

Response to reviewers comments on gmd-2020-43 “FORTE 2.0: a fast, parallel and flexible coupled climate model”

We would like to thank both reviewers for their time and effort in reviewing our manuscript. Their suggestions have helped to clarify several points and improve the description of FORTE2.0 in many areas. Reviewer 1 requested a second simulation (without the stratosphere) to be presented alongside the original. This has resulted in numerous changes to the text and figures throughout the manuscript. Where we have added/changed figures we note that it is easier to read the captions in the revised submission than in the latexdiff-generated pdf.

The remainder of this document comprises a point-by-point response to the individual reviewers comments followed by a latexdiff-generated version of the manuscript which highlights all the changes made between the original submission and the revised version of the manuscript. The reviewers comments below are reproduced in black text and our responses are given in red. Where specific points have been addressed we identify the relevant change(s), referring to the page (P) and line numbers (L) in the latexdiff-generated pdf document accompanying this response.

Response to RC1

We thank the reviewer for their time and effort in reviewing our manuscript.

1/ As it is presented, FORTE2.0 is an intermediate resolution model like many others. The fact that the model is relatively fast does not appear clearly as an advantage compared to similar models that should be more or less as fast if they are run at the same resolution. If I understand well, the tool seems to have two main advantages. First, the model can include or not the stratosphere. However, the stratospheric dynamics is not at all discussed. The minimum for me would be to present simulations with and without resolved stratosphere and see the impact of this choice on model result. 2/ It seems that the model is readily configurable, providing maybe more flexibility than other tools. This interesting aspect is mentioned but not developed enough to see if this is a real strength of the tool. The manuscript should thus insist much more on those potential strengths (and maybe on others).

FORTE 2.0's performance, and the use of the term 'Fast' is in part to retain the connection to earlier studies which used FORTE, and in part due to the choice of the components, which when FORTE was originally coupled were indeed 'fast'. The IGCM (Forster et al., 2000, Joshi et al., 2015) is a spectral atmosphere, and spectral models are well-known to integrate much faster than grid-point models. At the time it was written, MOMA was shown to yield significantly faster performance on array processors than the GFDL MOM code upon which it was based (Webb 1995).

To avoid repeating the description of IGCM4 (Joshi et al 2015) we referred the reader to that publication for details of the stratospheric dynamics. We have expanded the description of the atmosphere and make it clear to the reader where they may find more information (P3 L17-19).

We have performed a second simulation using the L20 configuration, and have now integrated a comparison of the simulations with and without the stratosphere into the manuscript. This has resulted in many changes throughout the text and figures, all of which are highlighted in the accompanying latexdiff-generated pdf accompanying this response.

FORTE2.0 is readily configurable. We refer in our introduction to previous studies that have used FORTE in a variety of configurations to illustrate this point. It is difficult to quantify configurability, but we expand the text to give some more details on this element of FORTE2.0 (P2 L6-19).

2/ The model evaluation is very general. Many times it is mentioned that the results of the model are satisfactory or within the range of other models but the model performance itself is not really quantified. The observations are shown for some quantities for comparison with model results (some figures in section 4.2, figures 12-14) but not for many others (section 4.1, figure 14). This makes the evaluation harder to follow. Furthermore, it is not clear from the text if the simulation presented is from a ‘standard configuration’ of the model that may be used as a future reference or just an illustrative version that is not supposed to last and will not be used later. If the configuration presented is not a standard one, this strongly diminishes the interest of any diagnostic performed with this configuration and I would recommend that such a standard version is obtained before presenting it.

Hardware and compiler differences aside, the code and configuration of FORTE that has been archived will reproduce the (now two) simulation(s) presented in this manuscript (using the L20 and L35 configurations of IGCM4). In that sense, this could be considered a ‘standard configuration’, and by archiving the code/configuration and publishing the resulting simulations it may be used as a future reference. As we state in the manuscript, we have not exhaustively calibrated the model, and ‘better’ climates almost certainly could be achieved. Furthermore, the potential applications of FORTE2.0 are wide-ranging, and we expect that many users will define their own ‘standard configuration’ adapted to suit their purposes. When considering the plots for the manuscript we tried to strike a balance between the number of figures/subpanels and what we think the readers would be interested to see. In the revised manuscript we now present difference plots between the modelled SAT and 20CR (Compo et al., 2011) (new Figure 4) and between the modelled summer and winter precipitation and 20CR (new Figure 5). All data and scripts for plotting the figures in the manuscript are provided as supplementary material, so it is possible to reproduce and compute differences from other models and observational datasets.

Compo et al., “The Twentieth Century Reanalysis Project” QJRM, 37, 654, Part A, 2011, Pages 1-28

3/ The model has no interactive sea ice. This is a strong limitation compared to similar tools and this should be mentioned earlier (in the abstract for instance) as this may be an important element for potential users.

The flux barrier that represents sea-ice is interactive. Once SST drops below a threshold the ice forms, its albedo changes, and its surface temperature is calculated and updated. However, we do acknowledge that such a simple representation of sea ice may be a strong limitation for some users. We now state clearly that the ice is represented by a simple flux barrier in the abstract (P1 L3-4).

Specific comments

Page 1, lines 16- 21. The distinction between ‘coarse resolution simplified models’, ‘intermediate resolution models’ and the ‘Earth Models of Intermediate Complexity (EMICs)’ (introduced page 2, line 30) is to very clear to me. For instance, I would personally put ECBilt in the list of EMICs, and thus among the ‘coarse resolution simplified models’ rather than within the ‘intermediate resolution models’.

We have moved ECBilt as you suggest (P1 L19).

Even if it is always better to use the most up-to date datasets, I do not think that using relatively old ones like the climatology of Levitus and Boyer (1998) - Levitus et al. (1998) (page 2, line 15) or the

heat transport of Trenberth and Caron (2001) (page 13, line 18) makes a big difference but stopping the analyses in 1997 for ENSO (page 16, line 11) may seem a bit too early to have a good evaluation.

We use the Levitus and Boyer (1998) and Levitus et al. (1998) T and S climatologies for the initial state of the simulation. Their use is historical, and as the reviewer suggests their age is unlikely to make a big difference to the result. For our ENSO analysis we now plot Gaussian distributions of the NINO 3.4 SST anomalies for both the L35 and L20 configurations, and for HadISST data extending from 1870-2019 (new Figure 13).

Page 3, line 28. It is not clear if the variable drag coefficient is applied both over land and ocean.

It is applied only over open ocean. We clarify this in the text (P4 L8).

Page 3, line 34. Not clear to me what is meant here by 'ice has melted' if there is no representation of sea ice

This has been rephrased to say "...will not reduce until the temperature rises above freezing point and the flux barrier deactivates." (P4 L13).

Page 4, line 9. What is the size of the 'polar island' ?

The polar island is a single row of ocean cells, so the northern extent of the ocean is 88°N. This detail is now added to the text (P4 L22).

Page 11, Figure 3. What is EN3? Not sure it is defined.

Thank you for spotting this. We had omitted the reference, and this is now given (P13 L9).

EN3 is a subsurface ocean T and S product from the UK Met Office which can be accessed here: <https://www.metoffice.gov.uk/hadobs/en3/>

Ingleby, B., and M. Huddleston, 2007: Quality control of ocean temperature and salinity profiles - historical and real-time data. *Journal of Marine Systems*, 65, 158-175 10.1016/j.jmarsys.2005.11.019

Page 13, Lines 9-14. Please specify where convection occurs in the model. The wording 'not uncharacteristic of coarse resolution ocean models' is another example of a general sentence where more substantial, quantified information would be required.

Convection occurs in MOMA where $d(\rho)/dz < 0$. We do not routinely output where this takes place, but the mixed layer depth is an indication of where deep convection occurs. Winter mixed layer depths in the southern Labrador Sea reach 2500 m in a few grid cells. Winter mixed layer depths south of the Denmark Strait, Iceland and the Faroe Bank Channel can reach 1000 m. Wintertime convection is too shallow in the Nordic Seas, with mixed layer depths reaching 125-150 m in the central and eastern Nordic Seas. We have improved the text describing the regions of deep convection

(P16 L8-11) and added a new figure to show the winter mixed layer depths in both the L35 and L20 configurations (i.e. simulations with and without the stratosphere) (new Figure 11).

Page 16, line 11. The evaluation of ENSO characteristics is based on a figure from a paper published in 1997 while it would be very easy to evaluate precisely the simulated Nino3.4 index compared to observed one.

We now compare the distributions of the Nino 3.4 SST index from both FORTE 2.0 simulations and an up-to-date time series from the gridded observation-based product HadISST (new Figure 13). The distributions simulated by FORTE 2.0 are too narrow compared with observations, and extreme values are approximately 0.5C too small. We have updated the text which discusses the ENSO (P18 L27-32)

Page 17, line 6. It is mentioned that ‘. Comparison of the corresponding principal component time-series (Fig. 12) suggests the presence of some higher frequency variability in observations that is not captured by FORTE 2.0’. This should be quantified both for the AO and the NAO.

The suggestion of higher-frequency variability in the AO principle component time series is a visual artefact because of the longer time series of the 20th Century Reanalysis (140 years vs the 100 years of FORTE2.0 that we present). We removed the sentence from the manuscript.

Response to RC2

We thank Dmitry for his time and effort in reviewing our manuscript.

A general question before downloading the code: in which programming language is FORTE written?

FORTE is written in FORTRAN. This is an important point, and we have added a statement to the abstract to make this clear to the reader (P1 L4).

Page 3, lines 2 and 3: It sounds like two different grids are being used in the atmosphere. I would therefore rephrase to something like “A longitudinally regular and Gaussian in latitude grid with a grid spacing of `_2.8_` is used for advection and diabatic processes.”

This sentence has been reworded as suggested (P3 L12-13).

Page 3, line 31 and below: “FORTE 2.0 does not include dynamic sea-ice representation. Instead, sea ice is represented by a barrier: : :” Do I understand this correctly that there is no dynamic sea ice nor the sea ice itself but the flux barrier? I am curious about the process of flux computation in this place. How the values for temperatures and albedo to parameterize the presence of sea ice were chosen? At the end of the page the authors say “...until the ice has melted”. Considering what is said above, is it

the same as ... until the atmospheric temperature becomes $> 271_K$? I assume the restoring of SST below the sea ice a part of the ocean component? Maybe it is worth mentioning this since this chapter describes the atmospheric component.

Yes. There is no dynamic sea ice in FORTE2.0 at the moment. In response to a comment by Reviewer 1 we added a statement to the abstract (P1 L3-4) to make this clear to the reader. The sea-ice representation is arguably the largest shortcoming in the current configuration, and top of the list of things we would like to address in the future. The albedo for sea ice in the real world typically ranges from 0.5 to 0.7. It is a tunable parameter in FORTE2.0. The simulations presented use a value of 0.6. The flux barrier becomes active once the sea surface temperature reaches 271K, and from this point IGCM4 computes the surface temperature in 'ice covered' regions. If the surface temperature continues to fall the albedo can increase further to mimic the effect of snow cover on sea ice. In reality, accumulation of snow cover on sea ice acts to increase the surface albedo to values as high as ~ 0.9 . Given the size of the grid cells in FORTE2.0 we opted for setting an upper bound of 0.8.

Page 4, line 13: How the topography was interpolated? Was it smoothed in between or not? conservatively?

The topography used for the simulations present and supplied in the repository is a bilinear interpolation of the HadCM3 bathymetry (Gordon et al., 2000). Due to the coarse grid this was followed by a manual process to adjust the widths of narrow channels. Note that with the Arakawa 'B' grid a single grid point channel does not permit flow, but diffusion of tracer quantities will occur.

Page 4, lines 18 to 20: Considering the model "biases" which are shown below in the paper I wonder whether the geometrical scaling of GM could improve the solution? Was there a run made without GM? Does it improve the SPG in the NA?

We have not implemented or tested a geometric scaling of GM, or run FORTE2.0 without GM. These are interesting suggestions, and we would be interested to explore these in future.

Page 5, lines 2 to 3: in the Table 1 the background vertical diffusivity is defined as a constant value but it is stability dependent here. Which mixing scheme is used above the background?

This was an error in Table 1. We have removed the vertical diffusivity quoted in the table (P5 Table 1). In correcting this we noted that two of the other quantities (isopycnal tracer diffusivity and the steep slope horizontal diffusivity) in the table did not reflect the values used in the simulations presented. We have corrected these also.

The background vertical diffusion is stability dependent following Gargett (1984), as we described in paragraph on P5 L1-8.

Page 5, section 3: it is worth repeating that the pre-industrial atmospheric concentrations of CO₂ were used.

This is now done in the revised manuscript (P5 L14).

Page 5, line 16: should there be the minus sign? The ocean warms initially but cools towards the end of the control run. Actually most of models simulate higher than observed ocean temperatures even under pre-industrial forcing (e.g. Griffies et al. 2011, doi:10.1175/2011JCLI3964.1; Lucarini and Ragone 2011).

We meant to say $\pm 0.2 \text{ W m}^{-2}$. From around 600 years onwards the long-time mean is slightly negative, but here we intended to say that the even on short timescales the surface heat flux imbalance in a control simulation remains within $\pm 0.2 \text{ W m}^{-2}$. This is now corrected (P5 L20).

Page 5, line 17: is the salinity trend caused by the use of the linear free surface ($W_{\text{surf}} * \text{SSS}$)?

This is a good suggestion. However, it is not the case. Taking into account the linear free surface the volume average salinity is of the order $1e-5$ PSU higher after 2000 years. There is a small positive trend in the linear free surface, such that after 2000 years the global mean sea surface is $2.4e-7$ m higher.

Page 6 line 8: the drop in AMOC happens abruptly. Do you have any idea of what has happened?

We believe the sudden drop is linked to the establishment of a fresh surface signature across the GIN and Irminger Seas (Figure 7f). The abrupt drop in AMOC has been a ‘feature’ of FORTE simulations, and it continues with FORTE2.0. As you note later, the common “cold bias” around Newfoundland is actually a warm anomaly in FORTE, and this extends into the Labrador Sea. This limits the dense water formation in FORTE2.0 to the Irminger and GIN seas. Hence the fresh anomaly that develops over these regions has a pronounced effect on the AMOC strength. We have added some text to explain this in the revised manuscript (P9 L 11-13).

Page 8 line 5: Is there a link between low ACC and GM (or is it because of winds)?

There is a link between GM and ACC strength. Kuhlbrodt et al (2012) examine coupled models submitted to IPCC AR4, and show that there is greater sensitivity of the ACC strength to the value of k (GM thickness diffusion) than there is to the zonal wind stress. Our simulations use a value of $k = 2000$. Looking at Fig. 1b of Kuhlbrodt et al (2012) FORTE2.0 has a stronger ACC than other models that use $k = 2000$. It is closer in strength to the models using values of $k = 700-1000$.

We have expanded the text discussing the ACC to include discussion of the link between GM and ACC strength (P9 L17-20).

T. Kuhlbrodt, R.S. Smith, Z. Wang, J.M. Gregory “The influence of eddy parameterizations on the transport of the Antarctic Circumpolar Current in coupled climate models” *Ocean Modelling* 52-53 (2012) 1–8

Page 8 line 9: I wonder why only 25 years? Do you expect any change in results if a longer period is considered?

Analysis of the climate state, either from models or observations is typically done for periods of a few decades. The choice of 25 years was arbitrary, and we would not expect any substantial change if a different duration or period was chosen.

Page 10: A pre-industrial run is compared with the present day climatology. Bias seems to be not the proper word then. Maybe it is also worth mentioning that the Levitus climatology is being used as a metric only.

I see your point about the use of the word ‘bias’ in this case. We have instead used the word ‘anomaly’ (P13 L10). Whilst addressing this point, we realized that ‘Levitus climatology’ should actually read ‘EN3 climatology’, as this is what is presented in Figure 7 (new Figure 8). We have rectified this.

Page 11, line 13: the commonly observed “cold bias” around Newfoundland is replaced by a warm anomaly instead. Something very different from most of the climate models is happening there. Same in SSH (page 13, line 5). Is it because of the winds? Does FORTE depict any MLD in the Labrador Sea or it is fully shifted towards high latitudes? Which role you expect GM to play in improving the NA SPG?

The extent of the subpolar gyre in this simulation is confined very much to the west. Correspondingly you can see the 10C and 14C contours in Fig. 7a extend further northwest than in EN3. The winds may play a factor in the structure seen here. FORTE2.0 does show some deep MLD in the Labrador Sea. We have monthly output for the final 25 years of the simulation, and have now added a figure of MLD for both the L35 and L20 configurations to the manuscript. In the period of monthly output we have, the L20 configuration shows stronger convection in the Labrador Sea and more generally across the high latitude N. Atlantic, whilst the L35 configuration depicts less extreme MLD that also occur further north into the Labrador Sea. As you alluded to earlier, a spatial/geometric scaling of GM would enable the user to choose GM that is more appropriate at both high and low latitudes, rather than seeking a compromise. This could improve the representation of the N. Atlantic subpolar gyre. Numerous studies, e.g. Decau and Myers (2005), Beismann and Redler (2003), have investigated the role of GM on N. Atlantic circulation and found positive results.

Decau, D. and Myers, P.G. “Effect of a Variable Eddy Transfer Coefficient in an Eddy-Permitting Model of the Subpolar North Atlantic Ocean”, *Journal of Physical Oceanography* (2005) 35 (3): 289-307.

Beismann, J-O. and Redler, R. “Model simulations of CFC uptake in the North Atlantic Deep Water: Effects of parameterizations and grid resolution”, *Journal of Geophysical Research*, Vol. 108, C5, 3159

Page 13, line 17: Was the OHT computed through the meridional velocities or the atmospheric heat flux?

It was computed through the meridional velocities.

Section5: were the EOFs computed for global fields or only for shown areas?

We followed the method of Hurrell (1995) for the AO and NAO analysis. We now state in the revised text over which regions we compute our EOFs (P21 L2, P21 L11-12 and P22 L2).

Page 17, line 19 (Summary): naming is incorrect: control simulation is only 25 years long and 2000 years simulation is attributed to as spin up throughout the text.

Thank you, this is now corrected (P22 L7).

FORTE 2.0: a fast, parallel and flexible coupled climate model

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Abstract.

FORTE 2.0 is an intermediate resolution coupled Ocean Atmosphere General Circulation Model (AOGCM) consisting of IGCM4, a T42 spectral atmosphere with 35 σ layers, coupled to MOMA, a $2^\circ \times 2^\circ$ ocean with 15 z layer depth levels. [Sea-ice is represented by a simple flux barrier. Both the atmosphere and ocean components are coded in FORTRAN.](#) It is capable of producing a stable climate for long integrations without the need for flux adjustments. One flexibility afforded by the IGCM4 atmosphere is the ability to configure the atmosphere with either 35 σ layers (troposphere and stratosphere) or 20 σ layers (troposphere only). This enables experimental designs for exploring the roles of the troposphere and stratosphere, and the faster integration of the 20 σ layer configuration enables longer duration studies on modest hardware. A description of FORTE 2.0 is given, followed by analysis of a 2000 year long control integration.

10 1 Introduction

Numerical models of the coupled (ocean-atmosphere) climate system are important tools for studying the Earth's climate. They provide insight into phenomena which are difficult to observe directly, such as the Atlantic Meridional Overturning Circulation (AMOC) or the effects of increasing atmospheric CO₂. They can also be used to test hypotheses about the global climate and the world we live in. In a climate model it is possible to study the climate response to extreme events such as loss of ice cover (and the resulting change in albedo). Whilst the results in terms of quantitative changes to temperature, precipitation, and other climate variables should be treated with caution, it is possible to examine the processes which lead to the predicted changes.

There is a broad spectrum of coupled climate models. At one end of the spectrum are coarse resolution simplified models designed to run millennial scale experiments quickly and for minimal computational cost, both in terms of computing power and memory resources (e. g. GENIE (Marsh et al., 2007), CLIMBER (Montoya et al., 2005), UVic (Weaver, 2004), [ECBilt \(Haarsma et al., 1996\)](#)). At the opposite end of the spectrum, high resolution (<0.1°- 0.5° ocean) models (e.g. those contributing to the CMIP6 HighResMIP (Haarsma et al., 2016) such as HadGEM3-GC3.1 (Roberts et al., 2019), and HiGEM (Shaffrey et al., 2009)). Between the two extremes are the intermediate resolution models (e.g. [ECBilt \(Haarsma et al., 1996\)](#), HadCM3 (Gordon et al., 2000), FAMOUS (Smith et al., 2008)), including most of the coupled climate models contributing to CMIP3

(Meehl et al., 2007), CMIP5 (Taylor et al., 2012) and CMIP6 (Eyring et al., 2016). It is worth noting that model development does not equate solely to increase in horizontal resolution. Inclusion of more, or better parameterised, Earth System processes can be equally if not more important developments (e.g. Sellar et al., 2019).

5 Sinha and Smith (2002) developed FORTE (Fast Ocean Rapid Troposphere Experiment), a fast and flexible coupled climate model, for the purposes of climate studies. FORTE's speed and flexibility meant that the original model was an ideal educational and research tool. ~~A The flexibility of FORTE is evident in the variety of experiments that used FORTE in which it has been used to study ocean and/or climate phenomena have been published (Buchan et al., 2014; Hunt et al., 2013; Sinha et al., 2012; Wilson et al., 2009) although there is no comprehensive, peer-reviewed publication describing the model itself. Examples include: Buchan et al. (2014), in which observed SST anomalies from 2009-10 were applied to the model SST field prior to the coupling time step, enabling~~
10 ~~the authors to examine the effect of observed SST anomalies in an otherwise free-running coupled model; Sinha et al. (2012), in which the simplicity of FORTE made it easy to examine the effect of orography on the Atlantic meridional overturning circulation; Wilson et al. (2009) used the flexibility to examine the roles of orography and ocean dynamics on atmospheric storm tracks, performing experiments with either an interactive ocean or the static mixed layer option in the IGCM atmosphere; Blaker et al. (2006) added initial condition perturbations to the Southern Ocean to study fast ocean teleconnection processes~~
15 ~~and Atkinson et al. (2009) performed similar experiments using both ocean-only and coupled configurations. Although most studies used FORTE with a T42 resolution atmosphere and 2° ocean, a version of FORTE using a T21 resolution atmosphere and 4° ocean has also been used for idealised experiments (e.g. Smith et al., 2004, 2006), featuring Pangean and aquaplanet configurations (e.g. Smith et al., 2004, 2006). Simulations of FORTE have also been analysed in other climate studies (Hunt et al., 2013; Gr~~
~~. However, until now there has been no comprehensive, peer-reviewed publication describing the model itself.~~

20 A new version of the atmosphere component of FORTE was released in 2015, and a desire to perform coupled experiments once again resulted in a refresh of FORTE. To avoid confusion with earlier endeavours, but at the same time make clear the ancestry of the model we decided to refer to the refreshed model as FORTE 2.0. This paper describes the coupled model and its components and demonstrates that FORTE 2.0 produces a realistic and stable climate without the need for flux adjustments. The control integration described is a 2000 year long integration starting from rest with the Levitus (temperature, salinity)
25 climatology (Levitus and Boyer, 1998; Levitus et al., 1998) and pre-industrial atmospheric concentrations of CO₂. The model is forced solely by incoming solar radiation at the top of the atmosphere. The rest of this paper is organised as follows: Section 2 gives a description of FORTE 2.0; Section 3 presents the model spin-up; Section 4 presents the control climate; Section 5 discusses the main modes of climate variability in the model; Section 6 concludes.

2 Model Description

30 FORTE 2.0 is a global coupled ocean-atmosphere general circulation model consisting of a 2° resolution configuration of the MOMA (Modular Ocean Model - Array) (Webb, 1996) ocean model coupled to a T42 (approximately 2.8°) configuration of the IGCM4 (Intermediate General Circulation Model 4) (Joshi et al., 2015) atmosphere model. FORTE 2.0 is an updated

incarnation of FORTE (Fast Ocean Rapid Troposphere Experiment) (Sinha and Smith, 2002; Smith et al., 2004), with the most significant change being an update of the atmosphere from IGCM3 (Forster et al., 2000) to IGCM4 (Joshi et al., 2015).

The ocean and atmosphere components of FORTE 2.0 are coupled once per model day using OASIS version 2.3 (Terray et al., 1999) and PVM version 3.4.6 (Parallel Virtual Machine, see <http://www.csm.ornl.gov/pvm/>, Geist et al. (1994)). Integration is relatively fast (~100 model years per wallclock day on a 28 core 2.4GHz Intel Broadwell CPU) and the model can be run on a desktop computer, making it ideal for experiments where more complex higher resolution models are resource limited. The retention of the full primitive equations for fluid flow in both atmosphere and ocean allows more realistic simulations than possible with Earth Models of Intermediate Complexity (EMICs). In addition, FORTE 2.0 is readily configurable, allowing experiments with [realistic and](#) idealized configurations of coastlines, orography, and ocean bottom topography.

10 2.1 The atmosphere component

The atmosphere component of FORTE 2.0 is IGCM4 (Joshi et al., 2015), run with a T42 spectral resolution. A longitudinally regular ~~grid is used for advection and diabatic processes, with a grid spacing of 2.8°, and a Gaussian grid in latitude, with an irregular and Gaussian in latitude grid with a~~ grid spacing of ~~approximately 2.8°~~ [is used for advection and diabatic processes](#). The resolution is sufficient to enable stable climate integrations without the need for flux adjustments. There are two pre-configured choices for the number of vertical levels: a troposphere only atmosphere represented by 20 σ levels (L20) which extends to around 25 km altitude, or a 35 σ level configuration (L35) which includes the stratosphere and extends to around 65 km altitude. [To avoid issues with \$2\Delta z\$ oscillations under certain conditions the NIKOSRAD radiation scheme in IGCM3 \(used previously in FORTE\) was replaced with a modified version of the Morcrette radiation scheme \(Zhong and Haigh, 1995\). For further details of the IGCM4 and its performance we refer the reader to Joshi et al. \(2015\) and references therein.](#) The model is run with 96 (L35) or 72 (L20) time steps per day. Orography is derived from the US Naval 1/6th degree resolution dataset. IGCM4 is MPI parallelised, and at this resolution integration on 16-32 cores achieves the best performance.

Atmospheric convection is dealt with via a Betts-Miller scheme (Betts and Miller, 1993). Low, medium and high layer cloud and convective clouds amount are represented, based on a critical relative humidity criterion (see the Appendix of Forster et al. (2000)). The formula which determines low-level cloud amount has an additional factor of 50% compared to that used by Forster et al. (2000) to correct a cold bias within the tropical ocean which led to unrealistic circulation in the Pacific. In addition to variation with solar zenith angle (and hence latitude), sea surface albedo is increased away from polar regions to compensate for the absence of aerosols which would otherwise scatter incoming solar radiation. Land grid boxes are assigned a vegetation index, one of 24 pre-defined vegetation types, which determine the albedo and roughness length.

Coupling to the dynamic ocean model requires some changes to the surface boundary layer. In order to conserve water it is necessary to account for soil moisture and implement river runoff. Soil moisture for each land grid box is represented as a bucket, or reservoir, 0.5 m in depth. Excess water, i.e. when the volume of water is greater than the volume of the bucket, is accumulated and added to the ocean as runoff at each coupling timestep. The land surface is divided into catchment basins and the accumulated runoff is distributed between a list of ocean cells that represent river mouths. Runoff accumulated over Antarctica is distributed uniformly over the ocean south of 55°S, as a simplistic representation of iceberg calving and melting.

Additionally, land snow cover is capped at a maximum thickness of 4 m. Excess snow over Antarctica and the Arctic region is treated separately as an additional runoff term that represents iceberg melting and calving. As with the soil moisture, runoff from excess snow over Antarctica is distributed uniformly over the ocean south of 55°S. Excess snow melt over the Arctic is handled similarly, with a uniform distribution over the ocean north of 66°N.

5 To improve the representation of the effects of sea surface roughness on momentum exchange a wind-dependent drag coefficient, C_d , is implemented, such that $C_d = C_d^0 + 5.6e^{-5} * \text{windspeed}$ (Wu, 1980). This gives a maximum $C_d = 0.003$ at windspeed of 40 m s^{-1} without ice cover. C_d^0 is the drag coefficient over ocean cells, calculated using a globally uniform value for surface roughness over open ocean.

At present FORTE 2.0 does not include dynamic sea-ice representation. Instead, sea ice is represented by a barrier to heat
10 fluxes between the ocean and atmosphere component, which is imposed when the sea surface temperature reaches 271 K, and surface albedo is increased to 0.6 to represent ice cover. The albedo continues to linearly increase, reaching 0.8 at 261 K as a means to represent the albedo effects of snow on ice. Once the albedo reaches 0.8 it will not reduce until the ~~ice has~~
meltedtemperature rises above freezing point and the flux barrier deactivates. There is no advection of sea ice, and salinity and runoff fluxes remain unaffected. Sea-surface temperature (SST) under ice is relaxed toward the freezing point of seawater
15 (-1.8° C) on a 10-day timescale.

2.2 The ocean component

The ocean component of FORTE 2.0 is MOMA (Modular Ocean Model - Array, Webb (1996)), a version of the GFDL MOM (Modular Ocean Model) (Pacanowski et al., 1990) coded to work more efficiently on array processors, which solves the primitive equations discretized using finite differences on an Arakawa B grid (Arakawa, 1966). It has a linear free surface
20 (Killworth et al., 1991) and uses ‘full cell’ ocean bathymetry. In the configuration used for this integration the ocean horizontal resolution is $2^\circ \times 2^\circ$, with 15 z -layer levels, increasing in thickness with depth from 30 m at the surface to 800 m at the bottom. A polar island, comprising the top row of grid cells (88-90°N), is required in the Arctic to prevent numerical instability due to convergence of lines of longitude. There are 64 baroclinic time steps per day (22.5 minute time steps) implemented using the modified split QUICK (MSQ) advection scheme (Webb et al., 1998). MOMA is parallelised using OpenMP and running on
25 4-6 cores is typically sufficient to match the IGC4 performance.

Bathymetry is derived from the ETOPO5 (1988) $1/12^\circ$ resolution dataset, and interpolated onto the model resolution. Due to the horizontal resolution, in order to encourage dense water formation and flow between the Nordic Seas and North Atlantic, bathymetry is manually excavated in a manner ~~similar~~-similar to HadCM3 (Gordon et al., 2000). The Bering, Gibraltar and Kattegat/Skagerrak Straits are represented by a single grid box which, due to the Arakawa B grid, means that there is no
30 advection through them, but diffusion of potential temperature (T) and salinity (S) does occur.

Ocean isopycnal mixing is represented in MOMA through the isoneutral mixing scheme of Griffies et al. (1998). The eddy-stirring process of Gent and McWilliams (1990) is introduced as a skew flux (Griffies, 1998). Where isopycnal slopes become large, exponential tapering scales isoneutral diffusivities to zero as the slope increases (Danabasoglu and McWilliams, 1995). The isopycnal mixing parameters used for the control simulation described in section 3 are shown in Table 1.

Parameter	Value (m ² s ⁻¹)
Horizontal viscosity	4.0 x 10 ³
Isopycnal tracer diffusivity	3.0 <u>2.5</u> x 10 ³
Isopycnal thickness diffusivity	2.0 x 10 ³
Steep slope horizontal diffusivity	2.0 <u>1.5</u> x 10 ³
Vertical diffusion coefficient	5.0 x 10⁻⁵
Vertical viscosity coefficient	1.0 x 10 ⁻³
Bottom drag coefficient	0.001
Max. slope of isopycnals	0.002

Table 1. Mixing parameters in MOMA.

To ameliorate some of the shortcomings identified in earlier FORTE simulations some additional changes have been made to MOMA. Firstly, the background vertical diffusion, κ , is set to be stability dependent (Gargett, 1984), albeit with the surface to sea floor potential temperature gradient as a simple proxy for stability, such that

$$\kappa_s = (0.3 + 1.7e^{-(0.15[\max(T_s, T_b) - T_b])^2}) \times 10^{-4} \text{ m}^2\text{s}^{-1},$$

$$\kappa = \kappa_s + (2 \times 10^{-4} - \kappa_s)z/H \text{ m}^2\text{s}^{-1},$$

where T_s is the surface potential temperature, T_b is the bottom potential temperature, z is depth and H is the local total depth of the ocean. Thus the vertical diffusivity takes a maximum value of $2 \times 10^{-4} \text{ m}^2\text{s}^{-1}$ at the sea floor and at high latitudes, with lower values, approaching $3 \times 10^{-5} \text{ m}^2\text{s}^{-1}$ in the upper ocean at low latitudes.

Secondly, starting from 5° N/S the horizontal diffusion in the surface layer increases towards the Equator from its default value to 20 times this value at the Equator, to counteract equatorial upwelling and, in a simple way, parameterise the eddy heat convergence associated with tropical instability waves which was highlighted by Shaffrey et al. (2009).

3 Spinup of the control integration

~~The control integration of FORTE 2.0 starts from rest using~~ To evaluate the performance of FORTE2.0 we run a pair of control integrations with pre-industrial CO₂ concentration using both the 35 σ layer atmosphere configuration and with and 20 σ layer atmosphere configurations. In each simulation FORTE 2.0 starts from rest with identical initial ocean temperature and salinity fields from Levitus and Boyer (1998) and Levitus et al. (1998) interpolated onto the ocean model grid. Figure 1 shows area and volume integrated quantities of the surface heat and fresh water fluxes, and ocean temperature and salinity from each of the two integrations. The surface heat flux into the ocean is initially positive (up to 1.5 W m⁻²) but the imbalance reduces to less than 0.5 W m⁻² after a few decades and then stabilises and remains within ~~0.1-0.2~~ ± 0.2 W m⁻² throughout the remainder of the integration (Fig. 1 a)). The time average water budget closes to within -0.2 mm/year, after an initial adjustment in the first year of the integration (Fig. 1 b)). The global average sea surface temperature (SST) settles within 100 years to a value

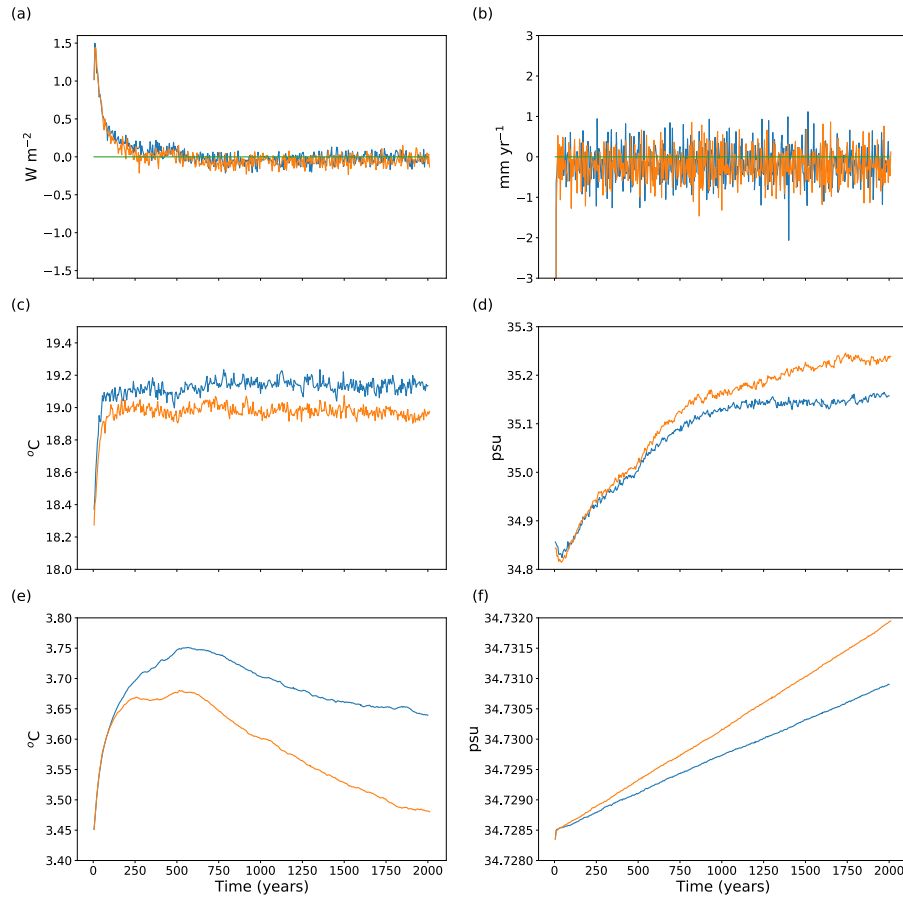


Figure 1. Time series of global mean a) surface heat flux (W m^{-2}) and b) surface water flux (mm/year) into the ocean, c) SST ($^{\circ}\text{C}$) and d) SSS, and volume averaged e) potential temperature and f) salinity. Cyan and orange lines show the quantities for the simulations run with the L35 and L20 configurations, respectively.

values around 19.1°C , whilst sea for the L35 configuration and 19.0°C for the L20 configuration (Fig. 1 c) . Sea surface salinity (SSS) in both configurations adjusts more slowly, with L35 maintaining a value of around 35.15 PSU after 1000 years of integration (Figs and L20 approaching 35.23 PSU towards the end of the 2000 year simulation (Fig. 1 e) and d)). The mean SST is 0.9°C warmer than the initial state provided by Levitus 1998 (18.2°C). The volume average ocean potential temperature warms by 0.3°C for L35 and 0.2°C for L20 over the first 500 years, and then cools more steadily, at a rate of approximately $0.005^{\circ}\text{C/century}$ for L35. After 2000 years the volume average temperature in the L20 configurations is close to the initial value. Salinity shows a gradual trend of $0.000125 \text{ PSU/century}$ after an initial adjustment) in L35, which is a reflection of the small imbalance in the fresh water fluxes. The trend in the L20 configuration is around 30% stronger.

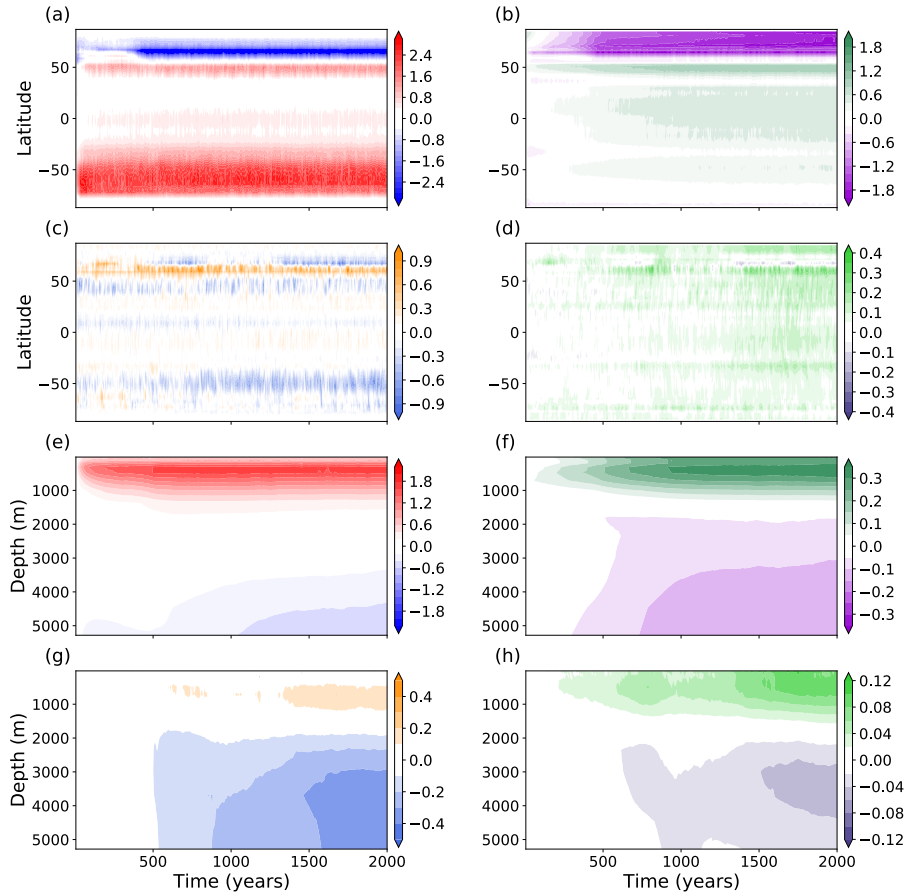


Figure 2. Time-latitude plots of drift in annual mean sea surface (a) temperature ($^{\circ}\text{C}$), and (b) salinity (PSU) in the L35 simulation. Differences (L20-L35) in annual mean sea surface (c) temperature ($^{\circ}\text{C}$), and time-depth (d) salinity (PSU). Time-depth series of global drift in annual mean (e) potential temperature ($^{\circ}\text{C}$) and (f) salinity (PSU). Differences (L20-L35) in annual mean (g) potential temperature ($^{\circ}\text{C}$) and (h) salinity (PSU). Drift is relative to initial conditions.

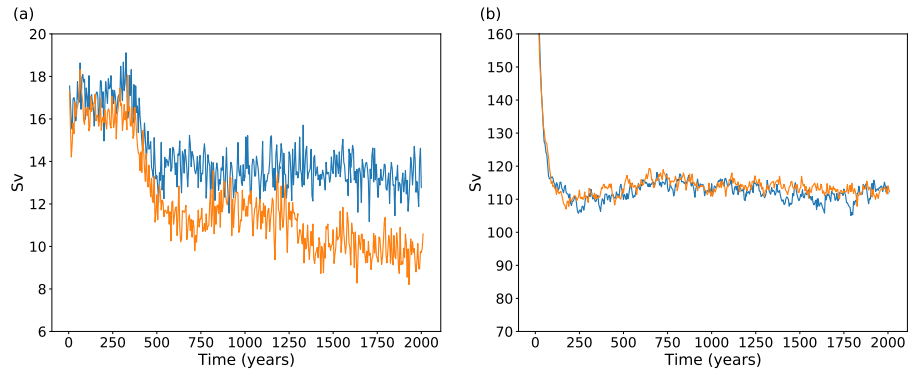


Figure 3. Time series of a) the 5-year mean Atlantic MOC, and b) Drake Passage transport in the control [integration](#)[integrations](#). [Cyan](#) (orange) lines show transports for the L35 (L20) configuration.

Global averaged time series of temperature and salinity as functions of latitude and depth are presented in Fig. 2. The time-latitude plots show an initial strong warming of the Southern Ocean that is not density compensated by an increase in salinity at the same latitudes. The onset of this warming occurs quickly and then remains stable for the remainder of the 2000-year integration. A minimal bias develops in the tropical and equatorial regions. In the northern hemisphere higher latitudes there is a strong cooling, that (partly) coincides with a freshening. [The differences in time-latitude evolution of the SST and SSS for the L20 configuration are shown in Figs. 2 c and d. High latitude SST is slightly cooler in L20 compared with L35, except for a narrow band around 55-65°N where a warming of a few tenths of a degree occurs. Surface salinity is marginally higher and to a large extent latitudinally uniform in L20. The difference in SSS is slightly more pronounced at the same latitude range as the narrow band of warming seen in the SSS.](#) Analysis of the spatial SST and SSS biases presented later in this paper shows that these anomalies are located in the Nordic Seas. This pattern develops over the first 500 years of the simulation, and then remains stable for the rest of the integration. The SST bias is within the range of that found in the CMIP5 ensemble (Flato et al., 2013).

The time-depth series of potential temperature (Fig. 2 ee) compares reasonably with those of other, higher resolution, models such as HadCM3, HadGEM1 and CHIME (Fig. 7 in Johns et al. (2006), Fig. 3 in Megann et al. (2010)). FORTE 2.0 warms above 1500 m, with the maximum difference from observed values reaching +1.6°C between 400 and 500 m depth. At depths below 4000 m the ocean cools initially, with differences from observations at 5000 m reaching -0.2°C. Differences in salinity from observations, again shown as a global averaged time-depth series, are small (Fig. 2 df). Differences of +0.3 PSU occur between 300 m and 600 m, whilst below 1500 m they are negative and reach a maximum of -0.15 PSU in the abyssal ocean. [Differences between L20 and L35 are shown in Figs. 2 g and h. L20 exhibits a stronger cooling trend in the deep ocean, such that below 2000 m it is around 0.3° cooler than L35 after 2000 years. The dipole structure that develops in the time-depth plot of salinity \(Fig. 2 f\) is more pronounced, with the biases at 500 m and 3500 m both 25 % stronger in L20 than in L35.](#)

The time series of the maximum AMOC at 30°N is presented in Fig. 3. During the first 300 years of integration a relatively stable 16-18 Sv is maintained, after which there is a reduction of around 3 in both the L35 and L20 configurations. After 300 years both configurations undergo a reduction, with the AMOC in L35 reducing by ~4 Sv to 13-15 Sv. These values—The AMOC in L20 reduces initially by ~4 Sv and then again around 1250 years into the integration, settling at a value around 10-11 Sv. The weaker AMOC in L20 is consistent with the cooling and freshening trends seen at depth, since a weaker AMOC allows a greater influence of Antarctic Bottom Water (AABW) in the abyssal ocean. The AMOC values in both simulations are maintained for the remainder of the 2000 year integration. These values—integrations and are within the range of those from the CMIP5 ensemble (Heuzé et al., 2015). The standard deviation of the AMOC based on monthly mean values is 3.5 Sv, which is in reasonable agreement with the magnitude of observed variability (McCarthy et al., 2012). Other than the adjustment in the first 500 years, there is little evidence of emergent decadal or multidecadal variability over the course of the L35 control integration, the peak-to-peak range over the last 1500 years of the integration being 3-4 Sv. The initial strong AMOC followed by a reduction after a few centuries is a common feature of FORTE integrations, and appears to be linked to a developing fresh bias over the GIN Seas (shown later).

Transport through Drake Passage weakens rapidly from an initial value of > 160 Sv and from year 200 it settles around 110-115 Sv. This is lower than the recent observation-based estimate of 173 Sv (Donohue et al., 2016) or previous estimates values of around 130-140 Sv (e.g. Cunningham et al., 2003), but within the range seen in other coupled climate models (Russell et al., 2006). (Beadling et al., 2020). Kuhlbrodt et al. (2012) show that the strength of the ACC correlates with the choice of GM thickness diffusion, with lower values of κ yielding stronger ACC transports. Both the L35 and L20 simulations use a value of $\kappa = 2000$. FORTE2.0 has a stronger ACC than other models that use $\kappa = 2000$ (see Fig 1b of Kuhlbrodt et al., 2012). It is closer in strength to other models using values of $\kappa = 700 - 1000$.

4 The control climate

After the 2000 year spinup, the frequency of output was increased to monthly and a 25 year long integration was performed. In this section the control climate during this 25 year period is presented.

4.1 The Atmosphere

Annual time mean surface air temperatures (SATs) in the tropics are 25°C, with some regions over land reaching 30-35°C. The Arctic reaches -20°C, with temperatures over Greenland reaching as low as -40°C and the interior of Antarctica reaches as low as -60°C (Fig. ??-a).

Contours of annual average mean sea level pressure anomalies, displayed 4 a). Anomalies of annual mean SAT from the early years (1871-1896) of the twentieth century reanalysis (20CR Compo et al., 2011) are presented in Fig. 6-a), show the expected bands of high pressure over the subtropical oceans (e. g. the Azores and North Pacific Highs) and over the polar regions and low pressure cells at mid-latitudes (e. g. Icelandic and Aleutian Lows) and over the Equatorial regions.

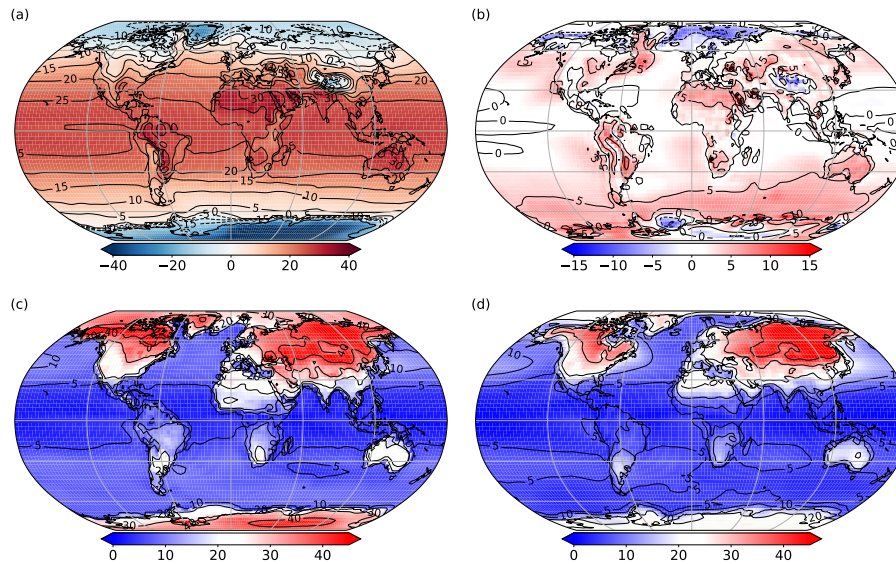


Figure 4. Time mean (years 2001-2025) plots [from the L35 configuration](#) of: surface air temperature ($^{\circ}\text{C}$) for a) annual mean, [b\) January anomaly from 20CR years 1871-1896](#), [c\) July](#), [g\) seasonal range](#) ; [in FORTE 2.0](#) and [precipitation \(mm/day\)](#) for [b\) annual mean](#), [d\) January](#), [f\) July](#), and [h\) seasonal range in 20CR years 1871-1896](#).

4 b. [FORTE 2.0](#) performs well at low latitudes, especially over the ocean. There is a pronounced warm anomaly of around 5°C over most of the Southern Ocean, consistent with the positive SST bias shown in section 4.2. A cold SAT anomaly with respect to 20CR also manifests over the Nordic Seas, extending into the Barents Sea. The L20 simulation exhibits very similar annual mean SATs (not shown). Values for L20 are within 1°C of those shown for the L35, except for two regions over the northern Labrador Sea and the Weddell Sea which are cooler in L20 by several degrees. These differences are likely due to the difference in the response of the flux barrier which represents sea ice. The SAT seasonal range for FORTE 2.0 and 20CR (1871-1896) are presented in Fig. 4 c and d. Seasonal SAT variability over the tropical ocean is low, whilst variations in SAT over land can be $15\text{-}20^{\circ}\text{C}$ (Fig. [?? b\), c\) and d\)](#) are much higher, reaching 40°C over the Eurasian continent. The seasonal range of FORTE 2.0 compares reasonably well with 20CR throughout most of the low and mid-latitudes. However, the seasonal ranges in SAT at high latitudes (both Arctic and Antarctic) are much larger than those in 20CR. Arctic and Antarctic seasonal SAT variability is $40\text{-}45^{\circ}\text{C}$, with the coldest regions of Antarctica reaching as low as -85°C during July. [Contours of sea level pressure show the intensification of the surface winds over the midlatitudes in both southern and northern hemispheres during the winter season. We note that the Siberian high is not very intense for mean January conditions and this appears to have the effect of allowing the Icelandic Low to expand and displace eastwards over Scandinavia, resulting in a displacement of the winter NAO pattern compared with observations \(see section 5\).](#)

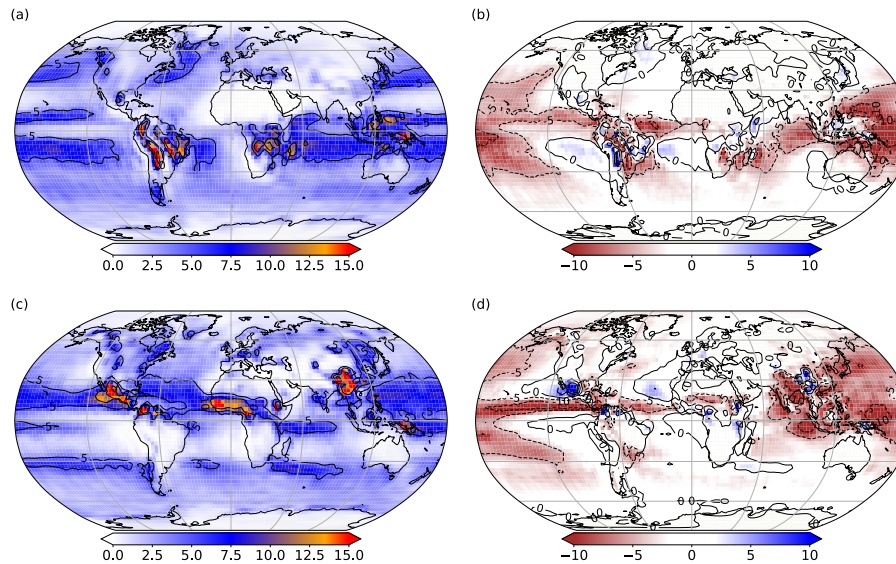


Figure 5. Time mean (years 2001-2025) plots from the L35 configuration of: sea-level-pressure-anomaly-precipitation (mbmm day^{-1}) for a) annual-mean DJF, b) January DJF anomaly from 20CR years 1871-1896, c) seasonal range JJA, and d) July JJA anomaly from 20CR years 1871-1896.

The pattern of annual mean precipitation Fig. 5 shows winter (DJF) and summer (JJA) mean precipitation and anomalies with respect to the 20CR 1871-1896 climatological mean. During DJF (Fig. ?? e)) shows reasonable agreement with observations (Adler et al., 2003), namely the 5 a), regions of high precipitation over the regions of the northern hemisphere oceanic western boundary currents (up to 6 mm/day and extending to northwestern Canada and north west Europe as in the observations) along the Gulf Stream and western boundary current track in the north west Atlantic are evident, as well as high values (10-12 mm/day) over tropical Africa and South America, Indonesia and over the Inter Tropical Convergence Zones in the Atlantic and Pacific Oceans. Very low values (0-1 mm/day) are seen over the polar regions, the subtropical desert regions (terrestrial and oceanic) and (unrealistically) over the equatorial Pacific. During summer (JJA) the ITCZ and the corresponding high levels of rainfall shift northward (Fig. 5 c). There is enhanced rainfall due to the Asian summer monsoon, though in FORTE 2.0 it does not extend sufficiently far east. The anomalies with respect to the 20CR 1871-1896 climatological DJF mean (Fig. 5 b) show that, particularly over the tropical Pacific, FORTE 2.0 simulates too little rainfall. This is most pronounced over the western tropical Pacific during DJF and also over the northern extent of the ITCZ in the eastern Pacific during JJA (Fig. 5 d). A major difference with the observed distribution is the South Pacific ITCZ, which is narrow and predominantly zonal in the model solution, whereas based on observations we would expect observations show a broader north-west to south-east oriented region. Figures ?? f), g) and h) show that the seasonal maxima in the ITCZ regions are frequently in excess of 15 mm/day. Conversely, the model predicts too little precipitation in the summer months in both hemispheres.

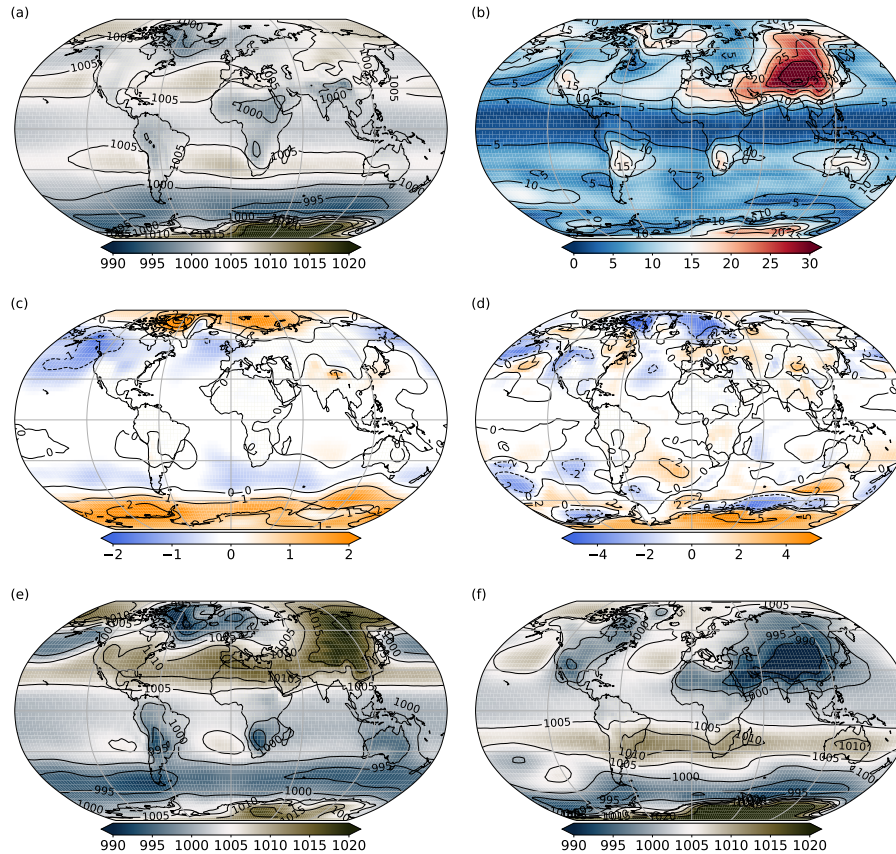


Figure 6. Time mean (years 2001-2025) plots of: sea level pressure (mb) for a) annual mean, b) seasonal range, c) difference in slp L20-L35, d) difference in seasonal range (L20-L35), plus values for the months e) January, f) July from the L35 simulation.

Contours of annual average mean sea level pressure, displayed in Fig. 6 a, show the expected bands of high pressure over the subtropical oceans (e.g. the Azores and North Pacific Highs) and over the polar regions and low pressure cells at mid latitudes (e.g. Icelandic and Aleutian Lows) and over the Equatorial regions. The seasonal range is largest over land (Fig. 6 b), particularly highlighting the seasonal variability over Siberia. Differences in the annual mean slp anomalies and seasonal range (L20-L35) are predominantly poleward of 60°N and S, (Figs. 6 c and d). The seasonal range is smaller in L20 over the Labrador and GIN Seas and over the high latitude Southern Ocean. Contours of sea level pressure show the intensification of the surface winds over the midlatitudes in both southern and northern hemispheres during the winter season (Figs. 6 e and f). We note that the Siberian high is not very intense for mean January conditions and this appears to have the effect of allowing the Icelandic Low to expand and displace eastwards over Scandinavia, resulting in a displacement of the winter NAO pattern compared with observations (see section 5).

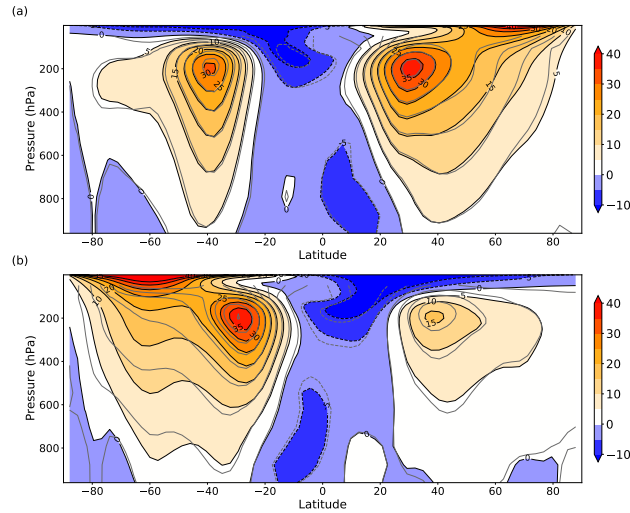


Figure 7. Time and zonal mean zonal wind velocities (m s^{-1}), for a) Winter (DJF) mean, and b) Summer (JJA) mean. The shading and black contours show the velocities for the L35 simulation, whilst the grey contours show the equivalent contours for the L20 simulation.

Time mean zonal wind for both summer and winter is shown in Fig. 7 as a function of latitude and pressure. The model exhibits northern and southern hemisphere jet streams at around 40°S and 40°N at 200 hPa. The southern jet stream exhibits a lower seasonal range ($28\text{--}36 \text{ m s}^{-1}$) than the northern jet stream ($12\text{--}36 \text{ m s}^{-1}$). Surface westerlies and easterlies are of order $\pm 0\text{--}4 \text{ m s}^{-1}$ in the annual mean. The most notable differences between the L20 and L35 configurations occur during JJA, with weaker winds at 60°S . The mid-latitude cores are also slightly stronger during JJA in L20. At 80°S the zero contour extends down to the surface, indicating a change in the mean wind direction from weak westerlies to weak easterlies.

4.2 The Ocean

Annual mean SST (Fig. 8 a) shows maximum temperatures in the Indian and tropical Pacific and Atlantic Oceans reach 26°C . Compared with the Levitus climatology (EN3 climatology (Ingleby and Huddleston (2007), Fig. 8 c) there is a cool bias-anomaly of around 1°C throughout the tropics (Fig. 8 e). Regions immediately west of the major land masses (coincident with regions of coastal upwelling) show warm SST errors of $2\text{--}3^{\circ}\text{C}$ magnitude, probably arising from a known issue in many coupled climate models related to the poor representation of marine stratocumulus cloud (Gordon et al., 2000). There is a substantial warm bias throughout the Southern Ocean and extending into the southern parts of the Pacific and Indian oceans, likely due to a combination of deficiencies in the physical representations of the ocean dynamics and cloud physics (Hyder et al., 2018). The Nordic Seas are several degrees cooler and up to 1.5 psu fresher (Fig. 8 f) than EN3, possibly due in part to the crude representation of sea ice, and in part due to the inadequate representation of ocean circulation in the Arctic and Nordic Seas in a 2° resolution ocean model. There is a positive salinity bias of around 3 psu further east in the Arctic, north

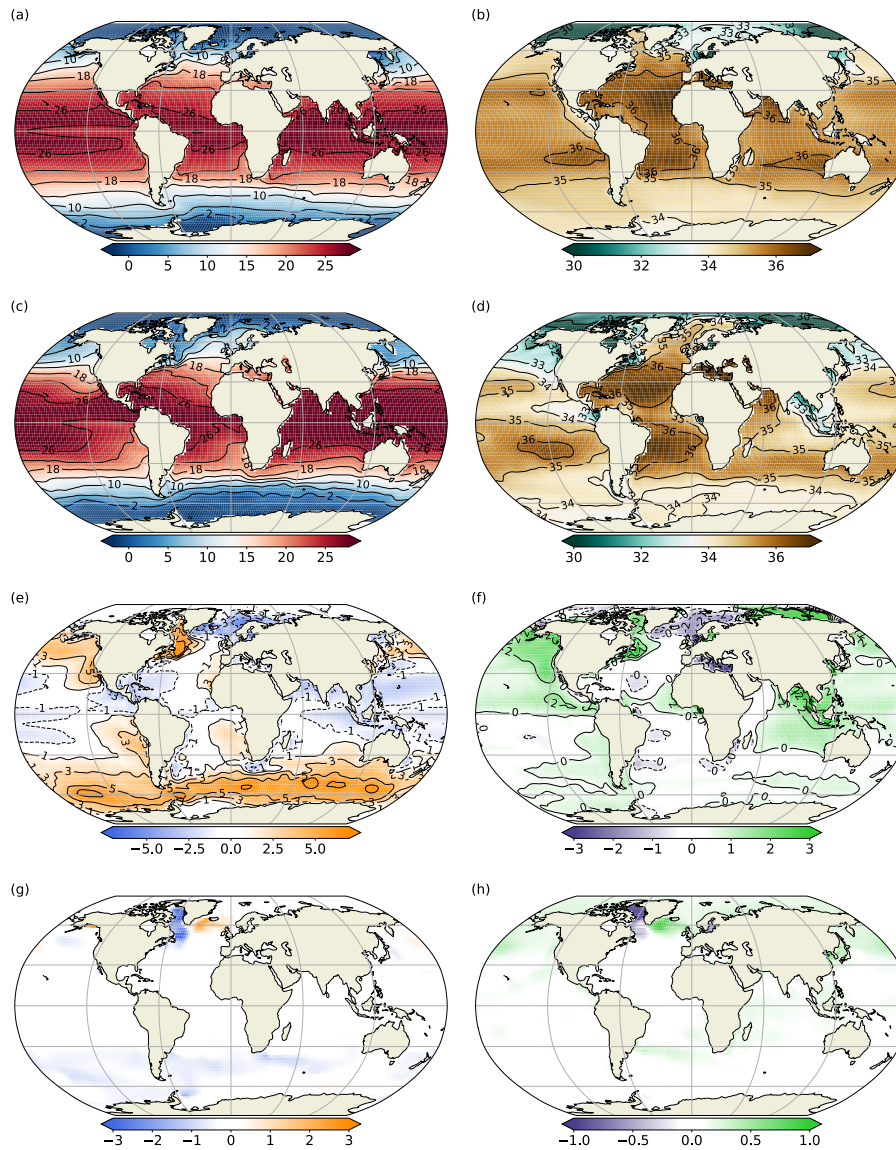


Figure 8. Time mean (years 2001-2025) of SST (left) and SSS (right) for FORTE 2.0 L35 (top a and b), and for EN3 (middle c and d). Panels e and f show FORTE 2.0 - EN3 L35 - EN3 SST and SSS anomalies, respectively, whilst panels g and h show SST and SSS anomalies for L20-L35.

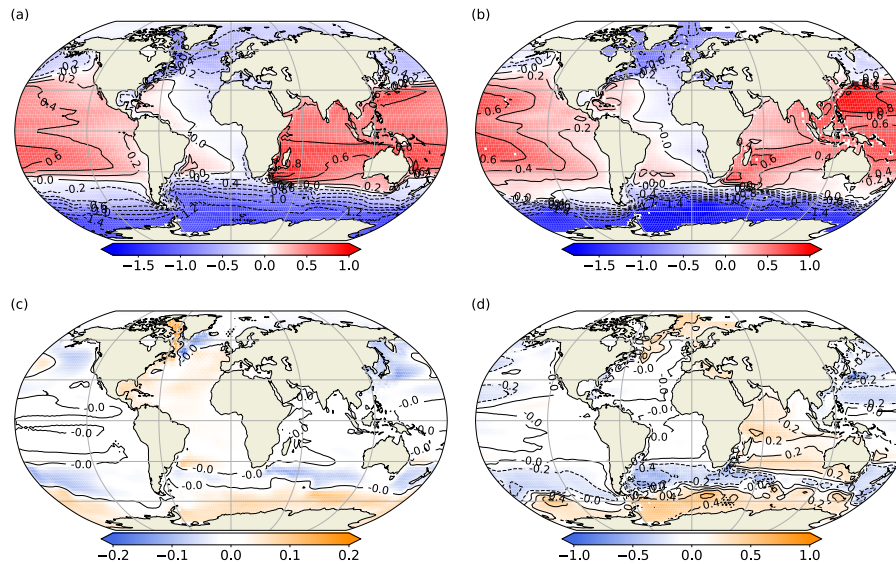


Figure 9. Time mean (years 2001-2025) of SSH (m) for a) FORTE 2.0 L35 and b) OCCA (2004-2006) climatology. Differences in SSH for c) L20-L35 and d) L35-OCCA.

of Siberia. Although large, the size of the salinity bias in the Arctic is not uncommon, even for models that do not require a polar island to prevent issues arising from the convergence of the grid at the north pole (Megann et al., 2010). Annual mean SSS is well represented throughout the southern hemisphere ocean, where errors are mainly confined to within +/- 0.5 psu (Fig. 8 f). Positive biases of order 1-1.5 psu occur in the Bay of Bengal and around the maritime continent and the northeast Pacific. The Labrador Sea and the region extending along the US coastline as far south as Cape Hatteras shows positive salinity biases between 0.5 and 2 psu, the latter coincident with a positive temperature bias that exceeds 5°C in a small region is indicative of the Gulf Stream separating too far north, bringing tropical waters too far north and west. Worth noting, though, is that the L20 simulation exhibits smaller biases in both SST and SSS in the Labrador and Irminger Seas (Fig. 8 g and h). There is also a slight improvement in the Southern Ocean warm bias in L20 compared with L35. Some of the model biases will arise from the relatively coarse horizontal and vertical resolution and missing physical processes. However, as indicated by the differences between the L20 and L35 simulations, it is likely that a substantial reduction of biases would be achieved with the application of a rigorous calibration methodology such as History Matching (Williamson et al., 2014).

Sea surface height provides insight into the wind driven ocean circulation (Fig.—9). The SSH from L35 and the OCCA climatology are shown in Figs. 9 a and b, respectively. Gyre circulation in all the major ocean basins is highlighted by the contours, along with regions of intensified flow, such as the Gulf Stream, the Kuroshio, and along the northern boundary of the ACC. However, the coarse resolution of the ocean model results in flows that are too broad and diffuse, weakening the SSH gradient across these intensified flows. The North Atlantic subpolar gyre appears constrained to the west of the basin. **The**

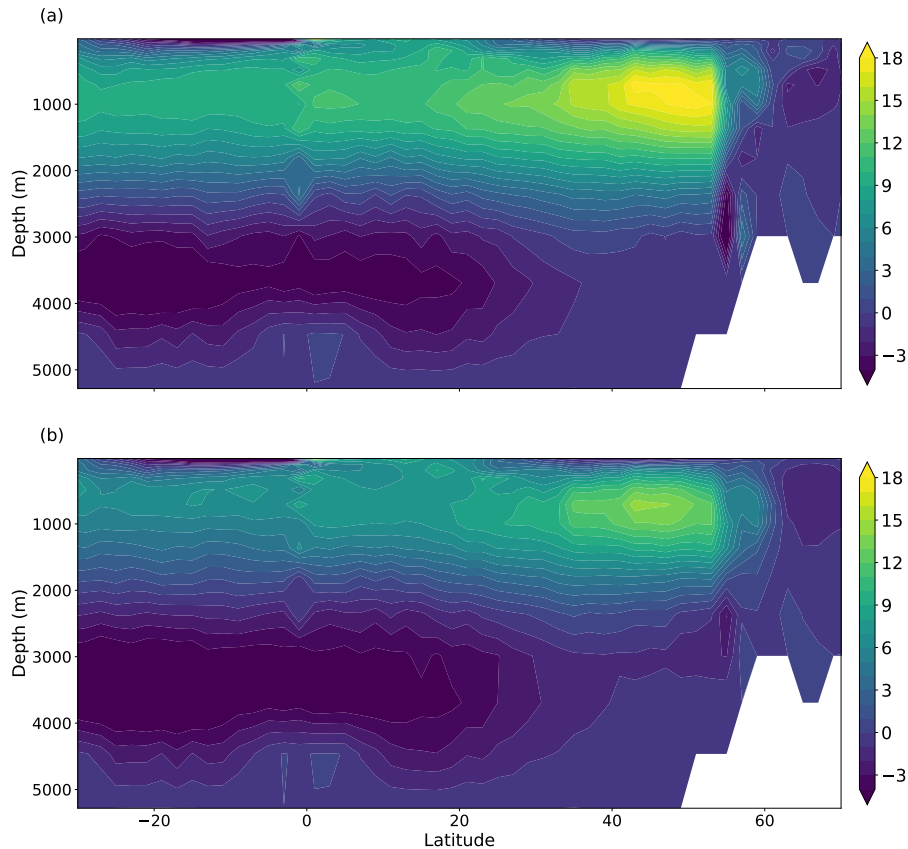


Figure 10. AMOC (Sv) as a function of latitude and depth, averaged over the control years 1900-2025 of a) the L35 integration, and b) the L20 integration.

slumping of the Slumping of the SSH gradient across the ACC is evident in the anomaly of L35 with respect to OCCA (Fig. 9 d), and corresponds to the weak ACC transport shown earlier (Fig. 3). The slope in SSH is also weaker in the N. Atlantic and extending into the Nordic Seas. Comparison with L20 (Fig. 9 c) shows a slight steepening of the gradient across the ACC in L20, a small reduction in the bias compared with the OCCA climatology.

- 5 A latitude depth plot of the AMOC shows a maximum around 50°N and at 1000 m depth (Fig. 10). Deep convection occurs in Closely packed streamlines at the high northern latitudes, and southward transport extends to around 3 indicate that much of the deep convection occurs abruptly in a narrow latitude band and southward North Atlantic Deep Water transport reaches around 2.5 km depth. The abrupt sinking at the high northern latitudes is characteristic of coarse resolution ocean models where flow into the Nordic Seas is poorly represented. Winter mixed layer depths in the southern Labrador Sea reach 2500 m in a few
- 10 grid cells, whilst winter mixed layer depths south of the Denmark Strait, Iceland and the Faroe Bank Channel can reach 1000 m (Fig. 11). Wintertime convection is too shallow in the Nordic Seas, with mixed layer depths reaching 125-150 m in the central

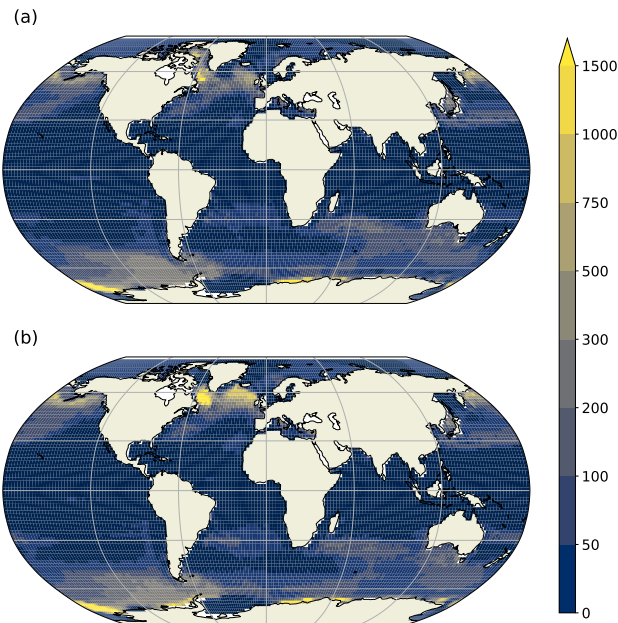


Figure 11. Meridional heat transport (PW) as a function of latitude for a) the Global-ocean L35 integration, Atlantic and Indo-Pacific, averaged over b) the control L20 integration. A 3-grid point smoother has been applied. The northern (southern) hemisphere shows mixed layer depths for the month of March (September). The mixed layer depth is defined as the depth at which a density difference from the top layer of 0.03 kg m^{-3} occurs.

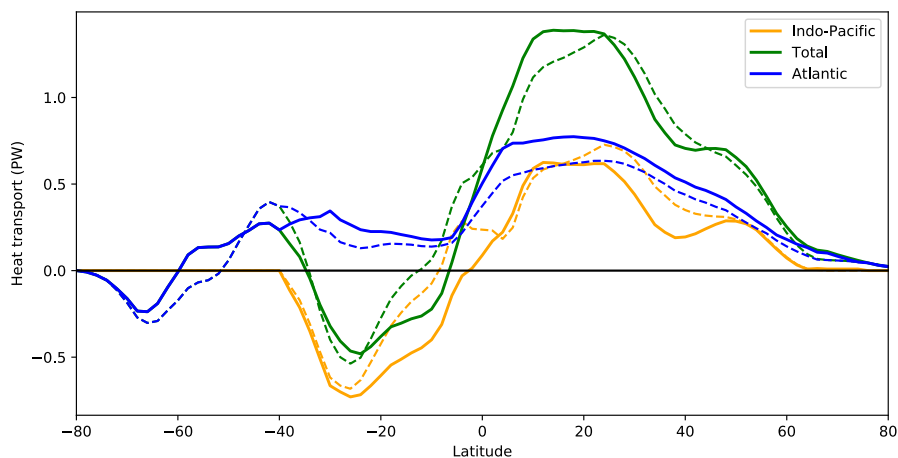


Figure 12. Meridional heat transport (PW) as a function of latitude for the Global ocean, Atlantic and Indo-Pacific, averaged over the control integration. A 5-grid point smoother has been applied. Solid (dashed) lines show the meridional heat transport for the L35 (L20) simulations.

and eastern Nordic Seas. The AMOC transport through 30°S is 10 Sv in L35 and 6 Sv in L20, and is stronger (~14 Sv in L35), ~10 Sv (L20) at 30°N. There is a strong Antarctic Bottom Water Cell (AABW cell) (~6 Sv) centered at about 3500 m depth, which weakens to about 2 Sv at 30°N. Sinking at the high northern latitudes occurs abruptly in a narrow latitude band, not uncharacteristic of coarse-resolution ocean models where flow into the Nordic Seas is poorly represented. As mentioned earlier,

5 the AABW cell in L20 is slightly stronger, and in Fig. 10 is shown to extend further north. There is evidence of two grid point noise at the Equator, which has been identified previously in Bryan-Cox models (Weaver and Sarachik, 1990). The structure of the AMOC is similar in both the L35 and L20 simulations, with the L20 configuration consistently around 30% weaker.

Ocean meridional heat transport (OHT) in FORTE 2.0 is around 60% that expected based on observational estimates, but consistent with the weaker than observed volume transport (Fig. 12). Atlantic OHT at 26°N is 0.74 PW in L35 and 0.63 PW
10 in L20, whilst observationally derived estimates suggest the current value is closer to 1.3 PW (Johns et al., 2011). Globally, the OHT reaches 1.4 PW, instead of the 2.1 ± 0.3 PW computed by Trenberth and Caron (2001). Over the Southern Ocean (35-65°S) OHT is northward, a characteristic seen previously in MOM-based ocean models (de Freitas Assad et al., 2009). This may be related to the strong warm SST bias present over region 40-60°S (Fig. 8) and its consequent effect on surface heat fluxes.

15 **5 Modes of variability**

A primary aim for any climate model is to adequately reproduce observed modes of climate variability sufficiently well that the model can be used to study the observed phenomena in a variety of contexts. In this section we present analysis of some of the most important modes using monthly mean ocean output for the years 1600-1950 of the control simulation and daily surface pressure output during years 1600-1699 of the control integration.

20 Composites of the SST anomaly during El Niño and La Niña years show the spatial pattern of the anomalies throughout the tropics (Fig. 13 a, b). Both phases of ENSO are weaker than observed, in particular nearer the eastern boundary. The composite temperature anomaly reaches a maximum of 1°C for the region 160°W-100°W, 5°S-5°N, whilst the characteristic region of observed strong SST anomalies near to the coast of central and southern America only reaches 0.7°C and is not strongly connected to the warm anomaly in the central Pacific. This is probably related to the fact that the South Pacific
25 Convergence Zone is too zonal and extends all the way across the Pacific, which is a common feature in coupled climate models (Niznik et al., 2015). The time series of temperature anomalies in the Niño 3.4 region shows a number of strong temperature anomaly events, although the magnitude is in general too small (Fig. 13 c, d). ~~The tails~~ We plot the distribution of SST anomalies for the Niño 3.4 region for both model configurations and for HadISST data for the period 1870-2019 (Rayner et al., 2003; Trenberth, 2020). The distribution of the histogram is too narrow compared with observations (Fig 13
30 d), and there is very little difference between the distributions for the L20 and L35 simulations. In both model configurations the extreme values extend to around $\pm 2^\circ\text{C}$ (Fig 13 d)), whilst ~~a similar plot of observations between 1950 and 1997 suggests observations suggest~~ the extremes should be closer to $\pm 2.5^\circ$ (Fig. 2 from Trenberth (1997)). C.

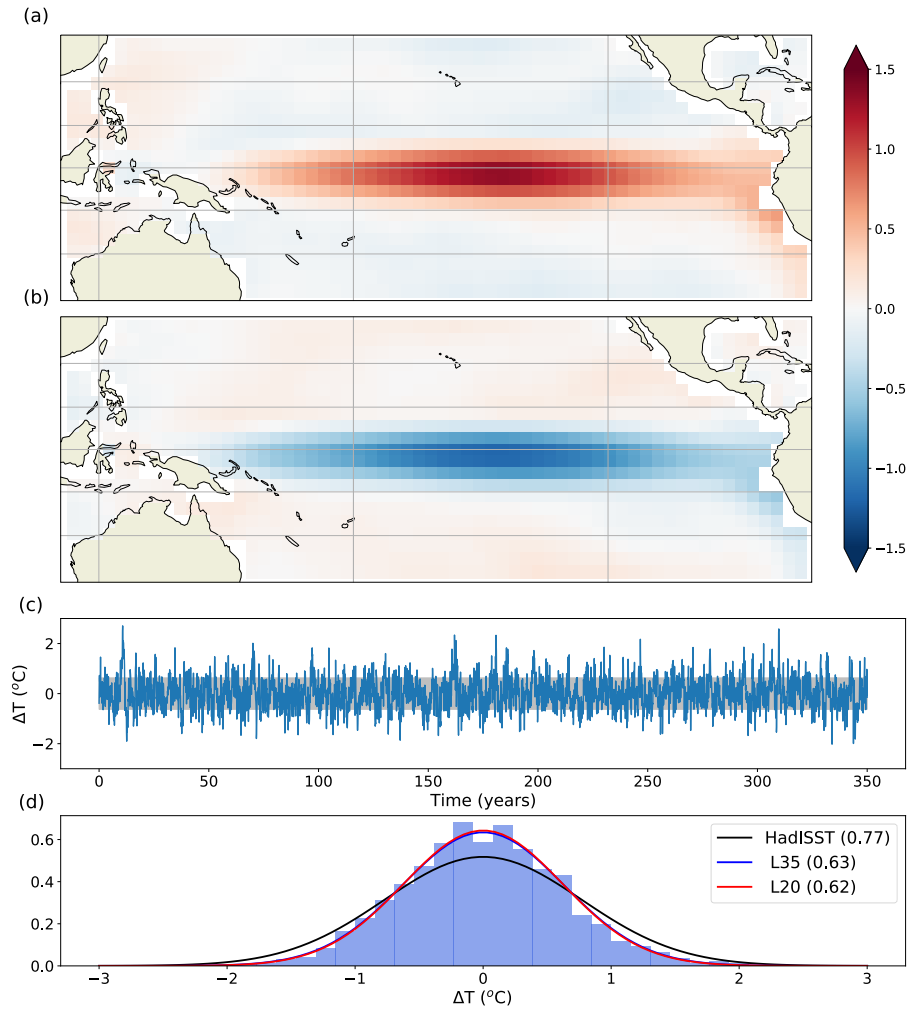


Figure 13. Composite anomaly of a) El Niño events, and b) La Niña events [from the L35 simulation](#). ENSO events are defined as those which exceed ± 1 standard deviation anomaly within the Niño 3.4 region. [c\)](#) SST anomaly time series [for years 1601-1950 \(c\)](#); and [histogram d\)](#) [Histogram](#) of SST anomaly distribution relative to the mean [\(d\)](#) for years 1601-1950 from the [region-L35 simulation](#). The Gaussian curves in d are fits to the distribution of Niño 3.4 SST anomalies for HadISST (black, [Trenberth \(2020\)](#)), L35 (blue), and L20 (red). The blue and red lines are very close and the red line mostly overlies the blue line. Standard deviations are given in brackets.

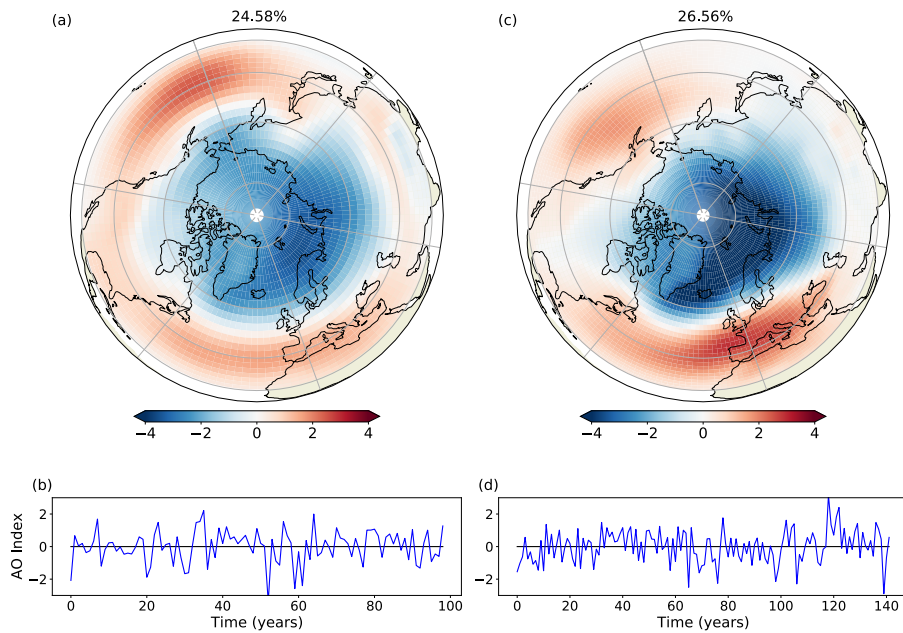


Figure 14. The AO as represented by the first EOF and PC computed using deseasoned and latitude weighted sea level pressure for FORTE 2.0 (a,b), and 20th Century Reanalysis (c, d)

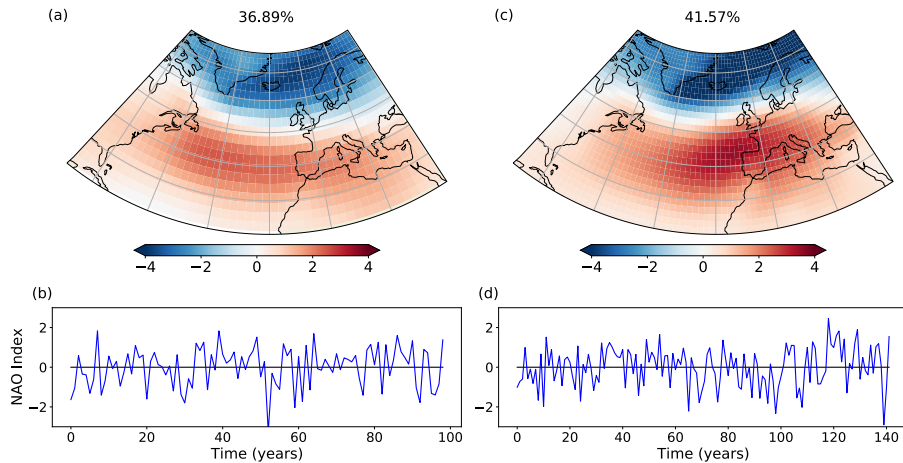


Figure 15. The NAO as represented by the first EOF and PC computed using deseasoned and latitude weighted sea level pressure for FORTE 2.0 (a, b), and 20th Century Reanalysis (c, d)

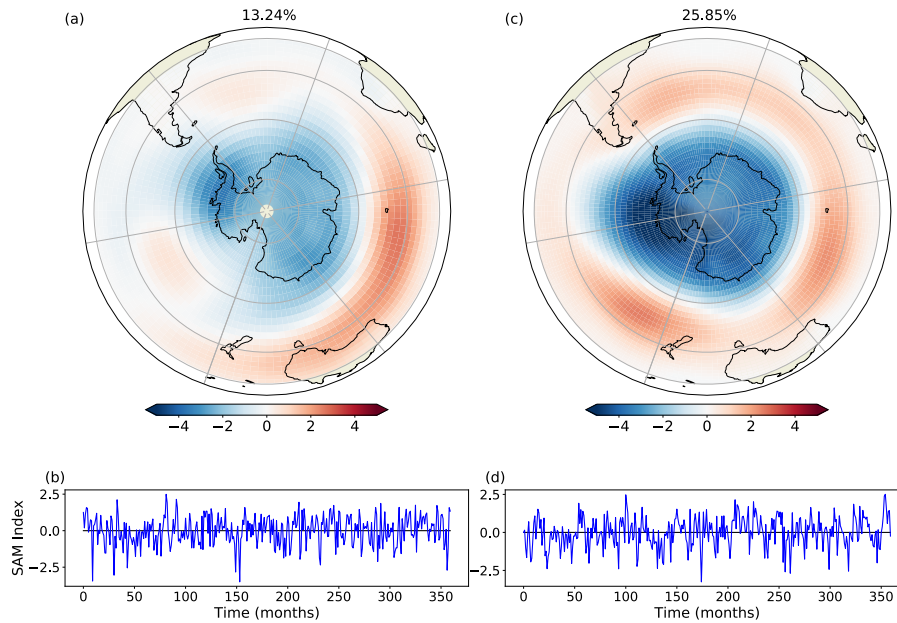


Figure 16. The SAM as represented by the first EOF and PC computed using deseasoned and latitude weighted sea level pressure for FORTE 2.0 (a, b), and 20th Century Reanalysis (c, d)

We also examine the main extratropical modes of variability predicted by FORTE 2.0 in the northern hemisphere. We compare 20°-90°N area weighted empirical orthogonal function (EOF) analysis of the deseasoned and latitude weighted sea level pressure fields from FORTE 2.0 and, for comparison, the 20th Century Reanalysis (Compo et al., 2011). FORTE 2.0 produces an annular mode structure as the main mode of variability, corresponding to the Arctic Oscillation in observed data. In agreement with observations (e.g. Thompson and Wallace, 2000; Ambaum et al., 2001), the model reproduces the two mid latitude centres of action over the North Pacific and North Atlantic, with the Pacific centre stronger and the Atlantic centre slightly weaker than those seen in the 20th Century Reanalysis and the locations of their maxima displaced westward towards the western half of each ocean basin (Fig. 14). The strength of the Arctic pole in FORTE is also weaker than observations. ~~Comparison of the corresponding principal component time-series (Fig. 14) suggests the presence of some higher frequency variability in observations that is not captured by FORTE 2.0.~~ The North Atlantic Oscillation (NAO) is closely related to the AO and is one of the principal modes of atmospheric variability in the North Atlantic sector (Hurrell, 1995). We compute area weighted EOFs for the NAO over the region 20°-80°N, 90°W-40°E. The first EOF and its accompanying principal component are presented in Fig. 15. In the North Atlantic there is a good approximation to the NAO pattern, but in FORTE 2.0 the centre of the southern lobe is displaced westward and the northern lobe extends further south over mainland Europe compared with the observed pattern. Again, the principal component suggests more high-frequency variability in observations than FORTE 2.0.

Similar to the northern hemisphere, the Southern Annular Mode, or Antarctic Oscillation represents the principal mode of climate variability in the southern hemisphere. [Here we compute area weighted EOFs over the region 20°-90°S.](#) FORTE performs less well in the southern hemisphere (Fig. 16), with the annular structure significantly weaker over the Pacific and Atlantic sectors. The variance explained by the first EOF is also greatly reduced in FORTE, approximately half that seen in the 20th Century Reanalysis, and is likely to be linked with the anomalously warm Southern Ocean SST.

6 Summary

We present an assessment of ~~a two~~ 2000 year ~~control simulation~~ [simulations](#) of the FORTE 2.0 coupled climate model, [one using the 35 \$\sigma\$ layer atmosphere including a stratosphere \(L35\), and one using the 20 \$\sigma\$ layer atmosphere without a stratosphere \(L20\).](#) The model integrates from rest and is sufficiently fast to enable studies of multi-centennial climate variability. The model is economic to run, and can be adapted and configured to study a wide range of climate questions.

The ~~simulation presented here is~~ [simulations presented here are](#) not optimally tuned for any specific purpose, but our assessment indicates that FORTE 2.0 is able to simulate a satisfactory climate state and climate variability. Biases that develop in the mean state are comparable to those found in other coupled climate models (Flato et al., 2013) and particularly those of similar complexity and resolution. A small imbalance in the fresh water budget (see Fig. 2) would need to be addressed for studies extending over timescales much longer than several millennia. Modes of climate variability in the northern hemisphere are represented well, though there are shortcomings in the southern hemisphere variability that are likely related to a strong SST bias over the Southern Ocean. Identifying the cause(s) of such biases is often a complex process in itself (Hyder et al., 2018), and beyond the scope of this current work. A further step would be to rigorously calibrate the model to improve the simulated climate and to better understand the limitations and behaviour of the modelled climate system.

7 Code availability

The code, compilation instructions and example run scripts, together with all necessary ancillary files are accessible at: <http://doi.org/10.5281/zenodo.3632569>. The configuration committed to the Zenodo archive is the one used to produce the simulation presented in this paper. Processing of the IGCM4 output requires the program BGFLUX, a copy of which is accessible from the FORTE2.0 GitHub repository linked to the Zenodo archive. A comprehensive user guide/manual for FORTE 2.0 does not currently exist. A folder titled Documentation has been added to the FORTE2.0 GitHub repository, and this contains relevant references and copies of technical documents from the original FORTE and component models.

8 Data availability

The code and data required to reproduce the figures presented in this paper are provided in a supplementary file.

Author contributions. ATB, MJ and BS developed the coupled model configuration from versions used in earlier studies. The original coupling of FORTE was performed by BS and RSS. All authors were involved in finalising the configuration presented here. MJ undertook all model simulations. ATB wrote the paper, analysed the output and prepared all tables and figures. All authors edited the paper text.

Competing interests. The authors declare that they have no competing interests.

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