

Reply to review comments

We thank both reviewers for assessing this manuscript and for their time and effort. The useful comments are much appreciated and helped to improve the presentation of our results. Conclusions remain unchanged.

The original review comments are given below in black, [our reply in blue](#), and quotes from the revised manuscript in gray. Please find attached to this reply a revised manuscript where text changes are highlighted.

1 Reviewer 1

General comments

The manuscript addresses the important issue of climate signal emergence in ocean oxygen concentrations using the Community Earth System Model (CESM). The authors employ the widely used Time of Emergence (ToE) signal-to-noise
5 metric. There is a new focus in the analysis on the impacts of natural external forcings such as volcanism over the last millennium, and projections are analysed over the 21st century (for dissolved oxygen and temperature fields). The work is accomplished, certainly relevant to the scope of BG, and some interesting conclusions are reached regarding spatial patterns in Time of Emergence
10 (ToE). The methods are appropriate and well justified, including a careful discussion of the de-trending (de-drifting) procedure. It's worth noting that this work is not entirely novel, and as the authors point out many other similar ToE studies have been done on CMIP5-class models, but as above I'm confident that the focus on natural external forcing and the last millennium is sufficiently
15 distinct to justify publication. However I have two general issues which require the authors attention in revision along with specific / technical comments listed below.

[Thank you for your general support and your constructive comments.](#)

20 1. Primarily the manuscript requires major revision in terms of language and readability. The paper would be significantly enhanced by a reduced word-count and tightening of the text, along with a close check for typos and grammar. There is need for improvements to sentence structure throughout. I have flagged some specific issues in the Technical Comments but this is not comprehensive
25 and will need to be re-reviewed with this in mind.

[We have carefully checked the manuscript for grammar and typos, with the help](#)

of native English speaking colleagues.

In addition, I suggest that the sections of the Results which test ToE methodological assumptions such as noise estimates (e.g. Sect. 3.3.2 – 3.3.3) should be
5 (at least) condensed or potentially moved to the Supplement. The Discussion also includes lots of sub-sections and is not very readable in its present form. Some of this is certainly a matter of opinion, but it would be great to see a more streamlined manuscript which focuses on the central ToE results and the separation of O₂ changes into AOU, solubility components.

10 We have substantially shortened section 3.3 and reduced the number of corresponding figures. Please see the attached manuscript for details. Nevertheless, we consider that the comparison between the different estimates of variability and their implications for estimating ToE is an essential and novel element. Studies that compare internal and naturally forced variability are rare and missing
15 for O₂ and T. We have also largely rewritten the discussion, and removed the subsections.

Also there are lots of maps in the Results which do not necessarily add much to the paper (e.g. Fig 4. panel) – are they all necessary? e.g. do we need surface, thermocline and full depth averaged maps? (see below).

We followed the suggestion:

-moved Fig. 6a, 6b, 6c, and 6d to the appendix

-removed the full depth averaged analysis (Fig. 4a and 4b).

25 2. The authors spend a lot of time talking about uncertainties in noise estimates and methodological approach, however only briefly mention (Sect. 4) the potentially major influence of model structural error in their analysis. Specifically, the study does not validate the CESM simulated pattern of historical oxygen change using observations (only the mean state in Fig A2) or compare
30 the magnitude of simulated internal variability to e.g. long-term oxygen time series data. It is likely that the widely reported (e.g. Stramma et al., 2012) lack of model-data agreement in reproducing observed low-latitude deoxygenation plays a major role in the authors reported (low) ToE in the tropics (e.g. Fig 2a). This limitation is true of all ToE studies and somewhat unavoidable,
35 however it needs to be explored more as a major source of uncertainty in the study. To this end I suggest the authors include a comparison of CESM simulated historical deoxygenation to observations (e.g. vs the global Schmidtke et al. [2017] dataset) since this influences considerably the interpretation of ToE estimates derived for the 21st century.

40 The authors also note in Sect.4 that observed variability in oxygen (at HOTS) may be a factor of two larger than simulated by CESM. Along with the forced trend mentioned above if the noise is underestimated this will considerably impact upon CESM derived ToE estimates. The authors also need to
45 more thoroughly address this source of uncertainty in the manuscript.

The simulated historical O₂ concentrations are now compared to the data set

from Schmidtko et al. (2017) (Fig. A3). Moreover, we refer to Long et al. (2016) who compared CESM large ensemble results with the time series from BATS, HOT, OSP stations. Though their analysis is done on isopycnal surfaces, the conclusion concerning the amplitude of the natural variability applies to our study. The corresponding text in section 2.1.3 reads:

5 The evaluation of the modelled variability remains difficult as observational data are sparse. Furthermore, there is an inherent mismatch in the spatial scale between local measurements and the model resolution, which is of the order of 100 km. The modelled data are thus spatially averaged as compared to the observations and their variability does not explicitly take into account mesoscale eddies and other small scale processes (Long et al., 2016). Figure A3 compares the reconstructed variability and trends in O₂ over recent decades at 300 m depths and for different basins (Schmidtko et al., 2017) with the model results. CESM simulated historical O₂ concentrations show multi-decadal variability, although 10 with a much smaller amplitude compared to the observations. Long et al. (2016) have compared historical time series from the Hawaii Ocean Time-Series (HOT) station, the Ocean Station Papa (OSP) and the Bermuda Ocean Time Series (BATS) to the CESM large ensemble. They show that modelled variability in annually-averaged O₂ is substantially smaller than observed. Taken at face value, beyond the limitations described above, these comparisons suggest that 20 variability in CESM may be biased low. This would tend to bias ToE towards early emergence.

We also slightly modified and expanded the paragraph where uncertainties are discussed (Sect. 4, p16):

25 However, there are uncertainties in our results, and some are linked to the relatively coarse resolution of the CESM model of order one degree. Larger variability may be found on smaller scales. For example, Long et al. (2016) document that interannual variability from the Hawaii Ocean Time-Series (HOT) station is about a factor of two larger than the variability at the same location in CESM. Another source of error is structural model uncertainty. Comparison with observations (Sect. 2.1.3) and multi-model studies show weaknesses of the current class of earth system models in simulating the observed O₂ distribution and variability. Projections of anthropogenic O₂ change are particularly uncertain in low oxygenated waters (Bopp et al., 2013; Cocco et al., 2013). 35

Specific comments

Line 9 – 10: “natural variability [: :] are systematically larger than internal variability”. This needs to be clearer. I think you mean control estimates are not good enough as they don’t include natural external forcings like volcanism, 40 not that model simulated variability is smaller than observed? (or both?)

The sentence has been rephrased to increase the clarity:

However, the natural variability of oxygen (O₂) and temperature (T) inferred from the last millennium period is systematically and significantly larger than the internal variability simulated in the corresponding control simulation. This renders estimates of natural variability from control simulations to be biased low 45

Page 1 Line 12: do you mean “anoxic” or suboxic?

The corresponding text has been removed following the request of reviewer 2 to shorten and streamline the introduction.

5

Introduction Page 1 line 18. Do you need to reference all these studies to introduce the well-known concept of ventilation age? And then the next statement that warming leads to solubility driven deoxygenation is not referenced. Again this text has been removed in the revised manuscript.

10

Page 2 Line 5: Long et al. do not use optimal fingerprinting in their assessment. Please distinguish between studies which use optimal fingerprinting and ToE (these approaches are substantially different since optimal detection studies include an observed change and ToE are primarily model based)

15

We removed this sentence to avoid confusion and for brevity. Andrews et al. (2013) used optimal fingerprinting to detect and attribute changes in marine O₂, while Long et al. (2016) evaluate the similarity of the spatial structures associated with natural variability and the forced trend.

20

Page 2 Line 6: For completeness there is another ToE ocean biogeochemistry study by Christian (2014) PLOS ONE Reference included as suggested.

25

Page 3 Line 10. As the authors note, multiple studies have done ToE on biogeochemistry for CMIP5-class models. It is necessary in the Introduction to highlight what this study does differently and why it is important. I’m confident this can be done e.g. focus on natural external forcings, millennial scale simulations etc.

30

As requested by both reviewers, the introduction has been streamlined. We point out what was missing in the literature and what is new in this study. Please see the attached MS with changes highlighted. A few quotes from the introduction are given here below.:

35

- Studies are missing that address the natural variability of marine O₂ and temperature during the recent millennium and that compare this variability with anthropogenic change.

40

- Studies that address the ToE for temperature in the thermocline are still missing. This is a gap as the observed and projected warming in the thermocline affects the physiology of fish and their habitat distribution in addition to changes in O₂ (Pörtner et al., 2014).

45

- Most of the earlier studies did not consider variability from natural external forcing (e.g. Rodgers et al., 2015; Frölicher et al., 2016; Henson et al., 2017) or only through indirect methods (e.g. Keller et al., 2014; Henson et al., 2016).

50

Page 3 line 32: here and elsewhere I think the use of the terms like “natural variations in external forcing factors” is confusing. Please use concise, clear terminology e.g. “natural external forcings”

This text has been removed in the revised manuscript, and the terminology "natural variations in external forcing factors" has been replaced by "natural external forcings" as suggested

5 Page 8. Section 2.2.3: More justification for the chosen standard deviation noise thresholds is required along with reference to the associated statistical confidence levels required.

As requested, the confidence interval has been added:

10 The threshold of two STD allows the distinction of the signal from the variability with a confidence interval of 95.45 %; this confidence level is selected following many earlier studies (e.g. Christensen et al., 2007).

Figure 1. The different y-axes between left (last millennium) and right (future forcings) and upper (global) and lower (surface) are understandable but
15 confusing given the amount of detail (AOU vs O_{2sol}) in the panel. This Figure needs to be reworked for clarity to focus on key results. E.g. is surface and full depth averaged oxygen concentration important? Or just the thermocline?

The surface and global time series have been moved to the Appendix. Moreover, the thermocline time series has been split into two panels in order to ease the
20 figure: - panel 1 with O₂ and T time series and - panel 2 with O₂ components time series.

Page 9 – 10 Sect. 3.2. and page 10 – 11 Sect 3.2. These sections are overlong and should be more concise to focus on the key messages.

25 Sect 3.2 has been condensed.

Figure 4. There is not much added information in this panel – could the Figure be condensed ?

Panel 4a and 4b have been removed.

30

Figure 5, Sect 3.3.2 and Figure 6, Section 3.3.3: Suggest to (at least) condense these predominantly methodological Sections.

Panels 6a, b, c and d have been removed from the main text. The text has been shortened as requested.

35 Page 13 Sect. 3.4.1 Lines 8 to 18. I suggest to move this extra analysis of Fig 1 back to Sect 3.1 or simplify Figure 1 and add another Figure here to look at AOU/solubility contributions.

Figure 1 has been simplified as suggested. Panel b) shows now the AOU and O_{2,sol} in the thermocline. We prefer to keep the information on O₂, T, and
40 AOU and O_{2,sol} within the same figure for easy comparison. Further, we prefer to keep the discussion on AOU and O_{2,sol} in one single section (Sect. 3.4). Note that section 3.1 to 3.3 discuss O₂ and T, but not AOU and O_{2,sol}. This clear separation allows us to briefly introduce the concept of AOU and O_{2,sol} at the start of section 3.4.

45

Page 16 Line 1 - 4. See overall comments on model uncertainty regarding

noise and forced response.

Please see our [response to your comment #2](#).

5 Section 4. The discussion should be re-written to be more concise and fo-
cused.

[The discussion has been shortened and re-structured.](#)

Technical comments

10 Abstract Line 1. “aggravate” is a little unclear here suggest to reword

[Below, the updated sentence:](#)

Marine deoxygenation and anthropogenic ocean warming are observed and projected to intensify in the future.

15 Introduction and throughout: many references are used to support each point. Please be more selective – 13 references for one statement is quite a lot.
[The number of citations has been reduced.](#)

Oceanic oxygen O₂ concentrations have been observed to decrease over the past 50 years (e.g. Stramma et al., 2008; Helm et al., 2011; Ito et al., 2017; Schmidtko
20 et al., 2017) and are projected to further decline under anthropogenic climate change (Sarmiento et al., 1998; Plattner et al., 2001; Keeling and Garcia, 2002; Shaffer et al., 2009; Cocco et al., 2013; Battaglia and Joos, 2018).

Introduction Page 1 line 20. Suggest to cite Capotondi et al. 2012 on strat-
25 ification

[The corresponding text has been removed during the rewrite of the introduction.](#)

Introduction Page 3 line 22. “by appropriately adding [.]” this is unclear
please rework sentence

30 [Below, the updated sentence:](#)

Others used STD from a model ensemble for the 1920-1950 period (Long et al., 2016) or added the STD of annual values and monthly values in addition to estimation of measurement uncertainty (Carter et al., 2016).

35 Introduction Page 3 line line 25 “are considered not at all” rephrase please

[This part has been removed.](#)

Introduction Page 3 line 33 “these externally forced variability” rephrase
please

40 [The corresponding sentence has been removed during the rewrite of the introduction.](#)

Introduction Page 3 line 34 repetition of “last millennium climate simulations” rephrase please

45 [Below, the updated sentence:](#)

These include analyses of the last millennium using climate reconstructions

(McGregor et al., 2015; PAGES 2k Consortium et al., 2015; PAGES2k Consortium et al., 2017), climate simulations (Crowley, 2000; Ammann et al., 2007; Fernández-Donado et al., 2013; Camenisch et al., 2016), and the few existing earth system model (ESM) simulations with enabled carbon and biogeochemical cycles (Jungclaus et al., 2010; Lehner et al., 2015; Brovkin et al., 2010; Chikamoto et al., 2016). Regarding biogeochemical cycles, a substantial role of natural forced variability is also found in simulations with and without volcanic forcing (Frölicher et al., 2009; Frölicher et al., 2011; Frölicher et al., 2013).

10 Introduction Page 4 line 12 remove “the” before ‘anthropogenic’
Modified as suggested.

Page 4 line 25: please rephrase (also replace with ”rely”)
Below, the updated sentence:

15 This version of the model was used in the Coupled Model Intercomparison Project (CMIP5). Its physics originates from the Community Climate System Model (CCSM4; Gent et al., 2011), which includes modules for the atmosphere, the land, the sea-ice and the ocean, all coupled by a flux coupler.

20 Page 5 line 3. Replace “stands for”
Below, the updated sentence:

The sea-ice component is the Community Ice Code (CICE4; Hunke et al., 2010). It operates on the same horizontal resolution as the ocean module.

25 Page 5 line 19. Of carbon?
Below, the update sentence:

The biomass of dead phytoplankton is distributed among dissolved and particulate organic and inorganic carbon and nutrient pools.

30 Page 6 line 5: Should supplemental figures be named in the order they are introduced? (applies to later sections)
The figure order has been updated.

Page 10. Replace “outweight” with “exceed”
35 Corrected as suggested.

Page 11 Line 26 “larger”
”typo corrected”

40 Page 13 – 14. Formatting issues with subscripts
This has been corrected.

Page 15 Line 25 missing word after “enables”
The corresponding sentence has been removed during the rewrite of the introduction
45

Page 17 Line 2 . Missing parentheses
Corrected.

Interactive comment on Biogeosciences Discuss., [https://doi.org/10.5194/bg-](https://doi.org/10.5194/bg-2018-523)
5 2018-523, 2019.

2 Reviewer 2

The authors has presented an interesting study, with a number of valuable analyses and interpretations regarding the Time of Emergence for oxygen and temperature in the ocean. Although the material presented in the manuscript
10 should be of value to the broader research community, it would benefit greatly from revisions to improve clarity, and also to become better anchored in a discussion of existing scientific literature. Suggestions for improving the scientific clarity and impact are detailed below.

15 MAIN COMMENTS

The Introduction is not sufficiently focused and was a bit all over the map (encyclopedias on multiple topics), and should be streamlined.

We thank the reviewer for his constructive comments. The introduction has been rewritten focusing on the core of the study. We emphasise that we apply
20 the ToE concept to estimate when environmental conditions become unusual compared to the natural variability of the last millennium. We have removed the textbook description on the O₂ cycle and shortened and rearranged the text at various places. We refer the editor and reviewers to the attached manuscript where these and other changes are highlighted.

25 It would be of great value to state clearly why trend detection is priority when interpreting observations, and to relate this to the realm of uncertainty in climate change projections. There are several sources of uncertainty and/or ambiguity in trend detection relating to the “noise” component of trend detection.
30 One issue (that emphasized in the manuscript) is the distinction between natural and internal variability, with there being a need to understand and quantify this distinction. This analysis is great, and warrants emphasis.

35 But a second issue is related to the way in which noise is calculated. In most studies that also emphasize initial condition large ensemble methods, the method of Deser et al. (2014) is used to estimate noise, with this typically involving linear trends calculated over decades rather than STD of annual means to calculate ToE. As the amplitude of inter annual and decadal variability is typically expected to be distinct, at face value it is not obvious how to connect
40 the estimates give here with more general research using large ensemble simulations. It’s very important to emphasize this point, while it seems also OK to point out that there is nothing inherently flawed or wrong with the method proposed in the manuscript, it is just somewhat different, and more similar

to methods that have been applied cross multiple models in inter comparison studies. As a related point, I believe it would be valuable to communicate the implications of this study to the broader community, given the discrepancies noted above.

5

We have added the following text to point to the work of Deser and colleagues in the introduction:

Studies that employ large model ensembles (Deser et al., 2014) highlight in particular the large contribution of internal natural variability to the spread in projected trends (Rodgers et al., 2015).

10

We also now explain that the ToE concept is applied for different questions and that we use it to detect "unfamiliar" environmental conditions and not to detect current trends. The corresponding paragraph in the introduction reads now:

15

The method applied for estimating ToE depends on the scientific questions. Most of the earlier studies on marine O₂ are directed towards the detection of the current anthropogenic trend by using modern measurements systems and, closely related, to quantify the uncertainty in projections arising from natural variability (Rodgers et al., 2015; Frölicher et al., 2016; Henson et al., 2016; Long et al., 2016). Studies that employ large model ensembles (Deser et al., 2014) highlight in particular the large contribution of internal natural variability to the spread in projected trends (Rodgers et al., 2015). Alternatively, Henson et al. (2017) address the question when ecosystems are exposed to conditions outside the range of previously experienced seasonal variability and, hence, ToE is estimated relative to preindustrial. In this study, we focus similarly on the detection of persistent unfamiliar conditions. We compare the modelled anthropogenic signal with the natural variability of the entire last millennium for both O₂ and temperature in the thermocline.

25

30

We provide information in the introduction on large ensemble simulations:

More recently, outputs from a large ensemble of 21st century simulations were used to estimate mean trends and the standard deviation in the projected trends in O₂ (Rodgers et al., 2015; Frölicher et al., 2016). This approach enables the characterisation of anthropogenically forced trends and the uncertainty in future trends due to internal variability on the same time scale. A drawback is that variability in decadal or, even, multi-decadal trends are difficult to estimate from existing measurements as these cover a short time period. It is therefore difficult to validate the results.

35

40

Is there a way to bridge the different methodologies with large ensemble methods, perhaps by sampling (randomly?) decadal trends from a 1000+ year Last Millennium simulation? That would still be different from what is done with large ensemble runs.

45

This is an interesting idea and may be part of a future study. It is not readily clear to us how the suggested comparison between methodologies should be

done. We do not have large ensemble results for temperature and oxygen available. Such a comparison appears beyond the scope of this study; we feel that our manuscript is already quite long, and we prefer not to expand it further by introducing a new topic.

5 Do the authors recommend at all major modeling centers that are embarking on large ensemble simulations also include Last Millennium simulations? Or for CMIP6 protocols (where the historical period goes through 2014) can potential biases be estimated by comparing full historical ensemble runs with greenhouse
10 CO₂-only (for example, for estimating internal variability) runs over 1850-2014? We appreciate this suggestion. We expanded the text in the discussion, section 4.2 to include this point:

Alternatively, large ensemble simulations for the industrial period and the future will become available within CMIP6. Different ensembles including or excluding anthropogenic forcing (Stott et al., 2000) and including or excluding natural
15 forcing may be used to disentangle the individual contributions to trends and variability. Some model centres may also wish to generate large ensemble simulations for the last millennium to study natural variability over the more recent preindustrial period (Jungclauss et al., 2010).

20 MINOR COMMENTS

(1) References Near the top of Pg. 3 the authors refer to Hawkins and Sutton (2012), where the methods considered for calculating Time of Emergence are not the same as those typically used with large ensemble methods (Deser et al., 2014). This should be clarified with regard to the comments above.
25 Done - please see answer to comments above

Also, are the authors sure that the Long et al. (2016) paper used the same
30 method to calculate noise as that of Hawkins and Sutton? The corresponding sentence and the reference to Long et al. has been removed for brevity.

(2) Model configuration is the CAM4 model considered here the same as
35 the atmospheric model component used by Kay et al. (2015)? More generally, how do the model components differ, and if so, how might this itself impact variability? Kay et al., 2014 use the same version of CESM1.0 as the one used in this study except for the atmospheric component. They used CESM1.0 with CAM5 where
40 here we use it with CAM4. CAM5 provides a better aerosol representation (through physical enhancements), in order to conduct advanced research on assessment of the aerosol impact on cloud properties. More specifically, it allows for estimating the impact of anthropogenic aerosol emissions on the radiative forcing of climate by clouds. The main differences between these two versions
45 of CAM are described in detail in Liu et al. (2012). Nevertheless, we list below some of these changes that may influence the variability of the system:

- updated radiation scheme to Rapid Radiative Transfer Method for GCMs (RRTMG). RRTMG has an extensive spectral representation of the water vapour continuum
- the 3-mode modal aerosol scheme (MAM3) has been implemented and provides accumulation and coarse aerosol modes
- revised cloud macrophysics scheme that imposes full consistency between cloud fraction and cloud condensate
- computation of an updraft vertical velocity which allows for aerosol-cumulus interactions

(3) ToE, Pg. 9, line 8 and ensuing paragraph The section header “ToE” needs to be expanded into “Time of Emergence (ToE)”, or something similarly appropriate.
Modified as suggested

It should also be stated explicitly in this paragraph which year is used as a “reference” for the ToE calculations (ToE relative to what year?)
The spline is applied from the year 1800 onward. The corresponding text reads as follows:
The low-frequency climate change, S , is diagnosed as the spline-fitted (Enting, 1987) anomalies using a cut-off period of 40 years, from the year 1800 in order to remove short-term variations over the industrial period.

(4) Fig. 2: Pg. 9, describing text The patterns and timescales should be compared with existing published literature for oxygen and temperature, with any caveats about the methods used to calculate noise.
We are not aware of any publication discussing ToE of T in the thermocline. However, ToE of O_2 is discussed in several publications. For example, Long et al. (2016) present results from a large ensemble of CESM simulations and Henson et al. (2017) from CMIP5 simulations.
... a rather early emergence is simulated in the eastern equatorial Atlantic and the Indian ocean subtropical gyre. These patterns are consistent with the results from Long et al. (2016) and Henson et al. (2017).

(5) LM, pg 11, line 25: The authors need to spell out LM as Last Millennium here.
Modified as suggested.

(6) pg 11, lines 30-34 It would improve the clarity of the presentation if a bit more detail were provided here. What are the percent differences, and over what regions?
Information added as requested. The text reads now:
There are many regions where the ratio between the STD from the forced versus the STD from the CTRL simulation is close to one indicating that internal and

total natural variability are approximately equal. In particular, forced and internal natural variability in O_2 is comparable in most thermocline regions (Fig. 4a). Indeed, natural variability exceeds internal variability in O_2 by more than 50 % in only 3 % of the thermocline, while deviations larger than 20 % are found in 18% of the thermocline. For the temperature, forced variability exceed internal variability by more than 20 % over a third of the thermocline and by more than 50 % over 10 % of the thermocline. The relative difference between natural and internal variability is often smaller for O_2 than for T in the thermocline.

10 (7) Section 4.1 on pg 16 The references described here are not appropriate for linking biogeochemistry and climate modes, with the exception of the Bacastow reference. For the case of ENSO it would be appropriate to reference the study of Winguth et al. (1990s?). I believe for the SAM there were the studies in 2006-2007 of LeQuere, Lenton, and Lovenduski, and for the PDO you might
15 consider the study of McKinley (2006).

The suggested references have been added. However, we disagree with the reviewer regarding the references: all studies cited concern the link between biogeochemical variables and a particular climate mode.

20 Interactive comment on Biogeosciences Discuss., <https://doi.org/10.5194/bg-2018-523>, 2019.

References

- 5 Ammann, C. M., Joos, F., Schimel, D. S., Otto-Bliesner, B. L., and Tomas, R. A.: Solar Influence on Climate during the Past Millennium: Results from Transient Simulations with the NCAR Climate System Model, Proceedings of the National Academy of Sciences, 104, 3713–3718, doi:10.1073/pnas.0605064103, 2007.
- 10 Andrews, O. D., Bindoff, N. L., Halloran, P. R., Ilyina, T., and Le Quéré, C.: Detecting an External Influence on Recent Changes in Oceanic Oxygen Using an Optimal Fingerprinting Method, Biogeosciences, 10, 1799–1813, doi:10.5194/bg-10-1799-2013, 2013.
- Battaglia, G. and Joos, F.: Hazards of Decreasing Marine Oxygen: The near-Term and Millennial-Scale Benefits of Meeting the Paris Climate Targets, Earth System Dynamics, 9, 797, 2018.
- 15 Bopp, L., Resplandy, L., Orr, J. C., Doney, S. C., Dunne, J. P., Gehlen, M., Halloran, P., Heinze, C., Ilyina, T., Séférian, R., Tjiputra, J., and Vichi, M.: Multiple Stressors of Ocean Ecosystems in the 21st Century: Projections with CMIP5 Models, Biogeosciences, 10, 6225–6245, doi:10.5194/bg-10-6225-2013, 2013.
- 20 Brovkin, V., Lorenz, S. J., Jungclaus, J., Raddatz, T., Timmreck, C., Reick, C. H., Segscheider, J., and Six, K.: Sensitivity of a Coupled Climate-Carbon Cycle Model to Large Volcanic Eruptions during the Last Millennium, Tellus B, 62, 674–681, doi:10.1111/j.1600-0889.2010.00471.x, 2010.
- 25 Camenisch, C., Keller, K. M., Salvisberg, M., Amann, B., Bauch, M., Blumer, S., Brázdil, R., Brönnimann, S., Büntgen, U., Campbell, B. M., et al.: The 1430s: A Cold Period of Extraordinary Internal Climate Variability during the Early Spörer Minimum with Social and Economic Impacts in North-Western and Central Europe, Climate of the Past, 12, 2107, 2016.
- 30 Carter, B. R., Frölicher, T. L., Dunne, J. P., Rodgers, K. B., Slater, R. D., and Sarmiento, J. L.: When Can Ocean Acidification Impacts Be Detected from Decadal Alkalinity Measurements?, Global Biogeochemical Cycles, 30, 2015GB005308, doi:10.1002/2015GB005308, 2016.
- 35 Chikamoto, M. O., Timmermann, A., Yoshimori, M., Lehner, F., Laurian, A., Abe-Ouchi, A., Mouchet, A., Joos, F., Raible, C. C., and Cobb, K. M.: Intensification of Tropical Pacific Biological Productivity Due to Volcanic Eruptions, Geophysical Research Letters, 43, 2015GL067359, doi:10.1002/2015GL067359, 2016.
- 40 Christensen, J., Hewitson, B., A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr, and P. Whetton: Regional Climate Projections. In: Climate Change 2007: The Physical Science Basis.

Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2007.

- 5 Cocco, V., Joos, F., Steinacher, M., Froelicher, T. L., Bopp, L., Dunne, J.,
Gehlen, M., Heinze, C., Orr, J., Oeschler, A., Schneider, B., Segsneider, J.,
and Tjiputra, J.: Oxygen and Indicators of Stress for Marine Life in Multi-
Model Global Warming Projections, *Biogeosciences*, 10, 1849–1868, doi:10.
5194/bg-10-1849-2013, wOS:000317010600040, 2013.
- 10 Crowley, T. J.: Causes of Climate Change Over the Past 1000 Years, *Science*,
289, 270–277, doi:10.1126/science.289.5477.270, 2000.
- Deser, C., Phillips, A. S., Alexander, M. A., and Smoliak, B. V.: Projecting
North American Climate over the Next 50 Years: Uncertainty Due to Internal
Variability, *Journal of Climate*, 27, 2271–2296, doi:10.1175/JCLI-D-13-00451.
1, 2014.
- 15 Enting, I. G.: On the Use of Smoothing Splines to Filter CO₂ Data, *Journal*
of Geophysical Research: Atmospheres, 92, 10 977–10 984, doi:10.1029/
JD092iD09p10977, 1987.
- 20 Fernández-Donado, J. F., Raible, C., Ammann, C. M., Barriopedro, D., Garcia-
Bustamante, E., Jungclaus, J. H., Lorenz, S. J., Luterbacher, J., Phipps,
S. J., Servonnat, J., Swingedouw, D., Tett, S. F. B., Wagner, S., Yiou, P.,
and Zorita, E.: Large-Scale Temperature Response to External Forcing in
Simulations and Reconstructions of the Last Millennium, *Climate of the past*,
9, 393–421, doi:info:doi:10.5194/cp-9-393-2013, 2013.
- 25 Frölicher, T. L., Joos, F., Plattner, G.-K., Steinacher, M., and Doney, S. C.:
Natural Variability and Anthropogenic Trends in Oceanic Oxygen in a Cou-
pled Carbon Cycle-Climate Model Ensemble, *Global Biogeochemical Cycles*,
23, n/a–n/a, doi:10.1029/2008GB003316, 2009.
- 30 Frölicher, T. L., Joos, F., and Raible, C. C.: Sensitivity of Atmospheric CO₂
and Climate to Explosive Volcanic Eruptions, *Biogeosciences*, 8, 2317–2339,
doi:info:doi:10.5194/bg-8-2317-2011, 2011.
- Frölicher, T. L., Joos, F., Raible, C. C., and Sarmiento, J. L.: Atmospheric CO₂
Response to Volcanic Eruptions: The Role of ENSO, Season, and Variability,
Global Biogeochemical Cycles, 27, 239–251, doi:10.1002/gbc.20028, 2013.
- 35 Frölicher, T. L., Rodgers, K. B., Stock, C. A., and Cheung, W. W. L.:
Sources of Uncertainties in 21st Century Projections of Potential Ocean
Ecosystem Stressors, *Global Biogeochemical Cycles*, 30, 1224–1243, doi:
10.1002/2015GB005338, 2016.
- Gent, P. R., Danabasoglu, G., Donner, L. J., Holland, M. M., Hunke, E. C.,
Jayne, S. R., Lawrence, D. M., Neale, R. B., Rasch, P. J., Vertenstein,

- M., Worley, P. H., Yang, Z.-L., and Zhang, M.: The Community Climate System Model Version 4, *Journal of Climate*, 24, 4973–4991, doi:10.1175/2011JCLI4083.1, 2011.
- Helm, K. P., Bindoff, N. L., and Church, J. A.: Observed Decreases in Oxygen Content of the Global Ocean, *Geophysical Research Letters*, 38, L23 602, doi:10.1029/2011GL049513, 2011.
- Henson, S. A., Beaulieu, C., and Lampitt, R.: Observing Climate Change Trends in Ocean Biogeochemistry: When and Where, *Global Change Biology*, 22, 1561–1571, doi:10.1111/gcb.13152, 2016.
- Henson, S. A., Beaulieu, C., Ilyina, T., John, J. G., Long, M., Séférian, R., Tjiputra, J., and Sarmiento, J. L.: Rapid Emergence of Climate Change in Environmental Drivers of Marine Ecosystems, *Nature Communications*, 8, 14 682, doi:10.1038/ncomms14682, 2017.
- Hunke, E. C., Lipscomb, W. H., Turner, A. K., Jeffery, N., and Elliott, S.: CICE: The Los Alamos Sea Ice Model Documentation and Software User’s Manual Version 4.1 LA-CC-06-012, T-3 Fluid Dynamics Group, Los Alamos National Laboratory, 675, 2010.
- Ito, T., Minobe, S., Long, M. C., and Deutsch, C.: Upper Ocean O₂ Trends: 1958–2015, *Geophysical Research Letters*, p. 2017GL073613, doi:10.1002/2017GL073613, 2017.
- Jungclauss, J. H., Lorenz, S. J., Timmreck, C., Reick, C. H., Brovkin, V., Six, K., Segschneider, J., Giorgetta, M. A., Crowley, T. J., Pongratz, J., Krivova, N. A., Vieira, L. E., Solanki, S. K., Klocke, D., Botzet, M., Esch, M., Gayler, V., Haak, H., Raddatz, T., Roeckner, E., Schnur, R., Widmann, H., Claussen, M., Stevens, B., and Marotzke, J.: Climate and Carbon-Cycle Variability over the Last Millennium, *Climate of the Past*, 6, 723–737, doi:10.5194/cp-6-723-2010, 2010.
- Kay, J. E., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., Arblaster, J. M., Bates, S. C., Danabasoglu, G., Edwards, J., Holland, M., Kushner, P., Lamarque, J.-F., Lawrence, D., Lindsay, K., Middleton, A., Munoz, E., Neale, R., Oleson, K., Polvani, L., and Vertenstein, M.: The Community Earth System Model (CESM) Large Ensemble Project: A Community Resource for Studying Climate Change in the Presence of Internal Climate Variability, *Bulletin of the American Meteorological Society*, 96, 1333–1349, doi:10.1175/BAMS-D-13-00255.1, 2014.
- Keeling, R. F. and Garcia, H. E.: The Change in Oceanic O₂ Inventory Associated with Recent Global Warming, *Proceedings of the National Academy of Sciences*, 99, 7848–7853, doi:10.1073/pnas.122154899, 2002.
- Keller, K. M., Joos, F., and Raible, C. C.: Time of Emergence of Trends in Ocean Biogeochemistry, *Biogeosciences*, 11, 3647–3659, doi:10.5194/bg-11-3647-2014, 2014.

- Lehner, F., Joos, F., Raible, C. C., Mignot, J., Born, A., Keller, K. M., and Frölicher, T. L.: Climate and Carbon Cycle Dynamics in a CESM Simulation from 850 to 2100 CE, *Earth System Dynamics*, 6, 411–434, doi:10.5194/esd-6-411-2015, 2015.
- 5 Liu, X., Easter, R. C., Ghan, S. J., Zaveri, R., Rasch, P., Shi, X., Lamarque, J.-F., Gettelman, A., Morrison, H., Vitt, F., Conley, A., Park, S., Neale, R., Hannay, C., Ekman, A. M. L., Hess, P., Mahowald, N., Collins, W., Iacono, M. J., Bretherton, C. S., Flanner, M. G., and Mitchell, D.: Toward a Minimal
10 Representation of Aerosols in Climate Models: Description and Evaluation in the Community Atmosphere Model CAM5, *Geoscientific Model Development*, pp. 709–739, doi:10.5194/gmd-5-709-2012, 2012.
- Long, M. C., Deutsch, C., and Ito, T.: Finding Forced Trends in Oceanic Oxygen, *Global Biogeochemical Cycles*, 30, 2015GB005310, doi:10.1002/2015GB005310, 2016.
- 15 McGregor, H. V., Evans, M. N., Goosse, H., Leduc, G., Martrat, B., Addison, J. A., Mortyn, P. G., Oppo, D. W., Seidenkrantz, M.-S., Sicre, M.-A., Phipps, S. J., Selvaraj, K., Thirumalai, K., Filipsson, H. L., and Ersek, V.: Robust Global Ocean Cooling Trend for the Pre-Industrial Common Era, *Nature Geoscience*, 8, 671–677, doi:10.1038/ngeo2510, 2015.
- 20 PAGES 2k Consortium, Ahmed, M., Anchukaitis, K. J., Asrat, A., Borgaonkar, H. P., Braida, M., Buckley, B. M., Büntgen, U., Chase, B. M., Christie, D. A., Cook, E. R., Curran, M. A. J., Diaz, H. F., Esper, J., Fan, Z.-X., Gaire, N. P., Ge, Q., Gergis, J., González-Rouco, J. F., Goosse, H., Grab, S. W., Graham, N., Graham, R., Grosjean, M., Hanhijärvi, S. T., Kaufman, D. S., Kiefer, T., Kimura, K., Korhola, A. A., Krusic, P. J., Lara, A., Lézine, A.-M., Ljungqvist, F. C., Lorrey, A. M., Luterbacher, J., Masson-Delmotte, V., McCarroll, D., McConnell, J. R., McKay, N. P., Morales, M. S., Moy, A. D., Mulvaney, R., Mundo, I. A., Nakatsuka, T., Nash, D. J., Neukom, R., Nicholson, S. E., Oerter, H., Palmer, J. G., Phipps, S. J., Prieto, M. R.,
25 Rivera, A., Sano, M., Severi, M., Shanahan, T. M., Shao, X., Shi, F., Sigl, M., Smerdon, J. E., Solomina, O. N., Steig, E. J., Stenni, B., Thamban, M., Trouet, V., Turney, C. S. M., Umer, M., van Ommen, T., Verschuren, D., Viau, A. E., Villalba, R., Vinther, B. M., von Gunten, L., Wagner, S., Wahl, E. R., Wanner, H., Werner, J. P., White, J. W. C., Yasue, K., and Zorita, E.:
30 Corrigendum: Continental-Scale Temperature Variability during the Past Two Millennia, *Nature Geoscience*, 8, 981–982, doi:10.1038/ngeo2566, 2015.
- PAGES2k Consortium, Emile-Geay, J., McKay, N. P., Kaufman, D. S., von Gunten, L., Wang, J., Anchukaitis, K. J., Abram, N. J., Addison, J. A., Curran, M. A. J., Evans, M. N., Henley, B. J., Hao, Z., Martrat, B., McGregor, H. V., Neukom, R., Pederson, G. T., Stenni, B., Thirumalai, K., Werner, J. P., Xu, C., Divine, D. V., Dixon, B. C., Gergis, J., Mundo, I. A., Nakatsuka, T., Phipps, S. J., Routsos, C. C., Steig, E. J., Tierney, J. E., Tyler, J. J., Allen, K. J., Bertler, N. A. N., Björklund, J., Chase, B. M., Chen,

- M.-T., Cook, E., de Jong, R., DeLong, K. L., Dixon, D. A., Ekaykin, A. A., Ersek, V., Filipsson, H. L., Francus, P., Freund, M. B., Frezzotti, M., Gaire, N. P., Gajewski, K., Ge, Q., Goosse, H., Gornostaeva, A., Grosjean, M., Horiuchi, K., Hormes, A., Husum, K., Isaksson, E., Kandasamy, S., Kawamura, K., Kilbourne, K. H., Koç, N., Leduc, G., Linderholm, H. W., Lorrey, A. M., Mikhalenko, V., Mortyn, P. G., Motoyama, H., Moy, A. D., Mulvaney, R., Munz, P. M., Nash, D. J., Oerter, H., Opel, T., Orsi, A. J., Ovchinnikov, D. V., Porter, T. J., Roop, H. A., Saenger, C., Sano, M., Sauchyn, D., Saunders, K. M., Seidenkrantz, M.-S., Severi, M., Shao, X., Sicre, M.-A., Sigl, M., Sinclair, K., George, S. S., Jacques, J.-M. S., Thamban, M., Kuwar Thapa, U., Thomas, E. R., Turney, C., Uemura, R., Viau, A. E., Vladimirova, D. O., Wahl, E. R., White, J. W. C., Yu, Z., and Zinke, J.: A Global Multiproxy Database for Temperature Reconstructions of the Common Era, *Scientific Data*, 4, 170088, doi:10.1038/sdata.2017.88, 2017.
- 15 Plattner, G.-K., Joos, F., Stocker, T. F., and Marchal, O.: Feedback Mechanisms and Sensitivities of Ocean Carbon Uptake under Global Warming, *Tellus B*, 53, 564–592, doi:10.1034/j.1600-0889.2001.530504.x, 2001.
- Pörtner, H.-O., Karl, D. M., Boyd, P. W., Cheung, W., Lluçà-Cota, S. E., Nojiri, Y., Schmidt, D. N., Zavialov, P. O., Alheit, J., and Aristegui, J.: Ocean Systems, in: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 411–484, Cambridge University Press, 2014.
- 20 Rodgers, K. B., Lin, J., and Frölicher, T. L.: Emergence of Multiple Ocean Ecosystem Drivers in a Large Ensemble Suite with an Earth System Model, *Biogeosciences*, 12, 3301–3320, doi:10.5194/bg-12-3301-2015, 2015.
- Sarmiento, J. L., Hughes, T. M. C., Stouffer, R. J., and Manabe, S.: Simulated Response of the Ocean Carbon Cycle to Anthropogenic Climate Warming, *Nature*, 393, 245–249, doi:10.1038/30455, 1998.
- 30 Schmidtko, S., Stramma, L., and Visbeck, M.: Decline in Global Oceanic Oxygen Content during the Past Five Decades, *Nature*, 542, 335–339, doi:10.1038/nature21399, 2017.
- Shaffer, G., Pedersen, J. O. P., and Olsen, S. M.: Long-Term Ocean Oxygen Depletion in Response to Carbon Dioxide Emissions from Fossil Fuels, *Nature Geoscience*, 2, 105, doi:10.1038/ngeo420, 2009.
- 35 Stott, P. A., Tett, S. F. B., Jones, G. S., Allen, M. R., Mitchell, J. F. B., and Jenkins, G. J.: External Control of 20th Century Temperature by Natural and Anthropogenic Forcings, *Science*, 290, 2133–2137, doi:10.1126/science.290.5499.2133, 2000.
- 40 Stramma, L., Johnson, G. C., Sprintall, J., and Mohrholz, V.: Expanding Oxygen-Minimum Zones in the Tropical Oceans, *Science*, 320, 655–658, doi:10.1126/science.1153847, 2008.

Assessment of time of emergence of anthropogenic deoxygenation and warming: insights from a CESM simulation from 850 to 2100 CE

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Abstract.

Marine deoxygenation and anthropogenic ocean warming are observed and projected to ~~aggravate under continued greenhouse gas emissions intensify in the future.~~ These changes potentially ~~adversely affect the functioning impact the functions~~ and services of marine ecosystems. A key question is whether marine ecosystems are already or will soon be exposed to environmental conditions not experienced during the last millennium. ~~We~~ Using a forced simulation with the Community Earth System Model (CESM) over the period 850 to 2100, we find that anthropogenic deoxygenation and warming in the thermocline ~~have today already left the bounds of exceeded~~ natural variability in respectively 60 % and 90 % of total ocean area ~~in a forced simulation with the Community Earth System Model (CESM) over the period 850 to 2100. Natural~~. Control simulations are typically used to estimate the preindustrial variability level. However, the natural variability of oxygen (O₂) and temperature (T) inferred from the last millennium period is systematically larger than the internal variability simulated in the corresponding control simulation. This renders natural variability from control simulations to be biased towards low estimates. Here, natural variability is assessed from last millennium the last millennium period (850-1800)-results considering CE), thus considering the response to forcing from explosive volcanic eruptions, solar irradiance, and greenhouse gases in addition to internal, chaotic variability. ~~Control simulations are typically used to estimate variability. However, natural variability in oxygen (O₂) and temperature (T) are systematically larger than internal variability (e.g. the latter amounts to 20 % for T and 60 % for~~ Results suggest that in the tropical thermocline, where biological and solubility-driven O₂ in the thermocline), rendering such estimates of natural variability to be biased low. Results suggest that changes counteract each other, anthropogenic change in apparent oxygen utilisation (AOU) and in O₂ solubility (O_{2, sol 2, sol}) are earlier detectable ~~by measurements than in O₂ in the tropical thermocline, where biological and solubility-driven than~~ O₂ changes ~~counteract each other~~. Both natural variability and change in AOU are predominantly driven by variations in circulation with a smaller role for productivity. ~~Ventilation becomes more vigorous in the tropical thermocline by~~ By the end of the 21st century, ventilation becomes more vigorous in the tropical thermocline, whereas ideal age in deep waters increases by more than 200 years ~~until 2100, relative to preindustrial~~. Different methodological choices are compared and the time for an anthropogenic signal to ~~emergee emerge~~ (ToE) is earlier in many thermocline regions when using variability from a ~~short period, the control~~ shorter period, from the control simulation,

or estimates from the industrial period instead of the variability from the last millennium. Our results highlight that published methods may lead to deviations in ToE estimates, calling for a careful quantification of variability and. They also highlight that realised anthropogenic change exceeds natural variations in many regions.

1 Introduction

5 Oceanic oxygen O₂ concentrations have been observed to decrease over the past 50 years (e.g. Stramma et al., 2008; Helm et al., 2011; ~~Talley et al., 2016~~; Ito et al., 2017; Schmidtke et al., 2017) and are projected to further decline under anthropogenic climate change (Sarmiento et al., 1998; Plattner et al., 2001; ~~Bopp et al., 2002~~; ~~Keeling and Garcia, 2002~~; ~~Schmittner et al., 2008~~; ~~Frölicher et al., 2009~~; ~~Keeling and Garcia, 2002~~; Shaffer et al., 2009; Cocco et al., 2013; ~~Bopp et al., 2013~~; ~~Bopp et al., 2017~~; ~~?~~; ~~Battaglia and Joos, 2018~~; ~~Fu et al., 2018~~ Battaglia and Joos, 2018). This deoxygenation, in combination with other stressors (Bopp et al., 2013; Cocco et al., 2013), such as ocean warming (IPCC, 2013), acidification (Orr et al., 2005) and declining primary productivity by phytoplankton (Steinacher et al., 2010; Laufkötter et al., 2015), ?, poses major risks for the function of marine ecosystems and the services they provide (~~Pörtner et al., 2014~~; ~~Gattuso et al., 2015~~; ~~Deutsch et al., 2015~~; Gattuso et al., 2015; Mislan et al., 2017; Breitburg et al., 2018).

~~The modern marine O₂ cycle is characterised by its low O₂ inventory. Only about half a percent of the freely available O₂ is stored in the ocean and waters are anoxic in tropical eastern boundary upwelling systems (Bianchi et al., 2012; Brandt et al., 2015). Surface O₂ concentrations are close to equilibrium with the atmosphere driven by a fast air-sea gas transfer (Gruber et al., 2001). Cold high latitude surface waters are characterised by high solubility and high O₂ compared to warm tropical and subtropical surface waters. Within the ocean, water is primarily consumed by aerobic remineralisation (Emerson and Bushinsky, 2014), roughly balancing net O₂ production in the surface. The O₂ concentrations in subsurface waters reflect a balance between physical O₂ supply by advection, mixing, and convection and biological consumption of organic matter exported to the deep (Frölicher et al., 2009; Gnanadesikan et al., 2013; Duteil et al., 2014; Keller et al., 2016; Azhar et al., 2017). Ongoing anthropogenic warming of the upper ocean leads to a solubility-driven decrease in O₂. It also leads to an increased stratification (Manabe et al., 1991). In turn, mixing and overturning generally slows and O₂ supply rates to the deep decrease, while more time is left for O₂ consumption in subsurface waters. This causes a corresponding O₂ decrease, though specific model responses in circulation, biological organic matter export and O₂ consumption and in O₂ concentrations are complex in space and time and regionally uncertain (e.g., Frölicher et al., 2009; Long et al., 2016; Azhar et al., 2017; Oschlies et al., 2017; Palter et al., 2018; Battaglia and Joos, 2018).~~

~~While it is expected that continued anthropogenic emissions of CO₂ and other greenhouse gases cause large scale deoxygenation, it is less clear whether and to which extent O₂ concentrations in the ocean have already left the bounds of natural variability of the recent millennia. Many~~ The natural climate variability of the recent past provides a range of "familiar" climate conditions to which many ecological and socio-economic systems are adapted ~~to the level of natural variability of the recent past. Therefore, forcing~~ forcing environmental conditions outside the bounds of recent natural variability may trigger adverse impacts (Pörtner et al., 2014). It is still an open question to which extent marine species and ecosystems are already confronted with "unfamiliar"

iar" environmental and climatic conditions not encountered during the last millennium. ~~There is in particular a lack of proxy reconstructions documenting how O₂ might have evolved during the current interglacial period and a lack of modelling studies addressing~~ A difficulty arises from the need to quantify natural variability that stems both from the partly chaotic internal variability of the climate system (Lorenz, 1963) and from natural external forcing factors including variations in solar energy output and explosive volcanic eruptions (e.g. Jungclauss et al., 2017). Studies that address the natural variability of marine O₂ and temperature during the recent millennium ~~, while observational information, though limited in space and time, is available on O₂ variability in the modern ocean (Mecking et al., 2008; Brandt et al., 2015; Long et al., 2016; Ito et al., 2017) and that compare this variability with anthropogenic change are missing .~~

The time of emergence (ToE) is an established metric to estimate when a forced anthropogenic change or "signal" ~~leaves the bounds exceed~~ of variability or "noise" (Christensen et al., 2007; Hawkins and Sutton, 2012). ToE is the point in time when the ~~signal anthropogenic changes~~ becomes larger than ~~the noise of variability. Thus, the magnitude of the anthropogenic signal is compared to the magnitude of the noise to compute ToE. Different attempts to detect and attribute O₂ change are using optimal fingerprinting methods and consider spatial patterns of change (Andrews et al., 2013; Long et al., 2016).~~ natural variability. ToE has been estimated for physical climate variables (e.g. ~~Mahlstein et al., 2013; Hawkins et al., 2014~~Christensen et al., 2007; Hawkins and Sutton, 2012; ~~Mahlstein et al., 2013; Deser et al., 2014~~; Frame et al., 2017), land carbon stocks and fluxes (Lombardozzi et al., 2014) and marine properties including ocean acidification impacts and alkalinity (Ilyina et al., 2009; Friedrich et al., 2012; Ilyina and Zeebe, 2012; Hauri et al., 2013), sea surface temperature, pH, CO₂ partial pressure and dissolved inorganic carbon (Christian, 2014; Keller et al., 2014), marine biological productivity, biological export fluxes, surface chlorophyll and surface nitrate (Henson et al., 2016) and air-to-sea carbon fluxes (McKinley et al., 2016).

~~Studies that address the ToE for temperature in the thermocline are nevertheless still missing. This is a gap as the observed and projected warming in the thermocline affects the physiology of fish and their habitat distribution in addition to changes in O₂ (Pörtner et al., 2014).~~ A limited number of studies ~~also~~ addressed the ToE for O₂ ~~concentrations~~ in the thermocline, often in combination for other tracers (Rodgers et al., 2015; Frölicher et al., 2016; Henson et al., 2016; Long et al., 2016; Henson et al., 2017). ~~Most of these ToE studies~~ ~~The results demonstrate a wide range of ToE associated with the range of different method used.~~

~~The method applied for estimating ToE depends on the scientific questions. Most of the earlier studies on marine O₂ are directed towards the detection of the current anthropogenic trend by using modern measurements systems and, closely related, to quantify the uncertainty in projections arising from natural variability (Rodgers et al., 2015; Frölicher et al., 2016; Henson et al., 2016; Long et al., 2016).~~ Thus, the question is how many years of modern measurements, starting in 1956 or later, are ~~needed to detect the anthropogenic O₂ signal. Alternatively, (Henson et al., 2017)~~ Studies that employ large model ensembles (Deser et al., 2014) highlight in particular the large contribution of internal natural variability to the spread in projected trends (Rodgers et al., 2015). Alternatively, Henson et al. (2017) address the question when ecosystems are exposed to conditions outside the range of previously experienced seasonal variability and, hence, ToE is estimated relative to preindustrial.

~~Published~~ ToE studies employ a wide range of different methods. For example, the anthropogenic signal is computed as a linear trend over a few decades (Keller et al., 2014; Rodgers et al., 2015) or a linear trend over the industrial period and the 21st

century (Henson et al., 2017) or by a polynomial fit to simulated data (Carter et al., 2016). Even a wider range of approaches ~~is are~~ used to estimate the variability or noise. ~~Noise is~~ It can be taken as the standard deviation (STD) of annual extrema from a control simulation (Henson et al., 2017) or STD remaining after removing anthropogenic trends (Keller et al., 2014; Henson et al., 2016) ~~or~~. Others used STD from a model ensemble for the 1920-1950 period (Long et al., 2016) ~~;~~ by appropriately adding ~~or added~~ the STD of annual values ~~plus monthly values plus from and monthly values in addition to estimation of~~ measurement uncertainty (Carter et al., 2016) ~~;~~ the. The amplitude of the simulated preindustrial annual cycle (Friedrich et al., 2012) ~~;~~ and the extrema simulated over the historical period (Mora et al., 2013) ~~;~~ were also applied as measures of noise. In these studies, decadal-scale anthropogenic change is compared with variability on the annual or seasonal scale. More recently, outputs from a large ensemble of 21st century simulations were used to estimate mean trends and the standard deviation in the projected trends ~~from model ensembles in O₂~~ (Rodgers et al., 2015; Frölicher et al., 2016). ~~A characteristic of these different estimates of variability~~ This approach enables the characterisation of anthropogenically forced trends and the uncertainty in future trends due to internal variability on the same time scale. A drawback is that variability ~~is generally estimated for a limited temporal period and, perhaps, more important that variations from natural forcing variations are considered not at all in decadal or, even, multi-decadal trends are difficult to estimate from existing measurements as these cover a short time period. It is therefore difficult to validate the results.~~

Most of the earlier studies did not consider variability from natural external forcing (e.g. Rodgers et al., 2015; Frölicher et al., 2016; Henson et al., 2017) or to a limited extent. For example only through indirect methods (e.g. Keller et al., 2014; Henson et al., 2016). Indeed, forcing from explosive volcanic eruptions (Sigl et al., 2015) and solar irradiance variations (Muscheler et al., 2007) are by design, by design, not included in model control simulations. And the indirect method to estimate natural variability using the residual variability from the simulation long-term trend, excludes the multi-decadal natural variability. These shortcomings may bias ~~such earlier~~ estimates of natural variability systematically low. As a consequence, the time when the anthropogenic signal leaves the bounds of natural variations would also be biased towards early emergence.

~~Earth system responses to natural variations in external forcing factors contribute to total natural variability in climate. A range of approaches suggest substantial variations in physical and biogeochemical variables. These externally forced variability is additional to the partly chaotic internal variability of the climate system. Last millennium in response to the volcanic eruptions and solar irradiance variations (Mignot et al., 2011; Schmidt et al., 2011; Jungclaus et al., 2017). These include analyses of the last millennium using climate reconstructions (?; McGregor et al., 2015; McGregor et al., 2015; ?; PAGES2k Consortium et al., 2017), last millennium climate simulations (Crowley, 2000; Ammann et al., 2007; Fernández-Donado et al., 2013; ?), and the few existing last millennium earth system model (ESM) simulations with enabled carbon and biogeochemical cycles (Lehner et al., 2015; Jungclaus et al., 2010; Lehner et al., 2015; Brovkin et al., 2010; ?) and studies using their output (Brovkin et al., 2010; Keller et al., 2015; Chikamoto et al., 2016a) all suggest substantial variations in physical and biogeochemical variables in response to the volcanic eruptions and solar irradiance variations (Schmidt et al., 2011; Jungclaus et al., 2017) of the last millennium (Chikamoto et al., 2016a).~~ Regarding biogeochemical cycles, a substantial role of natural forced variability is also found in ~~factorial~~ simulations with and without volcanic forcing (Frölicher et al., 2009; Frölicher et al., 2011; ?). ~~Frölicher et al. (2009) document in their ESM ensemble that volcanic eruptions cause~~ Particularly,

volcanic eruptions induce significant interannual and decadal variability in O_2 , ~~that volcanic perturbations in oceanic O_2 surface O_2 , which~~ gradually penetrate the ocean's top 500 m and persist for several years, ~~and that these forced variations are additional to modelled and observed O_2 variability associated with the North Atlantic and Pacific Decadal Oscillation (Frölicher et al., 2009).~~ These forced variations add to the internal natural O_2 variations. In conclusion, the available evidence ~~suggest suggests~~ that forced natural variability should not be ignored when comparing the relative importance of anthropogenic trends versus natural variability.

The goals of this study are to quantify when ~~the~~ anthropogenic marine deoxygenation and warming ~~leaves~~ leave the bound of natural variability of the last millennium ~~and to in the thermocline (ToE).~~ Moreover, we estimate the relative role of natural forced and internal variability in marine O_2 and temperature variations. A further goal is to document the influence of different methodological choices on estimates of ToE. We exploit results from one of the few available ESM simulations with active marine carbon and O_2 cycle that covers the entire last millennium, the industrial period and the 21st century (Lehner et al., 2015). We further document the variability ~~in terms of standard deviation~~ of apparent oxygen utilisation, the ~~solubility-driven~~ solubility-driven O_2 change, and their covariance as well as variability in ideal age and export production of particulate organic carbon ~~and the anthropogenic change in these variables.~~ This allows us to discuss the role of solubility, biological export, and circulation for O_2 variability and, similarly, for the anthropogenic signal.

2 Method

2.1 Model and simulations

2.1.1 Model description

The model used for this study is the Community Earth System Model version 1.0 (CESM1), released in 2010. It is a fully coupled state-of-the-art Earth system model (Hurrell et al., 2013). This version of the model was used in the Coupled Model Intercomparison Project (CMIP5). Its physics ~~rely on~~ originates from the Community Climate System Model (CCSM4; Gent et al., 2011), which includes modules for the atmosphere, the land, the sea-ice and the ocean, all coupled by a flux coupler. As compared with CCSM4, CESM1 additionally includes a fully interactive carbon cycle between the atmosphere, ocean and land modules.

The atmospheric module is the Community Atmosphere Model (CAM4; Neale et al., 2010), with a horizontal resolution of $1.25^\circ \times 0.9^\circ$ and 26 vertical levels. CAM4 provides an interactive coupled biogeochemistry module (~~CAM-chem~~ CAM-CHEM). The land module is the Community Land Model (CLM4; Lawrence et al., 2012). It operates on the same horizontal grid as the atmospheric component. The land surface is represented as a hierarchy of subgrid types, including glacier, lake, wetland, urban and vegetated land units. The ocean is simulated by POP2 (Parallel Ocean Program version 2; Smith et al., 2010; Danabasoglu et al., 2011), with 60 vertical levels. The horizontal resolution varies around 1° . It is higher at ~~low latitudes~~ low latitudes (around the equator) and around Greenland to where the North Pole is displaced in order to avoid singularity problems in the ocean model equations. Note that for convenience, the global maps shown here are re-gridded using a regular grid. The global

circulation model (POP2) also includes a water age tracer (ideal age). It is set to zero at the surface and ages every day in the ocean interior. The sea-ice component is the Community Ice Code (CICE4; ?) stands for the sea-ice component. It operates on the same horizontal resolution as the ocean module.

The Biogeochemical Elemental Cycling model (BEC; Moore et al., 2002 and 2004) is implemented in POP2. It is built on traditional phytoplankton-zooplankton-detritus food web models (Doney et al., 2009). It carries three different phytoplankton types: diatoms, diazotrophs, and small phytoplankton. The photosynthesis and associated production rate of oxygen depend on the phytoplankton type, the solar irradiance, and nutrient-limitation terms (Cullen, 1990). The nutrient-limitation terms are scaled by Redfield ratios, which represent the nutrient assimilation type; C:O varies depending on whether NH_3 or NH_4^+ is assimilated or N-fixed (Nitrogen fixation; only for diazotrophs). At the surface, the rate of air-sea oxygen transfer depends on the modelled wind speed, the temperature-dependent Schmidt number (Wanninkhof Rik, 1992) and the air-sea partial pressure difference in O_2 . The solubility component of O_2 ($\text{O}_{2,\text{sol},2,\text{sol}}$) is parametrised as function of temperature (T) and salinity (S) (Garcia and Gordon, 1992). It is defined as the O_2 concentration in equilibrium with an atmosphere of standard composition, fully saturated with water and with a total pressure of one atm. The oxygen content is homogenised within the mixed layer. The typical time scale to equilibrate the oxygen concentration in the mixed layer with the atmosphere by gas exchange is about one month.

The modelled consumption of oxygen occurs through remineralisation of organic material, respiration by zooplankton, and grazing of the phytoplankton. ~~After the death of the phytoplankton, the transformed biomass~~ The biomass of dead phytoplankton is distributed among dissolved, ~~particulate and inorganic and particulate organic and inorganic carbon and nutrient~~ pools. The distribution varies by the type of plankton and the type of mortality (Moore et al., 2004). Aggregated biomass is routed to the sinking Particulate Organic Matter (POM) pools and sinks at a rate of 20.0 m day^{-1} . Carbon export and remineralisation are following Armstrong et al. (2001). Remineralisation parameters of the detrital pools ~~is parameterised~~ are set with the condition that $[\text{O}_2] \geq 4 \text{ mmol m}^{-3}$ and a temperature-dependent function. The length scale of remineralisation for the sinking POM pool varies from 200 to 1000 m (Moore et al., 2002). Organic material reaching the ocean floor is remineralised instantaneously, i.e., no sediment module is included.

~~The global circulation model (POP2) also includes a water age tracer (ideal age). It is set to zero at the surface and ages every day in the ocean interior.~~

2.1.2 Description of the simulations

This study uses results from a forced, transient simulation spanning from 850 to 2100 CE (Common Era) and from a corresponding control simulation, both performed with CESM1.0.1. The experimental set-up is described in detail by Lehner et al. (2015) and further results of these runs are described by Bothe et al. (2015), Keller et al. (2015), ? and Chikamoto et al. (2016b). The reference simulation (CTRL) was branched from the CMIP5 CCSM4 (Gent et al., 2011) ~~pre-industrial~~ preindustrial control and run for 258 years with the 850 CE external forcing set to allow a spin up. ~~At nominal year 850 CE~~ After reaching the surface equilibrium, the forced simulation was branched off. The CTRL was continued for another 518 years ~~from 850 to 1368 CE~~ with unchanged forcing CE. The transient forcing largely follows the protocol of the Paleoclimate and Modelling

Intercomparison Project 3 (Schmidt et al., 2011), applying reconstructed variations of the volcanic forcing (Gao et al., 2008), land use changes (Pongratz et al., 2008; Hurtt et al., 2011), and fossil fuel emissions (1750 to 2005 CE, following Andres et al., 2012). The total solar irradiance is taken from the reconstruction by Vieira and Solanki (2010) ~~but; the original curve is~~ scaled to have an amplitude change from the Maunder Minimum to present day of 0.2 % rather than 0.1 %, consistent with Bard et al. (2000). Over the period 2005–2100 CE, the representative concentration pathway RCP8.5 (Moss et al., 2010) is used (see Fig. A1e-a for an overview of the forcings).

2.1.3 Model evaluation

We briefly compare model results for O₂ (average between 1986 and 2005) to observations (Garcia et al., 2013). ~~Earlier studies, The reader is referred to Doney et al. (2006) and Najjar et al. (2007) , have described strengths and weaknesses of the climate model CESM. And Lehner et al. (2015) discuss also the simulations analysed here.-~~

~~In the thermocline (here defined as the layer 200-600 m), the~~ for a more comprehensive evaluation of CESM. The model reproduces the main features of the O₂ distribution given by the World Ocean Atlas 2013 (Garcia et al., 2013) ~~as illustrated in in the thermocline (here defined as the layer 200-600 m~~ (Fig. A2a). O₂ concentrations are generally high at these intermediate depths in the mid- and high-latitudes of the Southern Hemisphere as well as in the mid-latitudes of the ~~Pacific and northern Atlantic-North Pacific and Atlantic basins~~. Both the model and the World Ocean Atlas show low concentrations in the equatorial thermocline and in the northern North Pacific thermocline (Moore et al., 2013). The model simulates too widely expanded Oxygen Minimum Zones (OMZs, defined here as areas where the oxygen concentration is below 20 mmol m⁻³; magenta contours) in the eastern Pacific, Atlantic and Indian oceans. Similar biases have been identified in other models and attributed to biases in the production and remineralisation of particulate organic matter and to deficiencies in the representation of the Equatorial Undercurrent ~~in Earth system models (Bopp et al., 2013; Cocco et al., 2013; Brandt et al., 2015; Cabré et al., 2015; Oschlies et al., 2017).~~

The evaluation of the modelled variability remains difficult as observational data are sparse. Furthermore, there is an inherent mismatch in the spatial scale between local measurements and the model resolution, which is of the order of 100 km. The modelled data are thus spatially averaged as compared to the observations and their variability does not explicitly take into account mesoscale eddies and other small scale processes (Long et al., 2016). Figure A3 compares the reconstructed variability and trends in O₂ over recent decades at 300 m depths and for different basins (Schmidt et al., 2017) with the model results. CESM simulated historical O₂ concentrations show multi-decadal variability, although with a much smaller amplitude compared to the observations. Long et al. (2016) have compared historical time series from the Hawaii Ocean Time-Series (HOT) station, the Ocean Station Papa (OSP) and the Bermuda Ocean Time Series (BATS) to the CESM large ensemble. They show that modelled variability in annually-averaged O₂ is substantially smaller than observed. Taken at face value, beyond the limitations described above, these comparisons suggest that variability in CESM may be biased towards low estimates. This would tend to bias ToE towards early emergence.

Regarding the temperature mean distribution (Fig. A2d), the model is able to simulate the isopycnal structure at intermediate depths reported by Locarnini et al. (2013): cold water masses at the poles, the centre of the subtropical gyres show higher

~~temperature~~ temperatures than the surroundings (Fig. A2b). Nevertheless, the model simulates colder water in the Southern Ocean and in the equatorial Pacific band and warmer water in the eastern North Atlantic (isotherm 14° C) in the thermocline compared to the observations.

2.2 Analysis tools

5 2.2.1 Correcting for model drift and removing millennial trends

~~At year 850 CE of the CTRL simulation, the~~ The upper 500 meters of the ocean are generally equilibrated with the forcing ~~resulting at the start of the simulations. This results~~ in negligible linear drifts of T (-2.810^{-2} °C per century), S (-5.010^{-3} ~~permil~~ ‰ per century), O₂ (0.22 mmol m⁻³ per century) and other properties in the CTRL (not shown). The drift, however, increases with depth. It starts to become noticeable compared to the variability around 500 m depth. In this study, we focus on variability
10 within the thermocline (200-600 m) where drifts are still small and do not affect conclusions (Fig. A1c). Nevertheless, we use the results from the CTRL to estimate and correct for model drifts in all the studied variables. ~~Because the control simulation drift seems to diminish~~ It appears that model drift diminishes by the end of the ~~period~~ control simulation. Hence, an exponential curve ($a(1 - e^{-b|t|}) + c$) was fitted to the annual outputs of the CTRL simulation at each grid cell and for each variable of interest, and extended to 2100 CE. The fit was then removed from the original output of the CTRL and ~~forced simulations the~~
15 forced simulation (Fig. A1 ~~a and b b and c~~; solid purple curve). ~~This results in the removal of any long-term trend in the CTRL and to a large extent in the surface ocean and the upper thermocline in the forced run.~~

Yet, ~~the in the last millennium simulation, the~~ drift-corrected ~~forced last millennium simulations~~ signal shows residual millennial-scale trends in the subsurface waters and the deep ocean. We do not exactly know the origin of the millennial-scale trends in the deep ocean, but we hypothesise that these trends are a ~~response to including volcanic forcing in the forced simulations, whereas volcanic forcings is absent in the CTRL and spin up. This leads on average to a negative radiative forcing compared to the spin up and control simulation (Gregory, 2010). The deep ocean only slowly adjusts to this averaged negative forcing possibly leading to long-term cooling and a corresponding increase in O_{2,sol} and O₂ in the deep ocean. slow and accumulative response to the volcanic forcing.~~ In this study, we are primarily interested in investigating variability on time scales ranging from years to many centuries in the upper ocean and to detect anthropogenic trends ~~from the background of natural interannual~~
25 ~~to centennial scale climate variations as representative for the last thousand years. Slow emerging from this variability. Slow natural~~ trends influence the computation of metrics such as the standard deviation around a mean value and Time of Emergence (ToE). Although ~~millennial scale trends they~~ are small in the surface ocean and the thermocline, we ~~fitted removed them from the forced simulation by fitting~~ a linear trend to the model output over the period 850-1800 CE at each grid cell and for each variable of interest. ~~This trend is then removed from the forced simulation to exclude millennial scale variability~~ (Fig. A1 ~~ab,~~
30 ~~c~~; red solid curve). Figure A1 ~~a and b b and c~~ illustrate the computation of drift- and trend-corrected fields from the original outputs for the globally averaged ocean and the thermocline depth range (200-600 m). We note that these corrections have a small influence on the results in the upper ocean, our main study area, and do not affect our main conclusions.

2.2.2 Separation of O₂ concentration into components

~~Marine~~ Following earlier studies (e.g. Frölicher et al., 2009; Bopp et al., 2017; Ito et al., 2017), marine O₂ concentration can be expressed as the sum of two components: O₂ solubility ($O_{2,sol}$) and Apparent Oxygen Utilisation (AOU) following earlier studies (e.g. Frölicher et al., 2009; Bopp et al., 2017; Ito et al., 2017). $O_{2,sol}$ is approximated by the saturation concentration as described in Sect. 2.1.1. It depends non-linearly on T and S, but the variations in $O_{2,sol}$ are mainly driven by the variations in temperature. AOUs are computed as a residual from modelled O₂ and diagnosed $O_{2,sol}$:

$$[O_2] = [O_{2,sol}] - AOU \quad (1)$$

AOU predominantly reflects O₂ respiration due to remineralisation of organic material in the model. It depends on the amount of organic matter sinking expressed in this study by the Particulate Organic Carbon production (POC production) availability of dead organic matter and on water mass age (ideal tracer) as-. We use the ideal age tracer to estimate water mass age which is dictated by circulation, mixing and convection. Production of particulate organic carbon (POC) is used as a diagnostic for available dead organic matter. For completeness, we note that the diagnosed AOUs are additionally influenced by deficiencies in the saturation concentration $O_{2,sol}$ to represent the solubility component. These arise due to the mixing of different source waters given the non-linear relationship between solubility and T, S as well as by incomplete air-sea surface equilibration of these source waters.

2.2.3 Estimation of the Time of Emergence

~~In order to detect the changes due to anthropogenic forcings, we use~~ We apply the Time of Emergence (ToE) concept (Hawkins and Sutton, 2012). We estimate the ToE when decadal-scale (e.g. (Hawkins and Sutton, 2012)) to detect anthropogenic change. ToE is the time when changes due to anthropogenic forcing in O₂, temperature and related variables emerge from natural variations (Eq. 2). ~~We express drift~~ Drift and trend-corrected concentrations are expressed as annual anomalies relative to a preindustrial reference period spanning from 1720 to 1800 CE (Hawkins et al., 2017). The natural variability or noise, N , is computed as one standard deviation (STD) of the anomalies of each variable of interest over the period from 850 to 1800 CE in the forced simulation and for each water volume (grid cell to global ocean) and variable of interest. Note that. When considering spatially-averaged variables, their standard deviation is computed from spatially-averaged the spatially-averaged values, rather than by taking the averaged deviations of the corresponding individual grid cells. The low-frequency low-frequency climate change, S , is diagnosed as the spline-fitted (Enting, 1987) anomalies using a cut-off period of 40 years (Enting, 1987) from the year 1800 in order to remove short-term variations over the industrial period. Similarly, as for N , S is computed on the spatially-averaged values when relevant. The ToE is determined as the time when the signal S becomes for the first time larger than twice the noise N (Eq. 2; Fig. A4).

$$\text{ToE} : \frac{S}{N} \geq 2 \quad (2)$$

$$\underline{ToE : \frac{S}{N} \geq 2}$$

The threshold of two STD allows the distinction of the signal from the variability with a confidence interval of 95.45 %; this confidence level is selected following many earlier studies (e.g. Christensen et al., 2007).

3 Results

5 3.1 Evolution for globally-averaged perturbations in ocean temperature and oxygen

~~We start the presentation of our results by first discussing~~ First, we discuss variability and trends for averaged temperature (T) and dissolved oxygen (O₂) ~~for at~~ in the surface, in the thermocline (200-600 m) and ~~for~~ for the whole ocean (Fig. 1 and A5). The magnitude of variability and anthropogenic trends is larger for the surface ocean and the thermocline than for the deep ocean (Fig. 1).

10 Globally-averaged T and O₂ show near exponential ~~perturbations evolution~~ at all depths (Fig. ~~A5~~, right) during the industrial period and the 21st century in response to the prescribed anthropogenic forcing. Globally-averaged T increases by 3.7, 2.0, and 0.7 °C from the preindustrial reference period (1720-1800 CE) until 2100 in the surface ocean layer, the thermocline and the whole ocean. ~~For comparison, the mean surface air temperature increase is 5.4 °C by 2100. The ocean mean warming is about a factor of five lower than the global mean surface ocean warming.~~ Regarding O₂, the anthropogenic

15 perturbation leads to a O₂ decrease by about 15 mmol m⁻³ (-6 %) in the spatially-averaged surface ocean, by 16 mmol m⁻³ (-11 %) in the thermocline and by 10.5 mmol m⁻³ (-5 %) when averaged over the whole ocean. The anthropogenic trends are qualitatively consistent with earlier observational (Keeling and Garcia, 2002; Keeling et al., 2010; Bakun, 2017; Ito et al., 2017; Schmidtko et al., 2017) and modelling studies (~~Frölicher et al., 2009~~; Bopp et al., 2013; Cocco et al., 2013; ~~IPCC, 2013~~?; Bopp et al., 2017).

20 Last millennium variability in averaged surface ocean T and O₂ appears to be dominated by interannual to decadal variability timescales, whereas large variations on multi-decadal and centennial time scales are simulated for the thermocline and the whole ocean (Fig. 1a, left). During the period 850 to 1800 CE, simulated global mean sea surface temperature (SST) varies generally within an interval of about ±0.3 °C and global mean surface O₂ within ±1.2 mmol m⁻³ relative to the reference period (1720-1800 CE). Large global mean SST changes of up to 2 °C cooling are modelled after large explosive volcanic eruptions. These are

25 accompanied by large positive anomalies in surface mean O₂ of up to 7 mmol m⁻³. The large post-eruption anomalies decay within a few years to decades in the surface ocean. In the averaged thermocline, annual T varies within -0.15 °C and +0.1 °C and O₂ between -0.7 and 4 mmol m⁻³ relative to the reference period. These variations occur on multi-decadal-to-centennial time scales. The imprint of large explosive eruptions ~~are is~~ is visible as abrupt, sudden perturbations (e.g. at the year 1258), followed by a long-term shrinking of these initial perturbations recovery. Variability for the whole ocean ~~shows a similar variations~~

30 as in is qualitatively similar to the thermocline, but with peak variations are an order of magnitude smaller peak variations than for the thermocline depth range.

3.2 ToE, natural variability and anthropogenic change in the thermocline

3.2.1 ~~ToE~~Time of Emergence

Figures 2a and b show the ~~ToE spatial patterns~~ spatial patterns of ToE for O_2 and T in the thermocline (200-600 m). ~~Here the ToE is indicative for the emergence of a signal on the horizontal scale of a grid cell and vertically-averaged between 200 and 600 m.~~ These figures show ~~well-defined~~ well-defined patterns, with zones of early emergence (before 2020) and ~~zone~~ zones of late (2020 < ToE < 2099) or no emergence (by 2099) of the anthropogenic signal.

In general, the human-induced O_2 changes in the thermocline emerge early (before 2020) in high- and mid-latitudes, whereas they emerge late or not at all in the tropics (Fig. 2a). ~~Nevertheless, late~~ Late or no emergence until 2100 is also found in the subtropical Atlantic, western South Pacific and Indian ocean, ~~while~~. In contrast, a rather early emergence is simulated in the eastern equatorial Atlantic and the Indian ocean subtropical gyre. These patterns are consistent with the results from Long et al. (2016) and Henson et al. (2017).

In the case of temperature (Fig. 2b), the anthropogenic signal emerges generally before the end of the 21st century in the thermocline, ~~except in~~. Exceptions are small areas in the North Atlantic and in the western North Pacific. In contrast to O_2 , early ~~emergences~~ emergence of the anthropogenic warming ~~are~~ is simulated in the subtropical Atlantic gyres, ~~and late~~ emergences are and in the equatorial regions. Late emergence is simulated in the subpolar North Atlantic and in the large gyres of the Pacific gyre regions. ~~The anthropogenic T signal emerges early in the equatorial regions, again in contrast to O_2 .~~

Interestingly, the spatial ~~patterns of ToE for O_2 and T seem generally inversely related in the thermocline.~~ As a result, the spatial pattern of the difference between ToE of T minus ToE of O_2 resembles the spatial pattern of ToE of O_2 (Fig. 2c). ~~In large regions, particularly in the tropics, the mid-latitude regions of the Atlantic and along the coast of South America, the~~ The anthropogenic T signal emerges in large regions much earlier than the O_2 signal in the thermocline (brown areas; Fig. 2c). ~~Because ocean temperature and ocean physics influence marine biogeochemical cycles and O_2 , one may expect T changes to emerge before O_2 changes.~~ These regions include the tropics, the mid-latitude Atlantic and the thermocline off the coast of South America. Yet in some areas, ~~such as the subtropical Pacific gyres, the Southern Ocean, the northern equatorial Atlantic, and the North Atlantic subpolar gyre~~ the anthropogenic signal emerges first in O_2 . The reasons for these results are analysed in Sect. 3.4. The following section is ~~first~~ dedicated to a more in-depth analysis of the signal and the noise that both define ToE.

3.2.2 Natural variability and anthropogenic changes

~~Considering that ToE is a signal-to-noise problem, we compare the magnitude of the signal (anthropogenic changes of O_2 and T).~~ We analyse the magnitude and spatial feature of the noise (Fig. 3e, d) ~~as well as of the noise (the amplitude of the natural variability; a, b) and of the signal~~ (Fig. 3a, bc, d) to understand why a signal emerges early or late. Natural variability of O_2 in the thermocline (Fig. 3a) ~~range~~ ranges from less than 1 mmol m^{-3} to more than 10 mmol m^{-3} (STD $\pm 2.50 \text{ mmol m}^{-3}$; 850 to 1800 CE). Variability is small in the core of the O_2 minimum zones ~~in the tropical Indian ocean and in the eastern tropical Pacific and Atlantic as O_2 remains depleted.~~ Variability. In contrast, variability is generally high at the edge of the major oceanic gyres, including transition zones to O_2 minimum regions.

The anthropogenic signal in O₂ remains relatively small in the O₂ minimum zones and the subtropical Atlantic gyres (Fig. 3b,c). O₂ is projected to increase in the thermocline in the southern subtropical Indian gyre region and in the tropical Pacific, whereas O₂ is projected but to decrease in mid- and high-latitudes in the thermocline. The largest decrease is found in the North Pacific, up to 50 by the end of the 21st century.

- 5 By definition, the areas of early emergence (late or no emergence) result from a high (low) signal-to-noise ratio. A local Locally, a signal may emerge early (late) compared to other regions due to a relatively low relatively weak (high) variability or a relatively high anthropogenic signal strong (weak) anthropogenic response, or a combination of both. For example in the region south 30° S, simulated O₂ shows generally a concentrations show generally relatively weak natural variability (± 2 mmol m⁻³; Fig. 3a) in the thermocline south of 30° S and a and large anthropogenic O₂ change changes (>+12 mmol m⁻³ by 2100 CE; Fig. 3c). In the north Pacific, however, the standard deviation is high (± 10), but the anthropogenic signal is very large as well resulting in early ToE. However, in the North Pacific, the early emergence arises from the large anthropogenic signal (-50 mmol m⁻³ by 2100 CE) despite the intense variability (± 10 mmol m⁻³). In the eastern tropical Atlantic, the O₂ signal is weak, but the natural variability is even weaker. In these three cited regions, anthropogenic changes emerge relatively early, but for different reasons.
- 15 weak changes and low natural variability result in early emergence. On the contrary, a low signal-to-noise ratio will induce a late or no emergence of the anthropogenic signal. The anthropogenic O₂ in the western tropical Pacific, the anthropogenic O₂ signal has not emerged by 2100 in the thermocline in the western tropical Pacific, the western coastal Indian and the subtropical Atlantic gyres because of a due to the combination of strong natural variability (± 10) and relatively weak changes in O₂ (-6 by 2100 CE). But in the southern tropical Indian Ocean, North Atlantic subpolar gyre and the eastern tropical Pacific, the O₂ changes outweigh the natural variability leading to emergence by the end of the 21st century.
- 20

In general, the temperature signal-to-noise ratio is high in the thermocline, and the emergence of human-induced changes occurs before the end of the 21st century. The thermocline temperature varies naturally by less than ± 1 °C (Fig. 3b) and the anthropogenic changes are between +1 °C and +4 °C by the end of the 21st century (Fig. 3d). However, the subtropical Pacific gyres, the northern tropical Atlantic and the subtropical Indian gyre show slightly more intense natural variations which delay the emergence of the anthropogenic signal. In parts of the western North Pacific and the North Atlantic, temperature variability in the thermocline is high and the anthropogenic changes remain within the range of natural variability.

25

3.3 Sensitivity of ToE to methodological differences

Different methodological choices were applied in earlier studies to estimate ToE for precipitation (Giorgi and Bi, 2009), air surface temperature (Károly and Wu, 2005; Diffenbaugh and Scherer, 2011; Hawkins and Sutton, 2012), SST, pCO₂, pH, dissolved inorganic carbon (Keller et al., 2014), primary production or O₂ (Rodgers et al., 2015; Carter et al., 2016; Frölicher et al., 2016; Henson et al., 2016; Long et al., 2016; Henson et al., 2017). Different These different definitions and methods are used to estimate the noise (or natural variability), the anthropogenic signal and the ToE. There seems to be no consensus on the method to estimate ToE. In the following part, in order to gain confidence in the ToE estimates presented above, the influence impact of different choices for the estimate on the estimate of ToE is investigated.

30

3.3.1 Noise estimated from internal variability of a control simulation

A prevailing way for estimating the ~~The~~ background noise is ~~to consider the internal variability, using estimated in many studies from~~ the temporal standard deviation (STD) of ~~the control simulation of the grid point or the averaged domain a control simulation (CTRL)~~ (Hawkins and Sutton, 2012; Maraun, 2013; Long et al., 2016; Henson et al., 2017). ~~We defined~~ the total natural variability as the combination of the internal variability and the naturally forced variability. ~~The comparing the internal and total natural O₂ variations, by using STD of the CTRL and forced simulation (LM) as metric shows that the~~ ~~In this way, only the internal chaotic variability is taken into account. Accounting for~~ external natural forcing ~~enlarges the estimated~~ ~~may enlarge the~~ natural O₂ variability ~~significantly~~ (Table 1). Indeed, the internal variability represents only 22 % of the total natural variability in the global O₂ inventory, 61 % ~~of the variability~~ in the O₂ inventory of the thermocline, and 47 % ~~of the variability~~ in the global mean surface O₂ concentration. ~~Moreover, Frölicher et al. (2009) show that explosive volcanic eruptions influence marine O₂ for several years in the top 500 m, in accordance to Fig. 1. Therefore, in the context of detection of the anthropogenic changes, considering only the internal variability seems to underestimate the range of natural variability arising from solar irradiance changes and volcanic eruptions, and leads to earlier emergence of anthropogenic changes on the global scale.~~

Figure 4 compares the externally forced natural variability with the internal variability in each grid cell in the surface layer ~~, and~~ in the thermocline (200-600 m) ~~, and in the entire water column~~ for O₂ and T, ~~again using STD as a metric~~. There are many regions where the ratio between the STD ~~of from~~ the forced versus ~~those the STD~~ from the CTRL simulation is close to one indicating that internal and total natural variability are approximately equal (Fig. 4). In particular, ~~total forced~~ and internal natural variability in O₂ is comparable in most thermocline regions (Fig. 4e). However, there are also ~~large regions where~~ the ratio of total to internal variability in O₂ and in T is substantially larger than one. Such regions include the tropical and mid-latitude Atlantic, the Arctic and a belt around Antarctica when considering the entire water column (Fig. 4e, f). ~~Total natural variability is up to a factor of two or more larger than internal~~ ~~regions where natural variability is much larger than internal variability. Indeed, natural~~ variability in T in the thermocline of the tropical and mid-latitude Atlantic, in the Arctic, in parts of the Southern Ocean and of the eastern tropical and subtropical Pacific (Fig. 4d). Surprisingly, the SST shows more variability at high latitudes in the control simulation rather than in the forced simulation (Fig. 4f). The exact reasons for these differences are beyond the scope of the present study. ~~But we hypothesise that the radiative cooling driven by explosive volcanic eruptions may decrease SST in high latitudes, leading to a more extended sea ice, and therefore reducing SST variability. Yet in general, variability in SST is in general larger in LM than in CTRL in low and mid latitudes.~~

~~Total natural~~ ~~exceeds internal~~ variability is not only substantially larger than internal variability for the vertically-integrated water column and thermocline but also on the level of the individual grid cell in the surface layer, in particular in tropical O₂ by more than 50 % in 3 % of the thermocline, while deviations larger than 20 % are found in 18 % of the thermocline. For the temperature, forced variability exceeds internal variability by more than 20 % over a third of the thermocline and by more than 50 % over 10 % of the thermocline. The relative difference between natural and internal variability is thus often smaller for O₂ than for T in the thermocline. Turning to the surface ocean, natural variability in O₂ and T is substantially larger than

~~internal variability in many low latitude regions (Fig. 4a,b). In other words, forced natural variability is not only important when integrating its imprint over large volumes, but may also be of importance on the local scale.~~

~~In conclusion c,d). Hence,~~ using results from a control simulation to estimate natural variability leads to an underestimation of total natural variability in ~~specific regions with corresponding consequences on the estimations of some specific regions.~~

5 ~~This affects~~ ToE as illustrated by Fig. 5. Nevertheless, the results from a control simulation appear to yield a reasonable approximation of simulated natural variability in O₂ and T on the local scale in the thermocline. Regions with ~~larger the largest~~ differences are located at the edges of the subtropical gyres in the North Pacific and the tropical Atlantic (Fig. 5a, b).

3.3.2 Noise estimated ~~from over the industrial period~~ 1720-1800

~~Estimates of noise may further be sensitive to the choice of period. Hawkins et al. (2017) define the time period 1720-1800~~

10 ~~CE as the optimal pre-industrial period. This pre-industrial period is justified by rather normal conditions during 80 years: relatively stable TSI and small volcanic eruptions.~~

~~A direct estimation of total natural variability is often not possible because ESM simulations typically start in the 19th century and apply natural plus anthropogenic forcings. Other studies have therefore estimated natural variability from the residual variability (e.g. Keller et al., 2014; Henson et al., 2016) after removing the anthropogenic response from the model output. The residual variability is then defined as the difference between the annual~~

15 ~~model output and a low-pass filtered signal. Here, a spline with a cut-off period of 40 years is used to compute the filtered signal. Then, the standard deviation of the residual variability is computed for the period 1850 to 2005 CE. Surprisingly, STD~~

~~of O₂ and T in the thermocline as computed from the residual variability is much smaller than as computed from the Last Millennium simulation (LM) in many regions (Fig. 6a, b). Particularly large differences (100 % of LM STD or more) are found in the Atlantic and high-latitude regions for T and O₂ and in large parts of the Pacific for O₂. The stronger variability in LM~~

20 ~~compared to the residual variability likely results from low-frequency variability included in LM but removed by the spline in the residuals. As a consequence O₂ and T in the thermocline emerge earlier when using STD from the residuals instead of STD~~

~~from the 850 to 1800 CE period to compute ToE (Fig. A1e)- 6c, d).~~

~~Estimates of noise may further be sensitive to the choice of the period. Because fully coupled millennial scale simulation~~

25 ~~simulations are expensive and relatively rare, we compare the STD of T and O₂ in the thermocline in the forced LM simulation for the period 850-1800 CE versus the shorter pre-industrial preindustrial reference period 1720-1800 CE (Fig. A6a, b).~~

~~for the period 850-1800 CE versus the shorter pre-industrial preindustrial reference period 1720-1800 CE (Fig. A6a, b).~~

In a large part of the thermocline, STD in T and O₂ are similar (within $\pm 10\%$), reflecting a similar estimated natural variability. Differences in STD are for example found in regions of the South Pacific, the eastern North Pacific, the Arctic Ocean and for O₂ in the Arabian Sea. ~~The resulting ToE are compared to the one using STD from the period 850 to 1800 CE~~

30 ~~(Fig. 6c, d). For O₂, substantially earlier ToE are estimated in large parts of the Pacific, the Arctic and the Southern Ocean when using the PI-period preindustrial period to approximate the natural variability. However (Fig. A6a). However,~~

~~changes in oxygen are estimated to appear later in some parts of the equatorial Atlantic, in the Arabian Sea and in a few grid cells in the Pacific and Arctic. Similarly, earlier ToE for T are found for example in large parts of the Pacific when using the variability from~~

the ~~PI-period~~ preindustrial period (Fig. A6b). The results ~~suggests~~ suggest that a century-long period of the forced simulation may not yield robust results for variability and ToE in all regions.

3.3.3 ~~Noise estimated from a simulation over the industrial period~~

5 Most available carbon-cycle-enabled ESM simulations addressing anthropogenic change begin in the 19th century. Then, the total natural variability cannot be directly assessed and the internal variability can only be determined if the corresponding control simulation has been also produced. Instead, Keller et al. (2014) and Henson et al. (2016) used the standard deviation of the residual variability to estimate natural variability. The residual variability is defined as the difference between the full signal and a low-pass filtered signal designed to extract the effect of the anthropogenic forcing. Here, a spline with a cut-off period of 40 years is used to compute the filtered signal from the year 1800. The standard deviation of the residual variability is computed for the period 1850 to 2005 CE.

Surprisingly, STD of O_2 and T in the thermocline as computed from the residual variability of the 1850 to 2005 CE period is much smaller than as computed from the Last Millennium (LM) simulation (850 to 1800 CE) in many regions (Fig. 6e, f). Particularly large differences between the estimates of STD (100% or more) are found in the Atlantic and high-latitude regions for T and O_2 and in large parts of the Pacific for O_2 .

15 The stronger variability in LM compared to the residual variability likely results from low-frequency variability included in LM but removed by the spline in the residuals. The residual variability included only the variability that does not pass the low-pass spline filter. Hence, it does not include periods much larger than the cut-off period of the spline, taken here to be 40 years. As a consequence of the smaller variability, ToE for O_2 and T in the thermocline is earlier when using STD from the residuals instead of STD from the 850 to 1800 CE period to compute ToE (Fig. 6g, h).

20 3.4 Apparent oxygen utilisation, O_2 solubility, ventilation, and organic matter cycling

In order to gain insight on the processes underlying O_2 variations, we analyse the variability, anthropogenic induced change, and ToE of the We analyse apparent oxygen utilisation (AOU) and ~~of the~~ O_2 solubility component ($O_{2,sol}$) ~~· $O_{2,sol}$ · $2_{,sol}$~~ in order to gain insight into the processes underlying O_2 variations. $O_{2,sol}$ variations are driven by SST changes and AOU variations mainly reflect the imprint of changes in water mass ventilation and in the remineralisation of organic matter. Here, ventilation is diagnosed by an ideal age tracer and changes in remineralisation of organic matter are linked to the production of organic matter.

3.4.1 Natural variability

Changes in AOU largely explain most of the preindustrial variations in O_2 with a generally small role for $O_{2,sol}$ ~~· $2_{,sol}$~~ both at the global scale and on average in the thermocline (Fig. 1a, b and A5a). The $O_{2,sol}$ ~~· $2_{,sol}$~~ component contributes nonetheless notably to the O_2 changes after the large volcanic eruptions in 1258 and 1452. ~~Furthermore, an anomalously warm phase with relatively low O_2 is simulated during the 12th and early 13th century. AOU anomalies are small over this period and the~~

perturbation in $O_{2,sol}$ dominates during this phase of very weak external forcing (Fig. 1a). Nevertheless, perturbations in AOU are in general much larger than in $O_{2,sol}$ during other PI periods. In contrast, This general dominance of AOU over $O_{2,sol}$ during PI contrasts with the industrial period, during which changes in $O_{2,sol}$ contribute for half of the global ocean O_2 decrease over the industrial and future period (Fig. 1A5a). An even larger relative contribution of $O_{2,sol}$ is simulated for the spatially-averaged thermocline signal (Fig. 1b), ~~while changes in AOU in the thermocline remain small over the industrial period due to the compensation of regionally opposed responses, as described below.~~ The O_2 variations at the surface are, unsurprisingly, primarily caused by changes in solubility ($O_{2,sol}$). ~~The influence of air-sea O_2 disequilibria, included in AOU, is on global average small over the entire duration of the simulation (Fig. 1c).~~ Fig. A5b).

Following Eq. 1, Quantification of the natural variability of O_2 can be split into the contribution of individual components: contributions from individual components given in Eq. 1 following:

$$Var(O_2) = Var(O_{2,sol}) + Var(-AOU) + 2COV(-AOU, O_{2,sol}) \quad (3)$$

Var() stands for the variance of the variable and equals the square of STD. Both metrics are positive by definition. ~~This implies that the sign of the covariance between $O_{2,sol}$ and -AOU (COV(-AOU, $O_{2,sol}$)) indicates whether the contributions from $O_{2,sol}$ and -AOU enhance or partly cancel each other. If COV(-AOU, $O_{2,sol}$) is negative, for example, the resulting Var(O_2) will be smaller than the sum of Var($O_{2,sol}$) and Var(-AOU) and the two components partly cancel each other. On the contrary, they have an additive effect when their covariance is positive.~~

Table 1 gathers the STD of O_2 and its components and the corresponding covariance in the global averaged surface ocean, thermocline and world ocean for the control simulation (CTRL; internal variability) and the forced simulation (LM; natural external and internal variability; 850-1800 CE). ~~COV(-AOU, $O_{2,sol}$) is negative in CTRL in all three water bodies. Hence, $O_{2,sol}$ and -AOU partly compensate each other in CTRL. COV(-AOU, $O_{2,sol}$) is negative in CTRL in all three water bodies. Hence, $O_{2,sol}$ and -AOU partly compensate each other in CTRL. COV(-AOU, $O_{2,sol}$) is also negative in LM for the surface ocean. This implies that changes in solubility are partly compensated by changes in air-sea O_2 disequilibrium. In contrast, COV(-AOU, $O_{2,sol}$) is positive in the LM simulation for the global ocean and the spatially-averaged thermocline during the preindustrial period. Hence, changes in $O_{2,sol}$ and -AOU are positively correlated and reinforce each other on average. In conclusion, the natural forcing leads to a positive correlation of -AOU and $O_{2,sol}$. This statistical analysis is consistent with the discussion on O_2 perturbations above: -AOU and $O_{2,sol}$ change hand in hand after large volcanic eruptions in the global mean and in the global thermocline (Fig. 1a, b). The variability in CTRL is not only smaller than in LM, but apparently also different in terms of underlying physical and biogeochemical mechanisms and in their interactions.~~

Consistent with this, the spatial pattern of the natural variability in O_2 (Fig. 3a) can largely be attributed to the natural variability in -AOU (Fig. 7a). $O_{2,sol}$ variations have generally a limited impact on the natural variability of O_2 in the thermocline (Fig. 7b). By definition, $O_{2,sol}$ is largely congruent with the previously discussed pattern of STD(T) (Fig. 3b). Nevertheless, in the high-variability region in the western North Pacific and the northern North Atlantic, STD($O_{2,sol}$) is of the same order of magnitude as STD(-AOU).

~~The pattern of STD(-AOU) The latter~~ resembles the pattern of STD for ideal age (Fig. 7a, d). This suggests that a significant fraction of the variability in -AOU (and thus O_2) is driven by changes in circulation and water mass age. Variability in ~~production of~~ particulate organic matter (POC) production in the surface layer (Fig. 7e), indicative of water column remineralisation of organic material, may also contribute to the variability in -AOU in the thermocline. For example, in the northern North Atlantic, STD in POC production and -AOU is relatively large, while STD in ideal age is low. On the other hand, the large STD in POC production in parts of the Southern Ocean are not reflected in STD(-AOU). ~~The pattern of STD($O_{2,sol}$) (Fig. 7b) is by definition largely congruent with the previously discussed pattern of STD(T) (Fig. 3b).~~

COV(-AOU, $O_{2,sol}$) shows a large negative amplitude in hot spot $O_{2,sol}$ is strongly negative in some regions with large variability in -AOU (Fig. 7c). These regions are, as discussed in Sect. 3.2, are located at the boundaries ~~between of~~ major gyres. This suggests that changes in -AOU and $O_{2,sol}$ partly compensate each other in these regions. An exception is the boundary region between the subtropical and subpolar gyres in the North Atlantic, where the two components tend to enhance each other, therefore increase O_2 variability.

3.4.2 Anthropogenic change

Next, we address the pattern of anthropogenic changes in $O_{2,sol}$ ($\Delta O_{2,sol}$) and in -AOU ($\Delta(-AOU)$) in the thermocline ~~and from PI to the end of the 21st century~~ (Fig. 8 and 9). $\Delta O_{2,sol}$ shows a spatially coherent decrease as dictated by the global warming pattern (Fig. 3d). In contrast, $\Delta(-AOU)$ shows a strong spatial pattern in the thermocline with positive values in the tropics, the Arctic, and subtropical Atlantic and negative values in the mid- and high-latitude Pacific as well as the Southern Ocean and the subtropical Indian and the Pacific Ocean. Regional changes in -AOU largely balance each other, explaining the small change in spatially-averaged -AOU (Fig. 1b). The anthropogenic increase in O_2 (Fig. 3c) in parts of the tropical thermocline is attributed to the increase in -AOU, partly offset by the decrease in $O_{2,sol}$, while the anthropogenic O_2 decrease in the northern Pacific and the Southern Ocean results from a decrease in both -AOU and $O_{2,sol}$.

$\Delta(-AOU)$ in the thermocline is mainly driven by changes in ventilation and modulated by changes in remineralisation rates (Fig. 8c, d). ~~This is similar as for the natural variability in -AOU.~~ The increase in ideal age and the increase in POC production (indicative of an increase in remineralisation rate) explain the decrease in -AOU in the Southern Ocean. By contrast, in the western tropical Pacific, the equatorial Indian and the Atlantic ocean, the combination of a decrease in water mass age and in POC production explains the increase in -AOU over the industrial period and the 21st century. In the eastern tropical Pacific and in the North Pacific, the impacts of changes in ventilation are partly mitigated by changes in organic matter remineralisation rate.

Below the thermocline and in the deep ocean, O_2 decreases over the industrial period and the 21st century as both -AOU and $O_{2,sol}$ decrease (Fig. 9). The decrease in -AOU is again mainly explained by an increase in ideal age. Changes in ideal age in the deep Atlantic, Southern Ocean and Pacific partly exceed 150 years and indicate a general reduction in the deep water mass formation over the industrial period and the 21st century in the simulation.

3.5 ToE of O₂ components

The ToE of oxygen depends on the O₂ variability over the last millennium on the one hand and the O₂ response to climate change on the other hand. We have shown that in the thermocline, both the variability and the anthropogenic signal of O₂ are mainly driven in the thermocline are driven primarily by changes in -AOU modulated, the former of which is influenced in part by changes in O_{2,sol}. The question arises whether the signal of -AOU or of O_{2,sol} emerge earlier than the signal of O₂. O₂ solubility and thus O_{2,sol} is a function of T, leading to ToE(O_{2,sol}) is very similar to ToE(T) and we refer to the previous discussion in on ToE(T) (Fig. 2b) and its difference to ToE(O₂) (Fig. 2c). Interestingly, the -AOU and O₂ signals seem to emerge at around the same time in the thermocline in the Pacific and Indian subtropical gyres (Fig. 10b). But the signal of -AOU emerges later in the thermocline in many regions including the subtropical oceans in the Southern Hemisphere, while it emerges earlier in the tropics and in the subtropical gyres of the Atlantic as well as south of Madagascar. This suggests that anthropogenic changes in -AOU might be detectable earlier in large oceanic regions. However, the specific results may be model-dependent and it needs need to be confirmed by other models or by observations whether the anthropogenic -AOU signal is detectable earlier than the O₂ signal in the identified regions. Earlier emergence of -AOU than O₂ is generally found in regions with a positive change in -AOU and thus in regions where -AOU and O_{2,sol} partly offset each other. Late emergence in -AOU is found in regions with a small anthropogenic change in -AOU.

4 Discussion and Conclusion

We have analysed the variability at interannual timescales and anthropogenic change in natural variability over the last millennium and anthropogenic trends of marine oxygen (O₂) and related physical and biogeochemical variables. We have also determined when the anthropogenic signal leaves the bound of natural variability using the time of emergence (ToE) concept (Hawkins and Sutton, 2012). Results are derived from a simulation performed with temperature (T) in simulations using the Community Earth System Model (CESM) covering the period 850 to 2100 CE and which is forced with reconstructed volcanic and solar forcing in addition to forcing from land cover changes, greenhouse gases, and other anthropogenic agents (Lehner et al., 2015). This simulation enables to put the anthropogenic changes in the context of the natural forced and internal variability of the last millennium. The relative roles of the internal and forced natural variability were quantified. We have also determined the time of emergence (ToE) of T, O₂, and apparent oxygen utilisation (AOU) in the thermocline.

We find that anthropogenic deoxygenation and warming in the thermocline has today already left the bounds of natural variability. In order to quantify this result, Fig. 11 shows the fraction of the ocean that emergences over the industrial and future period. In on the global scale. By 2020, these signals have emerged in over 60 % and 90 % of the thermocline area show anthropogenic deoxygenation and warming respectively, respectively (Fig. 11). By the end of this century, these values are approaching towards 100 % when if greenhouse gas emissions continue unabated with increasing risks. This presents an increasing risk for the function and services of marine ecosystem ecosystems (Pörtner et al., 2014). There are uncertainties in our results, and some are linked to the relatively coarse resolution of the CESM model of order one degree. Larger variability may be found on smaller scales. For example, Long et al. (2016) document that interannual variability from the Hawaii Ocean

Time-Series (HOT) station is about a factor of two larger than the variability at the same location in CESM. Another source of error is structural model uncertainty. Comparison with observations and multi-model studies show weaknesses of the current class of earth system model in simulating the observed O₂ distribution and that projections of anthropogenic O₂ is relatively early in the mid- and high-latitude thermocline and late in the tropical ocean and subtropical Atlantic, in agreement with earlier work (Long et al., 2016; Henson et al., 2017). Temperature ToE has not been analysed in the thermocline in earlier studies. In CESM, ToE is relatively early for T in the thermocline of eastern boundary systems, the subtropical Atlantic and in large parts of the Southern Ocean, but late in many subtropical regions and in large parts of the North Pacific.

A large O₂ change are particularly uncertain in low oxygenated waters (Bopp et al., 2013; Cocco et al., 2013). decline is simulated by CESM for the future in the North Pacific thermocline, in agreement with other models (Bopp et al., 2013; Cocco et al., 2013). This region is characterised by particularly large changes in ventilation. As an interesting consequence, the anthropogenic O₂ signal is detectable earlier than the anthropogenic temperature signal in large parts of the northern North Pacific. Along the same line, Keller et al. (2015) show that a potential weakening of the ENSO variability is verifiable earlier and more widespread for carbon cycle tracers than for temperature and Séférian et al. (2014) highlight the multi-year predictability of tropical productivity. This corroborates earlier suggestions by Joos et al. (2003) that measurements of O₂, or, more generally, multi-tracer observations, are critical in detecting or predicting anthropogenic changes.

4.1 Natural variability: forced and internal

For a better understanding of these results, we have analysed the natural variability and the anthropogenic response of the respiration (-AOU) and solubility (O_{2,sol}) components of O₂. Variations in AOU dominate variations in O₂ during the last millennium, as well as the local response to anthropogenic emissions in the thermocline. For the globally-averaged thermocline, internal variability in AOU and in O_{2,sol} are negatively correlated and partly offset each other. In contrast, the total natural variability of these two components are positively correlated and thus enforce variability in O₂ in the global thermocline (Tab. 1). Under human activities, changes in AOU and O_{2,sol} partly cancel each other in the tropical thermocline and in the subtropical Atlantic ocean, in accordance with Bopp et al. (2017). Moreover, AOU (thus O₂) variability and its signal are explained by changes in water mass ventilation, with a smaller role for changes in biological productivity (Fig. 8 and 9). Strongly reduced ventilation in the northern North Pacific, therefore, drives the early O₂ emergence. This suggests that weakened ventilation precedes warming in the thermocline in this region.

Both The comparison between the transient last millennium simulation and the corresponding control simulation shows that both the naturally forced and the internal variability contributed to the simulated climate and biogeochemical variations of the last millennium. The internal variability arises from the inherent and partly chaotic variability of the climate system (Baines, 2008; Frölicher et al., 2009; Deser et al., 2012; Frölicher et al., 2009; ?; Resplandy et al., 2015). It is also associated with climate modes such as the El Niño-Southern Oscillation (Bacastow, 1976; Keller et al., 2015), the North Atlantic Oscillation (Keller et al., 2012), the Pacific Decadal Oscillation (Duteil et al., 2018) or the Southern Annular Mode (Hauck et al., 2013). Important The natural forced climate variability on interannual to centennial time scales arise from explosive volcan-

ism and from changes in solar irradiance ~~superimposed on long-term trends from orbital variations (Wanner et al., 2008; ?; Lehner et al., 2015)~~ on interannual to centennial time scales (Wanner et al., 2008). The ~~comparison between the transient last millennium simulation and the corresponding control simulation shows that both natural forced and internal variability contribute significantly to variations in marine O₂ and temperature. While the role~~ relative importance of forced variability is particularly large when considering large-scale averages (Table 1, Fig. 4), ~~due to the more important smoothing effect on internal chaotic variability. Large explosive volcanic eruptions cause widespread ocean cooling and positive O₂ anomalies. The resulting temperature and O₂ perturbations last for decades and centuries in the thermocline and the deep ocean (Fig. 1). This implies~~ but can also be substantial on the local scale. Our results imply that natural forced variations should not be neglected when comparing century-scale anthropogenic climate change to natural climate variability. ~~Yet, earlier studies addressing ToE do not consider natural variability arising from solar and volcanic forcing during the last millennium.~~

4.1 Methodological aspects: Variability estimated from control and industrial period simulations is biased low

ToE is a signal-to-noise problem where a signal of change is compared to the noise of variability. Different assumptions are made in earlier studies (i) to estimate the noise of natural variability (e.g. Giorgi and Bi, 2009; Hawkins and Sutton, 2012; Mora et al., 2013; Keller et al., 2014; Rodgers et al., 2015; Carter et al., 2016; Frölicher et al., 2016; Long et al., 2016; Brady et al., 2017; Henson et al., 2017), (ii) the anthropogenic signal (e.g. Rodgers et al., 2015; Carter et al., 2016; Frölicher et al., 2016), (iii) the detection threshold (Rodgers et al., 2015) and (iv) the detection period (Henson et al., 2017). The detection period is typically taken to start around modern times in studies directed to detect the anthropogenic signal by measurements (Henson et al., 2016) or, as in this study, at the beginning of the preindustrial period.

ToE is here taken to be the time when the anthropogenic signal reaches twice the noise of Moreover, we show that ToE is highly sensitive to the method applied for estimating the natural variability. In the standard case, the noise is defined as the standard deviation of annual values over the period 850 to 1800 CE. It includes therefore internal and forced variability. We consider annual data as the main focus is on the thermocline where seasonal variability is smaller compared to the surface. The anthropogenic signal is defined in this study as the long-term change relative to year 1800 CE obtained by low-pass filtering the model output with a smoothing spline with a cut-off frequency of forty years (Enting, 1987). We consider this choice as more appropriate than a linear trend (Keller et al., 2014; Henson et al., 2017) because the anthropogenic signal increases in a non-linear way and is highly dependent on the window of time considered Carter et al., 2016. The applied detection threshold of two standard deviations excludes most extreme environmental conditions that are also unusual in the context of the last millennium (Fig. A4), while the application of one standard deviation as a threshold (Rodgers et al., 2015; Carter et al., 2016; Frölicher et al., 2016) enables a more rapid trend detection.

The way variability is estimated significantly influences estimates of ToE. In this study, ToE for O₂ and temperature in the thermocline is estimated using different estimates of variability within a self-consistent setting. Namely, variability is estimated from the forced simulation of We have estimated variability from a forced simulation over the last millennium (850 to 1800 CE) and, alternatively, for a short period (850-1800 CE), over the period 1720 to 1800 CE) and from the , and from a control simulation. As expected, using variability from the control and the short period yields in general, an earlier emergence of the

anthropogenic signal than when using variability from the last millennium simulation (Fig. 11). These two estimates of noise do not capture the full natural variability of the last millennium. Yet, differences in estimated ToE and noise are often modest on the local scale (Fig. 2, 4 and 11). ~~As last millennium earth system simulations extended towards the future period are still rare, it might be appropriate, though not ideal, to use the results from a control simulation to estimate natural variability.~~

5 In addition, we have tested the use of the "residual" variability of a time series to estimate noise. The long-term trend in the industrial period (~~1800–2005~~ 1850–2005 CE) data is removed by a low-pass-low-pass filter; the standard deviation of the remaining annual anomalies provides then an estimate of the noise. This yields a much smaller variability than estimated from the last millennium output and thus a much earlier ToE (Fig. 6 and 11). Applying a smoothing-spline cut-off period of 80 ~~and~~ or 100 years instead of 40 years ~~for the smoothing spline leads to~~ leaves a higher variability but ~~still underestimates the the~~
10 full last millennium variability is still underestimated (not shown). ~~The residual variability is readily estimated from existing and forthcoming measurement time series (e.g. Hawaii Ocean Time-series, Ocean Station Papa, Bermuda Atlantic Time-series Study), while temporally resolved ocean biogeochemical data are missing for the last millennium. Another published approach is to estimate linear trends and their uncertainty from an ensemble of model simulations (Rodgers et al., 2015; Frölicher et al., 2016; McKinley et al., 2016). This approach is insightful. However, there is only one realisation of the real climate system evolution and sufficiently long time series to estimate the uncertainty in long-term trends from observations are largely missing.~~

~~We have shown that the absolute ToE values are noise- and signal-definition dependent. The comparison across the published ToE analyses demonstrated as well a model dependency. However, the relative ToE ($ToE(T) - ToE(O_2)$) shows similar patterns and values across all the methods described and tested in this study (not shown). We conclude that the use of ToE of one variable in comparison to the ToE of another variable may bring more robust insights on the ToE analysis.~~

20 **4.1 Anthropogenic deoxygenation is earlier detectable than anthropogenic warming in some regions**

~~We find ToE for O_2 to be early in the mid- and high-latitude thermocline and late in the tropical ocean and subtropical Atlantic, in agreement with earlier work (Long et al., 2016; Henson et al., 2017). ToE for temperature has not been analysed in the thermocline in earlier studies. In CESM, ToE for temperature is early in eastern boundary systems, the subtropical Atlantic and in large parts of the Southern Ocean, but late in many subtropical regions and in large parts of the North
25 Pacific. A large O_2 decline is simulated by CESM, in agreement with other models (Bopp et al., 2013; Cocco et al., 2013), in the North Pacific thermocline, where changes in ventilation are particularly large. As an interesting consequence, the anthropogenic O_2 signal is earlier detectable than the anthropogenic temperature signal in large parts of the northern North Pacific. Keller et al. (2015) show that a potential weakening of the ENSO variability is earlier verifiable and more widespread for carbon cycle tracers than for temperature and Séférian et al. (2014) highlight the multi-year predictability of tropical
30 productivity. This corroborates earlier suggestions by Joos et al. (2003) that measurements of O_2 , or more general multi-tracer observations, are instrumental to better detect or predict anthropogenic change.~~

4.1 Anthropogenic trend for AOU may be earlier detectable than for O_2 in some regions

In conclusion, it might be appropriate, though not ideal, to use the results from a control simulation to estimate natural variability, as last millennium earth system simulations extended towards the future period are still rare.

We have presented results in terms of variability and anthropogenic change not only for O_2 and temperature, but also for variables indicating the role of physical and biological mechanisms. These are apparent oxygen utilisation (AOU), indicative of changes in the marine biological cycle, the solubility component of O_2 ($O_{2,sol}$), indicative of thermally (and salinity) driven changes in O_2 , ideal age, indicative of circulation changes and water mass ventilation, and production of particulate organic carbon (POC), indicative of biological export and the amount of organic matter remineralised in the water column. Alternatively, large ensemble simulations for the industrial period and the future will become available within CMIP6. Different ensembles including or excluding anthropogenic forcing (Stott et al., 2000) and including or excluding natural forcing may be used to disentangle the individual contributions to trends and variability. Some model centres may also wish to generate large ensemble simulations for the last millennium to study natural variability over the more recent preindustrial period (Jungclaus et al., 2010).

Most of the last millennium variability in O_2 is explained by variations in AOU and by changes in water mass ventilation, with a smaller role for solubility changes and changes in biological productivity. Variability in O_2 , AOU and ideal age is particularly large in boundary regions of the major gyres. In such regions, variations in AOU and $O_{2,sol}$ partly compensate each other as revealed by the covariance between the two variables. Turning to anthropogenic change, changes in AOU and $O_{2,sol}$ partly cancel each other in the tropical thermocline and in the subtropical Atlantic in accordance with Bopp et al. (2017). This results in an earlier ToE of AOU than O_2 . However, there are still some uncertainties in our results, and some are linked to the relatively coarse resolution of the CESM model of order one degree. Larger variability may be found on smaller scales. For example, Long et al. (2016) document that interannual variability from the Hawaii Ocean Time-Series (HOT) station is about a factor of two larger than the variability at the same location in CESM. Another source of error is structural model uncertainty. Comparison with observations (Sect. 2.1.3) and multi-model studies show weaknesses of the current class of earth system models in simulating the observed O_2 in parts of the tropical ocean. This suggests that anthropogenic change in AOU may be earlier detectable by measurements than in distribution and variability. Projections of anthropogenic O_2 in specific ocean regions.

4.1 Large deoxygenation in the deep ocean ahead

change are particularly uncertain in low oxygenated waters (Bopp et al., 2013; Cocco et al., 2013).

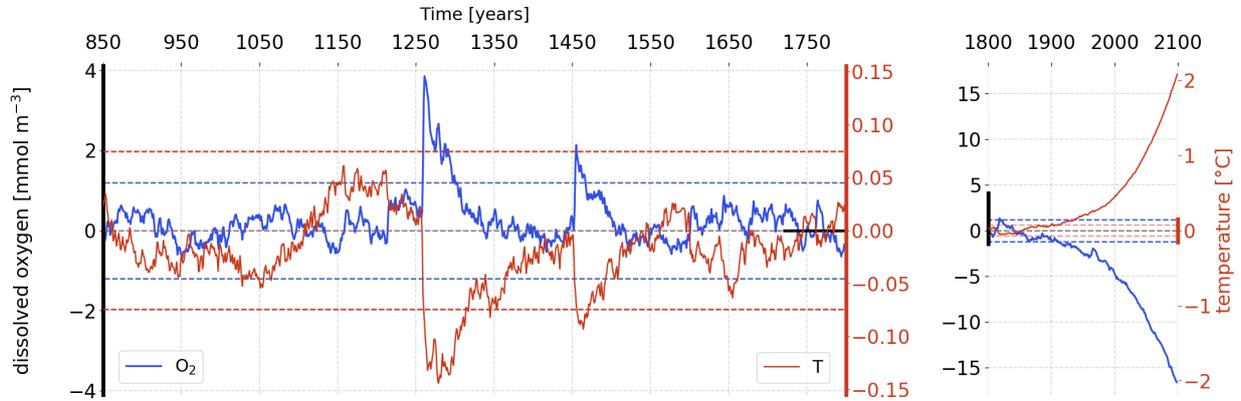
O_2 changes will likely continue beyond 2100 CE. We find a strong link between changes in O_2 , AOU and ideal age, with a shift to older water mass ages accompanied by a shift to lower O_2 . By 2100, ideal age in the near bottom waters of the Southern Ocean and the deep Pacific has increased by up to 240 years and O_2 decreased by around 16 to 20 mmol m^{-3} relative to preindustrial. These age and O_2 anomalies are likely to spread further into the deep ocean. A long-term reduction in deep ocean ventilation and O_2 under anthropogenic forcing is consistent with results from Earth System Models of Intermediate Complexity (Schmittner et al., 2008; Battaglia and Joos, 2018). For example, Battaglia and Joos (2018) find a large, transient

decline in deep ocean O₂ and in the global O₂ inventory by as much as 40 % in scenarios where radiative forcing is stabilised in 2300 CE. In their simulations, deoxygenation peaks about a thousand years after the forcing stabilisation and new steady-state conditions are established only after 8000 CE. The CESM results also support the notion of ~~a~~-long-term deep ocean deoxygenation.

- 5 In conclusion, we find that natural radiative forcing arising from explosive volcanism and solar irradiance changes ~~to~~ ~~contribute notably and in addition to internal climate variability~~ contributes notably to the overall ~~natural variability in past variability of~~ marine O₂ and temperature. We simulate large and widespread ocean deoxygenation under anthropogenic forcing and suggest that large parts of the thermocline ~~already experience~~ are already experiencing environmental conditions that are outside the range of natural variability of the last millennium.

5 Figures

(a) Anomalies of oxygen and temperature in the thermocline



(b) Anomalies of oxygen components (AOU and $O_{2, sol}$) in the thermocline

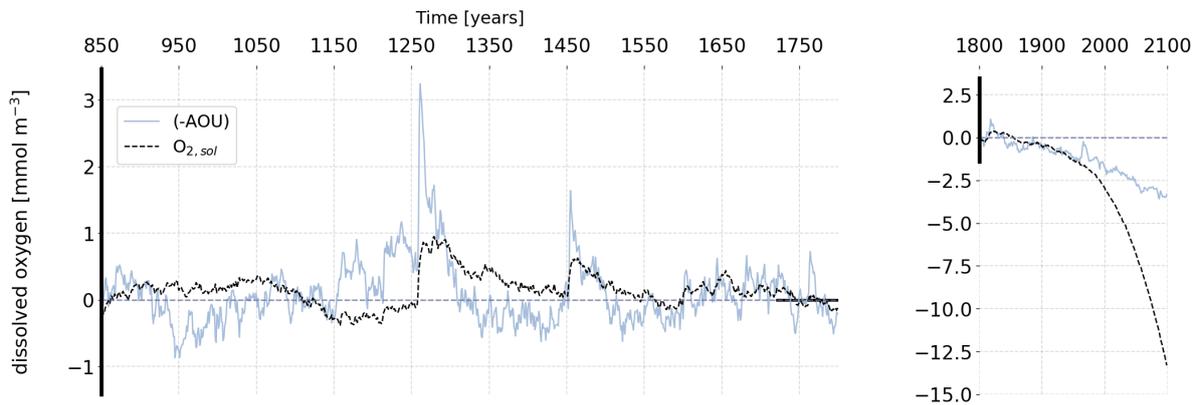


Figure 1. Temporal evolution of simulated anomalies in the thermocline (200-600 m) (a) global-mean-O₂ (dark blue) and T (red), and (b) -AOU (light blue) and the O₂ solubility component (dashed black) and T (red) over the last millennium (left) and the historical and future period (right). The horizontal dashed lines in (a) stand for the two standard deviations envelops for O₂ (blue) and T (red) computed over the period 850-1800 CE. (b) and (c) same as (a) but for the thermocline (200-600 m) and the surface, respectively. The anomalies are relative to the pre-industrial preindustrial reference period (1720-1800 CE).

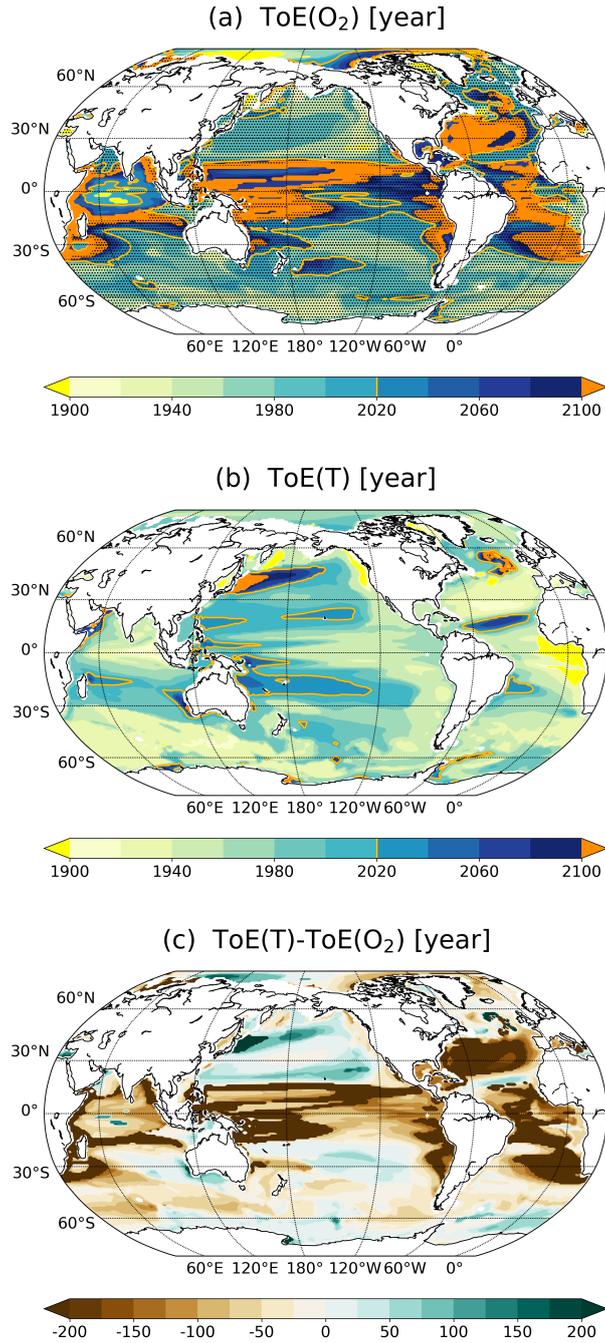


Figure 2. Time of Emergence (ToE) of (a) O₂, (b) T and (c) their difference in the thermocline (200-600 m). The dashed areas in (a) indicate where O₂ decreases under RCP8.5. Regions where the anthropogenic signal has not emerged by the end of the 21st century are indicated by orange.

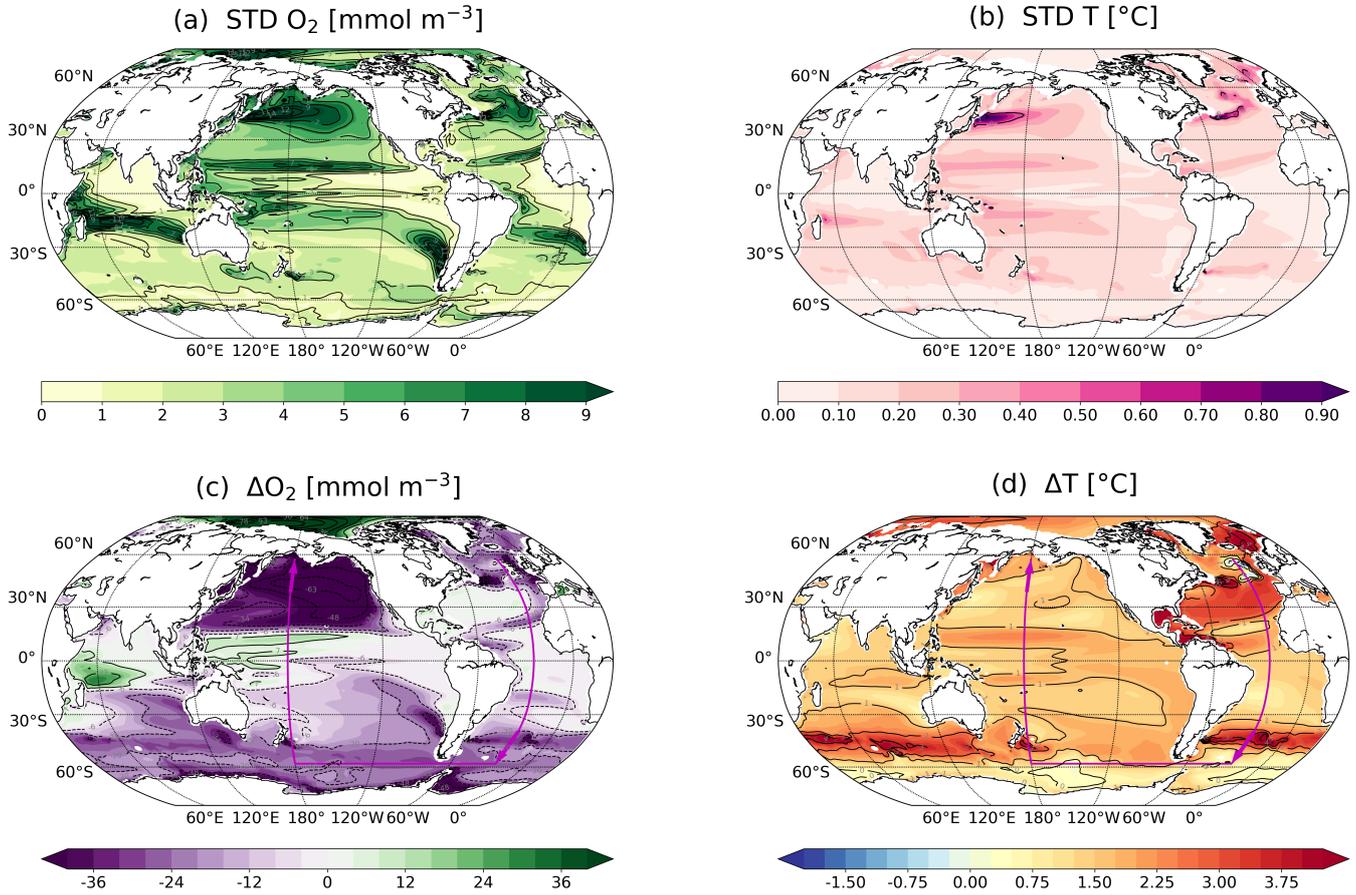


Figure 3. Standard deviations (STD) for (a) O_2 and (b) T as computed for the period 850 to 1800 CE for the thermocline (200-600 m). Anthropogenic changes ((2070-2099) minus (1720-1800)) in (c) O_2 and (d) T in the thermocline. O_2 and T are annually and vertically averaged and STD and changes are computed from these averaged values. The magenta arrows in (c) and (d) indicate the section shown in Fig. 9 (Atlantic: 25°W ; Southern Ocean: 60°S ; Pacific: 150°W).

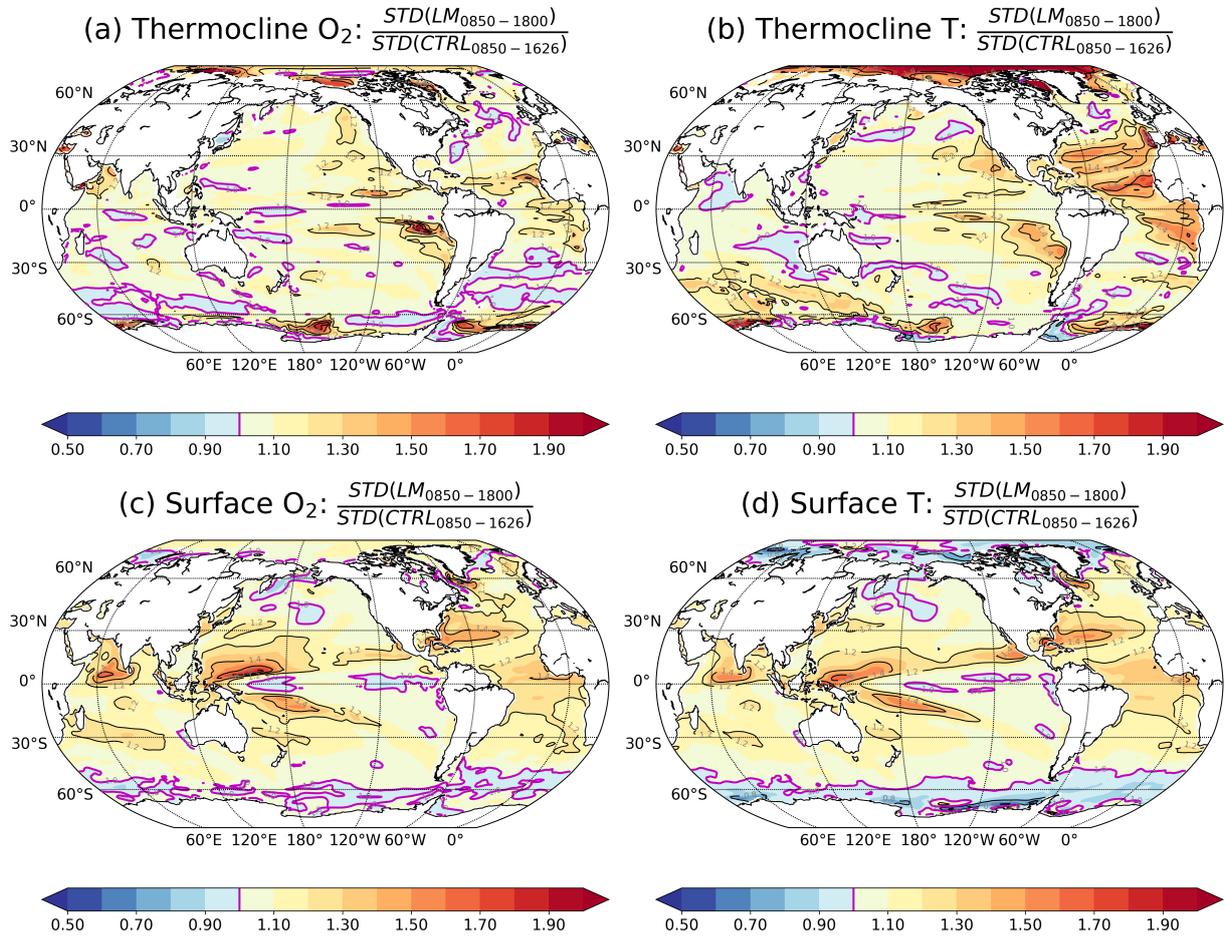


Figure 4. Ratio of the standard deviations (STD) from the forced simulation (0850-1800 CE) versus those from the control simulation (CTRL) for O₂ (left column) and T (right column) for (a, b) the **global-ocean**, (c, d) **the thermocline (200-600 m)** and (e, f) **the surface**. The magenta contours highlight the ratio equal to 1, i.e., where STD are equal in the forced and control simulation. STD are computed from annually (all panels) and vertically (panels a-d) averaged values.

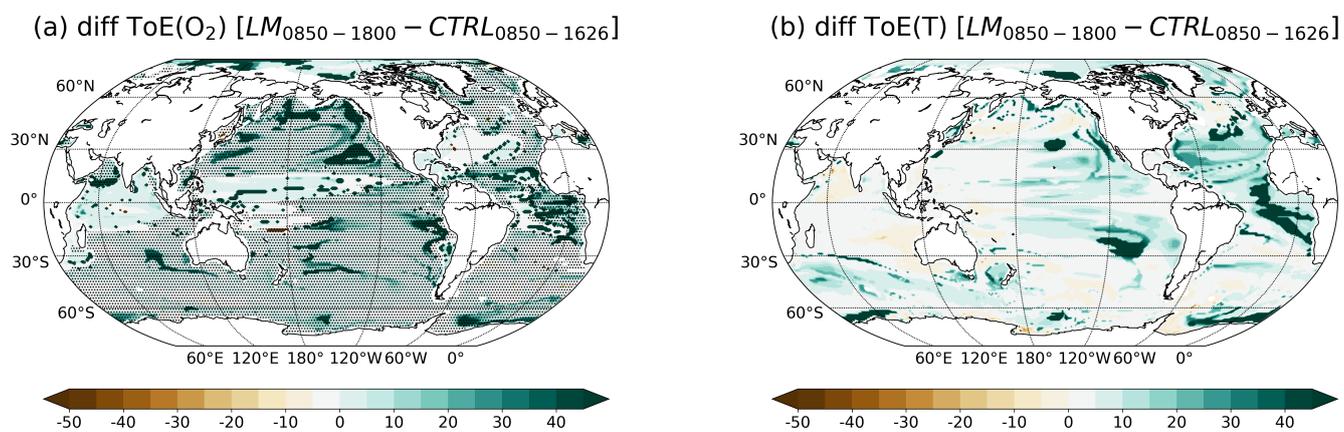


Figure 5. Difference of ToE for (a) O₂ and (b) T using the STD of the forced simulation (0850-1800 CE) minus the ToE using the STD of the control simulation. The dashed areas in (a) indicate where O₂ decreases under RCP8.5.

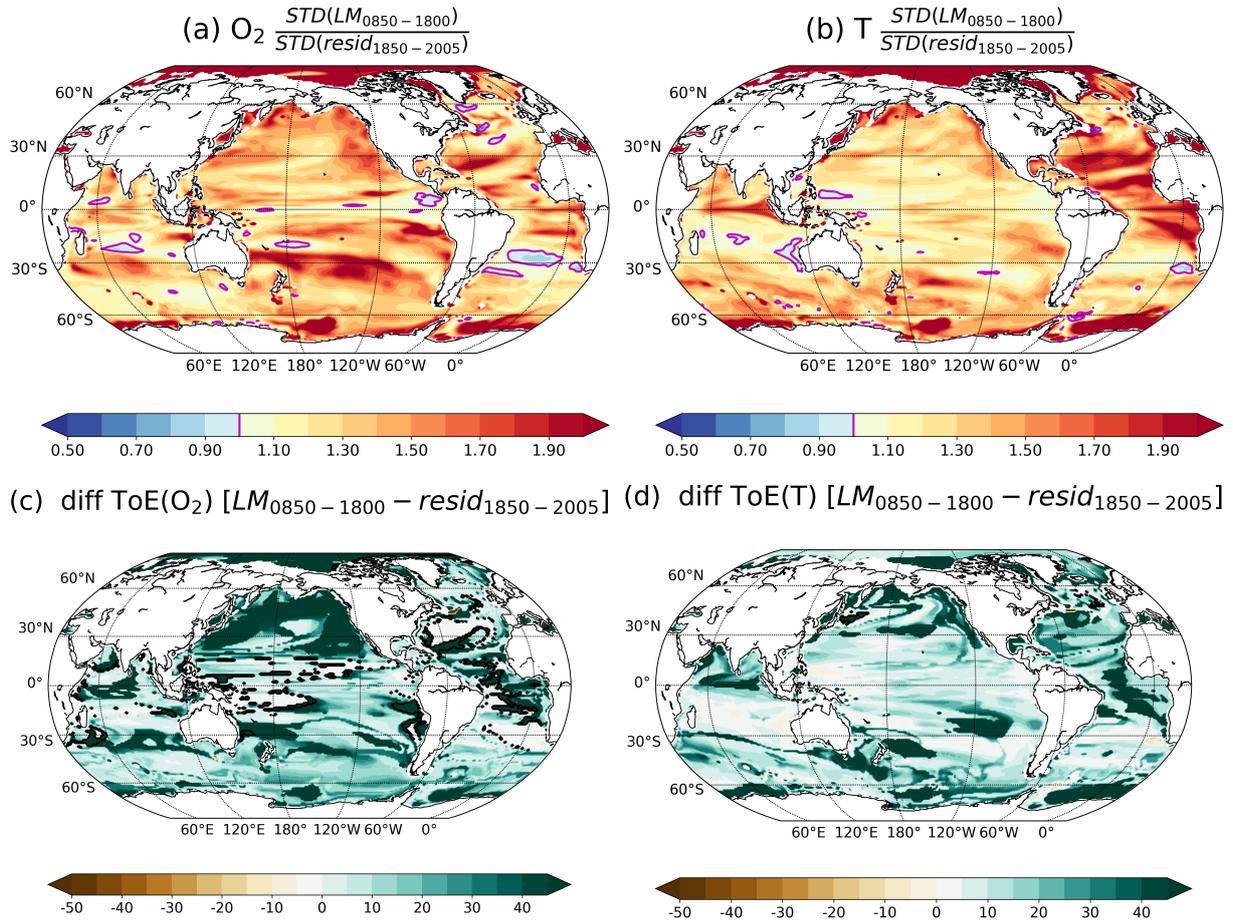


Figure 6. Ratio of the standard deviations (STD) of the forced simulation computed for-over the period 850-1800 CE versus (a, b) those for 1720-1800 CE from the forced simulation and versus (c, d) of the residual variability computed over the period 1850-2005 CE using a cut-off period of 40 years for O_2 (left panel a) O_2 and T (right panel b) T . Difference of ToE using the STD of the forced simulation during the last millennium (0850-1800 CE) minus (c, d) the ToE using the pre-industrial period (1720-1800 CE) and (g, h) the ToE using the residual variability for O_2 (left panel c) O_2 and T (right panel d) T . The magenta contours highlight the ratio equal to 1, i.e., where STD are equal. STD are computed from annually and vertically averaged values between 200 and 600 m. The dashed areas in (c, g) correspond to regions where oxygen decreases under RCP8.5.

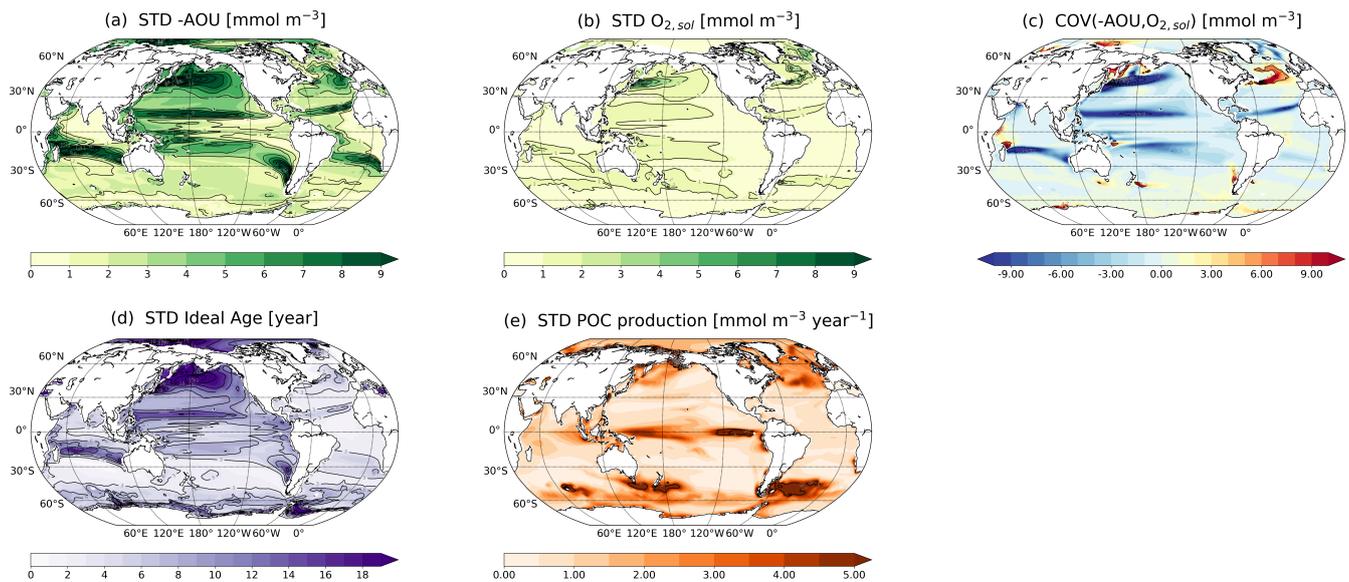


Figure 7. Standard deviation of annually and vertically-averaged (200-600 m) (a) -AOU, (b) O_{2, sol}, (d) ideal age, and (e) Particulate Organic Carbon production (POC production) during the last millennium (850-1800 CE) and (c) the corresponding covariance between -AOU and O_{2, sol}.

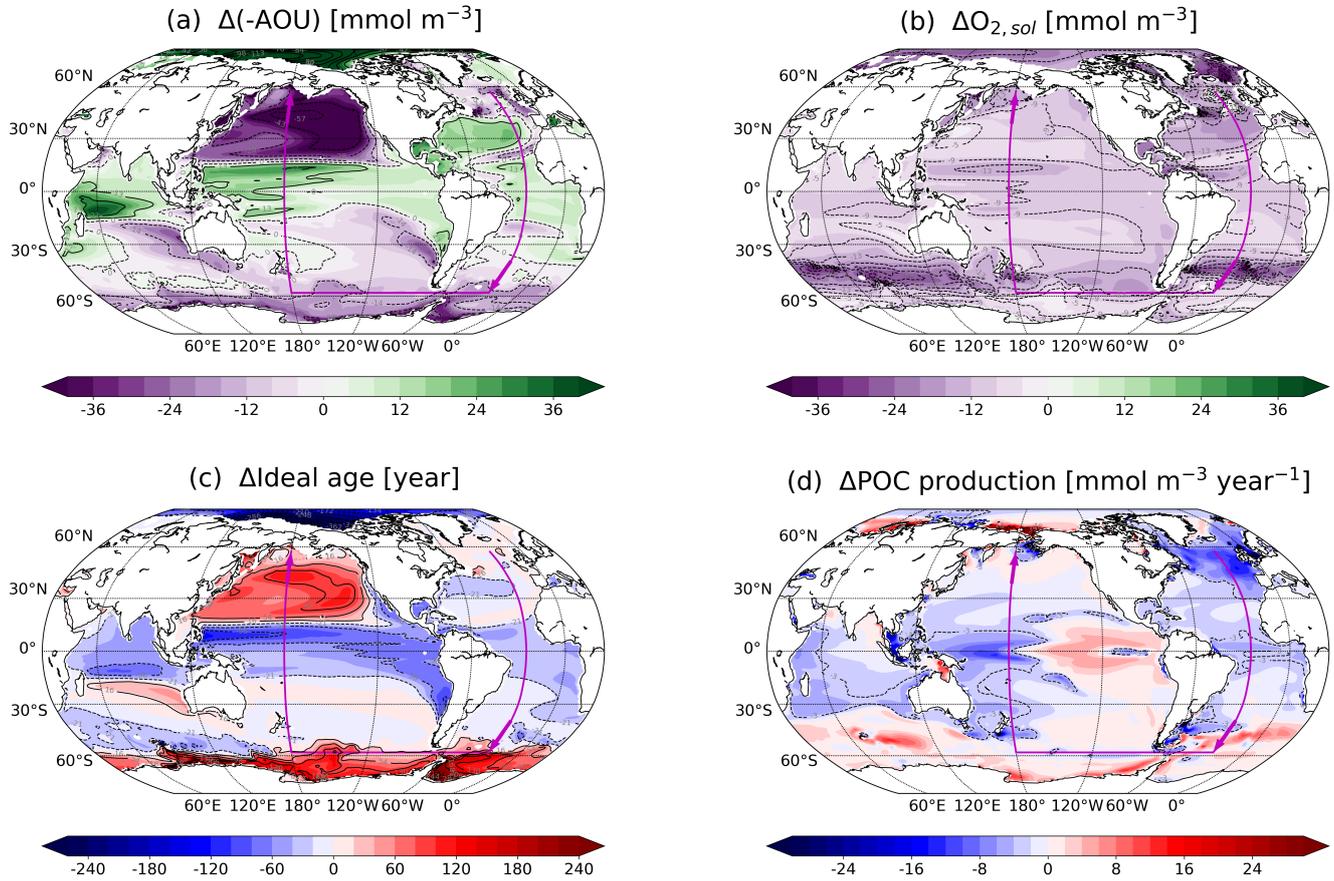


Figure 8. Anthropogenic changes ((2070-2099 CE) minus (1720-1800 CE)) in (a) -AOU, (b) $O_{2,\text{sol}}$, (c) ideal age and (d) Particulate Organic Carbon production (POC production). The results are averaged between 200 and 600 m, except for POC production which is averaged between the surface and 200 m. The magenta arrows indicate the section path used in Fig. 9 (Atlantic: 25° W; Southern Ocean: 60° S; Pacific: 150° W).

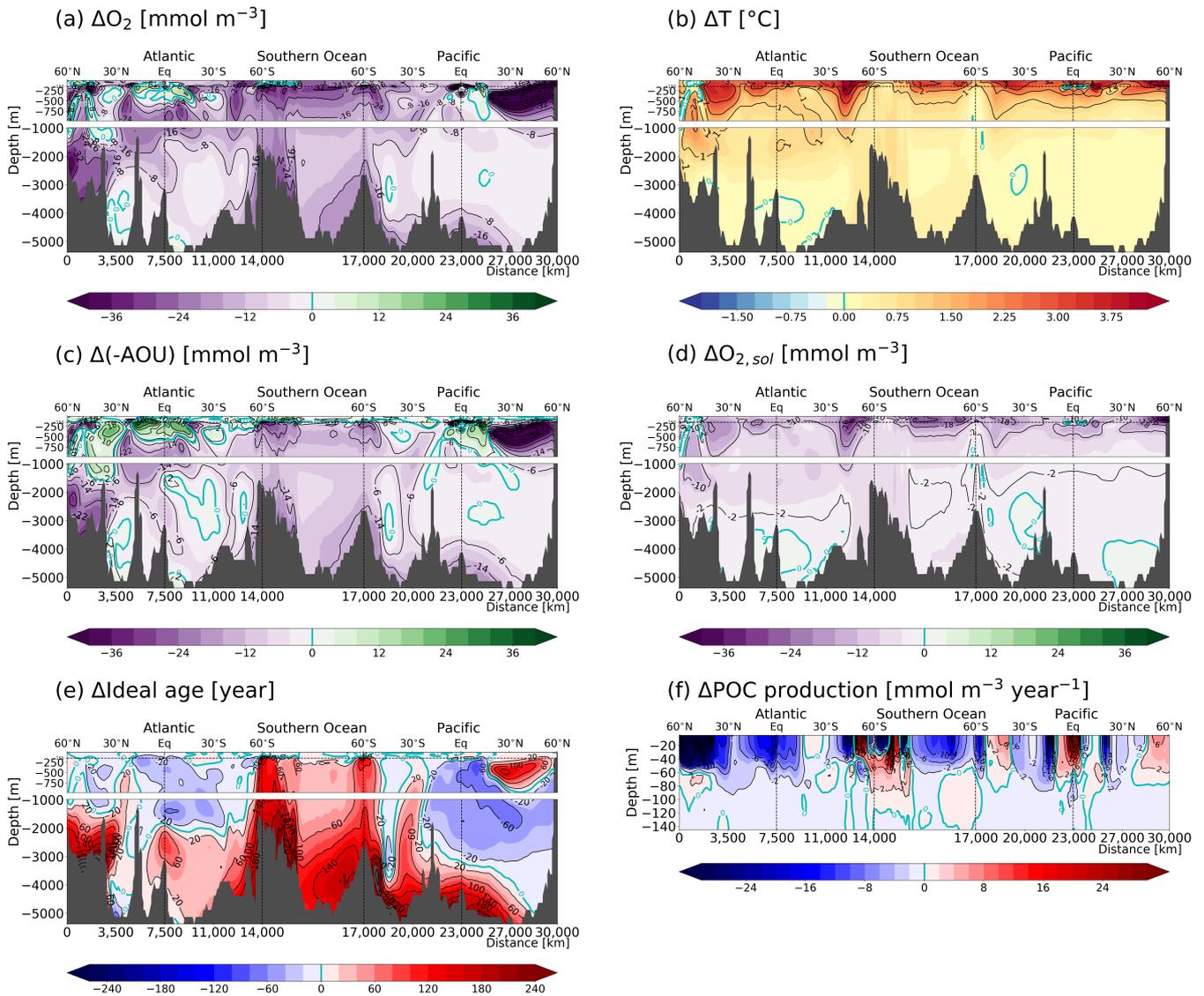


Figure 9. Anthropogenic changes ((2070-2099 CE) minus (1720-1800 CE)) in (a) O_2 , (b) T , (c) $-AOU$, (d) $O_{2,sol}$, (e) ideal age and (f) POC production. The sections are taken along $25^\circ W$ in the Atlantic, $60^\circ S$ in the Southern Ocean and $150^\circ W$ in the Pacific (Fig. 3b and d and in Fig. 8, magenta arrows).

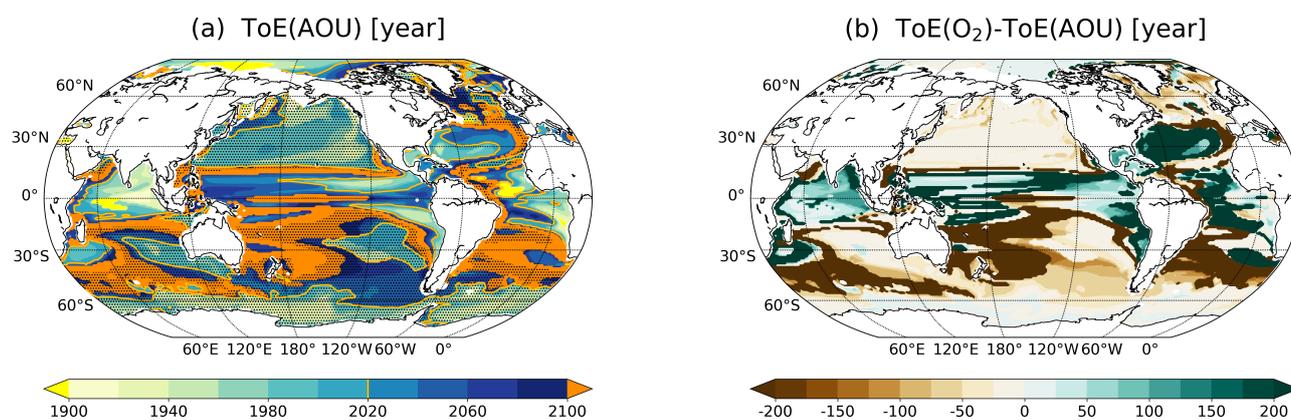


Figure 10. Time of Emergence (ToE) of (a) -AOU, (b) O_2 , *sol* in the thermocline (200-600 m). The dashed areas in (a) indicate where -AOU decreases under RCP8.5. Regions where the anthropogenic signal has not emerged by the end of the 21st century are indicated by orange for AOU. (b) Difference of the ToE for O_2 and the ToE of -AOU in the thermocline (200-600 m).

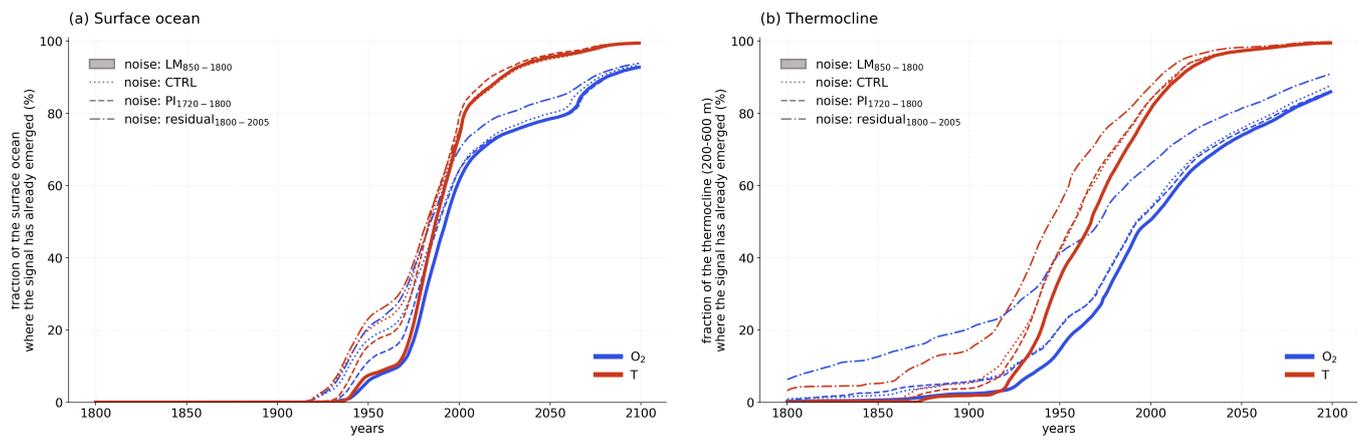


Figure 11. Fraction of the (a) surface ocean and (b) thermocline (200-600 m) where the signal has already emerged in oxygen (blue) and temperature (red) for different definitions of the background noise: (i) naturally forced variability during the last millennium (850-1800 CE, LM; solid), (ii) internal variability (CTRL; dotted), (iii) naturally forced variability during the ~~pre-industrial~~preindustrial period (1720-1800 CE, PI; dashed), (iv) residual variability using a ~~low-pass~~low-pass filter (cut off period of ~~40years~~40 years, residual; dashed dotted).

		Temperature	Standard deviation			COV(-AOU, O _{2,sol})
		[°C]	O ₂ [mmol m ⁻³]	-AOU [mmol m ⁻³]	O _{2,sol} [mmol m ⁻³]	
Global ocean	CTRL	0.3 10 ⁻²	3.6 10 ⁻²	4.9 10 ⁻²	3.4 10 ⁻²	-1.13 10 ⁻³
	LM	1.1 10 ⁻²	16.5 10 ⁻²	10.7 10 ⁻²	7.2 10 ⁻²	5.30 10 ⁻³
Thermocline (200-600 m)	CTRL	1.3 10 ⁻²	36.9 10 ⁻²	36.4 10 ⁻²	8.9 10 ⁻²	-2.13 10 ⁻³
	LM	3.7 10 ⁻²	59.8 10 ⁻²	48.2 10 ⁻²	24.4 10 ⁻²	32.9 10 ⁻³
Surface	CTRL	6.4 10 ⁻²	27.4 10 ⁻²	8.4 10 ⁻²	28.2 10 ⁻²	-5.75 10 ⁻³
	LM	14.6 10 ⁻²	58.8 10 ⁻²	10.5 10 ⁻²	63.5 10 ⁻²	-34.3 10 ⁻³

Table 1. Overview of the standard deviations of T, O₂, O_{2,sol} and -AOU, and the corresponding covariance between -AOU and O_{2,sol} for the global mean ocean, the thermocline (200-600 m) and the surface ocean for the control simulation (CTRL) and the forced simulation (850-1800; LM). STD and COV are computed from annually and spatially averaged data.

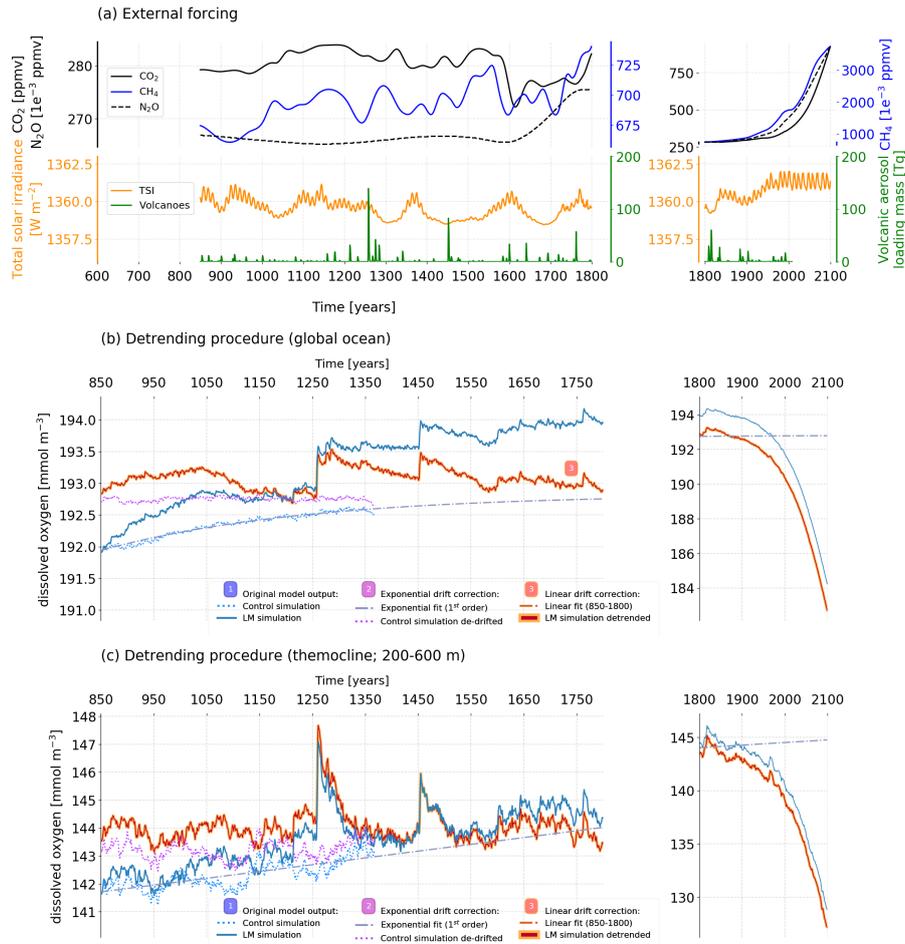


Figure A1. (a) Time series of the main external forcings applied to the forced simulation: total solar irradiance [W m^{-2}] at the top of the atmosphere in orange, stratospheric volcanic aerosol load [Tg] in green and the greenhouse gases CO_2 (solid black line), N_2O (dashed black line) and CH_4 (blue solid line) [ppmv].

Illustration of the two-step procedure to remove model drift and millennial scale trends at each grid point shown in (ab) the global mean ocean and (bc) the thermocline (200-600 m). The original, annually-averaged outputs from the control (CTRL) and the forced simulations are shown by dashed and solid blue lines, respectively [1]. The results of the CTRL are fitted by an exponential function with one time scale and extrapolated towards equilibrium (dashed line). The exponential curve is subtracted from and the equilibrium value added to the original outputs to obtain the purple curves [2] (dotted : CTRL, solid : forced simulation). The remaining multi-millennial trend in the forced simulation is removed using a linear fit (850-1800 CE), leading to the red curve [3]. (c) Time series of the main external forcings applied to the forced simulation: total solar irradiance W m^{-2} at the top of the atmosphere in orange, stratospheric volcanic aerosol Tg in green and the greenhouse gases CO_2 (solid black line), N_2O (dashed black line) and CH_4 (blue solid line) ppmv.

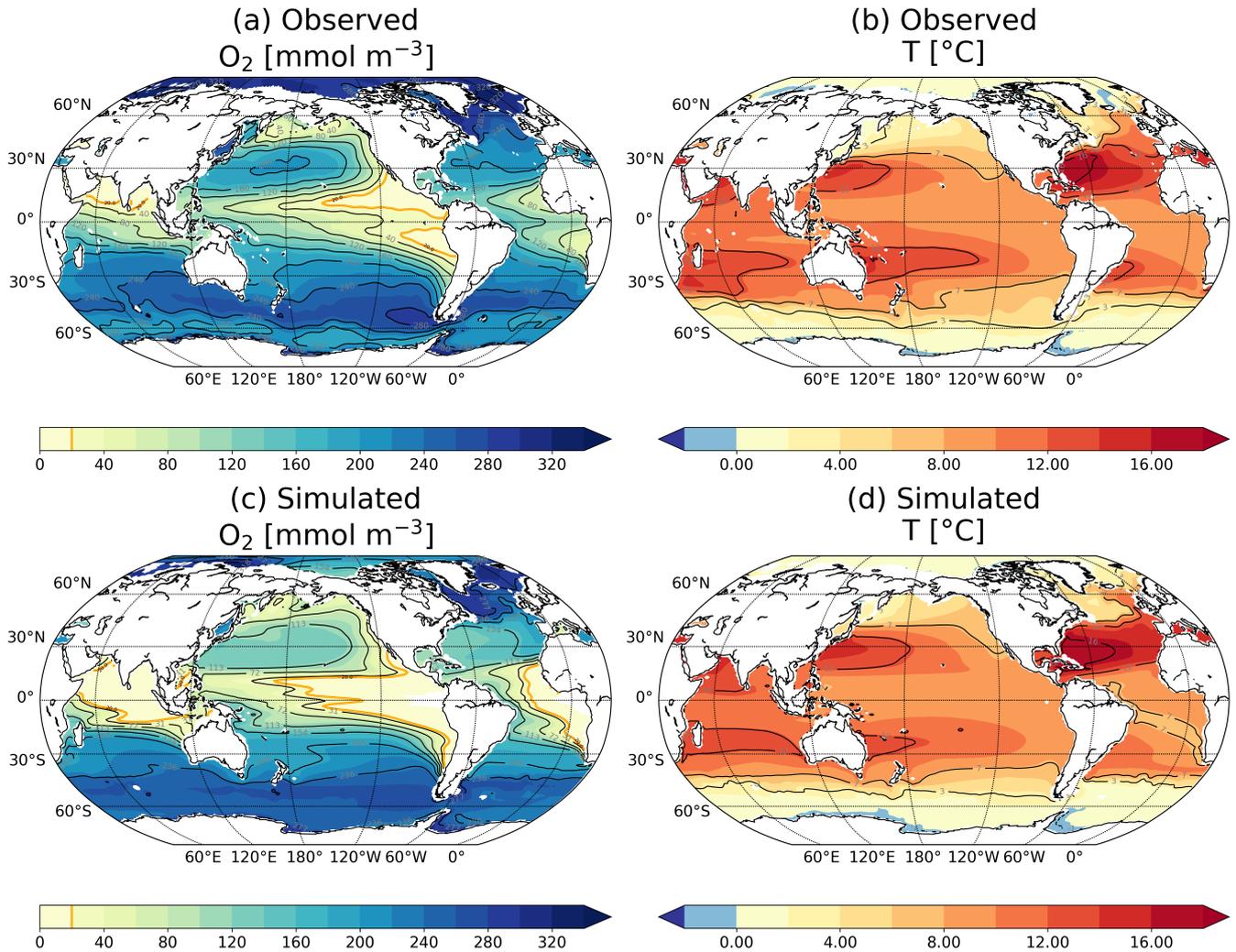


Figure A2. Observation-based (atop) Oxygen concentration from the data-based World Ocean Atlas versus simulated (Garcia et al., 2013 bottom: 1986-2005), (b) temperature observed from observation-based (Locarnini et al., 2013), the simulated oxygen concentration (a,c) oxygen and temperature (b,d) temperature by the model CESM during in the period 1986-2005. The maps show averages between thermocline (200 and 600 m). Data are from (a) Garcia et al., 2013 and (b) from (Locarnini et al., 2013).

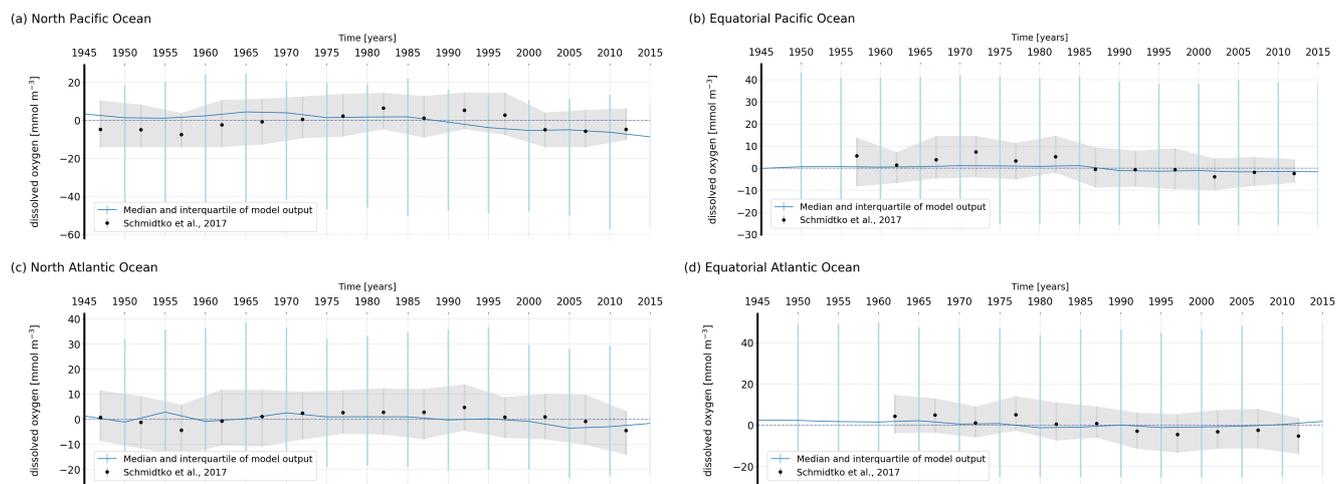


Figure A3. Comparison of the semi-decadal median and interquartile range of the simulated O₂ concentration (blue) and the historical data from Schmidt et al. (2017) (grey) over the (a) North Pacific, (b) Equatorial Pacific, (c) North Atlantic and (d) Equatorial Atlantic.

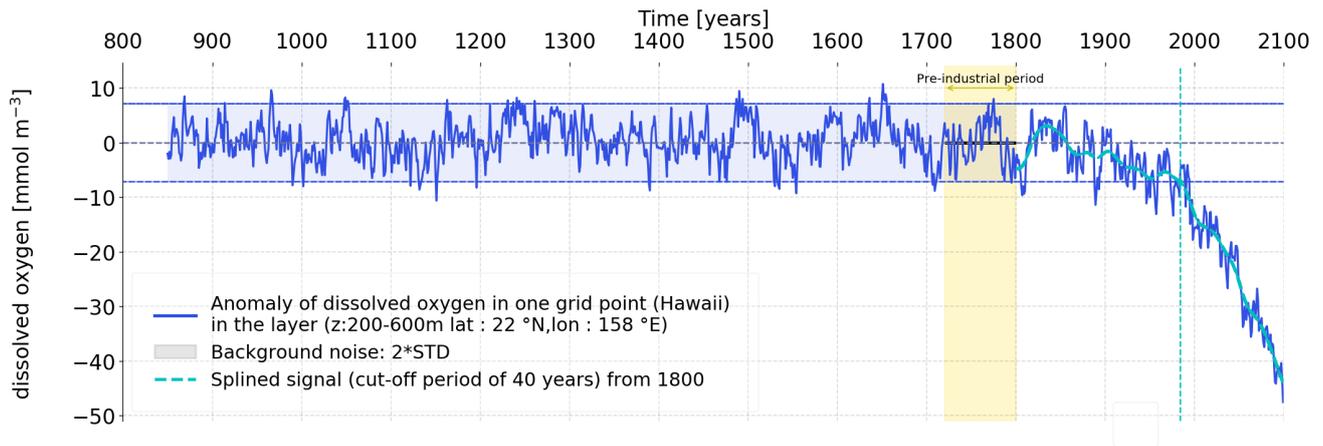
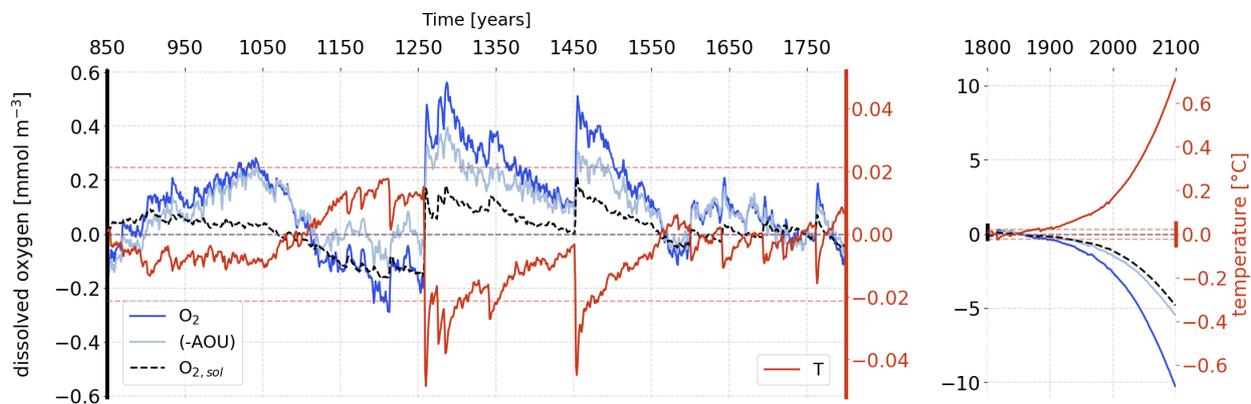


Figure A4. Illustration of the Time of Emergence (ToE) method. The example is for the thermocline (200-600 m) and grid cells located at 158° W and 22° N near Hawaii. The standard deviation (STD) of the detrended, annually and vertically (200-600 m) averaged data (blue) for the period 850-1800 CE is used to define the “noise” or bounds of natural variability which is set to $\pm 2\text{STD}$ (blue area). The annually and vertically averaged data are fitted with a spline using a cut-off period of 40 years (light blue). ToE is the point in time when the spline crosses and leaves the bounds of natural variability; here, ToE is 1984 and indicated by the vertical dashed line. All data are anomalies relative to the preindustrial period 1720-1800 CE (yellow).

(a) Global ocean mean anomalies of oxygen, its components and temperature



(b) Anomalies of oxygen, its components and temperature at the surface

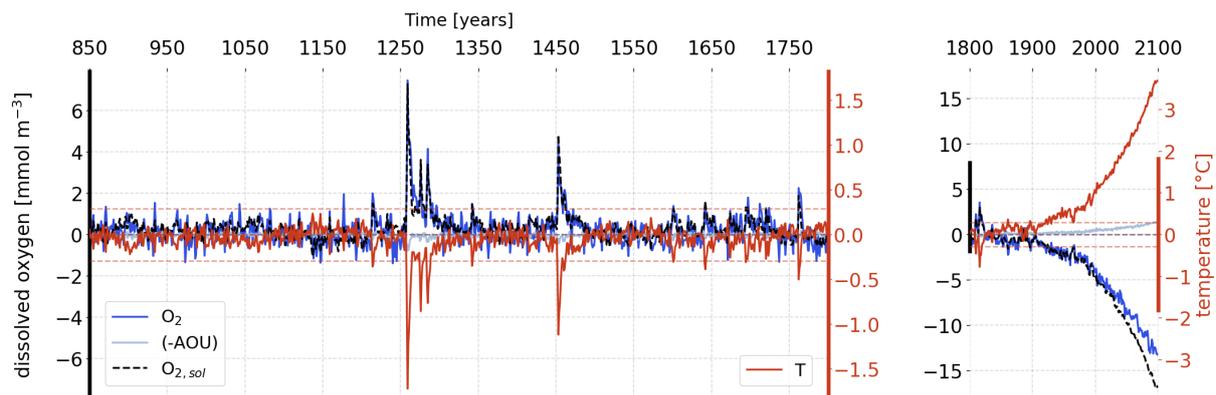


Figure A5. Temporal evolution of simulated anomalies in (a) global mean O_2 (dark blue), $-AOU$ (light blue), the O_2 solubility component (dashed black), and T (red) over the last millennium (left) and the historical and future period (right). The horizontal dashed lines stand for the two standard deviations envelopes for O_2 (blue) and T (red) computed over the period 850-1800 CE. (b) same as (a) but for the surface. The anomalies are relative to the preindustrial reference period (1720-1800 CE).

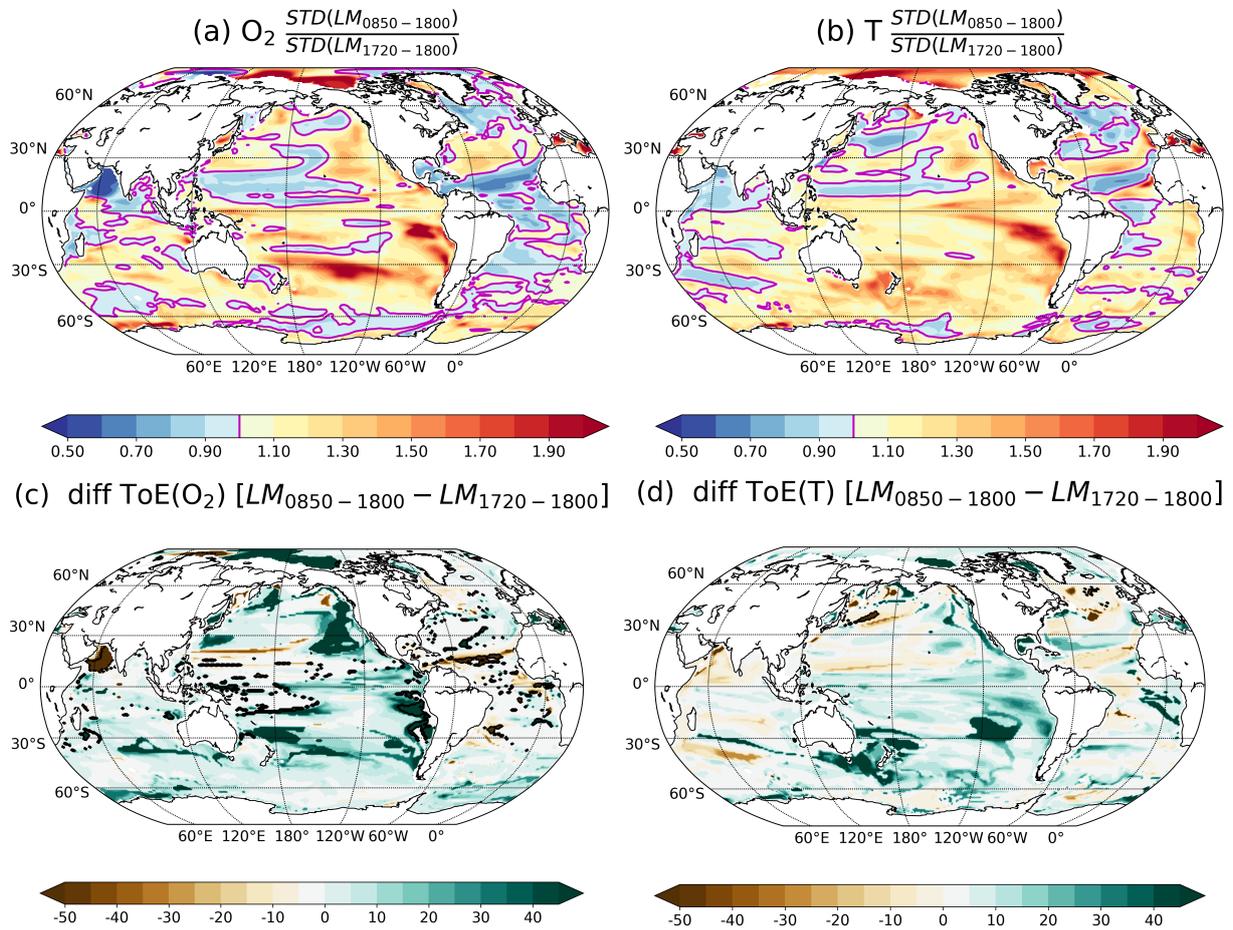


Figure A6. Ratio of the standard deviations (STD) of the forced simulation computed over the period 850-1800 CE and over the period 1720-1800 CE for (a) O_2 and (b) T. Difference of ToE using the STD of the forced simulation over the period 850-1800 CE minus the ToE using the STD of the same simulation but over the preindustrial period (1720-1800 CE) for (c) O_2 and (d) T. The magenta contours highlight the ratio equal to 1, i.e., where STD are equal. STD are computed from annually and vertically averaged values between 200 and 600 m.

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References

- Ammann, C. M., Joos, F., Schimel, D. S., Otto-Bliesner, B. L., and Tomas, R. A.: Solar influence on climate during the past millennium: Results from transient simulations with the NCAR Climate System Model, *Proceedings of the National Academy of Sciences*, 104, 3713–3718, doi:10.1073/pnas.0605064103, <https://www.pnas.org/content/104/10/3713>, 2007.
- 5 Andres, R. J., Boden, T. A., Bréon, F.-M., Ciais, P., Davis, S., Erickson, D., Gregg, J. S., Jacobson, A., Marland, G., Miller, J., Oda, T., Olivier, J. G. J., Raupach, M. R., Rayner, P., and Treanton, K.: A synthesis of carbon dioxide emissions from fossil-fuel combustion, *Biogeosciences*, 9, 1845–1871, doi:10.5194/bg-9-1845-2012, <https://www.biogeosciences.net/9/1845/2012/>, 2012.
- Andrews, O. D., Bindoff, N. L., Halloran, P. R., Ilyina, T., and Le Quéré, C.: Detecting an external influence on recent changes in oceanic oxygen using an optimal fingerprinting method, *Biogeosciences*, 10, 1799–1813, doi:10.5194/bg-10-1799-2013, <https://www.biogeosciences.net/10/1799/2013/>, 2013.
- 10 Armstrong, R. A., Lee, C., Hedges, J. I., Honjo, S., and Wakeham, S. G.: A new, mechanistic model for organic carbon fluxes in the ocean based on the quantitative association of POC with ballast minerals, *Deep Sea Research Part II: Topical Studies in Oceanography*, 49, 219–236, doi:10.1016/S0967-0645(01)00101-1, <http://www.sciencedirect.com/science/article/pii/S0967064501001011>, 2001.
- Azhar, M. A., Lachkar, Z., Lévy, M., and Smith, S.: Oxygen Minimum Zone Contrasts Between the Arabian Sea and the Bay of Bengal Implied by Differences in Remineralization Depth, *Geophysical Research Letters*, 44, 11,106–11,114, doi:10.1002/2017GL075157, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017GL075157>, 2017.
- 15 Bacastow, R. B.: Modulation of atmospheric carbon dioxide by the Southern Oscillation, *Nature*, 261, 116, 1976.
- Baines: Lorenz, EN 1963: Deterministic nonperiodic flow. *Journal of the Atmospheric Sciences* 20, 130–41.1, *Progress in Physical Geography*, 32, 475–480, 2008.
- 20 Bakun, A.: Climate change and ocean deoxygenation within intensified surface-driven upwelling circulations, *Phil. Trans. R. Soc. A*, 375, 20160327, doi:10.1098/rsta.2016.0327, <http://rsta.royalsocietypublishing.org/content/375/2102/20160327>, 2017.
- Bard, E., Raisbeck, G., Yiou, F., and Jouzel, J.: Solar irradiance during the last 1200 years based on cosmogenic nuclides, *Tellus B: Chemical and Physical Meteorology*, 52, 985–992, doi:10.3402/tellusb.v52i3.17080, <https://doi.org/10.3402/tellusb.v52i3.17080>, 2000.
- Battaglia, G. and Joos, F.: Hazards of decreasing marine oxygen: the near-term and millennial-scale benefits of meeting the Paris climate targets, *Earth System Dynamics*, 9, 797, 2018.
- 25 Bianchi, D., Dunne, J. P., Sarmiento, J. L., and Galbraith, E. D.: Data-based estimates of suboxia, denitrification, and N₂O production in the ocean and their sensitivities to dissolved O₂, *Global Biogeochemical Cycles*, 26, n/a–n/a, doi:10.1029/2011GB004209, <http://doi.wiley.com/10.1029/2011GB004209>, 2012.
- Bopp, L., Le Quéré, C., Heimann, M., Manning, A. C., and Monfray, P.: Climate-induced oceanic oxygen fluxes: Implications for the contemporary carbon budget, *Global Biogeochemical Cycles*, 16, 6–1, doi:10.1029/2001GB001445, <http://onlinelibrary.wiley.com/doi/10.1029/2001GB001445/abstract>, 2002.
- 30 Bopp, L., Resplandy, L., Orr, J. C., Doney, S. C., Dunne, J. P., Gehlen, M., Halloran, P., Heinze, C., Ilyina, T., Séférian, R., Tjiputra, J., and Vichi, M.: Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models, *Biogeosciences*, 10, 6225–6245, doi:10.5194/bg-10-6225-2013, <http://www.biogeosciences.net/10/6225/2013/>, 2013.
- 35 Bopp, L., Resplandy, L., Untersee, A., Mezo, P. L., and Kageyama, M.: Ocean (de)oxygenation from the Last Glacial Maximum to the twenty-first century: insights from Earth System models, *Phil. Trans. R. Soc. A*, 375, 20160323, doi:10.1098/rsta.2016.0323, <http://rsta.royalsocietypublishing.org/content/375/2102/20160323>, 2017.

- Bothe, O., Evans, M., Donado, L., Bustamante, E., Gergis, J., Gonzalez-Rouco, J., Goosse, H., Hegerl, G., Hind, A., Jungclaus, J. H., Kaufman, D., Lehner, F., McKay, N., Moberg, A., Raible, C., Schurer, A., Shi, F., Smerdon, J., Von Gunten, L., Wagner, S., Warren, E., Widmann, M., Yiou, P., and Zorita, E.: Continental-scale temperature variability in PMIP3 simulations and PAGES 2k regional temperature reconstructions over the past millennium, *Climate of the Past*, 11, 1673–1699, doi:10.5194/cp-11-1673-2015, 2015.
- 5 Brady, R. X., Alexander, M. A., Lovenduski, N. S., and Rykaczewski, R. R.: Emergent anthropogenic trends in California Current upwelling, *Geophysical Research Letters*, p. 2017GL072945, doi:10.1002/2017GL072945, <http://onlinelibrary.wiley.com/doi/10.1002/2017GL072945/abstract>, 2017.
- Brandt, P., Bange, H. W., Banyte, D., Dengler, M., Didwischus, S.-H., Fischer, T., Greatbatch, R. J., Hahn, J., Kanzow, T., Karstensen, J., Körtzinger, A., Krahnemann, G., Schmidtke, S., Stramma, L., Tanhua, T., and Visbeck, M.: On the role of circulation and mixing in the ventilation of oxygen minimum zones with a focus on the eastern tropical North Atlantic, *Biogeosciences*, 12, 489–512, doi:10.5194/bg-12-489-2015, <http://www.biogeosciences.net/12/489/2015/>, tO READ, 2015.
- 10 Breitburg, D., Levin, L. A., Oschlies, A., Grégoire, M., Chavez, F. P., Conley, D. J., Garçon, V., Gilbert, D., Gutiérrez, D., Isensee, K., Jacinto, G. S., Limburg, K. E., Montes, I., Naqvi, S. W. A., Pitcher, G. C., Rabalais, N. N., Roman, M. R., Rose, K. A., Seibel, B. A., Telszewski, M., Yasuhara, M., and Zhang, J.: Declining oxygen in the global ocean and coastal waters, *Science*, 359, eaam7240, doi:10.1126/science.aam7240, <http://science.sciencemag.org/content/359/6371/eaam7240>, 2018.
- 15 Brovkin, V., Lorenz, S. J., Jungclaus, J., Raddatz, T., Timmreck, C., Reick, C. H., Segschneider, J., and Six, K.: Sensitivity of a coupled climate-carbon cycle model to large volcanic eruptions during the last millennium, *Tellus B*, 62, 674–681, doi:10.1111/j.1600-0889.2010.00471.x, <https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1600-0889.2010.00471.x>, 2010.
- Cabré, A., Marinov, I., Bernardello, R., and Bianchi, D.: Oxygen minimum zones in the tropical Pacific across CMIP5 models: mean state differences and climate change trends, *Biogeosciences*, 12, 5429–5454, doi:10.5194/bg-12-5429-2015, <http://www.biogeosciences.net/12/5429/2015/>, 2015.
- 20 Carter, B. R., Frölicher, T. L., Dunne, J. P., Rodgers, K. B., Slater, R. D., and Sarmiento, J. L.: When can ocean acidification impacts be detected from decadal alkalinity measurements?, *Global Biogeochemical Cycles*, 30, 2015GB005308, doi:10.1002/2015GB005308, <http://onlinelibrary.wiley.com/doi/10.1002/2015GB005308/abstract>, 2016.
- 25 Chikamoto, M. O., Timmermann, A., Yoshimori, M., Lehner, F., Laurian, A., Abe-Ouchi, A., Mouchet, A., Joos, F., Raible, C. C., and Cobb, K. M.: Intensification of tropical Pacific biological productivity due to volcanic eruptions, *Geophysical Research Letters*, 43, 2015GL067359, doi:10.1002/2015GL067359, <http://onlinelibrary.wiley.com/doi/10.1002/2015GL067359/abstract>, 2016a.
- Chikamoto, M. O., Timmermann, A., Yoshimori, M., Lehner, F., Laurian, A., Abe-Ouchi, A., Mouchet, A., Joos, F., Raible, C. C., and Cobb, K. M.: Volcanic eruptions boost tropical Pacific biological productivity, *Geophysical Research Letters*, 43, doi:10.1002/2015GL067359, <https://orbi.uliege.be/handle/2268/192106>, 2016b.
- 30 Christensen, J., Hewitson, B., A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr, and P. Whetton: Regional Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2007.
- 35 Christian, J. R.: Timing of the Departure of Ocean Biogeochemical Cycles from the Preindustrial State, *PLOS ONE*, 9, e109820, doi:10.1371/journal.pone.0109820, <https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0109820>, 2014.

- Cocco, V., Joos, F., Steinacher, M., Froelicher, T. L., Bopp, L., Dunne, J., Gehlen, M., Heinze, C., Orr, J., Oschlies, A., Schneider, B., Segsneider, J., and Tjiputra, J.: Oxygen and indicators of stress for marine life in multi-model global warming projections, *Biogeosciences*, 10, 1849–1868, doi:10.5194/bg-10-1849-2013, wOS:000317010600040, 2013.
- 5 Crowley, T. J.: Causes of Climate Change Over the Past 1000 Years, *Science*, 289, 270–277, doi:10.1126/science.289.5477.270, <http://science.sciencemag.org/content/289/5477/270>, 2000.
- Cullen, J. J.: On models of growth and photosynthesis in phytoplankton, *Deep Sea Research Part A. Oceanographic Research Papers*, 37, 667–683, doi:10.1016/0198-0149(90)90097-F, <http://www.sciencedirect.com/science/article/pii/019801499090097F>, 1990.
- Danabasoglu, G., Bates, S. C., Briegleb, B. P., Jayne, S. R., Jochum, M., Large, W. G., Peacock, S., and Yeager, S. G.: The CCSM4 Ocean Component, *Journal of Climate*, 25, 1361–1389, doi:10.1175/JCLI-D-11-00091.1, <https://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-11-00091.1>, 2011.
- 10 Deser, C., Phillips, A., Bourdette, V., and Teng, H.: Uncertainty in climate change projections: the role of internal variability, *Climate Dynamics*, 38, 527–546, doi:10.1007/s00382-010-0977-x, <https://doi.org/10.1007/s00382-010-0977-x>, 2012.
- Deser, C., Phillips, A. S., Alexander, M. A., and Smoliak, B. V.: Projecting North American Climate over the Next 50 Years: Uncertainty due to Internal Variability, *Journal of Climate*, 27, 2271–2296, doi:10.1175/JCLI-D-13-00451.1, <https://journals.ametsoc.org/doi/full/10.1175/JCLI-D-13-00451.1>, 2014.
- 15 Deutsch, C., Ferrel, A., Seibel, B., Pörtner, H.-O., and Huey, R. B.: Climate change tightens a metabolic constraint on marine habitats, *Science*, 348, 1132–1135, doi:10.1126/science.aaa1605, <http://science.sciencemag.org/content/348/6239/1132>, 2015.
- Diffenbaugh, N. S. and Scherer, M.: Observational and model evidence of global emergence of permanent, unprecedented heat in the 20th and 21st centuries, *Climatic Change*, 107, 615–624, doi:10.1007/s10584-011-0112-y, <https://link.springer.com/article/10.1007/s10584-011-0112-y>, 2011.
- 20 Doney, S. C., Lindsay, K., Fung, I., and John, J.: Natural Variability in a Stable, 1000-Yr Global Coupled Climate–Carbon Cycle Simulation, *Journal of Climate*, 19, 3033–3054, doi:10.1175/JCLI3783.1, <https://journals.ametsoc.org/doi/abs/10.1175/JCLI3783.1>, 2006.
- Doney, S. C., Lima, I., Moore, J. K., Lindsay, K., Behrenfeld, M. J., Westberry, T. K., Mahowald, N., Glover, D. M., and Takahashi, T.: Skill metrics for confronting global upper ocean ecosystem-biogeochemistry models against field and remote sensing data, *Journal of Marine Systems*, 76, 95–112, doi:10.1016/j.jmarsys.2008.05.015, <http://www.sciencedirect.com/science/article/pii/S0924796308001164>, 2009.
- 25 Duteil, O., Böning, C. W., and Oschlies, A.: Variability in subtropical-tropical cells drives oxygen levels in the tropical Pacific Ocean, *Geophysical Research Letters*, 41, 2014GL061774, doi:10.1002/2014GL061774, <http://onlinelibrary.wiley.com/doi/10.1002/2014GL061774/abstract>, 2014.
- Duteil, O., Oschlies, A., and Böning, C. W.: Pacific Decadal Oscillation and recent oxygen decline in the eastern tropical Pacific Ocean, *Biogeosciences Discuss.*, 2018, 1–30, doi:10.5194/bg-2018-16, <https://www.biogeosciences-discuss.net/bg-2018-16/>, 2018.
- 30 Emerson, S. and Bushinsky, S.: Oxygen Concentrations and Biological Fluxes in the Open Ocean, *Oceanography*, 27, 168–171, doi:10.5670/oceanog.2014.20, <https://tos.org/oceanography/article/oxygen-concentrations-and-biological-fluxes-in-the-open-ocean>, 2014.
- Enting, I. G.: On the use of smoothing splines to filter CO₂ data, *Journal of Geophysical Research: Atmospheres*, 92, 10977–10984, doi:10.1029/JD092iD09p10977, <http://onlinelibrary.wiley.com/doi/10.1029/JD092iD09p10977/abstract>, 1987.
- Fernández-Donado, J. F., Raible, C., Ammann, C. M., Barriopedro, D., Garcia-Bustamante, E., Jungclaus, J. H., Lorenz, S. J., Luterbacher, J., Phipps, S. J., Servonnat, J., Swingedouw, D., Tett, S. F. B., Wagner, S., Yiou, P., and Zorita, E.: Large-scale temperature response to

- external forcing in simulations and reconstructions of the last millennium, *Climate of the past*, 9, 393–421, doi:info:doi:10.5194/cp-9-393-2013, <https://boris.unibe.ch/47713/>, 2013.
- Frame, D., Joshi, M., Hawkins, E., Harrington, L. J., and de Roiste, M.: Population-based emergence of unfamiliar climates, *Nature Climate Change*, 7, 407–411, doi:10.1038/nclimate3297, <https://www.nature.com/articles/nclimate3297>, 2017.
- 5 Friedrich, T., Timmermann, A., Abe-Ouchi, A., Bates, N. R., Chikamoto, M. O., Church, M. J., Dore, J. E., Gledhill, D. K., González-Dávila, M., Heinemann, M., Ilyina, T., Jungclaus, J. H., McLeod, E., Mouchet, A., and Santana-Casiano, J. M.: Detecting regional anthropogenic trends in ocean acidification against natural variability, *Nature Climate Change*, 2, 167–171, doi:10.1038/nclimate1372, <https://www.nature.com/articles/nclimate1372>, 2012.
- Frölicher, T. L., Joos, F., Plattner, G.-K., Steinacher, M., and Doney, S. C.: Natural variability and anthropogenic trends in oceanic oxygen in a coupled carbon cycle-climate model ensemble, *Global Biogeochemical Cycles*, 23, n/a–n/a, doi:10.1029/2008GB003316, <http://doi.wiley.com/10.1029/2008GB003316>, 2009.
- 10 Frölicher, T. L., Joos, F., and Raible, C. C.: Sensitivity of atmospheric CO₂ and climate to explosive volcanic eruptions, *Biogeosciences*, 8, 2317–2339, doi:info:doi:10.5194/bg-8-2317-2011, <https://boris.unibe.ch/10153/>, 2011.
- Frölicher, T. L., Rodgers, K. B., Stock, C. A., and Cheung, W. W. L.: Sources of uncertainties in 21st century projections of potential ocean ecosystem stressors, *Global Biogeochemical Cycles*, 30, 1224–1243, doi:10.1002/2015GB005338, <http://onlinelibrary.wiley.com/doi/10.1002/2015GB005338/full>, 2016.
- 15 Fu, W., Primeau, F., Moore, J. K., Lindsay, K., and Randerson, J. T.: Reversal of Increasing Tropical Ocean Hypoxia Trends With Sustained Climate Warming, *Global Biogeochemical Cycles*, 32, 551–564, doi:10.1002/2017GB005788, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017GB005788>, 2018.
- 20 Gao, C., Robock, A., and Ammann, C.: Volcanic forcing of climate over the past 1500 years: An improved ice core-based index for climate models, *Journal of Geophysical Research: Atmospheres*, 113, n/a–n/a, doi:10.1029/2008JD010239, <http://dx.doi.org/10.1029/2008JD010239>, 2008.
- Garcia, H. E. and Gordon, L. I.: Oxygen solubility in seawater: Better fitting equations, *Limnology and Oceanography*, 37, 1307–1312, doi:10.4319/lo.1992.37.6.1307, <http://onlinelibrary.wiley.com/doi/10.4319/lo.1992.37.6.1307/abstract>, 1992.
- 25 Garcia, H. E., Locarnini, R. A., Boyer, T. P., Antonov, J. I., Baranova, O., Zweng, M., Reagan, J., and Johnson, D.: World Ocean Atlas 2013, Volume 3: Dissolved Oxygen, Apparent Oxygen Utilization, and Oxygen Saturation, NOAA Atlas NESDIS, 3, 27, <https://www.nodc.noaa.gov/OC5/woa13/>, 2013.
- Gattuso, J.-P., Magnan, A., Billé, R., Cheung, W. W. L., Howes, E. L., Joos, F., Allemand, D., Bopp, L., Cooley, S. R., Eakin, C. M., Hoegh-Guldberg, O., Kelly, R. P., Pörtner, H.-O., Rogers, A. D., Baxter, J. M., Laffoley, D., Osborn, D., Rankovic, A., Rochette, J., Sumaila, U. R., Treyer, S., and Turley, C.: Contrasting futures for ocean and society from different anthropogenic CO₂ emissions scenarios, *Science*, 349, aac4722, doi:10.1126/science.aac4722, <http://science.sciencemag.org/content/349/6243/aac4722>, 2015.
- 30 Gent, P. R., Danabasoglu, G., Donner, L. J., Holland, M. M., Hunke, E. C., Jayne, S. R., Lawrence, D. M., Neale, R. B., Rasch, P. J., Vertenstein, M., Worley, P. H., Yang, Z.-L., and Zhang, M.: The Community Climate System Model Version 4, *Journal of Climate*, 24, 4973–4991, doi:10.1175/2011JCLI4083.1, <http://journals.ametsoc.org/doi/abs/10.1175/2011JCLI4083.1>, 2011.
- 35 Giorgi, F. and Bi, X.: Time of emergence (TOE) of GHG-forced precipitation change hot-spots, *Geophysical Research Letters*, 36, L06 709, doi:10.1029/2009GL037593, <http://onlinelibrary.wiley.com/doi/10.1029/2009GL037593/abstract>, 2009.

- Gnanadesikan, A., Bianchi, D., and Pradal, M.-A.: Critical role for mesoscale eddy diffusion in supplying oxygen to hypoxic ocean waters, *Geophysical Research Letters*, 40, 2013GL057 674, doi:10.1002/grl.50998, <http://onlinelibrary.wiley.com/doi/10.1002/grl.50998/abstract>, 2013.
- Gregory, J. M.: Long-term effect of volcanic forcing on ocean heat content, *Geophysical Research Letters*, 37, doi:10.1029/2010GL045507, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2010GL045507>, 2010.
- Gruber, N., Gloor, M., Fan, S.-M., and Sarmiento, J. L.: Air-sea flux of oxygen estimated from bulk data: Implications For the marine and atmospheric oxygen cycles, *Global Biogeochemical Cycles*, 15, 783–803, doi:10.1029/2000GB001302, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2000GB001302>, 2001.
- Hauck, J., Völker, C., Wang, T., Hoppema, M., Losch, M., and Wolf-Gladrow, D. A.: Seasonally different carbon flux changes in the Southern Ocean in response to the southern annular mode, *Global biogeochemical cycles*, 27, 1236–1245, 2013.
- Hauri, C., Gruber, N., McDonnell, A. M. P., and Vogt, M.: The intensity, duration, and severity of low aragonite saturation state events on the California continental shelf, *Geophysical Research Letters*, 40, 3424–3428, doi:10.1002/grl.50618, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/grl.50618>, 2013.
- Hawkins, E. and Sutton, R.: Time of emergence of climate signals, *Geophysical Research Letters*, 39, L01 702, doi:10.1029/2011GL050087, <http://onlinelibrary.wiley.com/doi/10.1029/2011GL050087/abstract>, 2012.
- Hawkins, E., Anderson, B., Diffenbaugh, N., Mahlstein, I., Betts, R., Hegerl, G., Joshi, M., Knutti, R., McNeall, D., Solomon, S., Sutton, R., Syktus, J., and Vecchi, G.: Uncertainties in the timing of unprecedented climates, *Nature*, 511, E3–E5, doi:10.1038/nature13523, <https://www.nature.com/articles/nature13523>, 2014.
- Hawkins, E., Ortega, P., Suckling, E., Schurer, A., Hegerl, G., Jones, P., Joshi, M., Osborn, T. J., Masson-Delmotte, V., Mignot, J., Thorne, P., and van Oldenborgh, G. J.: Estimating Changes in Global Temperature since the Preindustrial Period, *Bulletin of the American Meteorological Society*, 98, 1841–1856, doi:10.1175/BAMS-D-16-0007.1, <http://journals.ametsoc.org/doi/10.1175/BAMS-D-16-0007.1>, 2017.
- Helm, K. P., Bindoff, N. L., and Church, J. A.: Observed decreases in oxygen content of the global ocean, *Geophysical Research Letters*, 38, L23 602, doi:10.1029/2011GL049513, <http://onlinelibrary.wiley.com/doi/10.1029/2011GL049513/abstract>, 2011.
- Henson, S. A., Beaulieu, C., and Lampitt, R.: Observing climate change trends in ocean biogeochemistry: when and where, *Global Change Biology*, 22, 1561–1571, doi:10.1111/gcb.13152, <http://onlinelibrary.wiley.com/doi/10.1111/gcb.13152/abstract>, 2016.
- Henson, S. A., Beaulieu, C., Ilyina, T., John, J. G., Long, M., Séférian, R., Tjiputra, J., and Sarmiento, J. L.: Rapid emergence of climate change in environmental drivers of marine ecosystems, *Nature Communications*, 8, 14 682, doi:10.1038/ncomms14682, <http://www.nature.com/ncomms/2017/170307/ncomms14682/full/ncomms14682.html>, 2017.
- Hurrell, J. W., Holland, M. M., Gent, P. R., Ghan, S., Kay, J. E., Kushner, P. J., Lamarque, J.-F., Large, W. G., Lawrence, D., Lindsay, K., Lipscomb, W. H., Long, M. C., Mahowald, N., Marsh, D. R., Neale, R. B., Rasch, P., Vavrus, S., Vertenstein, M., Bader, D., Collins, W. D., Hack, J. J., Kiehl, J., and Marshall, S.: The Community Earth System Model: A Framework for Collaborative Research, *Bulletin of the American Meteorological Society*, 94, 1339–1360, doi:10.1175/BAMS-D-12-00121.1, <http://journals.ametsoc.org/doi/abs/10.1175/BAMS-D-12-00121.1>, 2013.
- Hurtt, G. C., Chini, L. P., Frothing, S., Betts, R. A., Feddema, J., Fischer, G., Fisk, J. P., Hibbard, K., Houghton, R. A., Janetos, A., Jones, C. D., Kindermann, G., Kinoshita, T., Goldewijk, K. K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., Vuuren, D. P. v., and Wang, Y. P.: Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands, *Climatic Change*, 109, 117, doi:10.1007/s10584-011-0153-2, <https://link.springer.com/article/10.1007/s10584-011-0153-2>, 2011.

- Ilyina, T. and Zeebe, R. E.: Detection and projection of carbonate dissolution in the water column and deep-sea sediments due to ocean acidification, *Geophysical Research Letters*, 39, doi:10.1029/2012GL051272, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2012GL051272>, 2012.
- Ilyina, T., Zeebe, R. E., Maier-Reimer, E., and Heinze, C.: Early detection of ocean acidification effects on marine calcification, *Global Biogeochemical Cycles*, 23, doi:10.1029/2008GB003278, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2008GB003278>, 2009.
- IPCC, I. P. o. C.: *Climate Change 2013: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, google-Books-ID: o4gaBQAAQBAJ, 2013.
- Ito, T., Minobe, S., Long, M. C., and Deutsch, C.: Upper ocean O₂ trends: 1958–2015, *Geophysical Research Letters*, p. 2017GL073613, doi:10.1002/2017GL073613, <http://onlinelibrary.wiley.com/doi/10.1002/2017GL073613/abstract>, 2017.
- 10 Joos, F., Plattner, G.-K., Stocker, T. F., Körtzinger, A., and Wallace, D. W. R.: Trends in marine dissolved oxygen: Implications for ocean circulation changes and the carbon budget, *Eos, Transactions American Geophysical Union*, 84, 197–201, doi:10.1029/2003EO210001, <http://onlinelibrary.wiley.com/doi/10.1029/2003EO210001/abstract>, 2003.
- Jungclaus, J., BARD, , Baroni, M., Braconnot, P., Cao, J., Chini, L., Egorova, T., Evans, M., González-Rouco, J. F., Goosse, H., Hurtt, G., Joos, F., Kaplan, J. O., Khodri, M., Klein Goldewijk, K., Krivova, N., LeGrande, A., Lorenz, S., Luterbacher, J., Man, W., Maycock, A., 15 Meinshausen, M., Moberg, A., Muscheler, R. R., Nehrass-Ahles, C., Otto-Bliesner, B., Phipps, S. J., Pongratz, J., Rozanov, E., Schmidt, G., Schmidt, H., Schmutz, W., Schurer, A., Shapiro, A., Sigl, M., Smerdon, J., Solanki, S., Timmreck, C., Toohey, M., Usoskin, I., Wagner, S., Wu, C.-J., Yeo, K. L., Zanchettin, D., Zhang, Q., and Zorita, E.: The PMIP4 contribution to CMIP6 – Part 3: The last millennium, scientific objective, and experimental design for the PMIP4 past1000 simulations, *Geoscientific Model Development*, 10, 4005–4033, doi:10.5194/gmd-10-4005-2017, <https://hal.archives-ouvertes.fr/hal-01757261>, 2017.
- 20 Jungclaus, J. H., Lorenz, S. J., Timmreck, C., Reick, C. H., Brovkin, V., Six, K., Segschneider, J., Giorgetta, M. A., Crowley, T. J., Pongratz, J., Krivova, N. A., Vieira, L. E., Solanki, S. K., Klocke, D., Botzet, M., Esch, M., Gayler, V., Haak, H., Raddatz, T., Roeckner, E., Schnur, R., Widmann, H., Claussen, M., Stevens, B., and Marotzke, J.: Climate and carbon-cycle variability over the last millennium, *Climate of the Past*, 6, 723–737, doi:10.5194/cp-6-723-2010, https://pure.mpg.de/pubman/faces/ViewItemOverviewPage.jsp?itemId=item_993781, 2010.
- 25 Karoly, D. J. and Wu, Q.: Detection of Regional Surface Temperature Trends, *Journal of Climate*, 18, 4337–4343, doi:10.1175/JCLI3565.1, <https://journals.ametsoc.org/doi/abs/10.1175/JCLI3565.1>, 2005.
- Keeling, R. E., Körtzinger, A., and Gruber, N.: Ocean deoxygenation in a warming world., *Annual review of marine science*, 2, 199–229, doi:10.1146/annurev.marine.010908.163855, 2010.
- Keeling, R. F. and Garcia, H. E.: The change in oceanic O₂ inventory associated with recent global warming, *Proceedings of the National Academy of Sciences*, 99, 7848–7853, doi:10.1073/pnas.122154899, <http://www.pnas.org/content/99/12/7848>, 2002.
- 30 Keller, D. P., Kriest, I., Koeve, W., and Oesch, A.: Southern Ocean biological impacts on global ocean oxygen, *Geophysical Research Letters*, 43, 2016GL069630, doi:10.1002/2016GL069630, <http://onlinelibrary.wiley.com/doi/10.1002/2016GL069630/abstract>, 2016.
- Keller, K., Joos, F., Raible, C., Cocco, V., Frölicher, T. L., Dunne, J. P., Gehlen, M., Bopp, L., Orr, J. C., Tjiputra, J., Heinze, C., Segschneider, J., Roy, T., and Metzl, N.: Variability of the ocean carbon cycle in response to the North Atlantic Oscillation, *Tellus B*, 1, 1–25, 35 doi:10.3402/tellusb.v64i0.18738, 2012.
- Keller, K. M., Joos, F., and Raible, C. C.: Time of emergence of trends in ocean biogeochemistry, *Biogeosciences*, 11, 3647–3659, doi:10.5194/bg-11-3647-2014, 2014.

- Keller, K. M., Joos, F., Lehner, F., and Raible, C. C.: Detecting changes in marine responses to ENSO from 850 to 2100 C.E.: Insights from the ocean carbon cycle, *Geophysical Research Letters*, 42, 2014GL062398, doi:10.1002/2014GL062398, <http://onlinelibrary.wiley.com/doi/10.1002/2014GL062398/abstract>, 2015.
- Laufkötter, C., Vogt, M., Gruber, N., Aita-Noguchi, M., Aumont, O., Bopp, L., Buitenhuis, E. T., Doney, S. C., Dunne, J. P., and Hashioka, T.: Drivers and uncertainties of future global marine primary production in marine ecosystem models, 2015.
- Lawrence, P. J., Feddesma, J. J., Bonan, G. B., Meehl, G. A., O'Neill, B. C., Oleson, K. W., Levis, S., Lawrence, D. M., Kluzek, E., Lindsay, K., and Thornton, P. E.: Simulating the Biogeochemical and Biogeophysical Impacts of Transient Land Cover Change and Wood Harvest in the Community Climate System Model (CCSM4) from 1850 to 2100, *Journal of Climate*, 25, 3071–3095, doi:10.1175/JCLI-D-11-00256.1, <http://journals.ametsoc.org/doi/full/10.1175/JCLI-D-11-00256.1>, 2012.
- 10 Lehner, F., Joos, F., Raible, C. C., Mignot, J., Born, A., Keller, K. M., and Frölicher, T. L.: Climate and carbon cycle dynamics in a CESM simulation from 850 to 2100 CE, *Earth System Dynamics*, 6, 411–434, doi:10.5194/esd-6-411-2015, <http://www.earth-syst-dynam.net/6/411/2015/>, 2015.
- Locarnini, R. A., Mishonov, A. V., J. I. Antonov, T. P. Boyer, H. E. Garcia, O. K. Baranova, M. M. Zweng, C. R. Paver, J. R. Reagan, D. R. Johnson, M. Hamilton, and D. Seidov: World Ocean Atlas 2013, Volume 1: Temperature. S. Levitus, Ed., A. Mishonov Technical Ed, 15 NOAA Atlas NESDIS, 1, 40, <http://www.vliz.be/nl/imis?module=ref&refid=117383&printversion=1&dropIMISitle=1>, 2013.
- Lombardozi, D., Bonan, G. B., and Nychka, D. W.: The emerging anthropogenic signal in land–atmosphere carbon-cycle coupling, *Nature Climate Change*, 4, 796–800, doi:10.1038/nclimate2323, <https://www.nature.com/articles/nclimate2323>, 2014.
- Long, M. C., Deutsch, C., and Ito, T.: Finding forced trends in oceanic oxygen, *Global Biogeochemical Cycles*, 30, 2015GB005310, doi:10.1002/2015GB005310, <http://onlinelibrary.wiley.com/doi/10.1002/2015GB005310/abstract>, 2016.
- 20 Lorenz, E. N.: Deterministic Nonperiodic Flow, *Journal of the Atmospheric Sciences*, 20, 130–141, doi:10.1175/1520-0469(1963)020<0130:DNF>2.0.CO;2, [https://journals.ametsoc.org/doi/abs/10.1175/1520-0469\(1963\)020%3C0130:dnf%3E2.0.CO;2](https://journals.ametsoc.org/doi/abs/10.1175/1520-0469(1963)020%3C0130:dnf%3E2.0.CO;2), 1963.
- Mahlstein, I., Daniel, J. S., and Solomon, S.: Pace of shifts in climate regions increases with global temperature, *Nature Climate Change*, 3, 739–743, doi:10.1038/nclimate1876, <https://www.nature.com/articles/nclimate1876>, 2013.
- 25 Manabe, S., Stouffer, R. J., Spelman, M. J., and Bryan, K.: Transient Responses of a Coupled Ocean–Atmosphere Model to Gradual Changes of Atmospheric CO₂. Part I. Annual Mean Response, *Journal of Climate*, 4, 785–818, doi:10.1175/1520-0442(1991)004<0785:TROACO>2.0.CO;2, [https://journals.ametsoc.org/doi/abs/10.1175/1520-0442\(1991\)004%3C0785:TROACO%3E2.0.CO;2](https://journals.ametsoc.org/doi/abs/10.1175/1520-0442(1991)004%3C0785:TROACO%3E2.0.CO;2), 1991.
- Maraun, D.: When will trends in European mean and heavy daily precipitation emerge?, *Environmental Research Letters*, 8, 014004, doi:10.1088/1748-9326/8/1/014004, <http://stacks.iop.org/1748-9326/8/i=1/a=014004>, 2013.
- 30 McGregor, H. V., Evans, M. N., Goosse, H., Leduc, G., Martrat, B., Addison, J. A., Mortyn, P. G., Oppo, D. W., Seidenkrantz, M.-S., Sicre, M.-A., Phipps, S. J., Selvaraj, K., Thirumalai, K., Filipsson, H. L., and Ersek, V.: Robust global ocean cooling trend for the pre-industrial Common Era, *Nature Geoscience*, 8, 671–677, doi:10.1038/ngeo2510, <https://www.nature.com/articles/ngeo2510>, 2015.
- McKinley, G. A., Pilcher, D. J., Fay, A. R., Lindsay, K., Long, M. C., and Lovenduski, N. S.: Timescales for detection of trends in the ocean carbon sink, *Nature*, 530, 469–472, doi:10.1038/nature16958, <http://www.nature.com/nature/journal/v530/n7591/abs/nature16958.html>, 2016.

- Mecking, S., Langdon, C., Feely, R. A., Sabine, C. L., Deutsch, C. A., and Min, D.-H.: Climate variability in the North Pacific thermocline diagnosed from oxygen measurements: An update based on the U.S. CLIVAR/CO₂ Repeat Hydrography cruises, *Global Biogeochemical Cycles*, 22, doi:10.1029/2007GB003101, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2007GB003101>, 2008.
- 5 Mignot, J., Khodri, M., Frankignoul, C., and Servonnat, J.: Volcanic impact on the Atlantic ocean over the last millennium, *Climate of the Past Discussions*, 7, 2511–2554, doi:10.5194/CPD-7-2511-2011, <https://hal.archives-ouvertes.fr/hal-00755362>, 2011.
- Mislan, K. a. S., Deutsch, C. A., Brill, R. W., Dunne, J. P., and Sarmiento, J. L.: Projections of climate-driven changes in tuna vertical habitat based on species-specific differences in blood oxygen affinity, *Global Change Biology*, 23, 4019–4028, doi:10.1111/gcb.13799, <http://onlinelibrary.wiley.com/doi/10.1111/gcb.13799/abstract>, 2017.
- Moore, J. K., Doney, S. C., Kleypas, J. A., Glover, D. M., and Fung, I. Y.: An intermediate complexity marine ecosystem model for the global domain, *Deep-Sea Research Part II: Topical Studies in Oceanography*, 49, 403–462, doi:10.1016/S0967-0645(01)00108-4, 2002.
- 10 Moore, J. K., Doney, S. C., and Lindsay, K.: Upper ocean ecosystem dynamics and iron cycling in a global three-dimensional model, *Global Biogeochemical Cycles*, 18, GB4028, doi:10.1029/2004GB002220, <http://onlinelibrary.wiley.com/doi/10.1029/2004GB002220/abstract>, 2004.
- Moore, J. K., Lindsay, K., Doney, S. C., Long, M. C., and Misumi, K.: Marine Ecosystem Dynamics and Biogeochemical Cycling in the Community Earth System Model [CESM1(BGC)]: Comparison of the 1990s with the 2090s under the RCP4.5 and RCP8.5 Scenarios, *Journal of Climate*, 26, 9291–9312, doi:10.1175/JCLI-D-12-00566.1, <https://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-12-00566.1>, 2013.
- 15 Mora, C., Frazier, A. G., Longman, R. J., Dacks, R. S., Walton, M. M., Tong, E. J., Sanchez, J. J., Kaiser, L. R., Stender, Y. O., Anderson, J. M., Ambrosino, C. M., Fernandez-Silva, I., Giuseffi, L. M., and Giambelluca, T. W.: The projected timing of climate departure from recent variability, *Nature*, 502, 183–187, doi:10.1038/nature12540, <https://www.nature.com/articles/nature12540>, 2013.
- 20 Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Vuuren, D. P. v., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P., and Wilbanks, T. J.: The next generation of scenarios for climate change research and assessment, *Nature*, 463, 747–756, doi:10.1038/nature08823, <https://www.nature.com/articles/nature08823>, 2010.
- 25 Muscheler, R., Joos, F., Beer, J., Müller, S. A., Vonmoos, M., and Snowball, I.: Solar activity during the last 1000yr inferred from radionuclide records, *Quaternary Science Reviews*, 26, 82–97, doi:10.1016/j.quascirev.2006.07.012, <http://www.sciencedirect.com/science/article/pii/S0277379106002460>, 2007.
- Najjar, R. G., Jin, X., Louanchi, F., Aumont, O., Caldeira, K., Doney, S. C., Dutay, J.-C., Follows, M., Gruber, N., Joos, F., Lindsay, K., Maier-Reimer, E., Matear, R. J., Matsumoto, K., Monfray, P., Mouchet, A., Orr, J. C., Plattner, G.-K., Sarmiento, J. L., Schlitzer, R., Slater, R. D., Weirig, M.-F., Yamanaka, Y., and Yool, A.: Impact of circulation on export production, dissolved organic matter, and dissolved oxygen in the ocean: Results from Phase II of the Ocean Carbon-cycle Model Intercomparison Project (OCMIP-2), *Global Biogeochemical Cycles*, 21, n/a–n/a, doi:10.1029/2006GB002857, <http://doi.wiley.com/10.1029/2006GB002857>, 2007.
- 30 Neale, R. B., Chen, C.-C., Gettelman, A., Lauritzen, P. H., Park, S., Williamson, D. L., Conley, A. J., Garcia, R., Kinnison, D., and Lamarque, J.-F.: Description of the NCAR community atmosphere model (CAM 5.0), NCAR Tech. Note NCAR/TN-486+ STR, 1, 1–12, 2010.
- 35 Orr, J. C., Pantoja, S., and Pörtner, H. O.: Introduction to special section: The ocean in a high-CO₂ world, *Journal of Geophysical Research-Oceans*, 110, C09S01, doi:10.1029/2005jc003086, <GotoISI>://WOS:000232111200004, 2005.

- Oschlies, A., Duteil, O., Getzlaff, J., Koeve, W., Landolfi, A., and Schmidtko, S.: Patterns of deoxygenation: sensitivity to natural and anthropogenic drivers, *Phil. Trans. R. Soc. A*, 375, 20160325, doi:10.1098/rsta.2016.0325, <http://rsta.royalsocietypublishing.org/content/375/2102/20160325>, 2017.
- PAGES2k Consortium, Emile-Geay, J., McKay, N. P., Kaufman, D. S., von Gunten, L., Wang, J., Anchukaitis, K. J., Abram, N. J., Addison, J. A., Curran, M. A. J., Evans, M. N., Henley, B. J., Hao, Z., Martrat, B., McGregor, H. V., Neukom, R., Pederson, G. T., Stenni, B., Thirumalai, K., Werner, J. P., Xu, C., Divine, D. V., Dixon, B. C., Gergis, J., Mundo, I. A., Nakatsuka, T., Phipps, S. J., Routson, C. C., Steig, E. J., Tierney, J. E., Tyler, J. J., Allen, K. J., Bertler, N. A. N., Björklund, J., Chase, B. M., Chen, M.-T., Cook, E., de Jong, R., DeLong, K. L., Dixon, D. A., Ekaykin, A. A., Ersek, V., Filipsson, H. L., Francus, P., Freund, M. B., Frezzotti, M., Gaire, N. P., Gajewski, K., Ge, Q., Goosse, H., Gornostaeva, A., Grosjean, M., Horiuchi, K., Hormes, A., Husum, K., Isaksson, E., Kandasamy, S., Kawamura, K., Kilbourne, K. H., Koç, N., Leduc, G., Linderholm, H. W., Lorrey, A. M., Mikhalenko, V., Mortyn, P. G., Motoyama, H., Moy, A. D., Mulvaney, R., Munz, P. M., Nash, D. J., Oerter, H., Opel, T., Orsi, A. J., Ovchinnikov, D. V., Porter, T. J., Roop, H. A., Saenger, C., Sano, M., Sauchyn, D., Saunders, K. M., Seidenkrantz, M.-S., Severi, M., Shao, X., Sicre, M.-A., Sigl, M., Sinclair, K., George, S. S., Jacques, J.-M. S., Thamban, M., Kuwar Thapa, U., Thomas, E. R., Turney, C., Uemura, R., Viau, A. E., Vladimirova, D. O., Wahl, E. R., White, J. W. C., Yu, Z., and Zinke, J.: A global multiproxy database for temperature reconstructions of the Common Era, *Scientific Data*, 4, 170088, doi:10.1038/sdata.2017.88, <https://www.nature.com/articles/sdata201788>, 2017.
- Palter, J. B., Frölicher, T. L., Paynter, D., and John, J. G.: Climate, ocean circulation, and sea level changes under stabilization and overshoot pathways to 1.5 K warming, *Earth System Dynamics*, 9, 817–828, 2018.
- Plattner, G.-K., Joos, F., Stocker, T. F., and Marchal, O.: Feedback mechanisms and sensitivities of ocean carbon uptake under global warming, *Tellus B*, 53, 564–592, doi:10.1034/j.1600-0889.2001.530504.x, <http://onlinelibrary.wiley.com/doi/10.1034/j.1600-0889.2001.530504.x/full>, 2001.
- Pongratz, J., Reick, C., Raddatz, T., and Claussen, M.: A reconstruction of global agricultural areas and land cover for the last millennium, *Global Biogeochemical Cycles*, 22, doi:10.1029/2007GB003153, <http://onlinelibrary.wiley.com/doi/10.1029/2007GB003153/full>, 2008.
- Pörtner, H.-O., Karl, D. M., Boyd, P. W., Cheung, W., Lluch-Cota, S. E., Nojiri, Y., Schmidt, D. N., Zavalov, P. O., Alheit, J., and Aristegui, J.: Ocean systems, in: *Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change*, pp. 411–484, Cambridge University Press, 2014.
- Resplandy, L., Séférian, R., and Bopp, L.: Natural variability of CO₂ and O₂ fluxes: What can we learn from centuries-long climate models simulations?, *Journal of Geophysical Research: Oceans*, 120, 384–404, doi:10.1002/2014JC010463, <http://onlinelibrary.wiley.com/doi/10.1002/2014JC010463/abstract>, 2015.
- Rodgers, K. B., Lin, J., and Frölicher, T. L.: Emergence of multiple ocean ecosystem drivers in a large ensemble suite with an Earth system model, *Biogeosciences*, 12, 3301–3320, doi:10.5194/bg-12-3301-2015, <https://www.biogeosciences.net/12/3301/2015/>, 2015.
- Sarmiento, J. L., Hughes, T. M. C., Stouffer, R. J., and Manabe, S.: Simulated response of the ocean carbon cycle to anthropogenic climate warming, *Nature*, 393, 245–249, doi:10.1038/30455, <http://www.nature.com/nature/journal/v393/n6682/abs/393245a0.html?foxtrotcallback=true>, 1998.
- Schmidt, G. A., Jungclaus, J. H., Ammann, C. M., Bard, E., Braconnot, P., Crowley, T. J., Delaygue, G., Joos, F., Krivova, N. A., Muscheler, R., Otto-Bliesner, B. L., Pongratz, J., Shindell, D. T., Solanki, S. K., Steinhilber, F., and Vieira, L. E. A.: Climate forcing reconstructions for use in PMIP simulations of the last millennium (v1.0), *Geosci. Model Dev.*, 4, 33–45, doi:10.5194/gmd-4-33-2011, <https://www.geosci-model-dev.net/4/33/2011/>, 2011.

- Schmidtko, S., Stramma, L., and Visbeck, M.: Decline in global oceanic oxygen content during the past five decades, *Nature*, 542, 335–339, doi:10.1038/nature21399, <http://www.nature.com/nature/journal/v542/n7641/full/nature21399.html>, 2017.
- Schmittner, A., Oschlies, A., Matthews, H. D., and Galbraith, E. D.: Future changes in climate, ocean circulation, ecosystems, and biogeochemical cycling simulated for a business-as-usual CO₂ emission scenario until year 4000 AD, *Global Biogeochemical Cycles*, 22, GB1013, doi:10.1029/2007GB002953, <http://onlinelibrary.wiley.com/doi/10.1029/2007GB002953/abstract>, 2008.
- 5 Shaffer, G., Pedersen, J. O. P., and Olsen, S. M.: Long-term ocean oxygen depletion in response to carbon dioxide emissions from fossil fuels, *Nature Geoscience*, 2, 105, doi:10.1038/ngeo420, <https://www.nature.com/articles/ngeo420>, 2009.
- Sigl, M., Winstrup, M., McConnell, J. R., Welten, K. C., Plunkett, G., Ludlow, F., Büntgen, U., Caffee, M., Chellman, N., Dahl-Jensen, D., Fischer, H., Kipfstuhl, S., Kostick, C., Maselli, O. J., Mekhaldi, F., Mulvaney, R., Muscheler, R., Pasteris, D. R., Pilcher, J. R., Salzer, M., Schüpbach, S., Steffensen, J. P., Vinther, B. M., and Woodruff, T. E.: Timing and climate forcing of volcanic eruptions for the past 2,500 years, *Nature*, 523, nature14565, doi:10.1038/nature14565, <https://www.nature.com/articles/nature14565>, 2015.
- 10 Smith, R., Jones, P., Briegleb, B., Bryan, F., Danabasoglu, G., Dennis, J., Dukowicz, J., Eden, C., Fox-Kemper, B., and Gent, P.: The parallel ocean program (POP) reference manual ocean component of the community climate system model (CCSM) and community earth system model (CESM), Rep. LAUR-01853, 141, 1–140, 2010.
- 15 Steinacher, M., Joos, F., Frölicher, T. L., Bopp, L., Cadule, P., Cocco, V., Doney, S. C., Gehlen, M., Lindsay, K., Moore, J. K., Schneider, B., and Segschneider, J.: Projected 21st century decrease in marine productivity: a multi-model analysis, *Biogeosciences*, 7, 979–1005, doi:10.5194/bg-7-979-2010, <https://www.biogeosciences.net/7/979/2010/>, 2010.
- Stott, P. A., Tett, S. F. B., Jones, G. S., Allen, M. R., Mitchell, J. F. B., and Jenkins, G. J.: External Control of 20th Century Temperature by Natural and Anthropogenic Forcings, *Science*, 290, 2133–2137, doi:10.1126/science.290.5499.2133, <http://science.sciencemag.org/content/290/5499/2133>, 2000.
- 20 Stramma, L., Johnson, G. C., Sprintall, J., and Mohrholz, V.: Expanding Oxygen-Minimum Zones in the Tropical Oceans, *Science*, 320, 655–658, doi:10.1126/science.1153847, <http://science.sciencemag.org/content/320/5876/655>, 2008.
- Séférian, R., Bopp, L., Gehlen, M., Swingedouw, D., Mignot, J., Guilyardi, E., and Servonnat, J.: Multiyear predictability of tropical marine productivity, *Proceedings of the National Academy of Sciences*, 111, 11646–11651, 2014.
- 25 Talley, L., Feely, R., Sloyan, B., Wanninkhof, R., Baringer, M., Bullister, J., Carlson, C., Doney, S., Fine, R., Firing, E., Gruber, N., Hansell, D., Ishii, M., Johnson, G., Katsumata, K., Key, R., Kramp, M., Langdon, C., Macdonald, A., Mathis, J., McDonagh, E., Mecking, S., Millero, F., Mordy, C., Nakano, T., Sabine, C., Smethie, W., Swift, J., Tanhua, T., Thurnherr, A., Warner, M., and Zhang, J.-Z.: Changes in Ocean Heat, Carbon Content, and Ventilation: A Review of the First Decade of GO-SHIP Global Repeat Hydrography, *Annual Review of Marine Science*, 8, 185–215, doi:10.1146/annurev-marine-052915-100829, <https://doi.org/10.1146/annurev-marine-052915-100829>, 2016.
- 30 Vieira, L. E. A. and Solanki, S. K.: Evolution of the solar magnetic flux on time scales of years to millenia, *Astronomy & Astrophysics*, 509, A100, doi:10.1051/0004-6361/200913276, <https://www.aanda.org/articles/aa/abs/2010/01/aa13276-09/aa13276-09.html>, 2010.
- Wanner, H., Beer, J., Bütikofer, J., Crowley, T. J., Cubasch, U., Flückiger, J., Goosse, H., Grosjean, M., Joos, F., and Kaplan, J. O.: Mid-to Late Holocene climate change: an overview, *Quaternary Science Reviews*, 27, 1791–1828, 2008.
- 35 Wanninkhof Rik: Relationship between wind speed and gas exchange over the ocean, *Journal of Geophysical Research: Oceans*, 97, 7373–7382, doi:10.1029/92JC00188, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/92JC00188>, 1992.