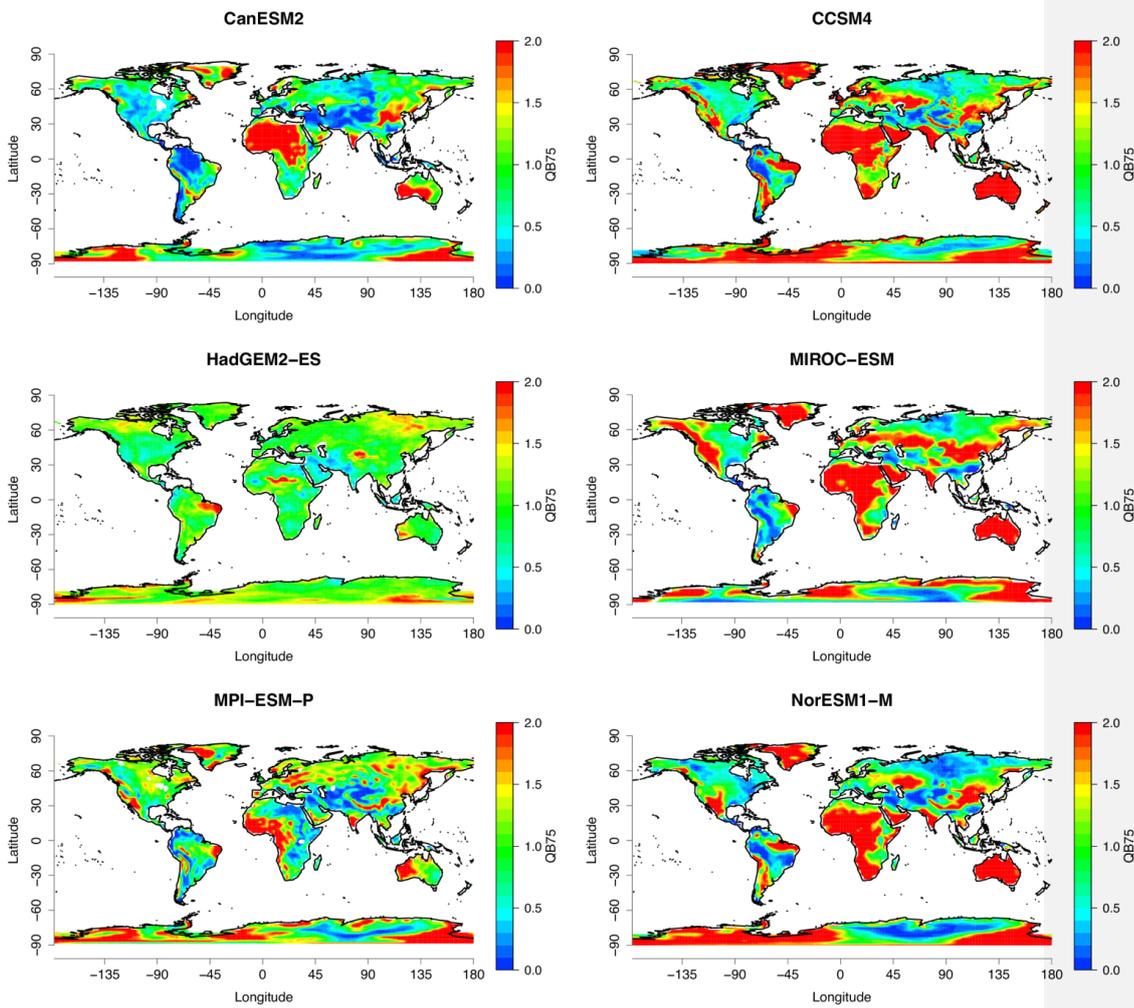
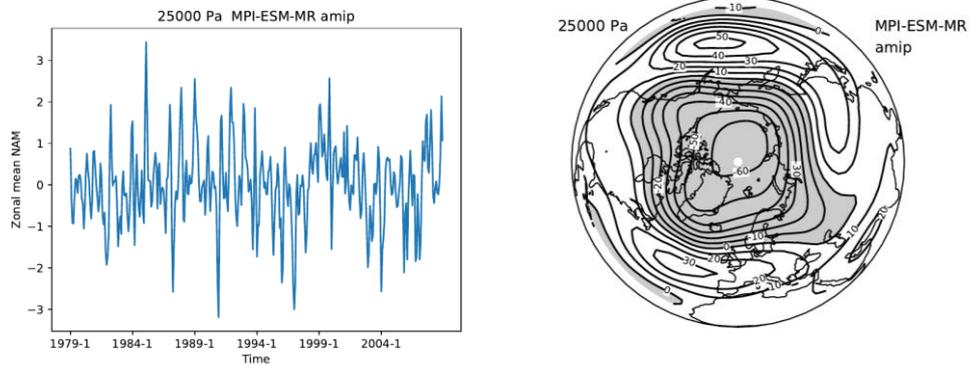


Figure 8. **Quantile-Precipitation quantile bias (75%) bias% level, unitless** evaluated for an example subset of CMIP5 models over the period 1979 to 2005 using GPCP-SG v 2.3 gridded precipitation as a reference dataset. **Biases depend on models and geographical regions but similar patterns can be recognized (see e.g., overestimation over Africa for models in the right column and the underestimation pattern crossing central Asia from Siberia, Similar to the Arabic peninsula). The HadGEM2-ES model show a largely reduced bias as compared to the other models in this subset. Similar to Mehran et al. (2014) Mehran et al. (2014) and produced with `recipe_quantilebias.yml`. See details in Section 3.2.2.**

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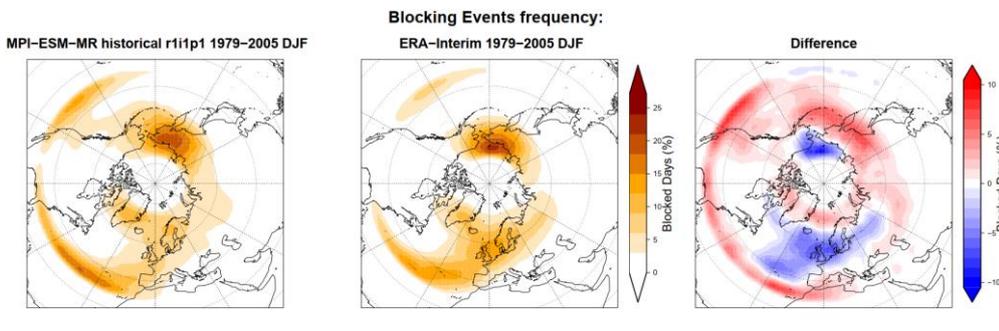
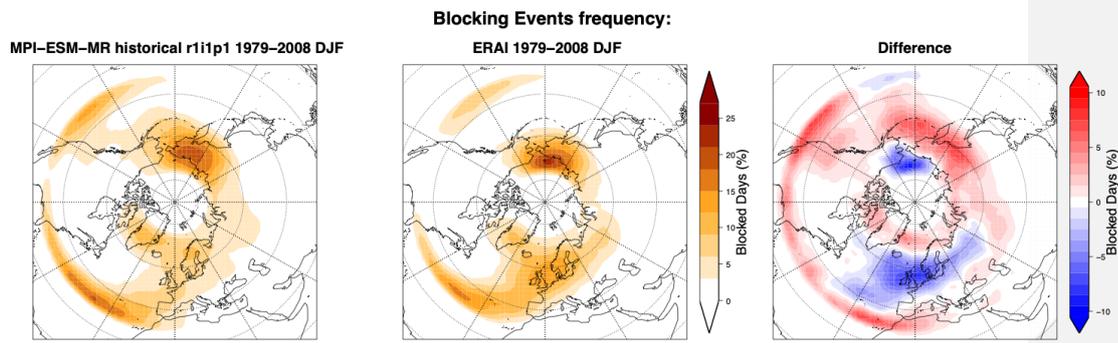


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Figure 9. The standardized zonal mean NAM index (left, unitless) at 250 hPa for the atmosphere-only CMIP5 simulation of the Max Planck Institute for Meteorology (MPI-ESM-MR) model, and the regression map of the monthly geopotential height on this zonal-mean NAM index (right, in meters). Note the variability on different temporal scales of the index, from monthly to decadal. The well-known annular pattern, with opposite anomalies between polar and mid-latitudes, can be appreciated in the regression plot. Similar to Figure 2 of Baldwin and Thompson (2009) and produced with `recipe_znam.yml`, see details in Section 3.2.3.1.

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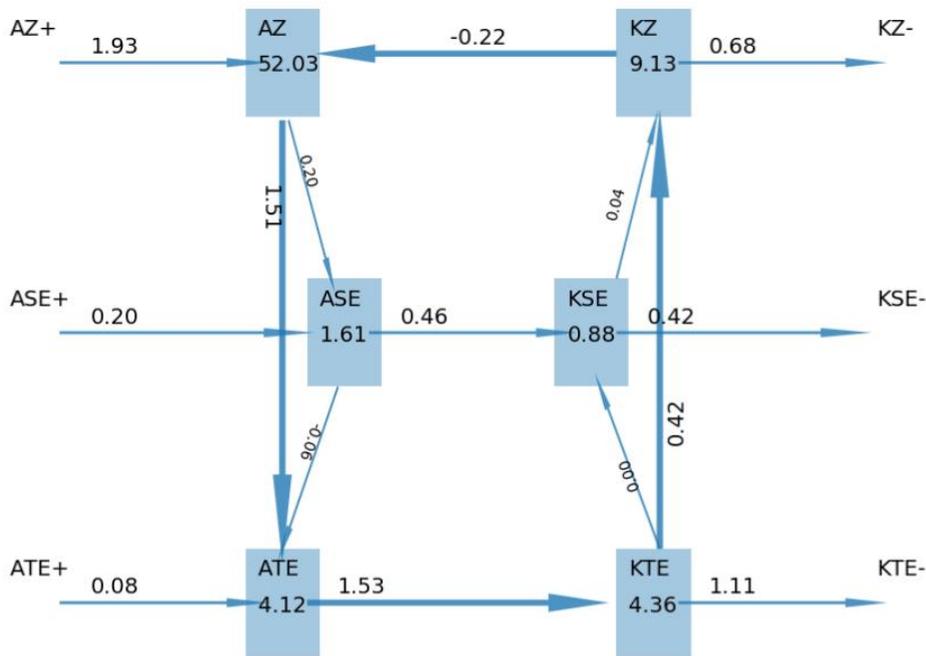
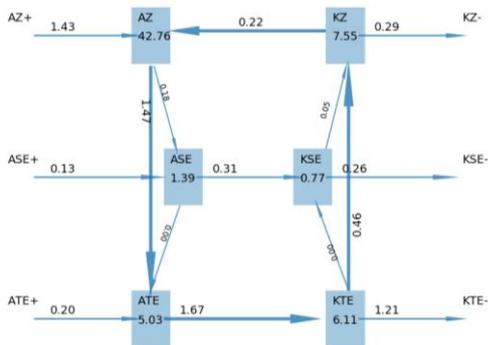
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**Figure 10.** 2-d Blocking Events frequency (percentage of blocked days) following the Davini et al. (2012) Davini et al. (2012) index over the 1979–2008/2005 DJF period for (left) CMIP5 MPI-ESM-MR historical r1i1p1 run (center) ERA-Interim Reanalysis and (right) their differences. ~~The MPI-ESM-MR shows the well-known underestimation of atmospheric blocking—typical of many climate models—over Central Europe, where blocking frequencies are about the half when compared to reanalysis. Slight overestimation of low-latitude blocking and North Pacific blocking can be also observed, while Greenland blocking frequencies show negligible bias.~~ Produced with `recipe_miles_block.yml`, see details in Section 3.2.3.2.

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Figure 11. A Lorenz Energy Cycle flux diagram for one year of a CMIP5 model pre-industrial control run (cf. Ulbrich et al., 1994), Ulbrich and Speth (1991)). “A” stands for available potential energy (APE), “K” for kinetic energy (KE), “Z” for zonal mean, “S” for stationary eddies, “T” for transient eddies. “+” indicates source of energy, “-” a sink. For the energy reservoirs, the unit of measure is  $J^2 m^{-1} m^{-2}$ , for the energy conversion terms, the unit of measure is  $W m^{-1} m^{-2}$ . Most of the energy is clearly stored in terms of APE in the zonal mean flux. The energy conversion happens almost instantly in converting APE energy from the zonal mean flow into the eddy and through them into KE. The two processes are usually referred to as “baroclinic conversion”. For a non-steady state equilibrium system, the APE source has to equal the KE dissipation (through frictional heating in the zonal mean flow and eddies). Similar to Figure 5 of Lembo et al. (2019) and produced with `recipe_thermodyn_diagtool.yml`, see details in Section 3.2.4.

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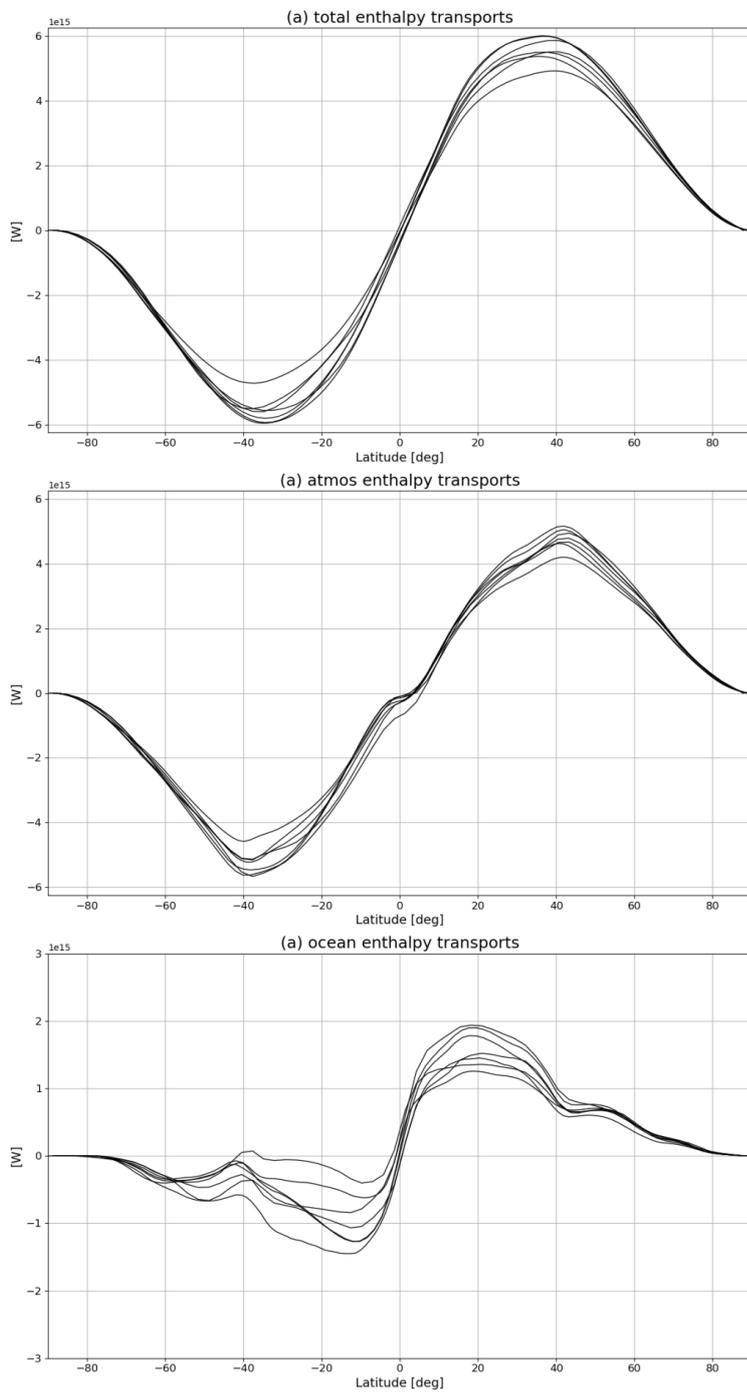
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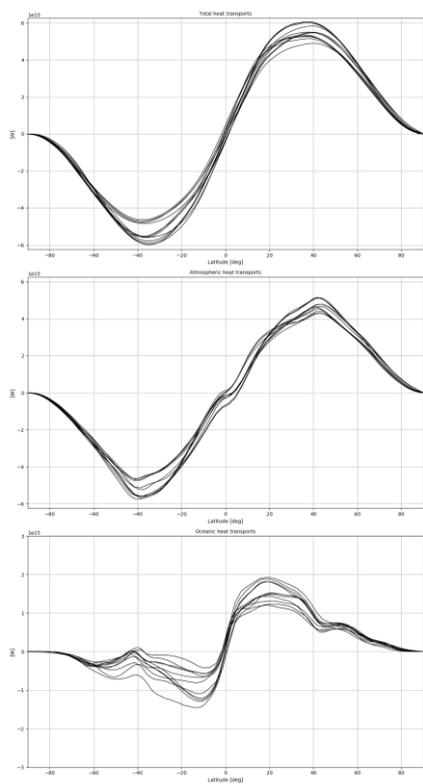
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**Figure 12.** Annual mean meridional sections of zonal mean meridional total (top), atmospheric (middle), oceanic (bottom) heat transports for 12 CMIP5 models control runs. Transports are implied from meridionally integrating TOA, atmospheric and surface energy budgets (Trenberth et al., 2001), then applying the usual correction accounting for energy imbalances, as in Carissimo et al. (1985). Values are in W. Similar to Figure 8 of Lembo et al. (2019) and produced with `recipe_thermodyn_diagtool.yml`, see details in Section 3.2.4.

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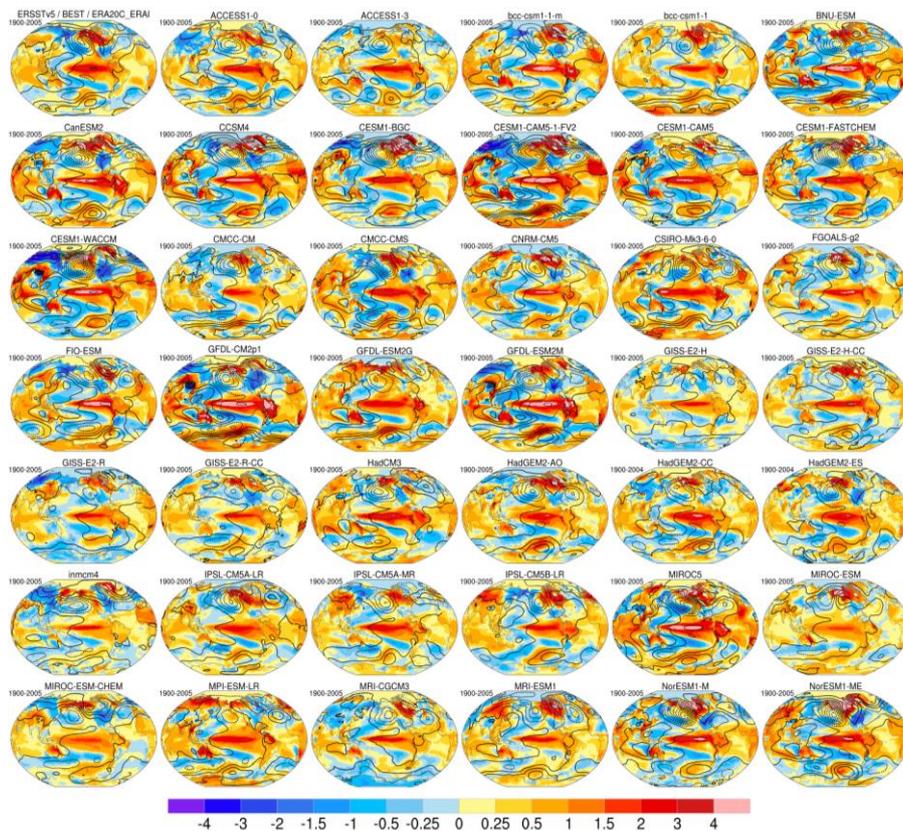


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**Figure 12. annual mean meridional sections of zonal mean meridional total (top), atmospheric (middle), oceanic (bottom) heat transports for 12 CMIP5 models control runs. Transports are implied from meridionally integrating TOA, atmospheric and surface energy budgets (cfr. Trenberth et al. (2001)), then applying the usual correction**

accounting for energy imbalances, as in Carissimo et al. (1985). Values are in W.

### Niño3.4 SST,TAS,PSL Spatial Composite (DJF<sup>+</sup>)



1365 ~~The model spread has roughly the same magnitude in the atmospheric and oceanic transports, but its relevance is~~  
~~much larger for the oceanic transports. The model spread is also crucial in the magnitude and sign of the atmospheric~~  
~~heat transports across the Equator, given its implications for the atmospheric general circulation. Add brief~~  
~~discussion of the results. Similar to Figure 8 of Lembo et al. (2019), and produced with recipe thermodyn\_diagtool.m,~~  
1370 ~~see details in Section 3.2.4.~~

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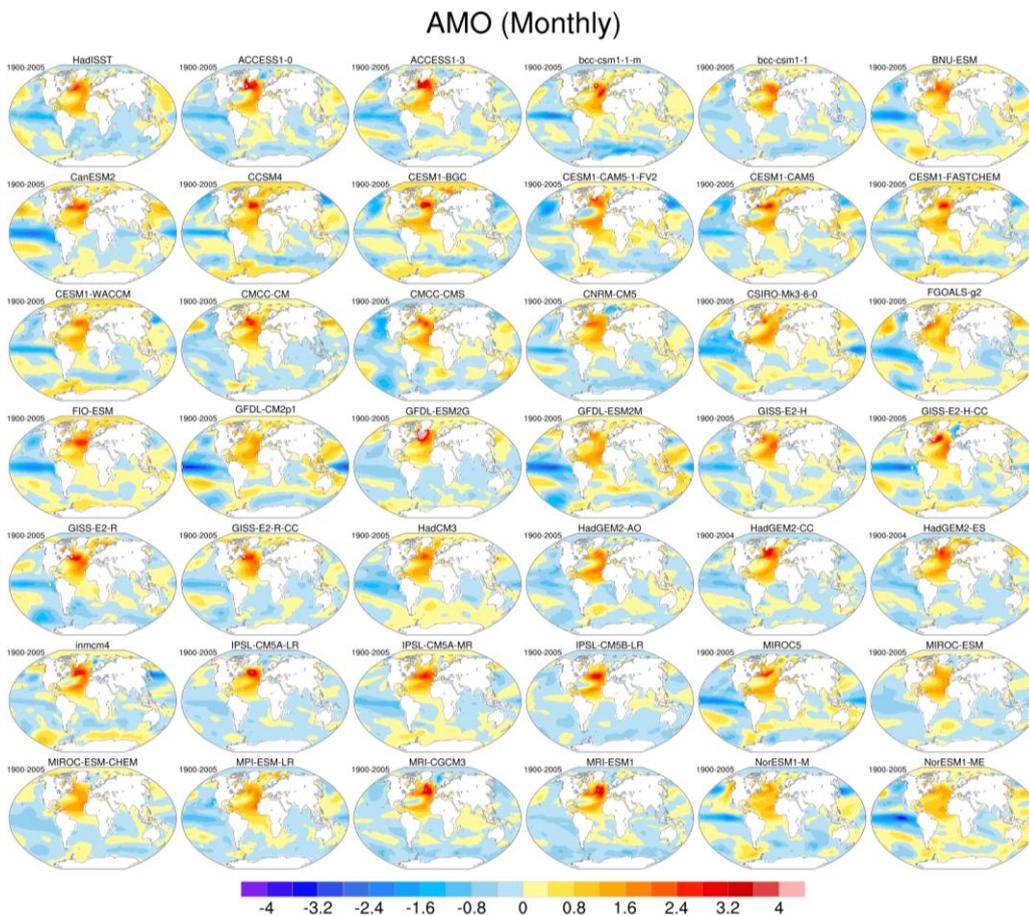
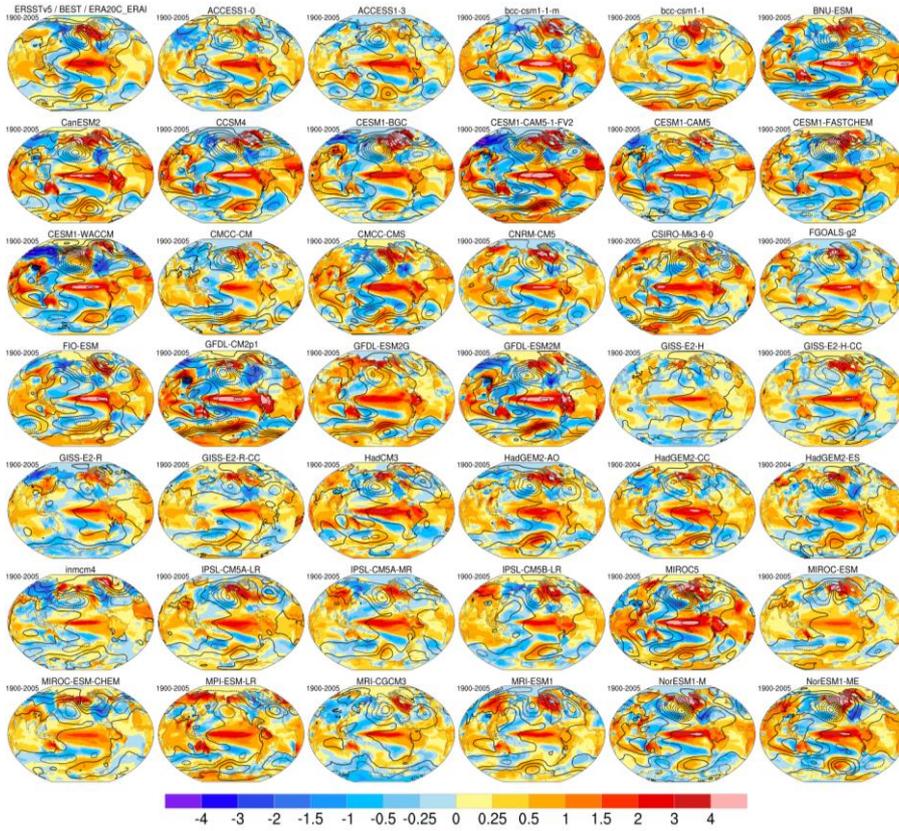


Figure 13. Global ENSO teleconnections during the peak phase (December-February) as simulated by 41 CMIP5 models (individual panels labelled by model name) and observations (upper left panel) for the historical period (1900-2005 for models and 1920-2017 for observations). These patterns are based on composite differences between all El Niño events and all La Niña events (using a  $\pm 1$  standard deviation threshold of the Niño3.4 SST Index) occurring in the period of record. Color shading denotes SST and terrestrial TREFHT ( $^{\circ}\text{C}$ ), and contours denote SLP (contour interval of 2hPa, with negative values dashed). The period of record is given in the upper left of each panel, and the number of El Niño and La Niña events that contribute to the composites are given in the upper right (for example, “18/14” denotes 18 El Niño events and 14 La Niña events). Observational composites use ERSSTv5 for SST, BEST for TAS and ERA20C updated with ERA-I for PSL. Figure produced with recipe CVDP.yml, see details in Section 3.2.5.1. Models produce a wide range of ENSO amplitudes and teleconnections. Note that even when based on over 100 years of record, the ENSO composites are subject to uncertainty due to sampling variability (Deser et al., 2017), Deser et al., 2018). Figure produced with recipe CVDP.yml, see details in Section 3.2.5.1.

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### Niño3.4 SST,TAS,PSL Spatial Composite (DJF<sup>+1</sup>)



### AMO (Monthly)

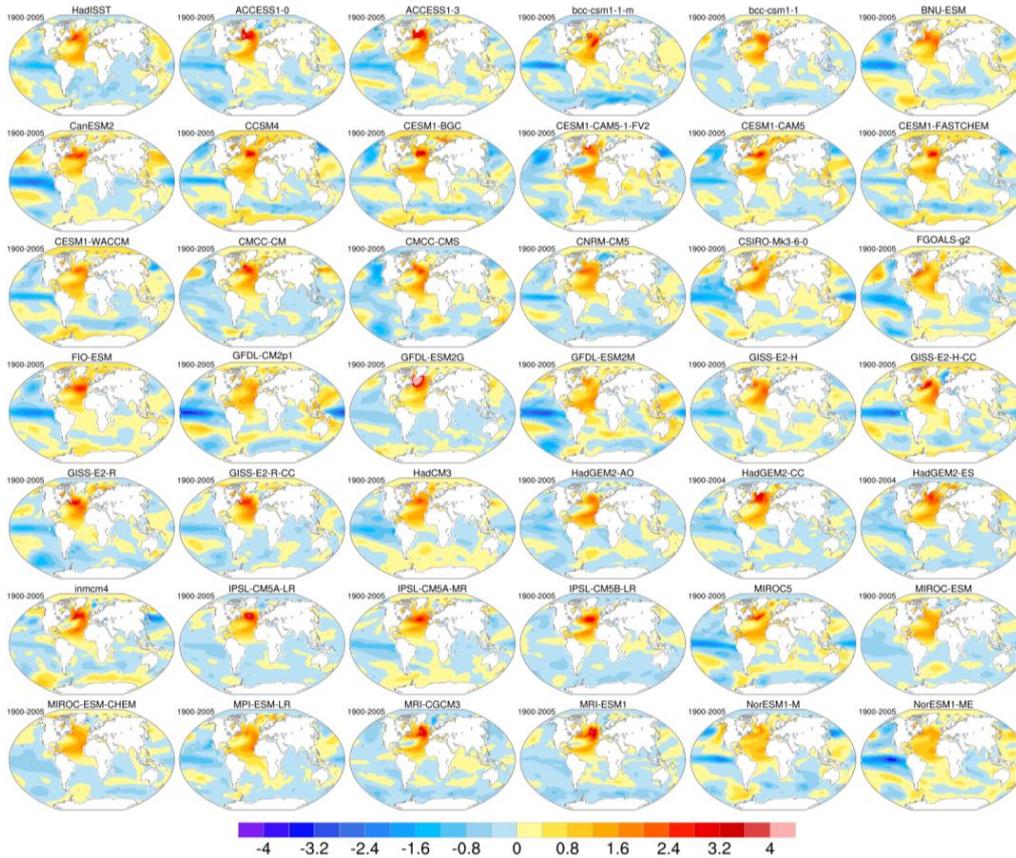


Figure 14. Representation of the AMO in 41 CMIP5 models (individual panels labelled by model name) and observations (upper left panel) for the historical period (1900-2005 for models and 1920-2017 for observations). These patterns are based regressing monthly SST anomalies (denoted SSTA\*) at each grid box onto the timeseries of the AMO SSTA\* Index (defined as SSTA\* averaged over the North Atlantic 0-60N, 80W-0W), where the asterisk denotes that the global (60N-60S) mean SSTA has been subtracted from SSTA at each grid box following Trenberth and Shea (2006). Trenberth and Shea (2006). The pattern of SSTA\* associated with the AMO is generally realistically simulated by models within the North Atlantic basin, although its amplitude varies. However, outside of the North Atlantic, the models show a wide range of spatial patterns and polarities of the AMO. Figure produced with recipe\_CVDP.yml., see details in Section 3.2.5.1.

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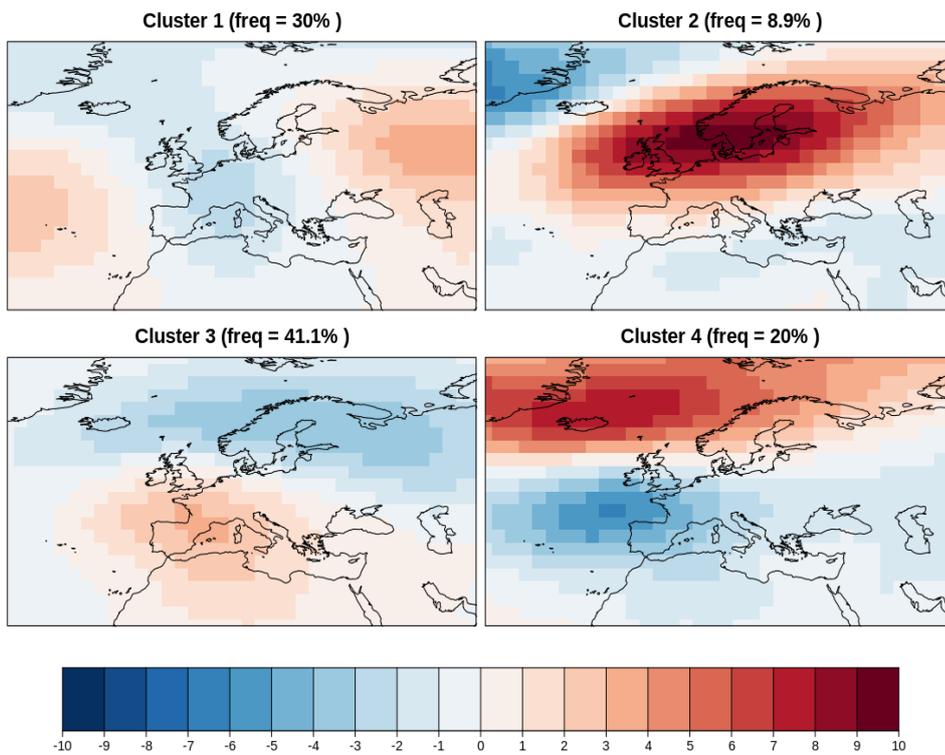


Figure 15. Four modes of variability for autumn (September-October-November) in the North Atlantic European Sector during the reference period 1971-2000 for the BCC-CSM1-1 historical simulations. The frequency of occurrence of each variability mode is indicated in the title of each map. The four clusters are reminiscent of the Atlantic Ridge, the Scandinavian blocking, the NAO+ and the NAO- pattern, respectively. Result for *recipe\_modes\_of\_variability.yml*, see details in Section 3.2.5.2.

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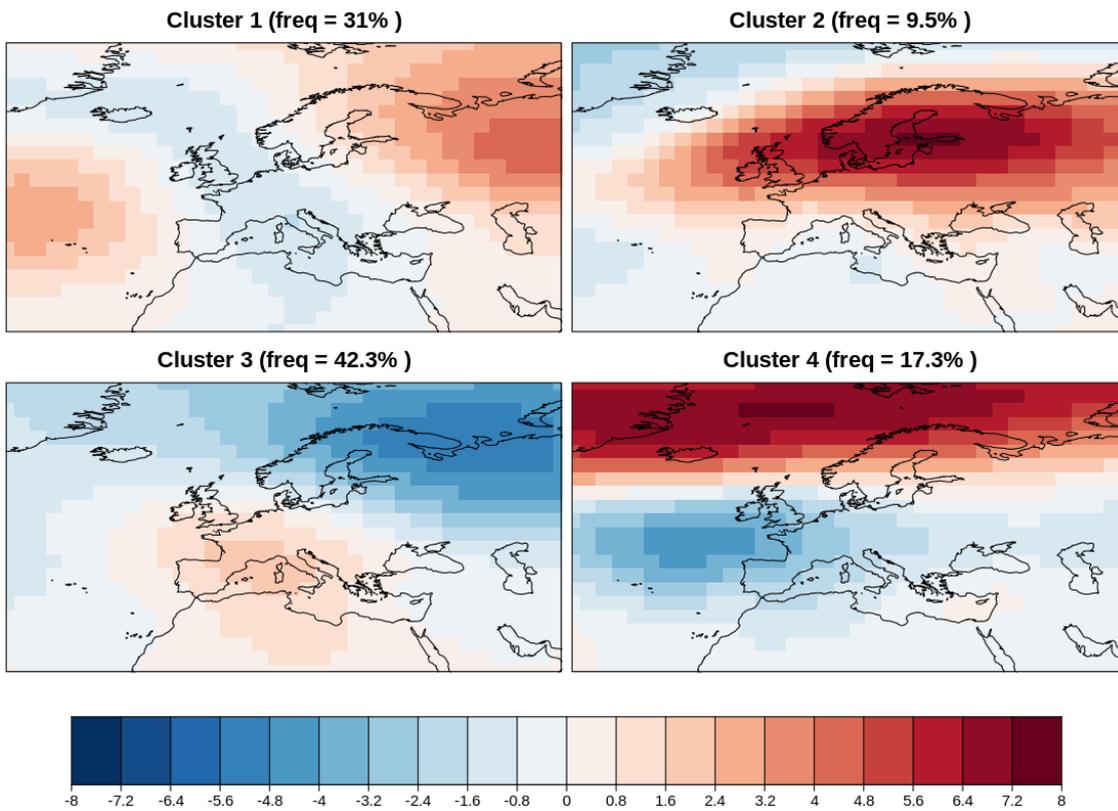


Figure 16. Four modes of variability for autumn (September-October-November) in the North Atlantic European Sector for the RCP 8.5 scenario using BCC-CSM1-1 future projection during the period 2020-2075. The frequency of occurrence of each variability mode is indicated in the title of each map. The four clusters are reminiscent of the Atlantic Ridge, the Scandinavian blocking, the NAO+ and the NAO- pattern, respectively. Result for *recipe\_modes\_of\_variability.yml*, see details in Section 3.2.5.2.

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	Obs 1	Obs 2	Obs 3	Obs 4
Pre 1	107.49	349.18	304.09	375.63
Pre 2	280.68	149.67	405.82	449.04
Pre 3	303.96	497.06	112.14	505.27
Pre 4	415.69	529.9	491.15	122.16

1410 Figure 17. RMSE between the spatial patterns obtained for the future ‘Pre’ (2020-2075) and the reference ‘Obs’  
 (1971-2000) modes of variability from the BCC-CSM1-1 simulations in autumn (September-October-November). **Low**  
 RMSE values along the diagonal show that the modes of variability simulated by the future projection (Figure 16)  
 match the reference modes of variability (Figure 15). Result for `recipe_modes_of_variability.yml` see details in Section  
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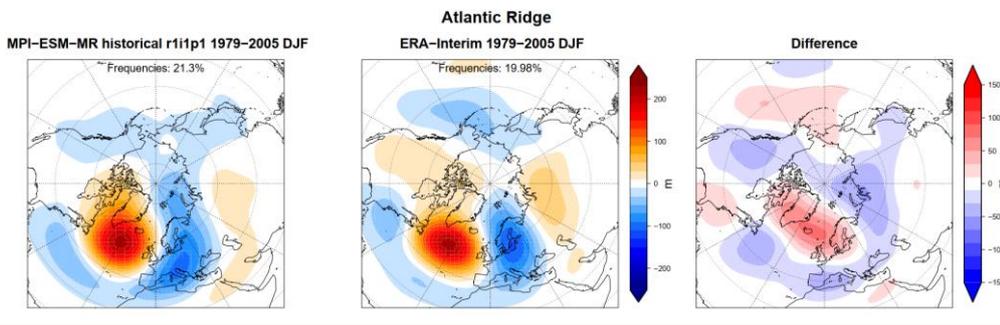
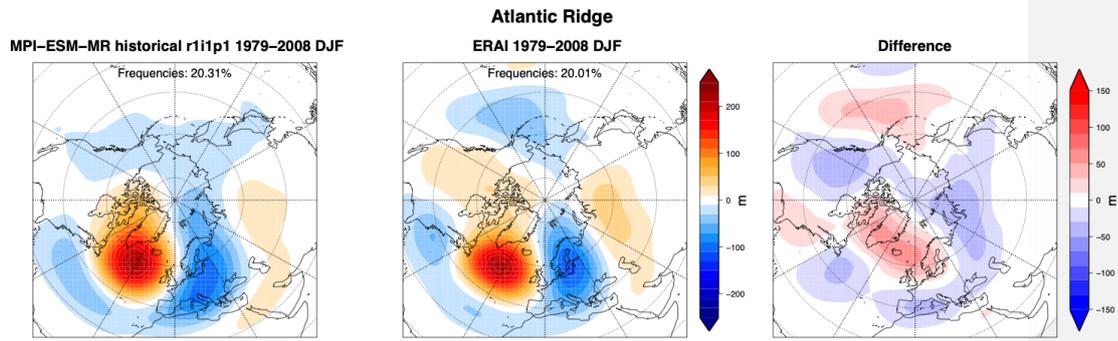
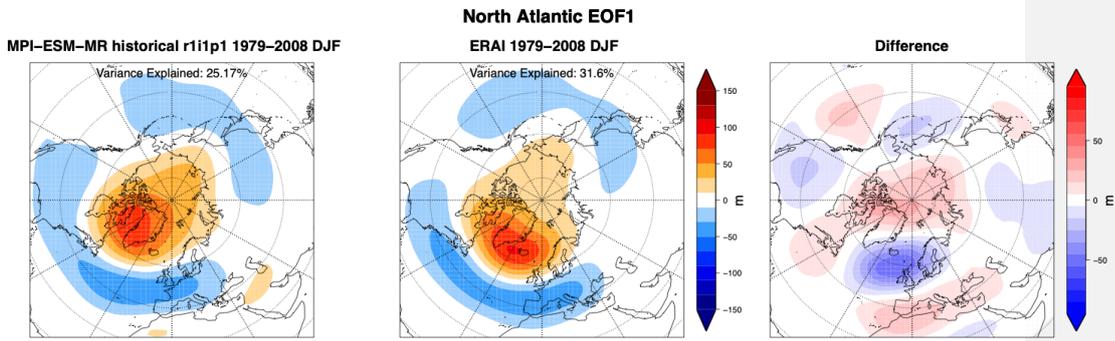


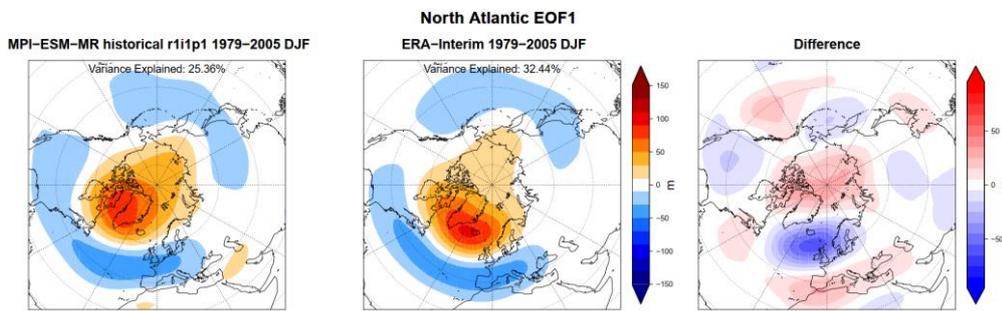
Figure 18. 500 hPa geopotential height anomalies [m] associated ~~to~~with the Atlantic Ridge weather regime over the 1979-2008~~2005~~ DJF period for (left) CMIP5 MPI-ESM-MR historical r1i1p1 run (center) ERA-Interim Reanalysis~~reanalysis~~ and (right) their differences. The frequency of occupancy of each regime is reported on the top of each panel. ~~The Atlantic ridge regimes, which is usually badly simulated by climate models, it is reproduced with the right frequency of occupancy and pattern in MPI-ESM-MR when compared to ERA-Interim reanalysis.~~ Produced with `recipe_miles_regimes.yml`, see details in Section 3.2.5.2.

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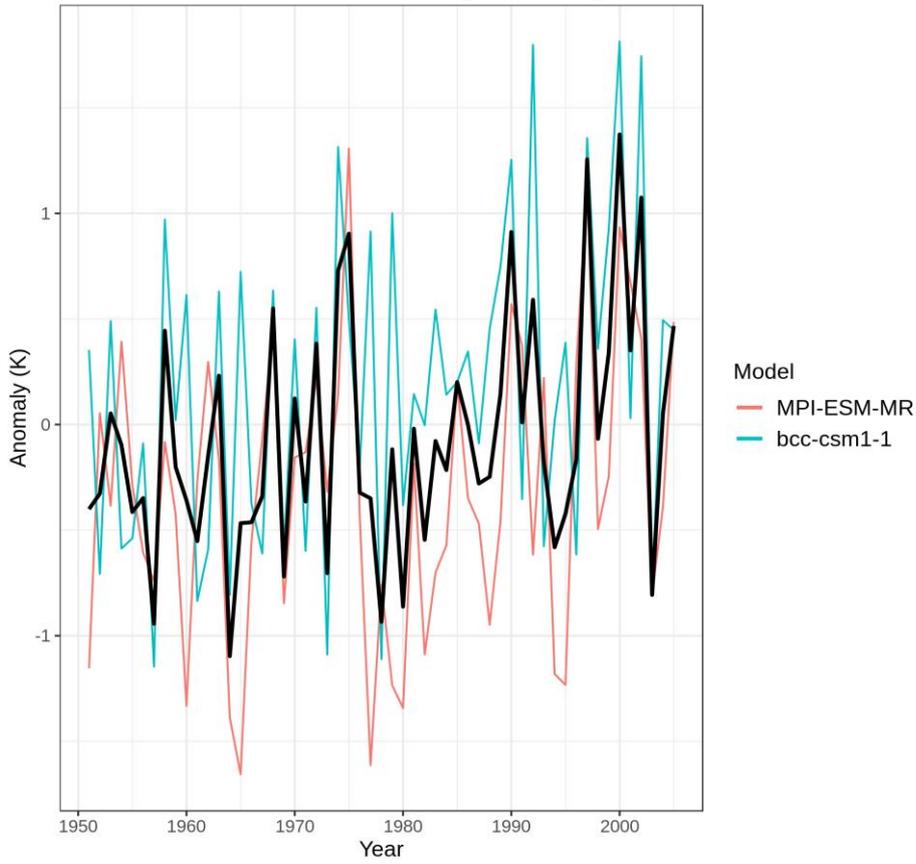


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Figure 19. Linear regression over the 500hPa 500 hPa geopotential height [m] of the first North Atlantic EOF (i.e. the North Atlantic Oscillation, NAO) over the 1979-2008-2005 DJF period for (left) CMIP5 MPI-ESM-MR historical r1i1p1 run (center) ERA-Interim Reanalysis and (right) their differences. The variance explained is reported on the top of each panel. It is possible to see how the NAO is well represented by MPI-ESM-LR, although the variance explained is underestimated and the northern center of action, which is found close to Iceland in reanalysis, is westward displaced over Greenland. Produced with recipe\_miles\_eof.yml, see details in Section 3.2.5.3.

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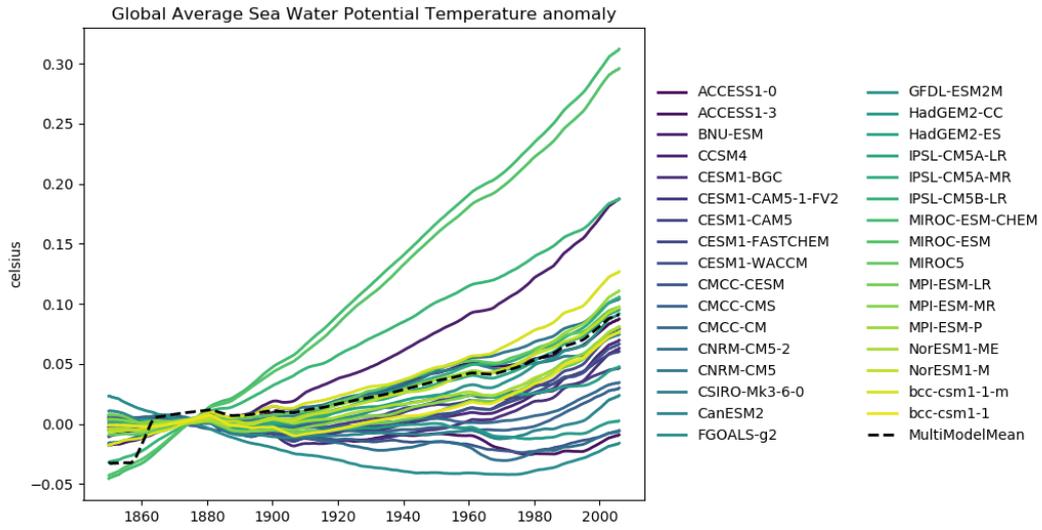
Nino3.4 index for tos on Dec-Feb (1950-2005)



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Figure 20. Time series of the standardized sea surface temperature (tos) area averaged over the Nino 3.4 region during the boreal winter (December-January-February). The time series correspond to the MPI-ESM-MR (red) and BCC-CSM1-1 (blue) models and their mean (black) during the period 1950-2005 for the ensemble ~~recipe\_combined\_indices.yml~~ of the historical simulations. Produced with *recipe\_combined\_indices.yml*, see details in Section 3.2.5.4.

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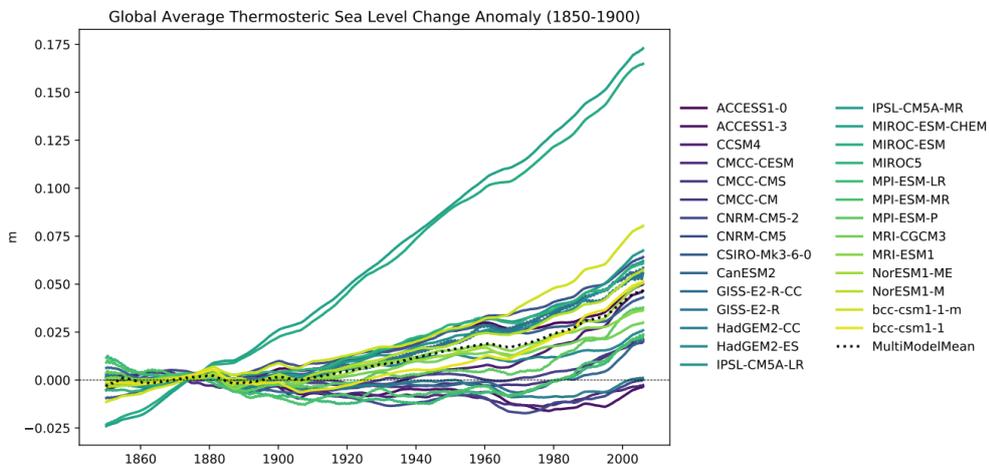
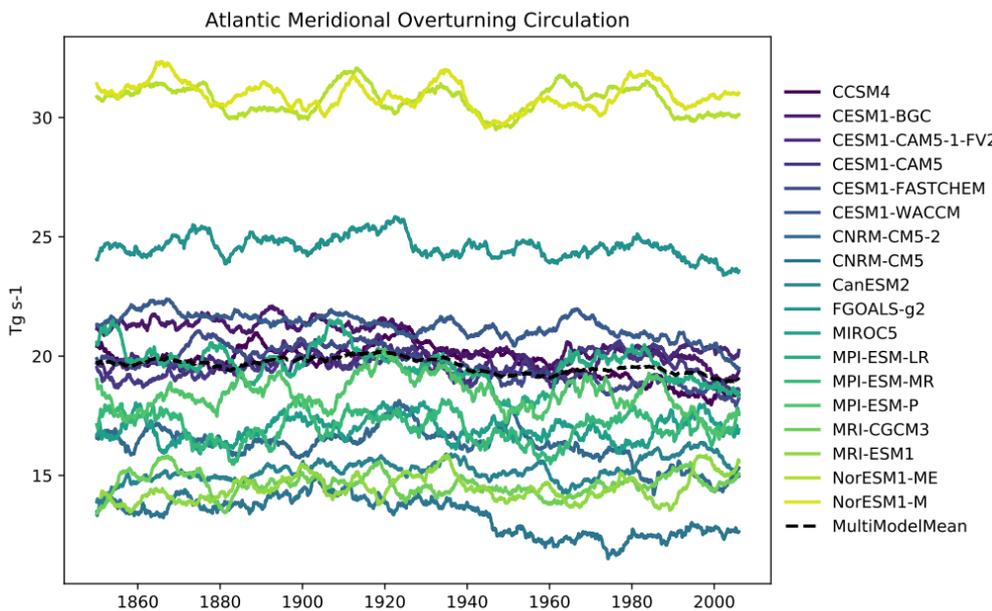
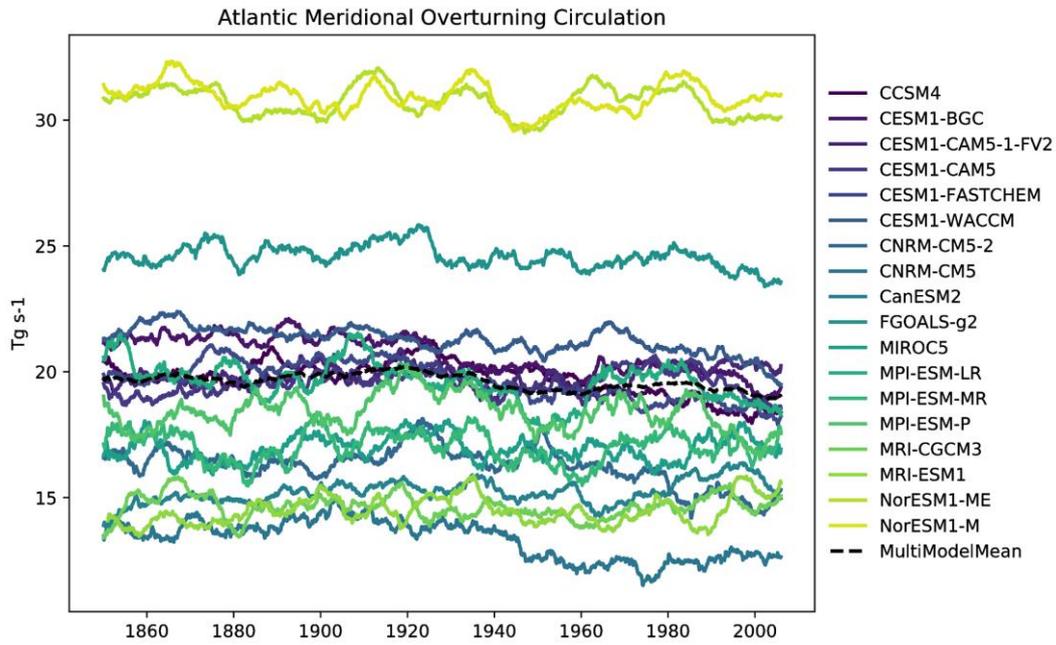


Figure 21. The volume weighted global-mean temperaturethermosteric sea level change anomaly in several CMIP5 models, in the historical experiment, in the r1i1p1 ensemble member, with a 6 year moving average smoothing function. The anomaly is calculated against the mean of all years in the historical experiment before 1900. The multi-model mean is shown as a dashed line. Nearly all CMIP5 models show an increase in the mean temperature of the ocean over the historical period. Produced with recipe\_ocean\_scalar\_fields.yml described in Section 3.3.1.

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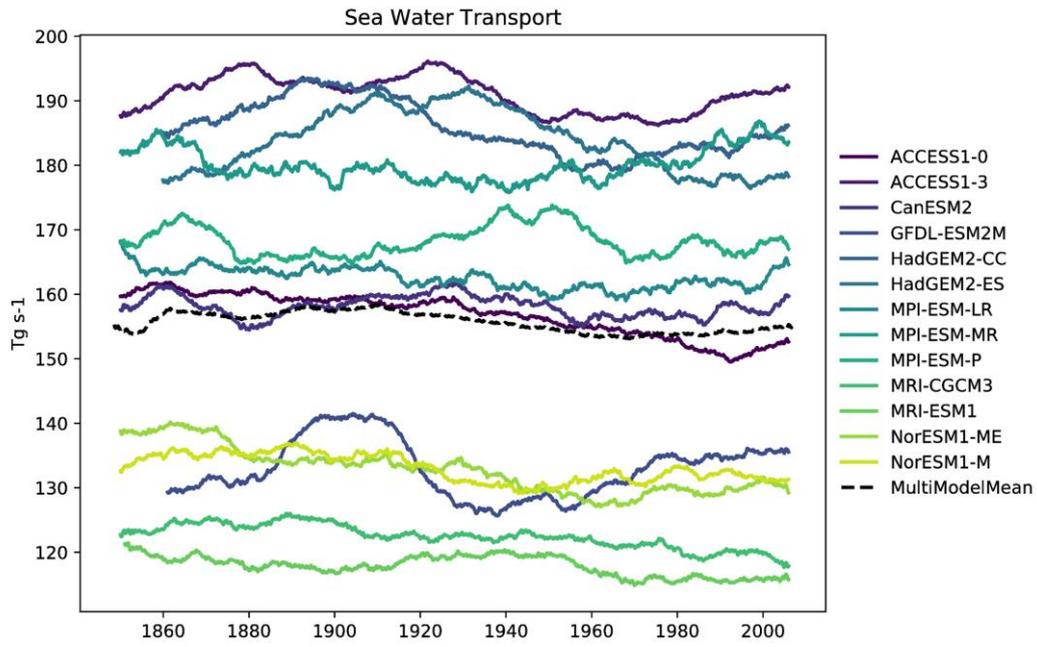
1450 **Figure 22.** The Atlantic Meridional Overturning Circulation (AMOC) in several CMIP5 models, in the historical experiment, in the r4i1p1 ensemble member, with a 6 year moving average smoothing function. The multi-  
 1455 **model mean is shown as a dashed line. The AMOC indicates the strength of the northbound current and this current transfers heat from tropical water to the North Atlantic. All CMIP5 models show some interannual variability in the AMOC behaviour, but it is not clear whether the decline in the multi model mean over the historical period is statistically significant.** Produced with `recipe_ocean_amoc.yml` described in Section 3.3.1.

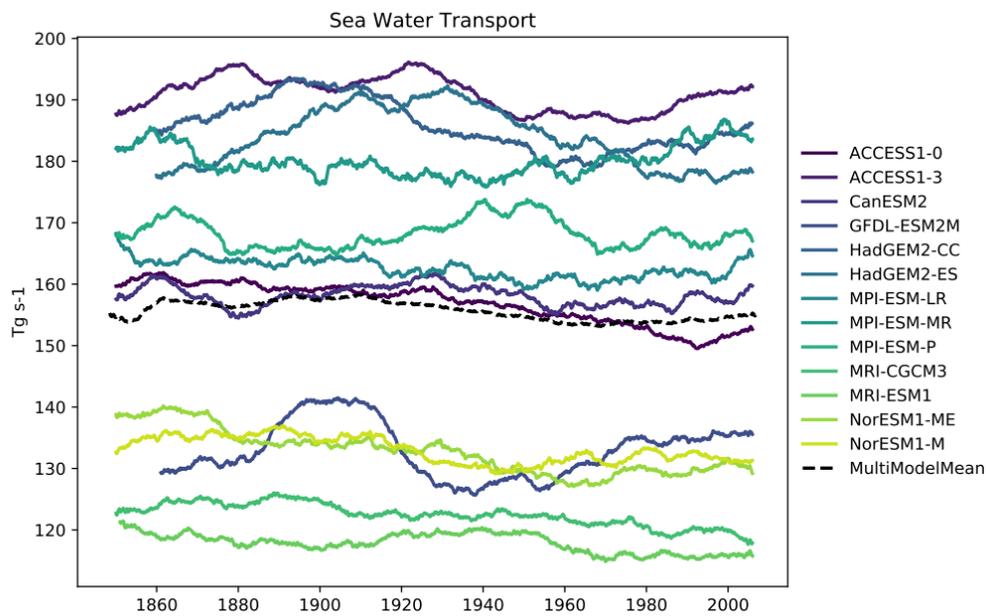
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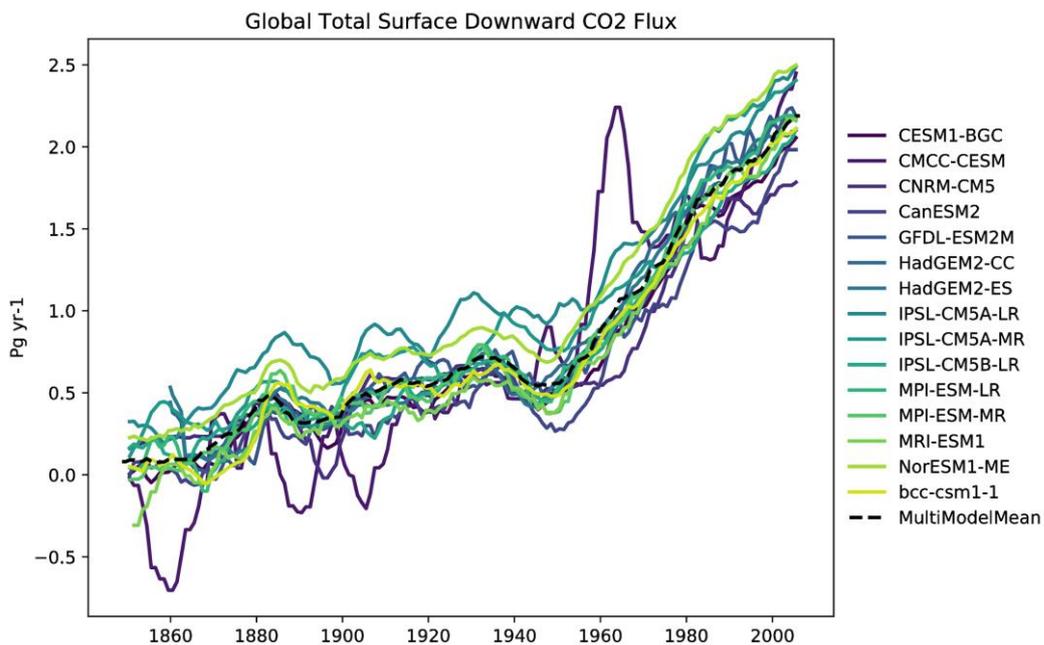
Figure 23. The Antarctic circumpolar current calculated through Drake Passage for a range of CMIP5 models in the historical experiment in the r4i1p1 ensemble member, with a 6 year moving average smoothing function. The multi-model mean is shown as a dashed line. The ACC was recently measured through the Drake Passage at  $173.3 \pm 10.7 \text{ Sv}$  (Donohue et al., 2016), and four of the CMIP5 models fall within this range. Produced with `recipe_ocean_amoc.yml` described in Section 3.3.1.

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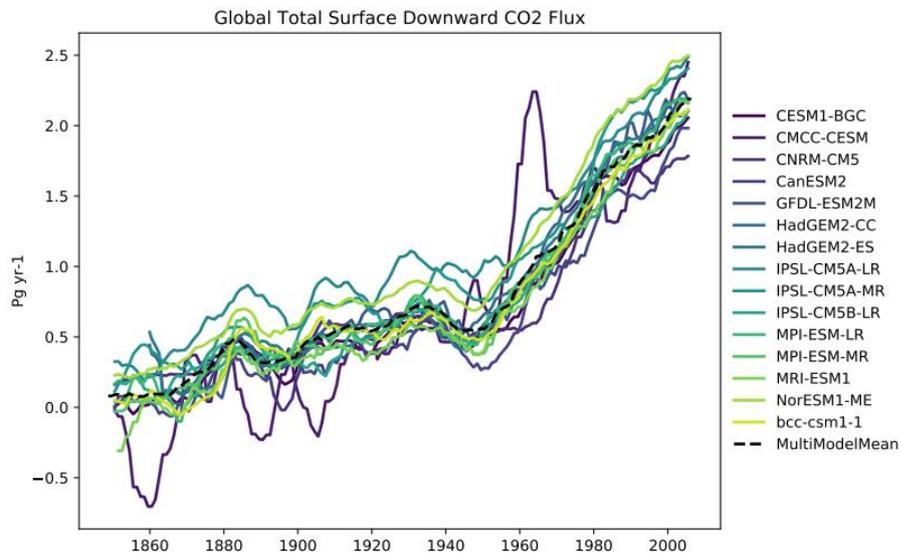


Figure 24. The global total air to sea flux of CO<sub>2</sub> for a range of CMIP5 models in the historical experiment in the r1i1p1 ensemble member, with a 6 year moving average smoothing function. The multi-model mean is shown as a dashed line. These models agree very closely on the behaviour of the air to sea flux of CO<sub>2</sub> over the historical period; all models show an increase from close to zero, and rising up to approximately 2 Pg of Carbon per year by the start of the 21<sup>st</sup> century. Produced with *recipe\_ocean\_scalar\_fields.yml* described in Section 3.3.1.

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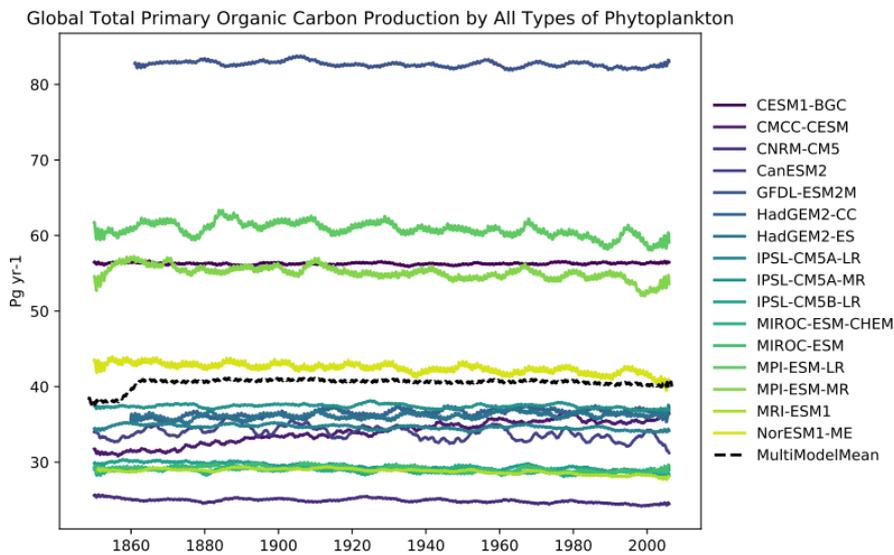
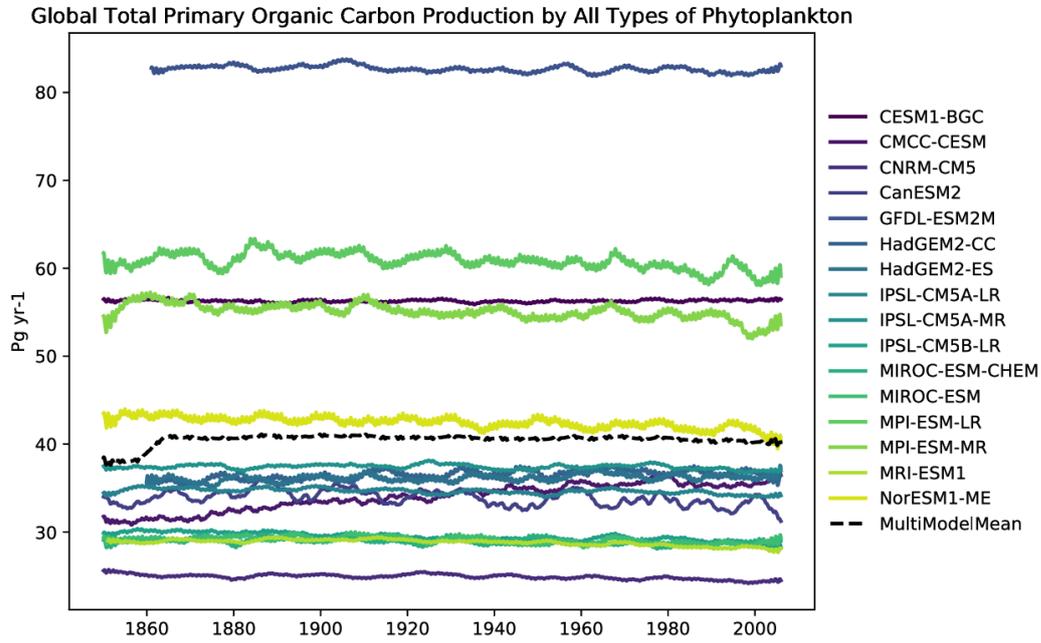
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1475 **Figure 25.** The global total integrated primary production from phytoplankton for a range of CMIP5 models in the historical experiment in the rHjrrllpl ensemble member, with a 6 year moving average smoothing function. The multi-model mean is shown as a dashed line. All CMIP5 models show little inter-annual variability in the integrated marine primary production, and there is no clear trend in the multi model mean. Produced with recipe\_ocean\_scalar\_fields.yml described in Section 3.3.1.

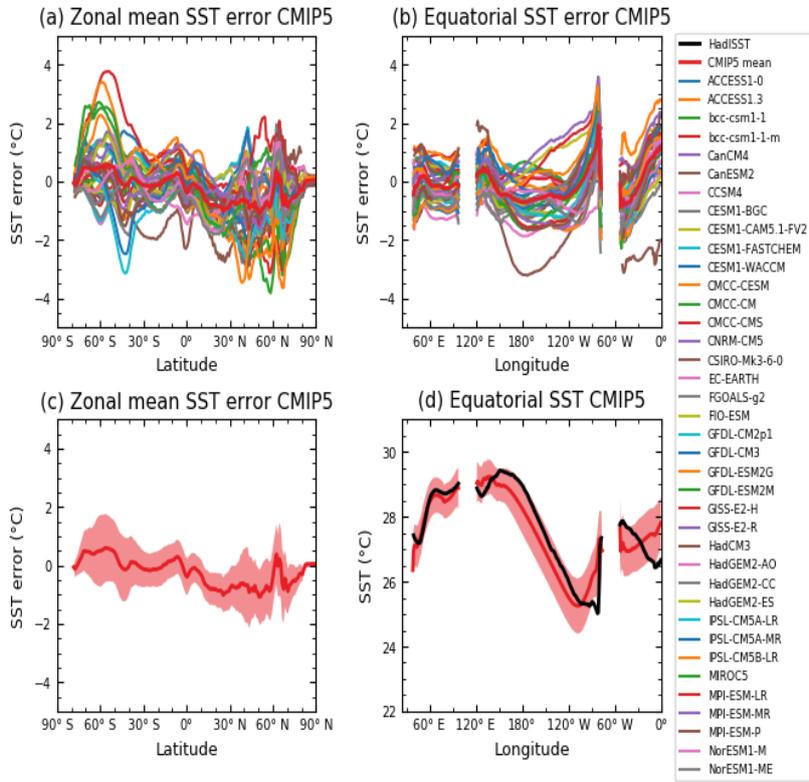
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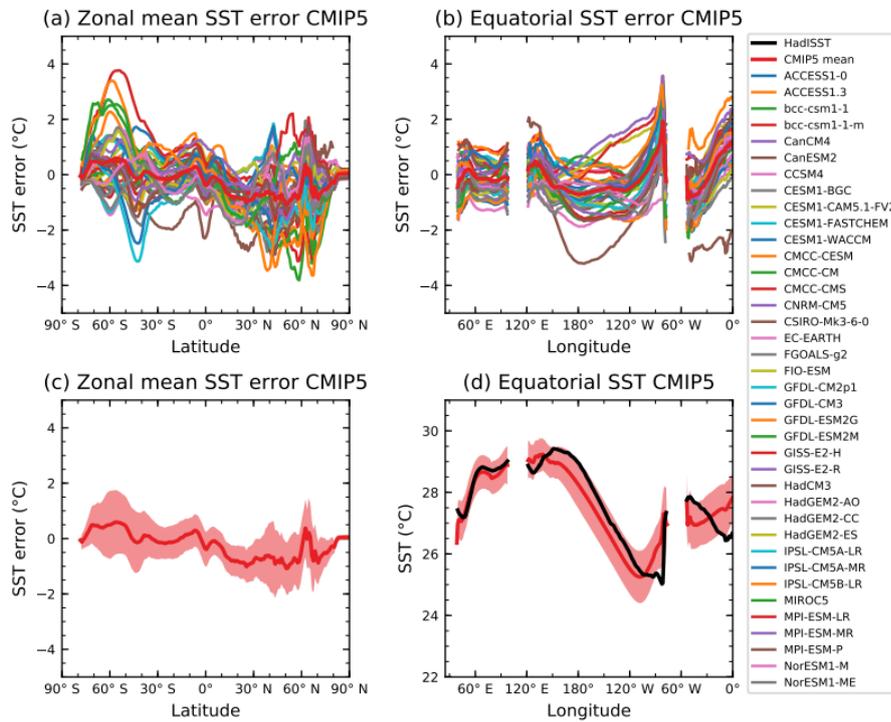


Figure 26. (a) Zonally averaged sea surface temperature (SST) error in CMIP5 models. (b) Equatorial SST error in CMIP5 models. (c) Zonally averaged multi-model mean SST error for CMIP5 together with inter-model standard deviation (shading). (d) Equatorial multi-model mean SST in CMIP5 together with inter-model standard deviation (shading) and observations (black). Model climatologies are derived from the 1979-1999 mean of the historical simulations. The Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) (Rayner et al., 2003) observational climatology for 1979-1999 is used as a reference for the error calculation (a), (b), and (c); and for observations in (d). This figure is a reproduction of Fig. 9.14 of AR5 and shows the overall good agreement of the CMIP5 models among themselves as well as compared to observations, but also highlights the global areas with largest uncertainty and biggest room for improvement. This is an important benchmark for the upcoming CMIP6 ensemble of models. It is produced as part of recipe\_flato13ipcc.yml and documented in Section Updated from Fig. 9.14 of IPCC WG I AR5 Chapter 9 (Flato et al., 2013) and produced with recipe\_flato13ipcc.yml, see details in 3.3.1.

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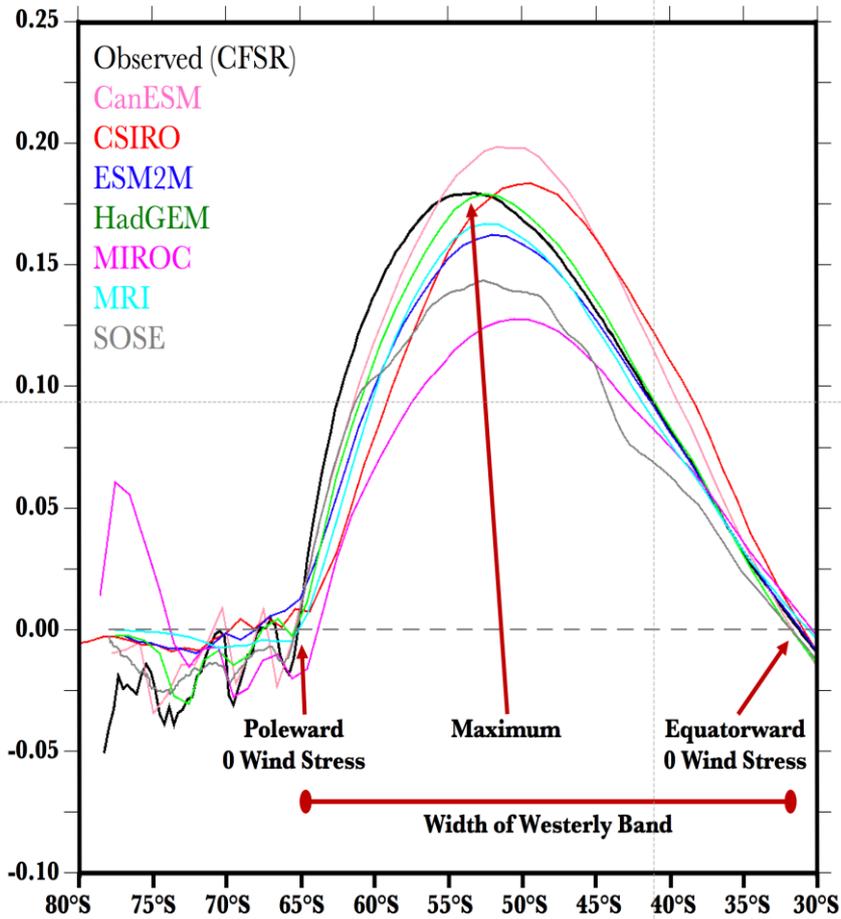


Figure 27. The zonal and annual means of the zonal wind stress ( $N/m^2$ ) for the reanalysis, six of the CMIP5 simulations and the BSOSE state estimate—note that each of the model simulations (colors) and B-SOSE (gray) have the peak wind stress equatorward of the observations (black). Also shown are the latitudes of the observed “poleward zero wind stress” and the “equatorward zero wind stress” which delineate the “width of the westerly band” that is highly correlated with total heat uptake by the Southern Ocean. Enhanced from figure produced by *recipe\_russell18jgr.yml*. see Section 3.3.2. ~~For further discussion of this figure, see the original in Russell et al. (2018).~~ For further discussion of this figure, see the original in Russell et al. (2018).

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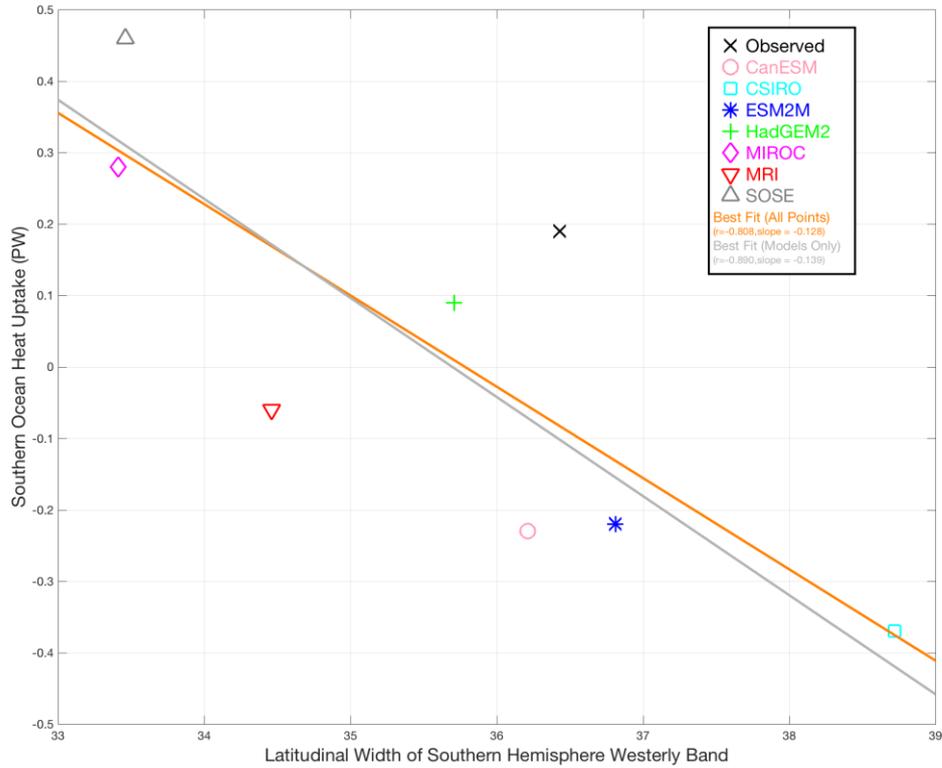
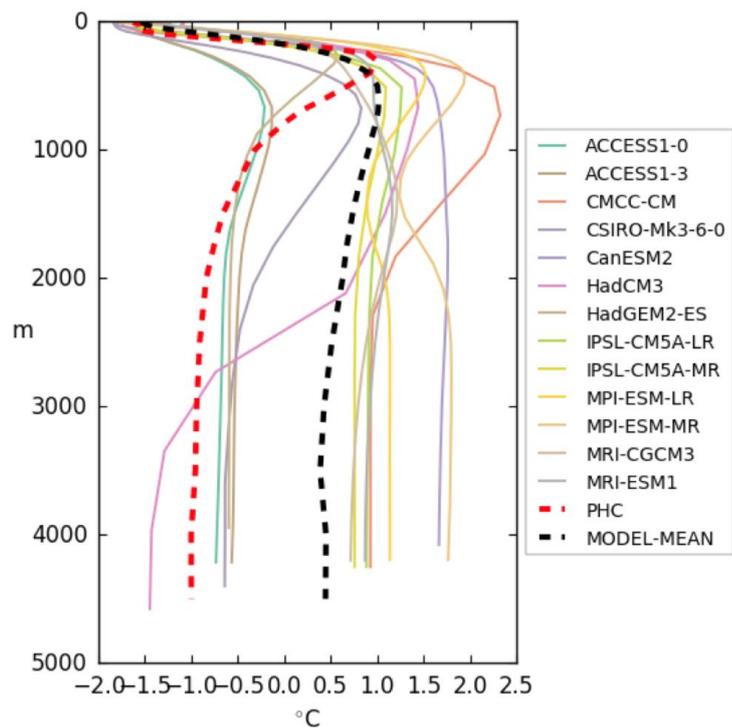
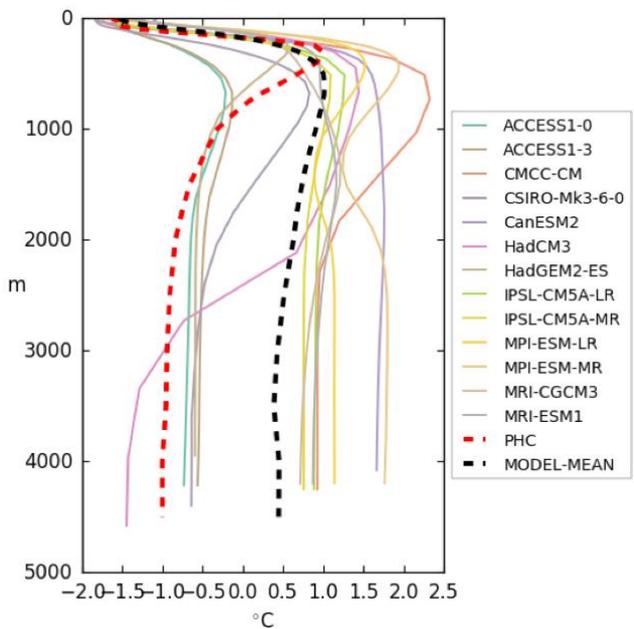


Figure 28. Scatter plot of the width of the Southern Hemisphere westerly wind band (in degrees of latitude) against the annual-mean integrated heat uptake south of 30°S (in PW—negative uptake is heat lost from the ocean), along with the “best fit” linear relationship for the models and observations shown. Enhanced from figure produced by *recipe\_russell18jgr.yml*. see in Section 3.3.2. For further discussion of this figure, see the original in [Russell et al. \(2018\)](#). The calculation of the “observed” heat flux into the Southern Ocean is described in the text. The correlation is significant above the 98% level based on a simple t test.

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Figure 29. Mean (1970-2005) vertical potential temperature distribution in the Eurasian basin for CMIP5 coupled ocean models, PHC3 climatology (dotted red line) and multi-model mean (dotted black line). Models tend to overestimate temperature in the interior of the Arctic Ocean and have too deep Atlantic water depth. Similar to Figure 7 of Heak, et al. 2016 Ilcak et al. (2016) and produced with recipe\_arctic\_ocean.yml, see details in Section 3.3.3.

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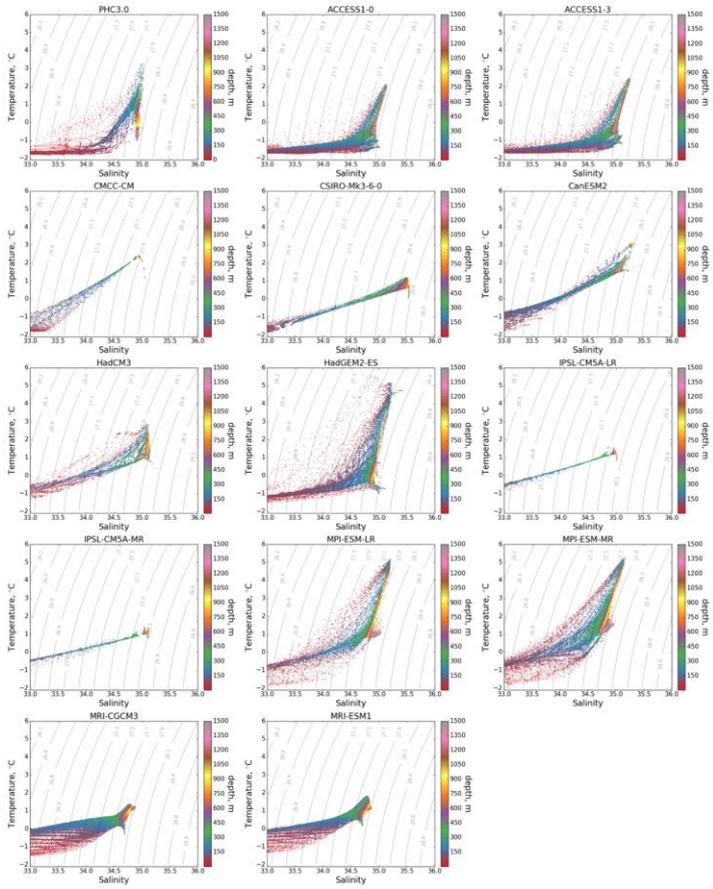
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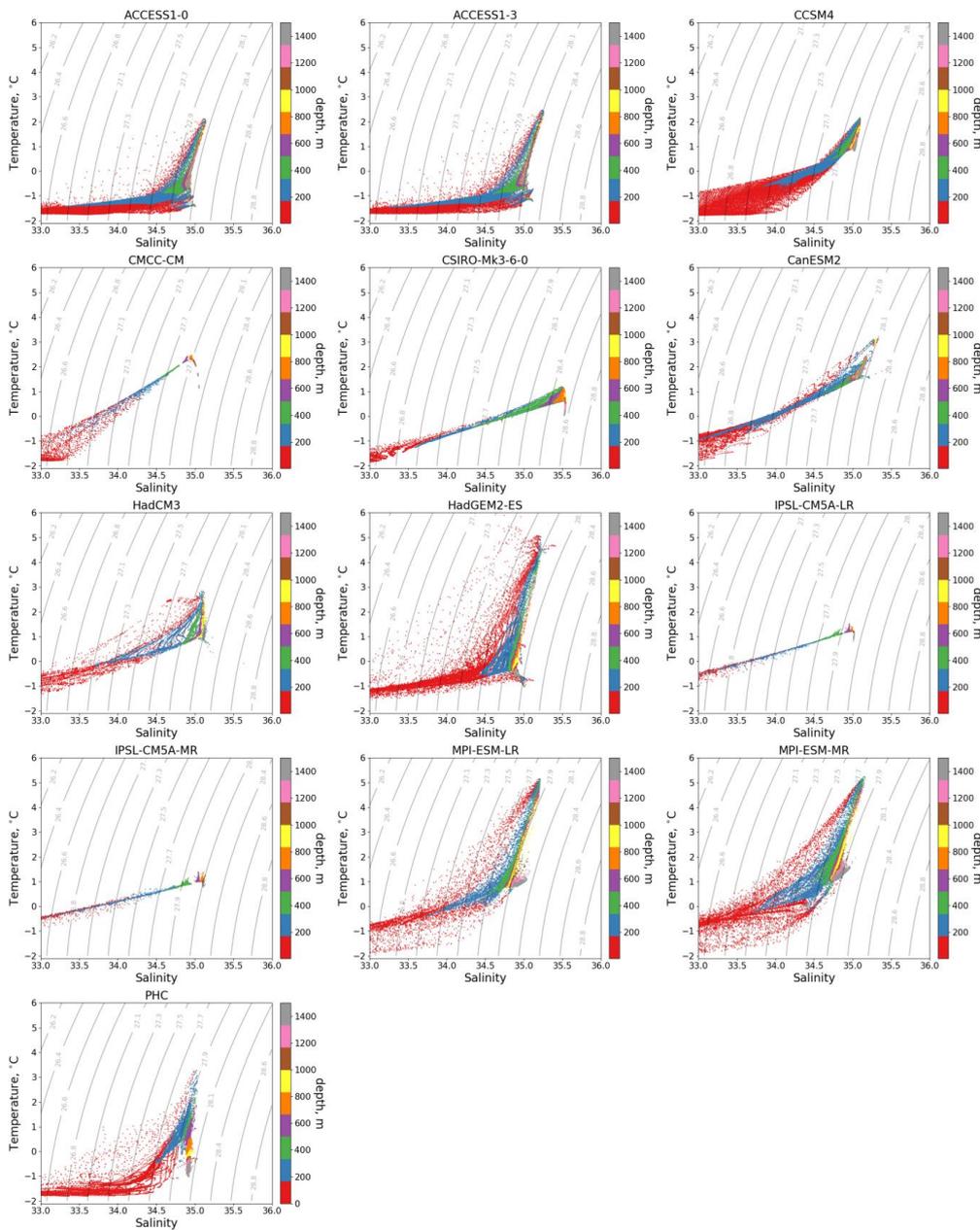
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**Figure 30. Mean (1970-2005) T-S diagrams for Eurasian Basin of the Arctic Ocean. PHC3.0 shows climatological values for selected CMIP5 models and PHC3.0 observations. Most models can't properly represent Arctic Ocean water masses and other have wrong values for temperature and salinity or miss specific water masses completely. Produced with recipe\_arctic\_ocean.yml, see details in Section 3.3.3.**

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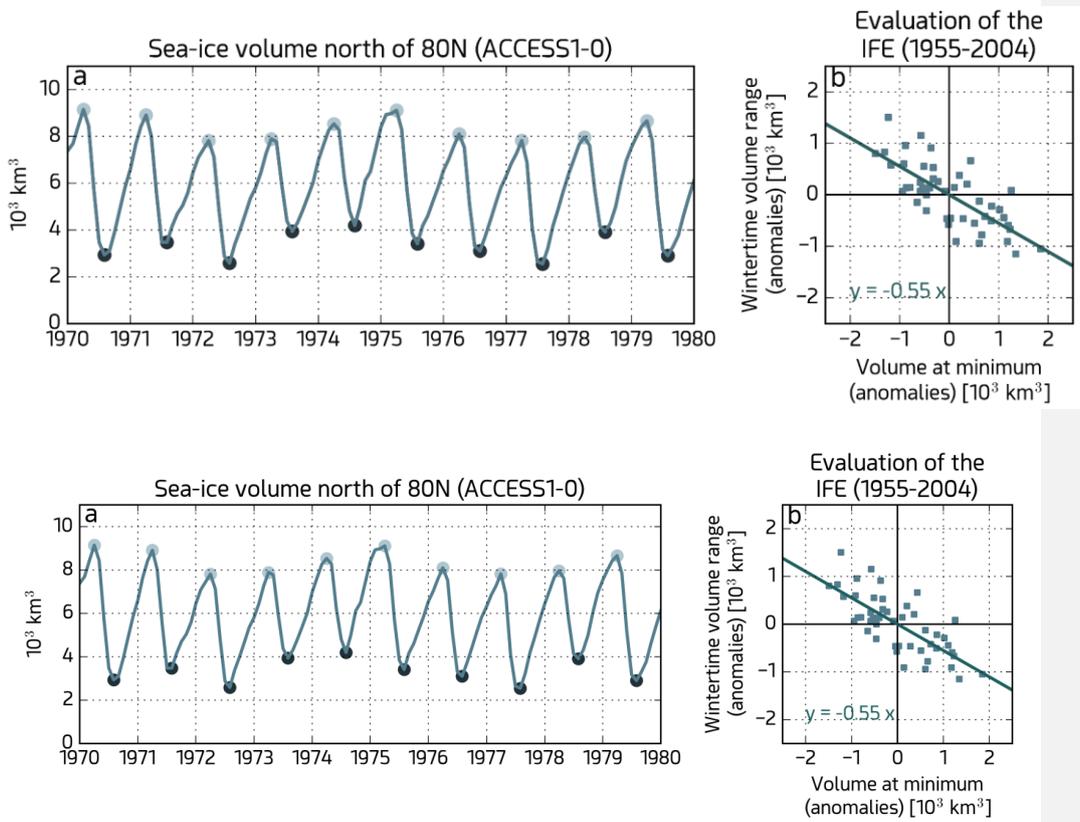
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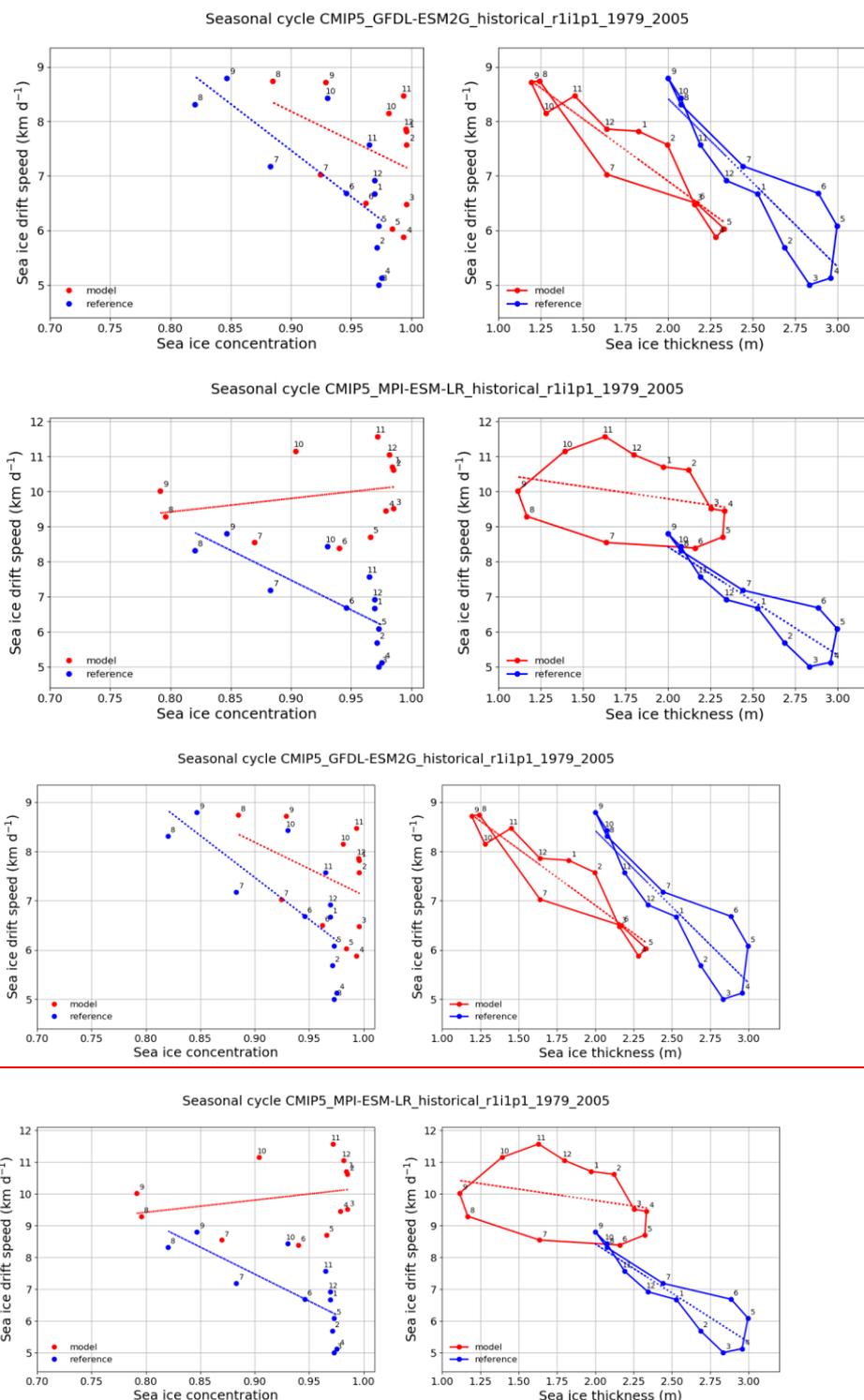
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**Figure 31. Quantitative evaluation of the Ice Formation Efficiency (IFE).** (a) Example time series (1970-1979) of the monthly mean Arctic sea-ice volume north of 80°N of one CMIP5 model (ACCESS1-0), with its annual minimum and maximum values marked with the dark and light dots, respectively. (b) Estimation of the IFE, defined as the regression between anomalies of sea-ice volume produced during the growing season (difference between one annual maximum and the preceding minimum) and anomalies of the preceding minimum. A value IFE = -1 means that the late-summer ice volume anomaly is fully recovered during the following winter (strong negative feedback damping all anomalies), while a value IFE = 0 means that the wintertime volume production is essentially decoupled from the late-summer anomalies (inexistent feedback). Similar to Extended Data Figure 7a-b of [Massonnet et al. \(2018\)](#) and produced with `recipe_seaice_feedback.yml`, see details in Section 3.3.4.

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Figure 32. Scatter plots of modelled (red) and observed (blue) monthly mean sea-ice drift speed against sea-ice concentration (left panels) and sea-ice thickness (right panels) temporally averaged over the period 1979–2005 and spatially averaged over the SCICEX box. Top panels show results from the GFDL-ESM2G model and bottom panels show results from the MPI-ESM-LR model (CMIP5 historical runs). Observations/reanalysis are shown in all panels

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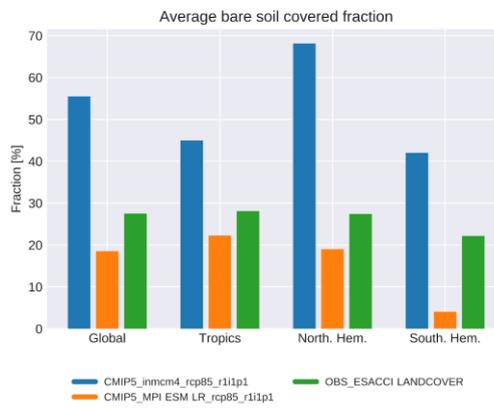
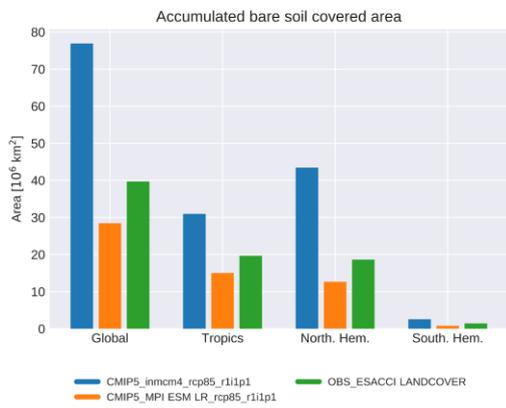
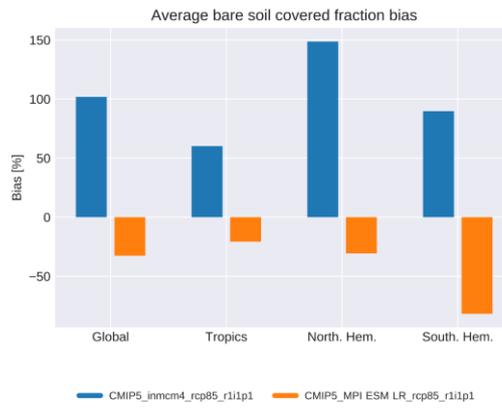
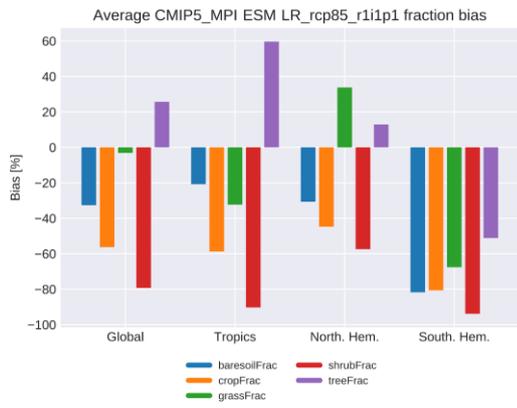
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(IABP for drift speed, OSI-450 for concentration, and PIOMAS for thickness). Numbers denote months. Dotted lines show linear regressions. ~~Results show that the GFDL-ESM2G model can reproduce the sea-ice drift speed concentration/thickness relationships compared to observations, with higher drift speed with lower concentration/thickness, despite the too thin ice in the model, while the MPI-ESM-LR model cannot reproduce this result. This figure was produced in a similar way as Figure 4 of Docquier et al. (2017). This figure was produced in a similar way as Figure 4 of Docquier et al. (2017), with `recipe_sea_ice_drift.yml`, see details in Section 3.3.4.~~

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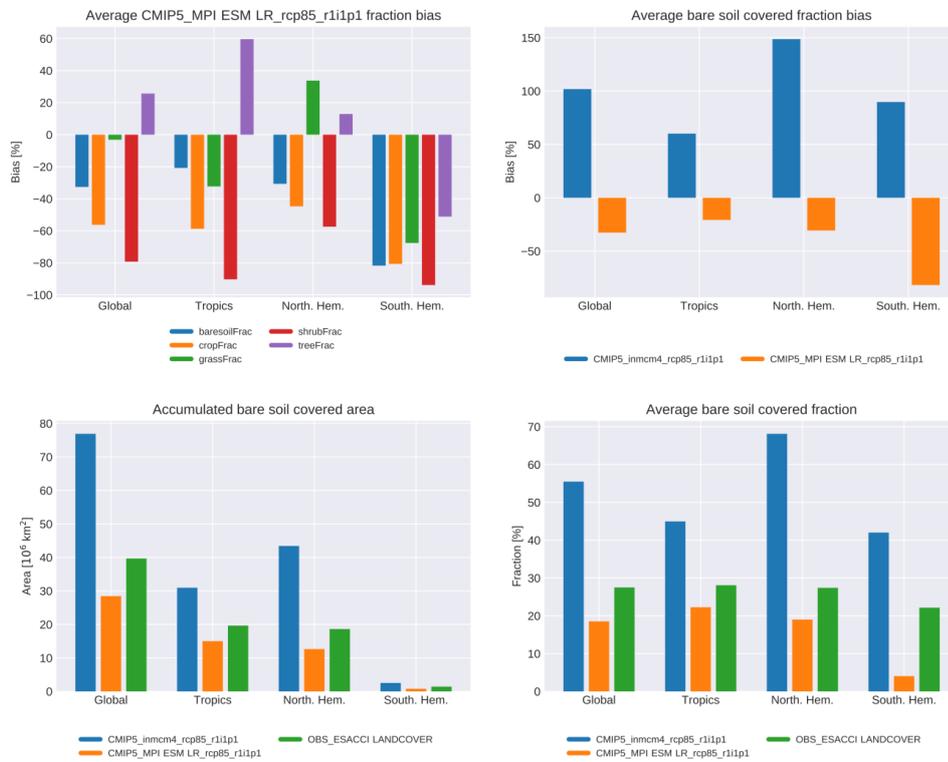
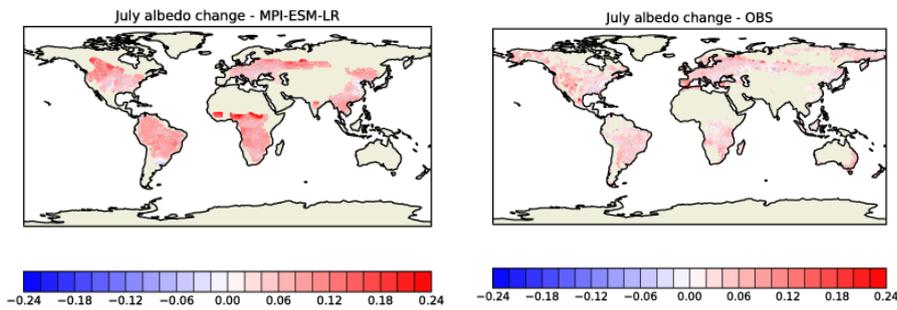


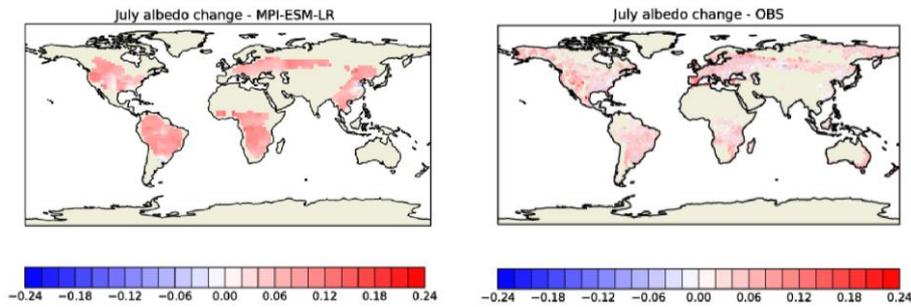
Figure 33. The panels show plots produced by the metric recipe *landcover.yml* using model output from historical CMIP5 simulations (period 2008-2012) of the ESMs MPI-ESM and INMCM4 compared to land cover observations provided by ESA CCI for different regions. The upper two panels display the relative bias [%] between the models  $M$  and the observations for observation  $O$  computed as  $(M - O) / O \times 100$ . This can be visualized either for one model (i.e. MPI-ESM) and several land cover types (upper, left) or for one land cover type (i.e. bare soil fraction) and all selected models (upper, right). The lower plots display the accumulated area [10<sup>6</sup> km<sup>2</sup>] covered by a specific land cover type (i.e. bare soil fraction) for given regions (lower, left) as well as the average cover fraction [%] (lower, right) for a selected land cover type (bare soil fraction) and all selected models and observations for different with respect to the total area of the regions. Thus, the landcover analysis provides a quick overview for major land cover types and the ability of different models to reproduce them. The metric is based on the analysis presented in Lauer et al. (2017) and Georgievski et al. (2018) and discussed in section Lauer et al. (2017) and Georgievski and Hagemann (2018) and discussed in Section 3.4.1.

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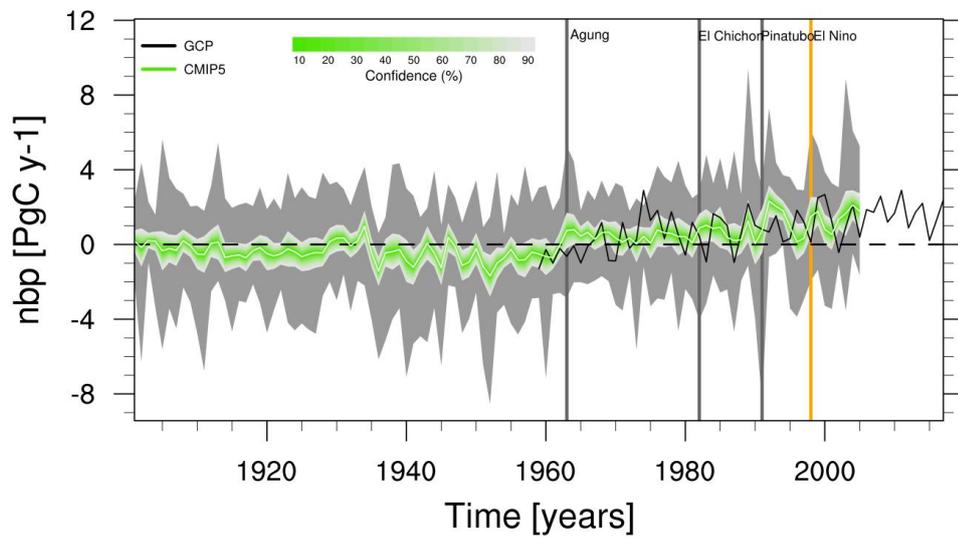
Figure 34. Albedo change due to a transition from landcover type 'tree' to 'crops and grasses' calculated through fitting, for each grid cell, a multiple linear regression model to the different land cover fractions (predictors) and albedo (predictant) within a window encompassing 5X5 grid cells centered over that grid cell of interest. Results are shown for (left) the MPI-ESM-LR model (2001-2005 July mean) and (right) the observational dataset from Duveiller et al. (2018) (2008-2012 July mean). July albedo difference between trees and crops or grasses is about at least twice as high in the MPI-ESM-LR model as in the observations, strongly suggesting that the simulated summer albedo increase from historical land cover changes is overestimated in this model.



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Figure 34. Potential albedo change due to a transition from landcover type 'tree' to 'crops and grasses' calculated through a multiple linear regression between the present-day land cover fractions (predictors) and albedo (predictands) within a moving window encompassing 5° x 5° grid cells. Results are shown for (left) the MPI-ESM-LR model (2001-2005 July mean) and (right) the observational dataset from Duveiller et al. (2018a) (2008-2012 July mean). Produced with *recipe\_landcoveralbedo.yml*, see details in Section 3.4.2 and in Lejeune et al. (2020).

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The results reveal that the July albedo difference between trees and crops or grasses is about at least twice as high in the MPI-ESM-LR model as in the observations, strongly suggesting that the simulated summer albedo increase from historical LCC is overestimated in this model. Produced with recipe\_landcover\_albedo.yml, see details in Section 3.4.2.

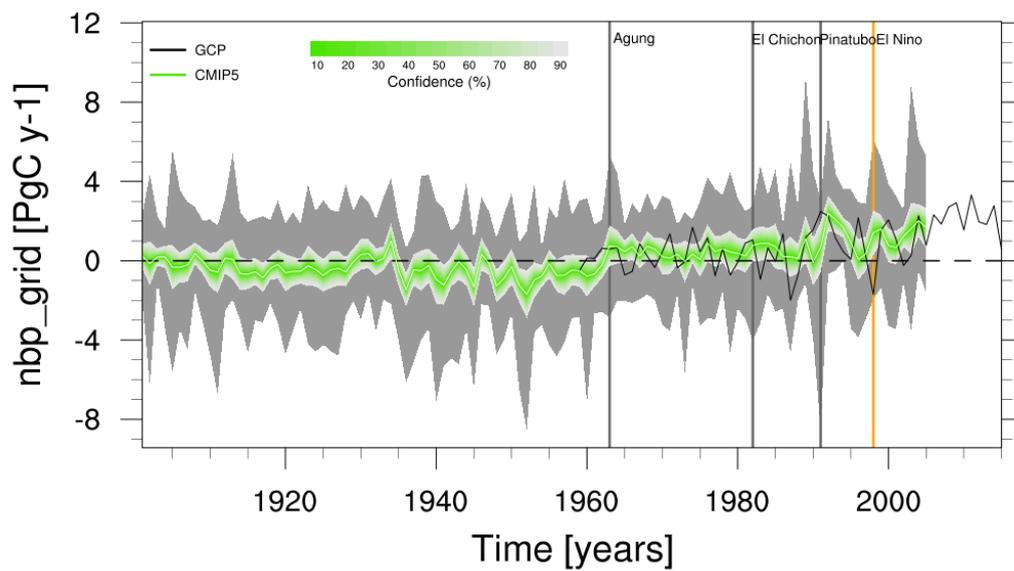


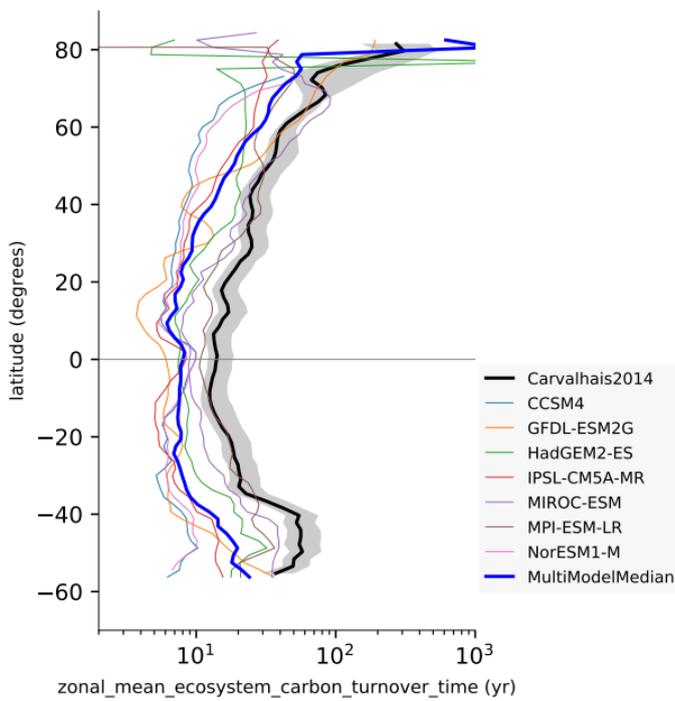
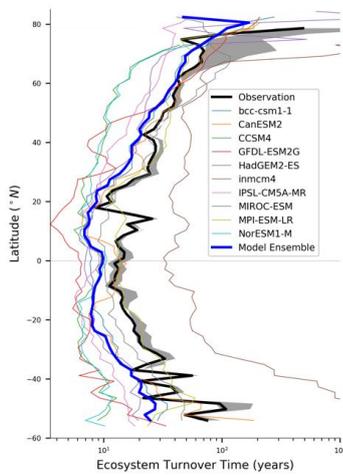
Figure 35. Timeseries plot of the global land-atmosphere CO<sub>2</sub> flux (*nbp*) for CMIP5 models compared to observational estimates ~~by from GCP, Le Quere et al. (2018)) (Le Quere et al., 2018)~~ (black line). Gray shading represents the range of the CMIP5 models, green shading shows the confidence interval evaluated from the CMIP5 ensemble standard deviation assuming a *t* distribution centered at the multi-model mean (white line). Vertical lines indicate volcanic eruptions (grey) and El Niño events (orange). ~~As positive values correspond to a carbon uptake of the land, the plot shows a slight increase in the land carbon uptake over the whole period. Similar to Figure 5 of Anav et al. (2013)~~ Similar to Figure 5 of Anav et al. (2013) and produced with *recipe\_anav13jclim.yml*, see details in Section 3.5.1.

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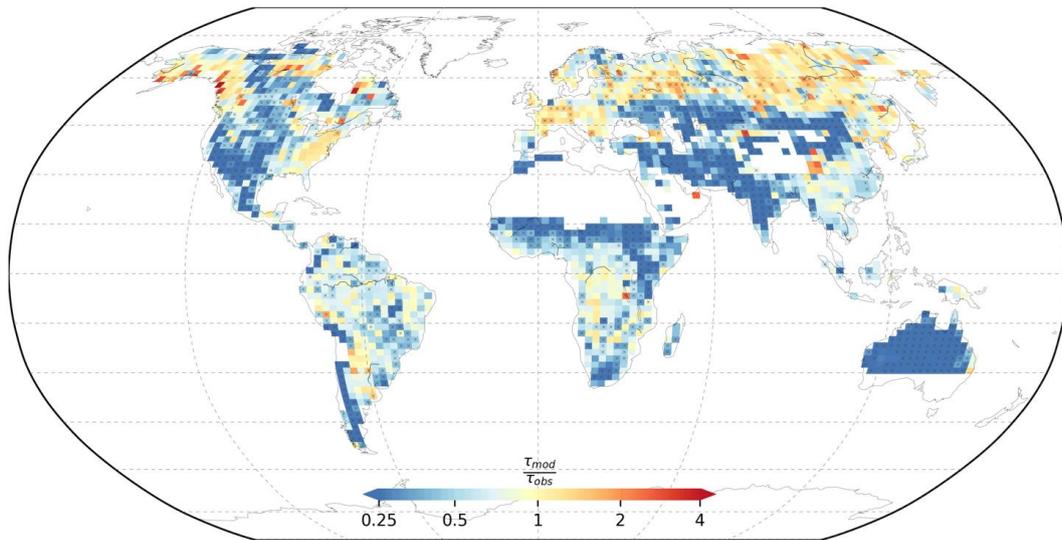


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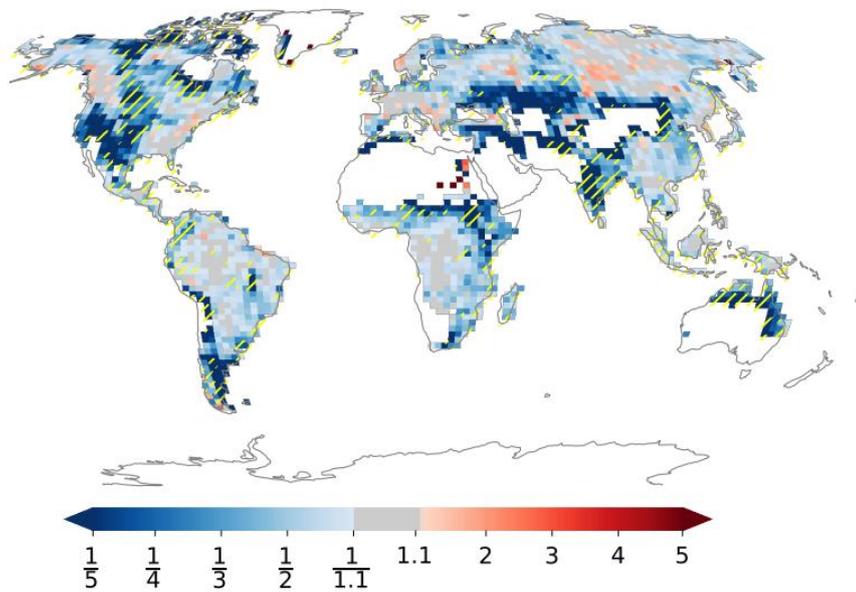
Figure 36. Zonal distribution of ecosystem turnover time of carbon (in years). The zonal values are calculated as the ratio of total carbon stock and the gross primary productivity per latitude. The individual models are plotted in coloured thin lines, the multimodel ensemble in thick blue line, and the observation-based estimate (Carvalhais et al., 2014) (Carvalhais et al., 2014) in thick black line with shaded region showing the observational uncertainty. The median of all models is adopted as the multimodel ensemble. Note the logarithmic horizontal axis. The models follow the gradient of increasing turnover times of carbon from tropics to higher latitudes, much related to temperature decreases, as observed in observations. However, for most of the latitudinal bands, with the exception of one model, most simulations reveal turnover times that are faster than the observations. Produced with recipe\_carvalhais2014nat.yml, see details in Section 3.5.2.

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multimodel bias and agreement (-)  
ecosystem\_carbon\_turnover\_time



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Figure 37. Global distribution of the biases in the multi-model ensemble ecosystem turnover time of carbon (years) and the multi-model agreement in CMIP5 models. The bias is calculated as the ratio between multi-model ensemble and observation-based estimate (Carvalhois et al., 2014). The stippling indicates the regions where only two or fewer models (out of 10) are within the range of observational uncertainties (5<sup>th</sup> and 95<sup>th</sup> percentiles). Produced with recipe\_carvalhois2014nat.yml, see details in Section 3.5.2. A generalized underestimation of turnover times of carbon is apparently dominant in water-limited regions. In most of these regions most models show estimates outside of the observational uncertainties (stippling). These results challenge the combined effects of water and temperature limitations on turnover times of carbon and suggest the need for improvement on the description of the water cycle in terrestrial ecosystems. Produced with recipe\_carvalhois2014nat.yml, see details in Section 3.5.2.

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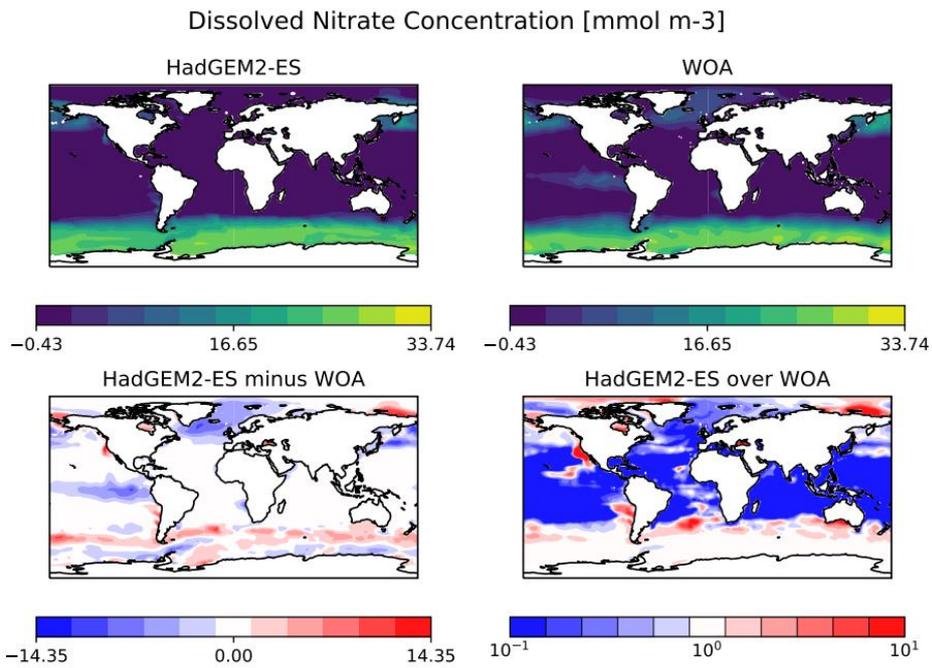
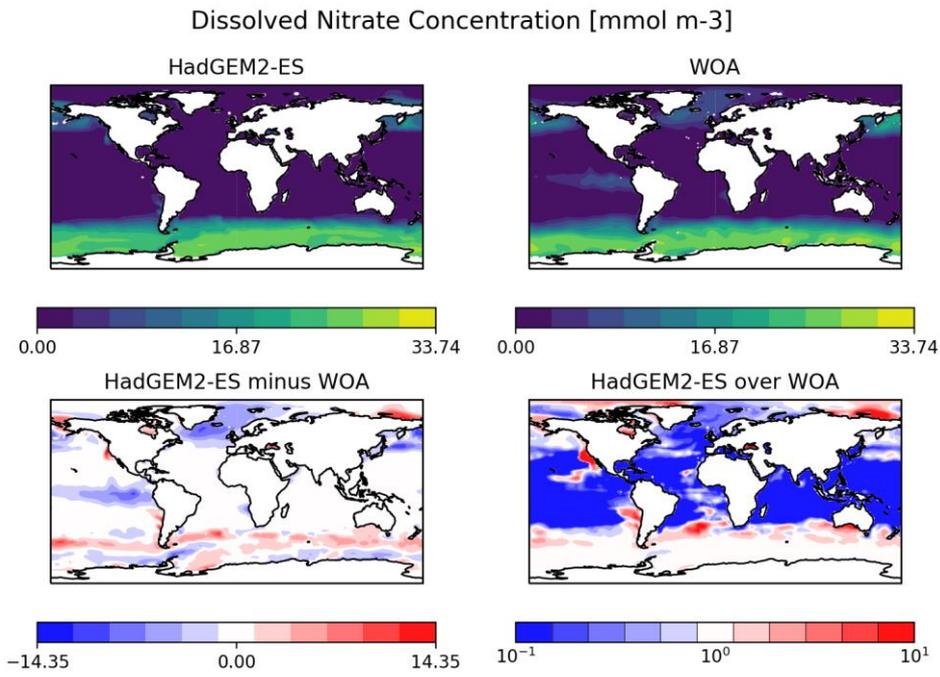


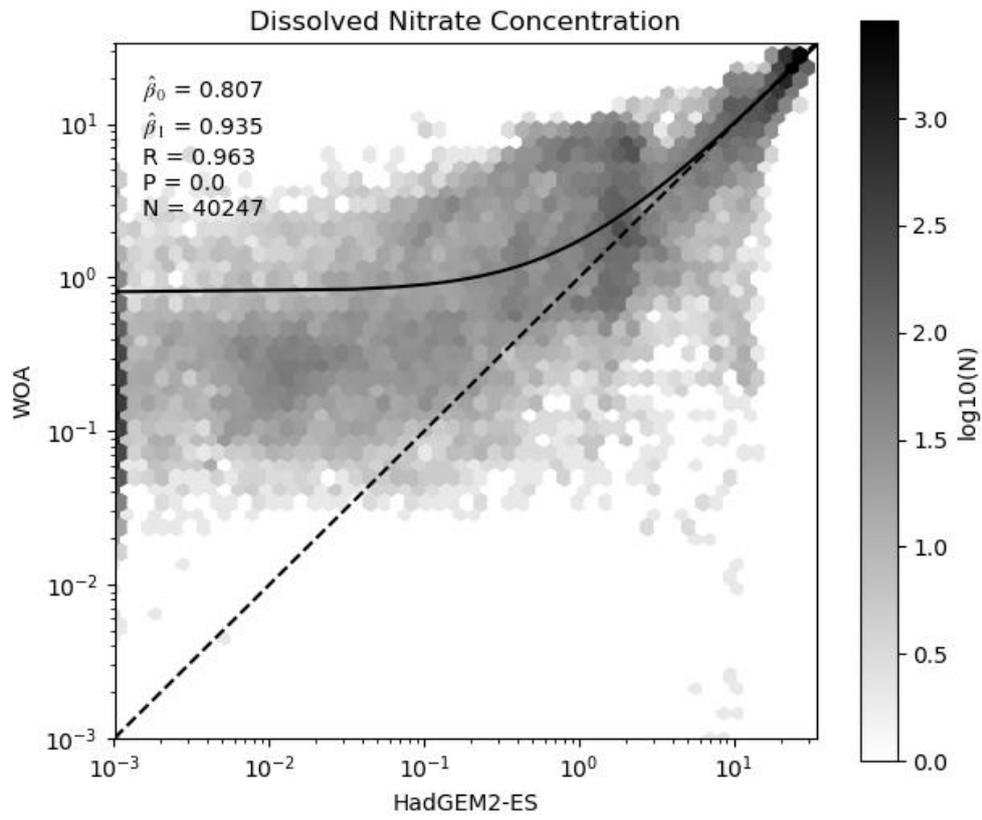
Figure 38. The surface dissolved nitrate concentration in the CIP5 HadGEM2-ES model compared against the World Ocean Atlas 2013 nitrate. The top two figures show the surface fields, the bottom two show the difference and the quotient between the two datasets. ~~This figure highlights that the HadGEM2-ES model is proficient at~~

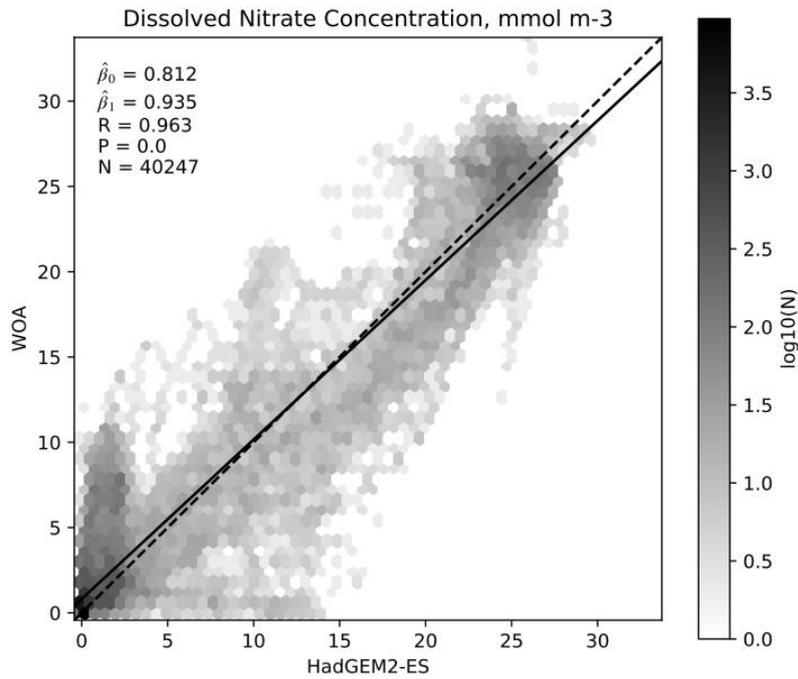
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~~reproducing the surface nitrate concentration in the Atlantic ocean, and in mid latitudes, but may struggle to reproduce observations at high latitudes.~~ Produced with *recipe\_ocean\_bgc.yml*, see details in Section 3.5.3.

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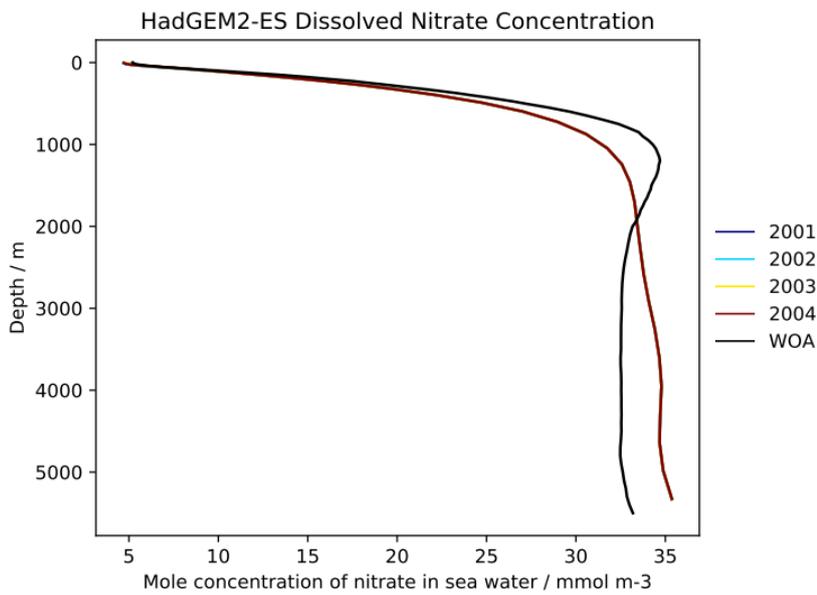
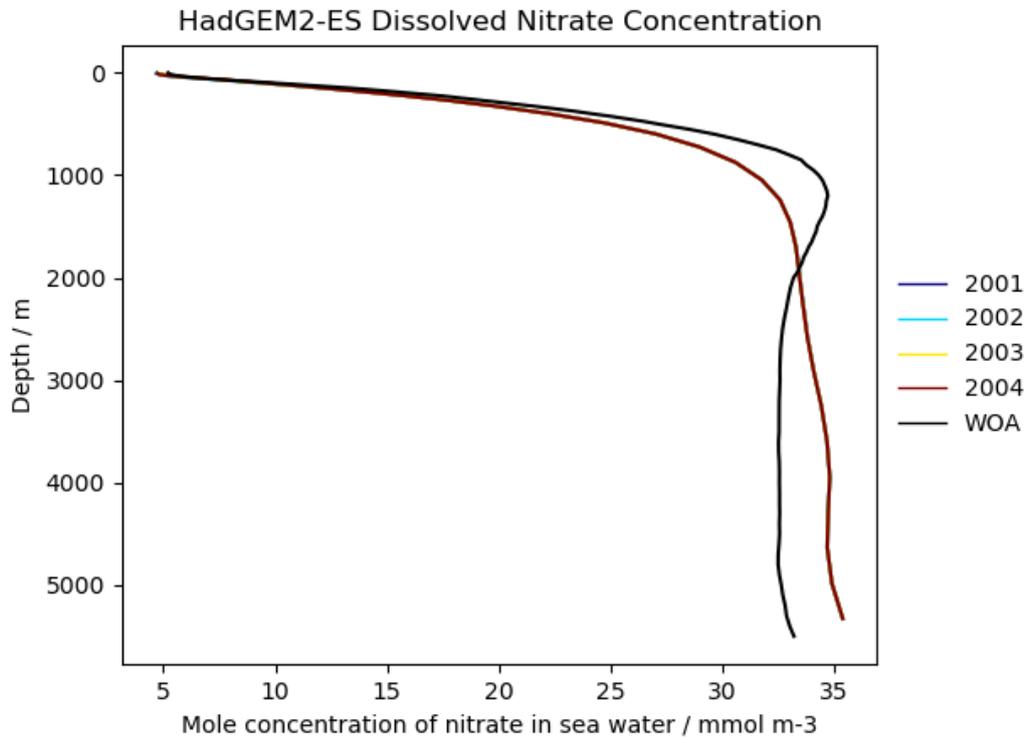


1635 **Figure 39.** The surface dissolved nitrate concentration in the CMIP5 HadGEM2-ES model [ $\log_{10}(N)$ ] compared  
 1640 against the World Ocean Atlas 2013 nitrate. This figure shows the paired model and observational datasets. A linear  
 regression line of best fit is shown as a black line. A dashed line indicates the 1:1 line. The result of a linear regression  
 are shown in the top left corner of the figure, where  $\hat{\beta}_0$  is the intercept,  $\hat{\beta}_1$  is the slope, R is the correlation, P is the P  
 value, and N is the number of data point pairs. ~~As both the fitted slope and the correlation coefficient are near one,  
 the HadGEM2-ES simulation excelled at reproducing the observed values of the surface nitrate concentration.~~  
 Produced with *recipe\_ocean\_bgc.yml*, see details in Section 3.5.3.

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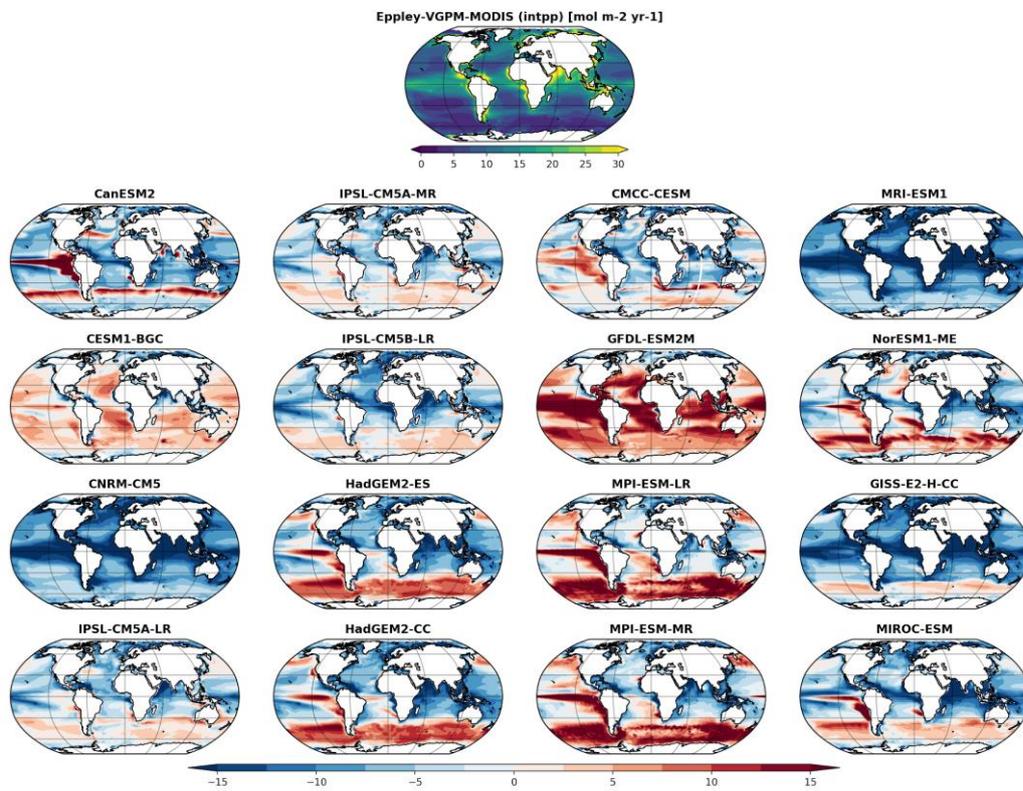
Figure 40. The global area-weighted average depth profile of the dissolved nitrate concentration in the CMIP5 HadGEM2-ES model and against the World Ocean Atlas 2013. This figure shows that while the model and the observations both show a similar overall depth structure, the model is not able to produce the observed maximum

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~~nitrate concentration at approximately 1000 m depth and overestimates the nitrate concentration deeper in the water column.~~ Produced with *recipe\_ocean\_bgc.yml*, see details in Section 3.5.3.

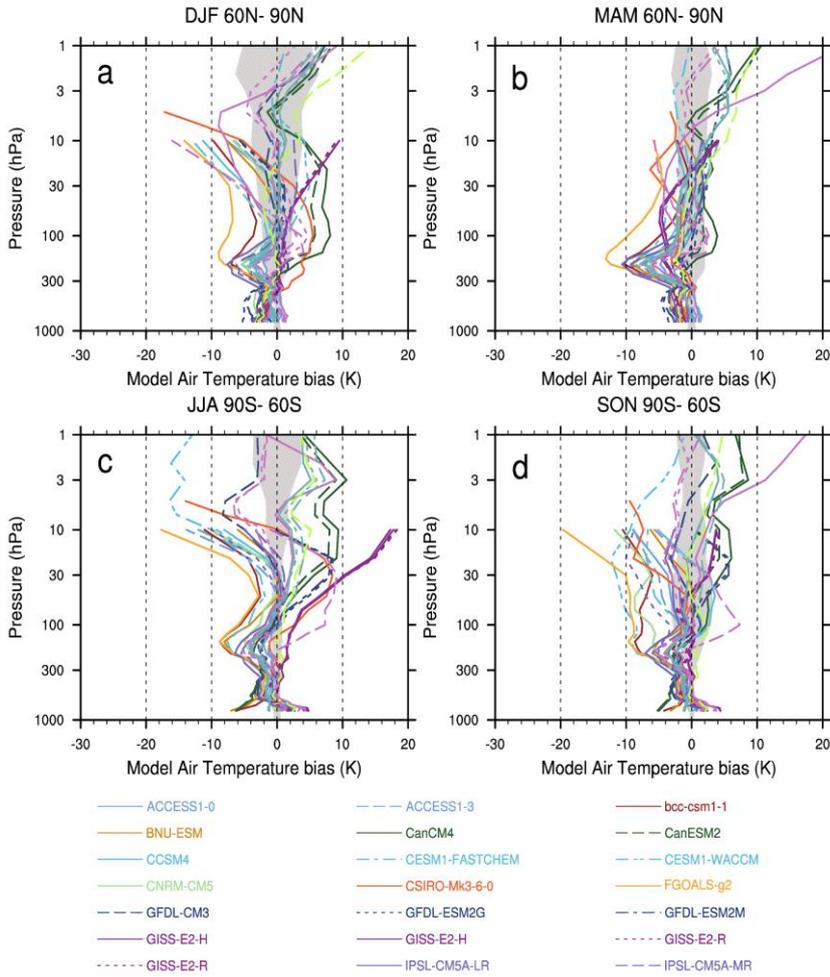
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Figure 41. Global maps of marine Primary Production as carbon (mol m-2 yr-1) estimated from MODIS satellite data using Eppley-VGPM algorithm (Top panel) and differences computed for 16 CMIP5 models data averaged over the period 1995-2004. **Systematic biases characterize all models mainly in the equatorial Pacific and Antarctic regions, in some cases with opposite sign, and coastal ocean productivity is generally underestimated with major deviations in the equatorial zone.** See Section 3.5.3 for details on *recipe\_ocean\_bgc.yml*.

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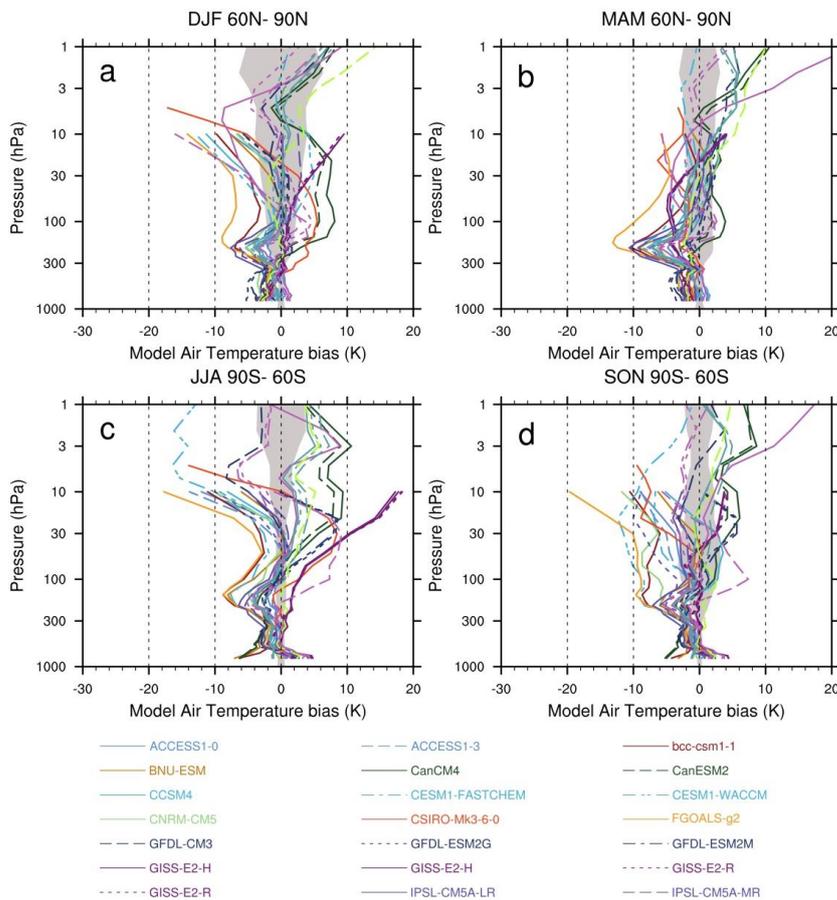
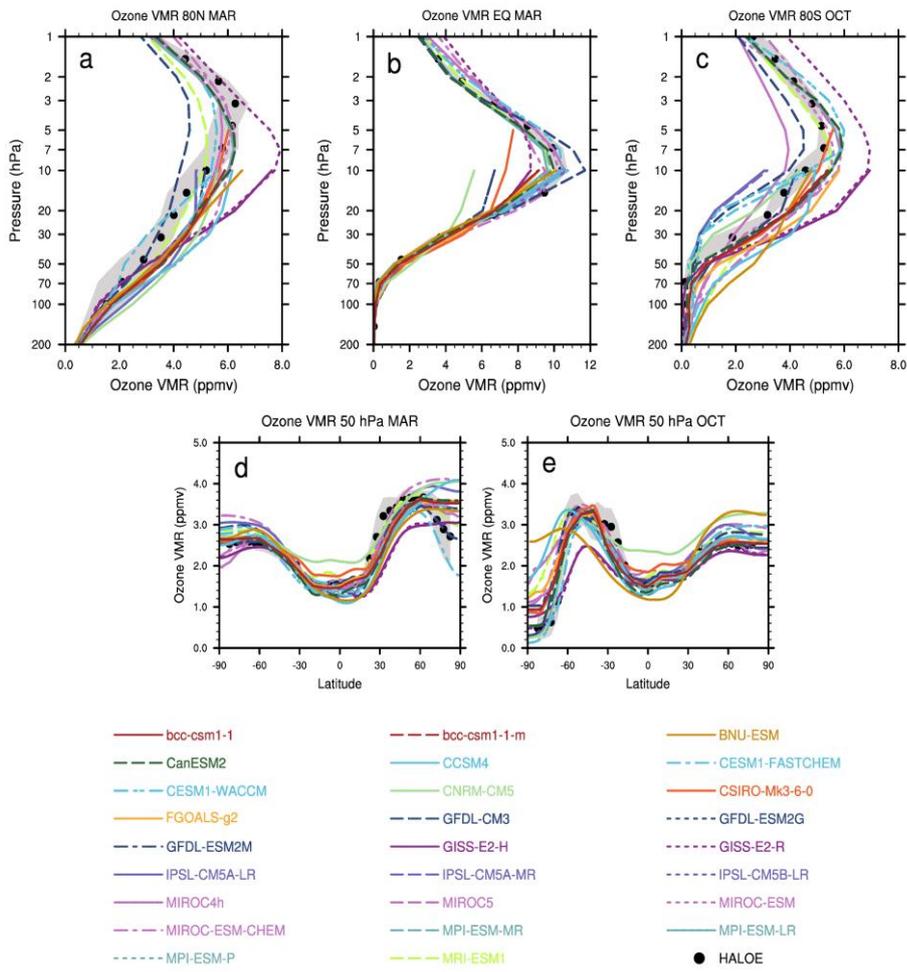


Figure 42. Climatological mean temperature biases for (top) 60–90N and (bottom) 60–90S for the (left) winter and (right) spring seasons. The climatological means for the CCMs and NCEP data from 1980 to 1999 and for UKMO from 1992 to 2001 are included. Biases are calculated relative to ERA-40 reanalyses. The grey area shows ERA-40 plus and minus 1 standard deviation about the climatological mean. High-latitude temperatures in winter and spring are particularly important for correctly modelling PSC-induced polar ozone depletion. In the middle stratosphere there are large variations between the analyses and most models, with no clear bias direction, whereas the temperature bias in the troposphere between analyses and models is somewhat smaller, but is in most models negative around 200hPa. The upper stratosphere is only available for a few models, and while for most shown seasons the agreement is relatively good, the spread between analyses and models is very large for the Antarctic polar regions in JJA. Similar to Figure 1 of Eyring et al. (2006), produced with the recipe\_eyring06jgr.yml. See details in Section 3.5.4.

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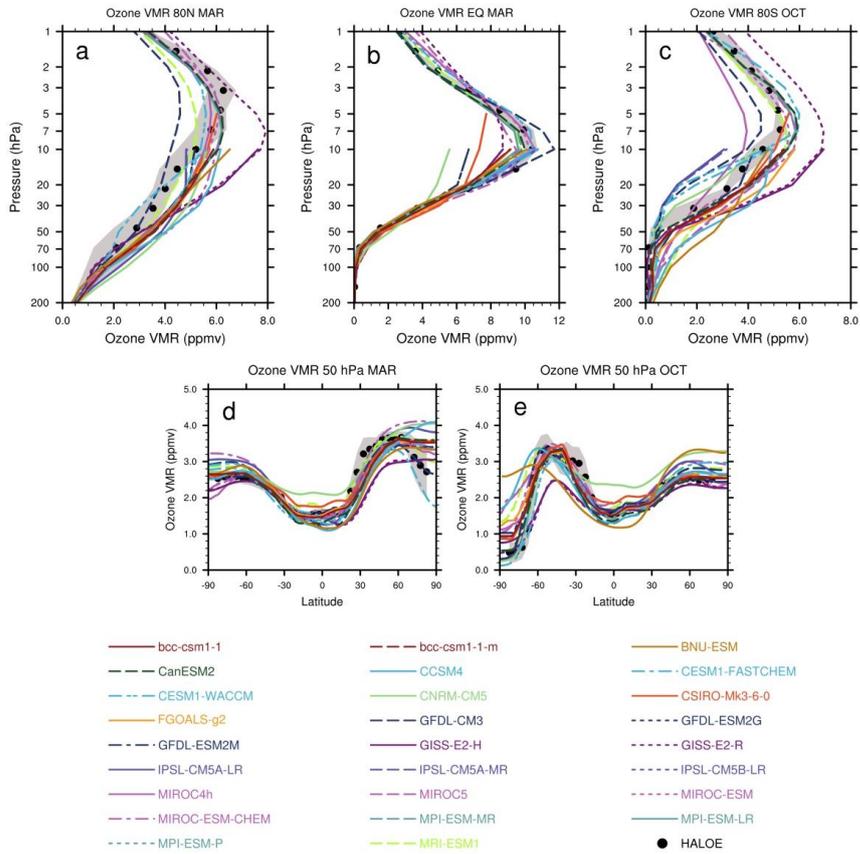


Figure 43. Climatological zonal mean ozone mixing ratios from the CMP5 simulations and HALOE in ppmv. Vertical profiles at (a) 80N in March, (b) 0 in March, and (c) 80S in October. Latitudinal profiles at 50 hPa in (d) March and (e) October. The grey area shows HALOE plus and minus 1 standard deviation (s) about the climatological zonal mean. **Similar to Figure 5 of Eyring et al. (2006), ozone is clearly overestimated by most models, compared to the observations, in the Northern high latitudes between 50 hPa and 10 hPa, which becomes also apparent in the climatological zonal mean at 50 hPa. Southern high latitudes are slightly better represented in the models at 50 hPa with a more general spread around the observations, but at lower pressure levels an overestimation of ozone compared to the observations becomes apparent in some models. Similar to Figure 5 of Eyring et al. (2006),** produced with the `recipe_eyring06jgr.yml`. See details in Section 3.5.4.

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