The impact of resolving the Rossby radius at mid-latitudes in the ocean: results from a high-resolution version of the Met Office GC2 coupled model by H. T. Hewitt et al.

Review by Stephen Griffies

We thank Dr. Griffies for his constructive comments and address them here.

This is generally a well written and concise entree into a suite of coupled climate models run for 20 years. To my knowledge the finest resolution model, GC2.1-N512O12, is the state-of-the-science, at least for global models run for more than a few years. This point is worth emphasizing.

- A sentence has been included (p3, line1) to emphasise that with the resolution of atmosphere and ocean components and hourly coupling, this model is state of the art.

The tasks required are immense to produce a sensible simulation, even for the rather brief 20 years considered here. I applaud this effort, though note it is far from complete!

Yet as an introduction to the model suite, this is a useful contribution to the literature, and it provides an important peer-reviewed touchpoint for the developers. This manuscript is appropriate for GMD. I recommend publication after minor revisions.

Others who have developed models of this resolution with refined coupling periods (hourly or smaller) sometimes have problems related to coupled ocean/sea ice instabilities as discussed by Hallberg (CLIVAR Exchanges, No.65 (Vol 19 No.2) July 2014). It would serve the reader to know if you encountered any similar instabilities, and if so, what methods were used to suppress them. If you did not encounter such instabilities, it would be useful to state that as well.

- We did not experience instabilities associated with the hourly coupling. This is stated (p4, lines 24-25)

The Weddell Sea polynya in GC2.1-N512O12 warrants more discussion. In similar models at GFDL, we have seen that such polynyas can increase ACC transport, much as noted on page 10, lines 10-22. Do any of the other models in your suite have a polynya? Is the polynya large in area and going very deep? How long does it last? I am puzzled that the SST biases in

Figures 2 and 3 show no sign of the polynya. In other models I have seen, such polynyas increase SST due to release of mid-depth heat. That SST signature is missing here. Perhaps the polynya is only for a year or two, and is averaged out by the 10 year mean? Please discuss, as this is an important feature to expose.

- Further investigation shows that the polynya first appears in year 12 and varies from year-to-year. In years without a polynya, the maximum mixed layer depth is less than 1000m. However, in year 15, the maximum mixed layer depth is 1556 m and in year 20 it is 2070m. More information about the polynya and its variability is given on p8, line 7, p10, lines 6-10 and in the new figure 9.

Pg1, line18: I appreciate that it is the surface ocean that the atmosphere cares about, and the sentence is referring to air-sea fluxes. But the sentence can be construed, incorrectly, to mean that ONLY surface eddies and boundary currents are necessary to do air-sea coupling right. As the authors show in this paper, there is more to air-sea fluxes than the surface ocean. For example, overflows and the AMOC are key. So I recommend finding a different way to write this sentence.

- Sentence has been changed in abstract (p1, line 17-18)

Pg1,line23: Admittedly a picky point, but worth being precise: hours are listed here as "frequency" for coupling (1-hour versus 3-hour). In fact, these are the "coupling periods" not the "coupling frequencies".

- P1, line 23 frequency changed to period (also p4, line 14 and in table 1)

Pg3,line5: Behrens et al. (2013) should be Behrens (2013). This citation refers to a single-authored PhD thesis.

- P3, line 8 reference corrected

Pg4,line9: again, "3-hourly to hourly" refers to "coupling period" not "coupling frequency

- P4, line 14 corrected to period

Pg4,line11: it is not clear what model is being referred to here when discussing the time step. I assume the ocean, but it should be clearly stated.

- P4, line 16 ocean inserted

Pg4,line27: Viscosity is a positive number. The biharmonic operator carries the negative sign. Please change. Doing so will also make the sentence correct. Namely, it presently reads "a reduction in the bilaplacian viscosity from -5e11 to -0.25e10". With the minus sign, this is

not a reduction, but an increase! Again, just drop the minus signs on the viscosity so that all will make sense.

- P5, line 4 viscosity sign corrected

Pg5,line5: Including tides generally increases the flow speed in simulations. So what you mean here is that there is missing "tidal dissipation" in the model. That is, you are not suffering from missing tides, but instead suffering from missing tidal dissipation.

- P5, line 15 tides changed to tidal dissipation

Pg5,line6: what is "atmospheric theta"? Please define the jargon.

- P5, line 17 theta changed to temperature.

Pg5,line28: what sort of "instabilities" do you find enhanced with the finer atmosphere? Those instabilities discussed earlier near the UK due to missing tidal dissipation? Something else?

- P6, lines 7- 8 clarification added to the instabilities

Pg8,lines10-11: More heat into the ocean interior is NOT what Griffies et al (2015) found with the GFDL CM2.6 simulation (1/10th degree ocean) relative to the coarser ocean (1/4th degree) in CM2.5. Instead, enhanced mesoscale eddy actitivity led to less heat entering the ocean. So...why does GC2.1-N512O12 get warmer in the interior than GC2-N512? Could it be an increase in spurious diapycnal diffusion from advection errors? It is useful to speculate here, even if you do not perform a budget analysis as in Griffies et al.

- Paragraph has been inserted p8, lines 26-32 to discuss the heat uptake issue and contrast with Griffies et al. (2015)

Pg9, It is useful to state how the mixed layer depth is computed.

- This has been added to a footnote on p9

Pg 10,line6: a more recent Denmark St overflow measurement paper is Jochumsen et al. (2012), 10.1029/2012JC008244

- P11, line 4 Jochumsen reference added

pg10,line18: a more recent Drake Passage transport paper is Meredith et al. (2011) 10.1029/2010RG000348

- P11, line 13 Meredith reference added

*Pg10, equation (1): dS is not defined. I presume it is dS = dx * dz. Please specify.*

- P12, lines 4-6 definition of dS and also dA added

pg10,line31: A_iso is not the "isopycnal diffusion". Instead, it is the "isopycnal diffusivity". Or more properly, it is the "isoneutral diffusivity", which is consistent with terminology used elsewhere in this manuscript.

- P12 line 3 changed to isoneutral diffusivity and on p14, lines 25-26

pg11, line1-3: I puzzled by this discussion. You state that the isoneutral fluxes are smaller than other terms, but then state, parenthetically, that the dianeutral diffusive fluxes are very small when integrated over the full depth. I think there is some confusion here. In particular, the dianeutral diffusive fluxes, which are computed as vertical diffusion in NEMO, should have a zero depth integral since vertical diffusion only redistributes heat within a column. In contrast, the depth integrated isoneutral diffusion fluxes have a nonzero depth integral. Are you arguing that the depth integrated isoneutral diffusive heat fluxes are small?

- P12 line 7 This comment is correct. The wording has changed to isoneutral

pg11, lines23-24: I fail to see how removing a global mean from the right hand side of equation (1) will not be seen by the left hand side of equation (1). Is that what you want? Please detail more of what you mean by "subtracting the global mean imbalance from the surface fluxes before integrating zonally and meridionally." It is vague as stated.

- Removing the global mean surface flux from the rhs of (1) is equivalent to removing the global integral of the temperature drift from the lhs of (1). This means that the imbalance represents the residual local drifts. Text has been added to make this clear (p12, line 31 – p13, line 4)

pg12, line13-ff: Again, I wonder how much of what you are seeing relates to the Weddell Sea polynya

- A caveat has been added on p13, line 31-p14, line 1

pg13,line32: GFDL prediction folks claim that eddying oceans are too expensive for initialization schemes. So they are not pursuing ocean resolution. That contrasts with your motivation at the Met Office. The community would be well served to know more about your initialization strategies with an eddying ocean. It is worth at least a paragraph.

- A short paragraph on initialisation has been included on p15 lines 26- p16, line 2

Figure 1: legend font is tiny; needs to be larger.

- Figure 1: legend size increased

Figures 2,3,4: is the land/sea mask based on the model grid, or based on an observed topography dataset? It looks like observed. I suggest it more useful and honest for a modelling paper to show the land/sea mask based on the model grid.I also dislike white land since there is also a white part of the colour bar for ocean fields. I suggest colouring the land light brown or light gray, in order to clearly distinguish water from land.

- Figures 2,3,4: land has been changed to grey and mask from model grid used

Figure 3: the colour range should be smaller in order to better see the anomalies.

- Figure 3: range reduced to -2 to 2

Figure 5: the HadISST values should be coloured to better distinguish from the many model lines. The present light gray shading does not come through well.

- Figure 5: HadISST values coloured. Legend changed to GC2.1-N512O12

Figure 6: how deep does the MLD penetrate in the saturated regions? This issue goes to the question about how significant is the polynya.

- Figure 6: Maximum MLD in the average is 788m. However, as seen in the extra figure, the polynya only appears in the last 9 years of the simulation and then it is only in the final year that it extends down to below 2000m. Land has been changed to grey and definition of sea ice edge added to caption.

Figure 9: The bottom topography appears nearly the same across the ocean resolutions. Are you sure you are showing the proper bottom? Does the model make use of the partial bottom cells? If so, then the bottom shown here does not appear to reflect the partial cells; this instead figure looks like it is showing full cells. Again, it is preferable to show the what the model is actually using.

Figure 9 (now figure 10): The model does use partial cells and the average topography is changing between ORCA025 and ORCA12

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Review by Andy Hogg

We thank Dr Hogg for his constructive comments and address them here.

This manuscript describes the development of a version of the UKMO GC2 coupled climate model with enhanced resolution in both atmosphere and ocean, as well increased coupling frequency. The development of this model is a significant achievement – and at 1/12 ocean resolution is, to my knowledge the highest resolution coupled model available. In addition, and contrary to many previous coupled models with high ocean resolution, the authors systematically include the effect of enhanced atmospheric resolution.

However, the technical achievements outlined here are not quite matched by the depth of analysis of the model results. In many cases, changes between results from different simulations are causally attributed with only a superficial analysis. I accept that, for GMD readers, the attribution of different physical effects may be of secondary importance to the technical achievement; but if the authors want to imply causality then a more rigorous analysis is required. In a number of cases (details below) the authors could sidestep this issue by rephrasing the text - i.e., by making it clear that they are speculating on the cause rather than attributing, and pointing out where additional experiments will enable them to resolve the uncertainty. If these issues are addressed I would be happy to recommend this paper as a suitable contribution to GMD.

We have made a number of revisions which we hope address the comments.

On p.4 (line 26) it is noted that the transition from ORCA025 to ORCA12 is accompanied by a reduction in the isoneutral diffusivity from 300 to 125 m^2/s. It would help to have a justification of this change - in particular, if eddies are fully resolved, why do we need isoneutral diffusivity at all? If it is needed, then on what basis do we choose 125?

This question is relevant because, for example, the reduction in SST biases is attributed to resolution (p. 6, line 24). However, this result (at least for the Southern Ocean warm bias) might alternatively be be attributed to reduced parameterised upwards eddy heat flux. This effect may be consistent with the analysis on p.11, which shows a reduction in the time-mean southward heat transport at southern latitudes.And, finally, in the discussion there is reference to previous experiments in which changes in isoneutral diffusivity are associated with high-latitude cooling, but the authors argue that this "is believed to be a secondary effect" due to the long timescales associated with that paper. This is one example where the

authors need to pose one of two possible causes (with further experiments to tease out the root cause) or else perform a more in-depth analysis. For this case there are some clear, but simple, tests which could be performed. The isoneutral diffusivity contribution to the southward (or upwards) heat flux could be calculated explicitly. Alternatively, this question could be resolved by one additional GC2.1 simulation with reduced isoneutral diffusivity.

- We agree that the isoneutral diffusivity needs more discussion.
- We include the following text on p5, lines 7-11 'While reducing the isoneutral tracer diffusivity is consistent with the increase in resolution, we note that results may have some sensitivity to its magnitude. Experiments to investigate the impact of this parameter in GC2 were not performed but will be pursued in future work with GC3 (the next version of the coupled model).'
- In the discussion, the following text has been included on p14, lines 28-32 'Given that the results here exhibit some consistency with those of Pradal and Gnanadesikan (2014) in the Southern Ocean, further work is required to quantify the role of isoneutral diffusivity in producing changes in SST on decadal timescales.'

I wasn't entirely convinced by the description of the MOC changes (bottom of p. 9). Firstly, it is argued that changes are dominated by the cell associated with NADW - this may be true, but the other cells are not shown. This manuscript would be much more complete if the full MOC were shown, including the Southern Ocean (which would require transforming the overturning analysis into density space). In addition, the attribution of both NADW formation and Denmark Strait outflow increases to higher resolution seems fraught; the GC2.1 case sees a modest increase in both of these quantities, implying that the higher coupling frequency is partly response for the changes.

- Unfortunately, we did not have 5 day means of the full velocity field saved to allow calculation of the overturning in density space. As many authors have shown, this field is not entirely meaningful unless the eddy component is included. Calculations of the overturning in density space with monthly means suggest that the changes in NADW due to resolution and coupling period are robust but we can't be certain about the AABW cell. The 5 day mean velocity fields was an oversight in setting up the model diagnostics and we will address this issue in future runs with the GC3 model for CMIP6. A comment has been added to the paper on this point (p10, lines 28-30).
- We have however modified the text on p10, lines 21-26 to reflect that the coupling frequency plays a role as well as on p11, line 6 and p14, lines 12-13

On p.10, l. 17, the ACC transport increase at higher resolution is noted as being consistent with both enhanced NADW and the Weddell Sea polynya. It seems unlikely that NADW formation can affect ACC transport in a short 20 year run (see Allison et al.,JMR, 2011) - meaning that it is most likely that the Weddell Sea effect is dominating. Either way, both effects probably need to be supported in the form of a reference to existing literature. On a similar note, it seems likely that the small ACC transport in these simulations may be linked to weak AABW formation because of the Southern Ocean SST bias. This point could be further clarified if the full MOC were shown as suggested above.

- P11, lines 20-23 we have included a reference to Jones et al. (2011) who show that transient responses in the ACC can be seen within 10 years in their idealised experiments.
- References have been added for the NADW and the Weddell Sea links to the ACC (p11, lines 17-18)

The paragraph starting on p. 12, l. 29, is somewhat unconvincing. The case is made that refining both atmosphere and ocean resolution is important to gain the full benefit of resolution improvements. Yet, for almost all the metrics shown here, the N512 case showed only minor differences from GC2 (as noted in the first paragraph in this section). It may be that there are other metrics on which the N512 case performs well, but they are not shown here, so should not be included in the summary of this paper.

- The paragraph p15, lines 11-17 has been changed in response to the comments to state that ocean resolution and coupling frequency is important and states that further work is required to quantify whether a high resolution atmosphere component is required.

p. 4, line 22: I'm not sure I would call this an aspect ratio. Maybe just ratio?

- P4, line 29 aspect deleted

p. 6, line 9: It seems to me that the Southern Ocean SST biases here are largerthan they were for CMIP-5. If true, then this should be explicitly stated, along with a reference to the published bias (it looks as if you're hiding something by stressing the pattern, rather than magnitude, of the bias).

- Comments on the magnitude of SST biases in GC2 have been added on p6 lines 21-25. Basically the SST warmed everywhere in GC2 relative to the CMIP5 model HadGEM2-AO (see figure 1 of Williams et al., 2015) leading to improvements in the Northern hemisphere and degradations in the Southern hemisphere.

Several times through the manuscript the N512O12 simulation is listed as N512-ORCA12 - best to be consistent if possible. (p. 6, l.24; p. 7, l.24; legend of Fig. 5)

- Corrected to GC2.1-N512O12 in text and figures 5, 7, 8, 11, 12

p.10, l.31: isopyncnal -> isopycnal

- Changed isopycnal to isoneutral p12, line 3

p. 11, l.4: There are four instances of "change/s" in the one sentence here, which becomes a little repetitive.

- Text on p12, lines 18-22 changed to improve reading

p. 12, l.17: I'm not convinced that we expect more slumping of ACC isopycnals inthe eddy-resolving simulation - changes in eddy KE are more likely to control the ACC through enhanced vertical momentum transport - but if there is a previously published expectation supporting this statement then I suggest a reference.

- Text has been changed on p13, lines 27- p14, line 1 to reflect the discussion on the ACC

The reference to "seamless" prediction makes little sense to those outside the UKMO community, and I suggest it should be either explained to great depth, or removed.

- P15, line 18 seamless removed

p. 35, l.6: specify "north pole".

- P49. North Pole specified

The impact of resolving the Rossby radius at mid-latitudes in the ocean: results from a high-resolution version of the Met Office GC2 coupled model

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Abstract

There is mounting evidence that resolving mesoscale eddies and western boundary currents ~~in the surface ocean field~~ as well as topographically-controlled flows can play an important role in air-sea interaction associated with vertical and lateral transports of heat and salt. Here we describe the development of the Met Office Global Coupled Model version 2 (GC2) with increased resolution relative to the standard model: the ocean resolution is increased from 1/4° to 1/12° (28km to 9km at the Equator), the atmosphere resolution increased from 60km (N216) to 25km (N512) and the coupling period ~~frequency increas~~reduced from 3-hourly to hourly. The technical developments that were required to build a version of the model at higher resolution are described as well as results from a 20 year simulation. The results demonstrate the key role played by the enhanced resolution of the ocean model: reduced Sea Surface Temperature biases, improved ocean heat transports, deeper and stronger overturning circulation and a stronger Antarctic Circumpolar Current. Our results suggest that the

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improvements seen here require high resolution in both atmosphere and ocean components as well as high frequency coupling. These results add to the body of evidence suggesting that ocean resolution is an important consideration when developing coupled models for weather and climate applications.

1 Introduction

On the scale of the Rossby radius, the ocean is rich with mesoscale eddies (Chelton et al., 2011) and oceanic fronts. There is mounting evidence from satellite observations that mesoscale features in the Sea Surface Temperature (SST) field can drive comparable variations in atmospheric winds and surface fluxes (Chelton and Xie, 2010; Frenger et al., 2015). While at the basin scale, observed correlations between SST and surface winds are negatively correlated, indicating that the atmosphere is driving the ocean, in frontal regions with high mesoscale activity, such as those associated with Western boundary currents, SST and surface winds are positively correlated, implying that the ocean is driving the atmosphere (Bryan et al., 2010). While the primary response to SST takes place in the atmospheric boundary layer (Chelton and Xie, 2010), there is also evidence that divergence of surface winds may give rise to vertical motions which may penetrate high into the troposphere affecting storm tracks and clouds (e.g., Minobe et al., 2008; Sheldon and Czaja, 2014). Of particular note is the intense rain band in the North Atlantic that follows the path of the Gulf Stream/North Atlantic Current.

The recent CMIP5 ocean models have a horizontal resolution of between 1° and 1/4°. However, with a resolution of 28km at the Equator down to 6km in the Canadian archipelago (due to the tripolar grid), even 1/4° remains insufficient to resolve mesoscale eddies which have a typical scale of 50km in the deep ocean at mid-latitudes (Hallberg, 2013). Several climate modelling groups have now built global coupled models with an “eddy resolving” component (e.g., McClean et al., 2011; Bryan et al., 2010; Delworth et al., 2012; Small et al., 2014; Griffies et al., 2015). In this paper, we describe results from coupling the 1/12° ocean model (ORCA12) produced by the Drakkar group (Marzocchi et al., 2015; Deshayes et al., 2013; Treguier et al., 2012) to a 25 km (N512) resolution version of the Met Office Unified Model (MetUM) atmosphere. This is the first version of the HadGEM3/GC series (Hewitt et al., 2011; Williams et al., 2015) to resolve the Rossby radius in the ocean at mid-latitudes (with a resolution of 9km at the Equator down to 2km in the Canadian archipelago) and the

first coupled experiment with the NEMO ORCA12 ocean configuration. The development of a global coupled model with atmosphere and ocean components of this resolution as well as hourly coupling is the current state of the art for global climate modelling.

Evidence from forced ocean simulations demonstrates that resolution enables a more realistic representation of both eddy kinetic energy (Hurlburt et al., 2009; Griffies et al., 2015), narrow boundary currents (e.g., Marzocchi et al., 2015) and representation of complex topography, in particular the sills which connect ocean basins (e.g., improved overflows in the VIKING model at 1/20° resolution; Behrens ~~et al.~~, 2013). In this paper we investigate how ocean resolution drives large-scale changes not only in the ocean but also in the climate system. Changes in the ocean circulation could be important both for present and future climate; for example, in an ocean-only model with a simple domain, Zhang and Vallis (2013) have shown that the changes in mean circulation due to eddy-resolving resolution can affect the net ocean heat uptake under global warming scenarios.

In this paper, the model is described in section 2. Our results (section 3) describe the relative impact of the three changes to the model; ocean resolution, atmosphere resolution and coupling frequency. Finally in section 4 we summarise and discuss the results.

2 Model description

The development of the high resolution coupled climate model is based on the Met Office Global Coupled model version 2 (GC2; Williams et al., 2015). GC2 is comprised of the Met Office Unified Model (MetUM; GA6) atmosphere, the JULES land surface model (Best et al., 2011; GL6), the NEMO ocean model (Madec, 2014; GO5: Megann et al., 2014) and the Los Alamos CICE sea-ice model (Hunke et al., 2010; GSI6: Rae et al., 2015). The standard configuration for GC2 has a 60km resolution atmosphere coupled to 1/4° (28km at the Equator reducing polewards) ocean (N216-ORCA025) with coupling between the components (as described in Hewitt et al., 2011) every three hours. GA6 has 85 vertical levels while GO5 has 75 vertical levels with 1m resolution in the top 10m of the ocean (Megann et al., 2014). Although vertical resolution is not explored here, we include details of the vertical levels in appendix A.

In addition to GC2, this paper describes three modified versions of GC2 with increased atmosphere resolution, increased coupling frequency and increased ocean resolution. The different model experiments are described below and summarised in Table 1.

GC2 has been run with a high 25km (N512) atmosphere resolution and the standard (ORCA025) resolution ocean and we will refer to this as GC2-N512. The scientific differences between N216 and N512 are minimal, as described in Walters et al. (in prep), and are principally associated with the time step (modified from 15min to 10min) and the resolution of the external boundary conditions such as the orography.

To facilitate direct scientific comparison with the 1/12˚ ORCA12 (9km at the Equator reducing polewards) configuration of NEMO, which was developed using NEMO v3.5 rather than 3.4 (Marzocchi et al., 2015), a modified configuration of GC2, referred to here for convenience as GC2.1 was developed. The key scientific and technical changes made to GC2.1 are:

- ~~An increase~~ a reduction in the coupling period ~~frequency~~ from 3-hourly to hourly
- an upgrade to the non-linear free surface scheme rather than the linear free surface
- a small reduction in the ocean timestep from 1350s to 1200s (to accommodate hourly coupling)
- small changes associated with river outflows; outflows prescribed over 15m rather than 10m with an enhanced vertical mixing in the outflow region of $1x10^{-3}m^2s^{-1}$ rather than $2x10^{-3}m^2s^{-1}$
- an upgrade of the sea ice model from CICE4 to CICE5 (Hunke et al., 2015). This upgrade was for technical reasons and the science of the sea ice configuration remains unchanged.

The reduction of the coupling period in GC2.1 did not lead to coupled ocean/sea ice instabilities as described by Hallberg (2014).

To assess the impact of ocean resolution, a traceable GC2.1 configuration with ORCA12 was then built (further technical details and model performance issues are discussed in appendix B). We chose to increase the atmosphere resolution to N512 in order to maintain a similar ~~aspect~~ ratio of atmosphere to ocean grids. We will refer to this configuration as GC2.1-N512O12 (i.e., increased atmosphere and ocean resolution).

The differences between ORCA025 and ORCA12 in GC2.1 are:

- a reduction in the time step from 1200s to 240s
- a reduction in the isoneutral tracer diffusion from 300 m^2s^{-1} to 125 m^2s^{-1}
- a reduction in the bilaplacian viscosity from -1.5x10^{11} m^2s^{-1} to -1.25x10^{10} m^2s^{-1}

We note here that the parameter settings in GC2.1-N512O12 have not been tuned for the coupled model; the model was run using the majority of parameter settings from the forced ocean-only ORCA12 runs of Marzocchi et al. (2015). While reducing the isoneutral tracer diffusivity is consistent with the increase in resolution, we note that results may have some sensitivity to its magnitude. Experiments to investigate the impact of this parameter in GC2 were not performed but will be pursued in future work with GC3 (the next version of the coupled model).

GC2.1-N512O12 was found to be very sensitive to features that had not proved to be a problem in previous ocean-only integrations (e.g., Marzocchi et al., 2015). For example, the model became unstable on the east coast of the UK every 6-12 months of simulation due to extreme values in the velocity field, likely due to the lack of tidal~~s~~ dissipation in the model which is ~~are~~ very important in this region. The model was restarted from these failures with a small random perturbation to the atmosphere temperature~~ic theta~~ field in a similar way to treatment of "grid-point instabilities" previously seen in atmosphere models (e.g., Mizielinski et al 2014). The underlying problem with this unstable ocean point will be addressed in future developments of the ORCA12 configuration.

The GC2 and GC2.1 experiments were run for 20 years with fixed atmospheric radiative forcing representative of the present day (with greenhouse gas and aerosol values for the year 2000). All experiments were initialised in the following way:

- atmosphere: N216 and N512 both from September year 18 of the model state of a previous N512 GA6 (Walters et al., in prep) forced atmosphere integration with forcing representative of the year 2000, so that the land surface properties are at quasi-equilibrium;
- ocean: temperature and salinity from the EN3 observational dataset (Ingleby and Huddleston, 2007) 2004-8 September average with velocities initialised to zero;
- sea ice: 20 year September mean from a HadGEM1 (Johns et al., 2006) experiment representative of a period centred on 1978.

- These latter two are the standard method for initialisation of "present day" coupled simulations at the Met Office.

The choice of the most appropriate ratio between ocean and atmosphere resolution remains an open research question worthy of further study. Short (two year) integrations using both higher and lower atmosphere resolutions coupled to ORCA12 were completed, although due to the short length of the integrations, they are not analysed here. In particular, a configuration using an N768 (17km) atmosphere led to a marked increase in the frequency of the type of model instabilities described earlier (from 1-2 per year to 5-6 per year).

3 Impact of model resolution on surface properties, heat transport and ocean circulation

The results shown in this section derive from 20 year simulations of the four experiments described in table 1, initialised and forced in an identical way.

a. Surface Properties

The pattern of large-scale biases in SST fields in Hadley Centre coupled climate models have remained largely unchanged since the models first ran without flux correction (e.g., Gordon et al., 2000); the large-scale biases exhibit warming in the Southern Ocean, cooling in the North Pacific and North Atlantic and warming in upwelling/stratocumulus regions off the western coasts of South America and Africa. Many of these biases are also very common in other models (e.g. Small et al., 2014). In contrast to the pattern, the magnitude of the SST biases has changed between model versions; in particular, comparing GC2 and HadGEM2-AO (Figure 1 of Williams et al., 2015), shows that the magnitude of the Northern hemisphere cooling was reduced in GC2 while the magnitude of the Southern Ocean warming was increased.

The time-series of the global mean Top of Atmosphere (TOA) radiation imbalance in the four models (Figure 1a) shows that the experiments with high (N512) atmosphere resolution have TOAs that are generally higher at the start of the experiments. However after 20 years all the experiments are starting to converge to a similar net TOA, as the shortwave and long-wave components adjust. Although the TOA-SST relationship is poorly defined (since the TOA imbalance is related to the rate of change of net ocean heat content; Palmer and McNeall,

2014), the integrated effect of the higher net TOA in the N512 experiments can be seen in the timeseries of the global mean SST (Figure 1b) with GC2-N512 and GC2.1-N512O12 having higher global mean SSTs.

In spite of the differences in global mean SST, major changes to the pattern and magnitude of SST biases are only seen with both high atmosphere and ocean resolution (Figure 2). In GC2.1-N512-ORCA12, the large-scale underlying SST biases are reduced relative to GC2 and GC2.1 (Figure 3): the warm bias in the Southern Ocean; cold bias in North Atlantic and North Pacific and warm biases in stratocumulus regions. Similar reductions in SST biases with high atmosphere and ocean resolution were also seen in Small et al. (2015). The increase in ocean resolution is key to this improvement: when only atmosphere resolution is increased (compare Figures 2a and b), there is only a small reduction in the warm bias associated with stratocumulus regions (west of South America and Africa), while increased coupling frequency (compare Figures 2a and c) shows only minor changes in SST biases.

In GC2 there is a cold bias in the North Atlantic subpolar gyre (SPG), Greenland-Iceland-Norwegian (GIN) Seas and the Arctic. GC2.1-N512O12 shows a warming of several degrees in the SPG and GIN seas relative to GC2 (see reduced cold bias in Figure 2d) and a very large warming in the Central Arctic. The warming in the Central Arctic is associated with a warming in the subpolar gyre, enhanced northward heat transport into the Arctic and melting back of the sea ice edge in the Arctic (see below).

Resolution appears to have less of an impact on Sea Surface Salinity (SSS; Figure 4). Nevertheless, there are reductions in high salinity biases in the Indian Ocean and the Pacific (in particular, in the salinity maximum in the subtropical gyre of the South Pacific) as well as reductions in the Arctic biases (although these are very sensitive to the distribution of sea ice).

b. Sea ice

The changes to the SST also affect sea ice distribution in both hemispheres. The seasonal cycle of ice extent in the Arctic (Figure 5a) shows that the warm SSTs in GC2.1-N512O12 at high Northern latitudes reduce the ice extent throughout the year. The March ice concentrations in the Arctic (Figure 6) clearly demonstrate that the impact on the sea ice is concentrated in the GIN seas with the sea ice edge in GC2.1-N512O12 much further north than seen in GC2 with the edge being north of Spitzbergen and into the Barents Sea.

In comparison, the reduction in the warm bias in the Southern hemisphere leads to only modest increases in the total sea ice extent (Figure 5b); the overall warming bias associated with the lack of super-cooled liquid clouds (Bodas-Salcedo et al., 2014; Bodas-Salcedo et al., in press) still dominates the melting of sea ice. The small increase in sea ice extent is very inhomogeneous; indeed, some regions in the Southern Ocean such as the Weddell Sea actually show reductions in sea ice extent in GC2.1-~~-~~N512-O~~RCA~~12 (Figure 6). The reduction in the Weddell Sea is associated with the formation of ~~a~~ polynyas in that region (see below).

c. Sub-surface ocean drifts

Conservation of heat within the climate system implies that the net heat uptake by the ocean should nearly balance the net radiative imbalance at the TOA. GC2.1-N512O12 has the highest TOA imbalance of the four models (Table 2) and therefore will have the greatest net heat uptake. Both models with increased atmosphere resolution (GC2-N512 and GC2.1-N512O12) have a higher TOA imbalance than the models with lower atmosphere resolution (GC2 and GC2.1).

The global temperature profiles (Figure 7a) show that GC2-N512 and GC2.1-N512O12 do indeed have greater increases in temperature as a function of depth than either of the low resolution models (GC2 and GC2.1), which is consistent with the higher TOA imbalance. The main difference between GC2-N512 and GC2.1-N512O12 is that the increase in heat uptake extends deeper in GC2.1-N512O12. This difference is also apparent in the global mean SST anomaly (Table 2); the SST anomaly for years 11-20 in GC2.1-N512O12 is 0.44 K compared with 0.60 K in GC2-N512, while the TOA imbalance is 2.02 W/m^2 and 1.79 W/m^2 respectively. This shows that the ORCA12 version of the model is able to transport heat to depth more effectively.

An increase in heat uptake in GC2.1-N512O12 relative to GC2-N512 is unexpected when considering the results of Griffies et al. (2015). Griffies et al. (2015) show that an increase in eddy activity produces upward eddy transport with a net effect of reduced heat uptake. Our results do not show a similar result suggesting that either the mean circulation is more effectively transporting heat downwards (which is consistent with an increased overturning circulation) or perhaps that there is an increase in spurious diapycnal mixing. Producing a budget analysis in the future would help to address this issue.

The distribution of the subsurface temperature changes varies depending on the latitudinal range. South of 30°S (Figure 7b), near surface warming is reduced in GC2.1-N512O12 relative to the other models. In the Tropics (30°S-30°N; Figure 7c), GC2.1-N512O12 shows increased warming shallower than 500m relative to the low resolution models but reduced relative to GC2-N512. The Tropics also show increased warming at depth in GC2.1-N512O12. The largest increase in near surface temperatures in GC2.1-N512O12 relative to the other models occurs north of 30°N (Figure 7d) with the surface warming displacing a cold bias to deeper in the water column. The warming is particularly concentrated north of 65°N (Figure 7e) where it has previously been shown that Arctic sea ice melts back.

Drifts in sub-surface salinity show that GC2.1-N512O12 generally has larger salinity drifts between 500 and 1000m (Figure 8a) which is largely associated with the region south of 30°S (Figure 8b). In the northern hemisphere, drifts in salinity between 1000 and 2000m are also more pronounced in GC2.1-N512O12 than the other models (Figure 8d). In contrast, large fresh biases north of 65°N in most of the models is much reduced in GC2.1-N512O12 (Figure 8e). Understanding salinity drifts and their relationship to freshwater forcing is complex (eg, Pardaens et al. 2003) and this aspect of the model performance will require further investigation.

d. Mixed layer depths

In general over the open oceans, the mixed layer depths[1] (Figure 6) are very similar across the different models and it is in the deep water formation regions where we see inter-hemispheric changes. Winter mixed layers in the Northern hemispheres in GC2.1-N512O12 show a reduction in the North Atlantic subpolar gyre. Most notably, in GC2.1-N512O12 deep mixed layers are less extensive south of Greenland than in GC2 and are confined to the centre of the Labrador Sea. Similar changes in Labrador Sea deep convection have been seen in sensitivity experiments when overflow properties are improved (Graham et al., in prep.). The deeper

[1] Mixed layer depth is calculated as the depth at which density changes by 0.01 kg m^{-3} relative to the density at 10m

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mixed layers in the Arctic in GC2.1-N512O12 are consistent with warmer SSTs and reduced sea ice extent in that region exposing open water.

The similarity of the mixed layer depths across the Southern Ocean demonstrate that it is not changes to the mixed layer depths that lead to a reduction in the Southern Ocean warm bias. As mentioned in the previous section, in the Weddell Sea, GC2.1-N512O12 has very deep mixed layers (maximum of 800m in the decadal mean) linked to the formation of~~a~~ polynyas. Polynya formation varies both spatially and on an interannual basis over the last 9 years of the simulation (Figure 9); the polynya first appears in year 12 and persists for 5 years before disappearing, starting to re-emerge in year 18 and reaching a depth of 2070m in year 20. ~~,~~ ~~which~~ The appearance of the polynya in this decade explains the lack of increase of sea ice extent in that region (as seen in Figure 6). Deeper winter mixed layers in GC2.1-N512O12 are also evident through the mid-latitudes in the formation zones for Sub-Antarctic Mode Waters and Antarctic Intermediate Waters. These could be due to the reduced warm bias (cooler SSTs) in these regions (Figure 2).

e. Ocean Circulation

The improvements seen in the large-scale SST biases with high atmosphere and ocean resolution (Figure 3) represent an overall improvement in the model simulation with warming in the Northern hemisphere and cooling in the Southern hemisphere. This pattern is reminiscent of inter-hemispheric modes that occur as a result of changes in the large-scale thermohaline circulation (Vellinga and Wu, 2004). The meridional overturning at 24°N in our simulations increases by O(1.5 Sv) ~~changes only~~ in GC2.1 and in~~the~~ GC2.1-N512O12~~, with an increase of~~ by a further O(1.5~~3~~ Sv) (Table 2). At 30°S, a change of O(3 Sv) is only seen in GC2.1-N512O12. ~~both in the North and South Atlantic, and is therefore~~ The enhanced meridional overturning is therefore attributed to the increased ocean resolution in combination with the increased coupling frequency. The changes in the meridional overturning circulation (Figure ~~9~~10) are dominated by changes in the cell associated with North Atlantic Deep Water (NADW) with changes extending into the Southern hemisphere. Examination of the overturning in density space would further support this analysis but this was not possible with the diagnostics available from this simulation and will be addressed in future simulations.

At the northern end of the NADW cell, we see increases in the volume flux of dense overflows between the GIN Seas and the Atlantic (Table 2) that are consistent with the

NADW cell being strengthened both by the GIN sea sources and better representation of sills. The volume flux of overflow waters across Denmark Straits generally reduces fairly rapidly in ORCA025 runs (Figure 1~~0~~a) but in GC2.1-N512O12 the overflow remains closer to the observed value of 2.9 - 3.7 Sv (Dickson and Brown, 1994; Macrander et al., 2005; Jochumsen et al., 2012). This appears to also contribute to a deeper (as well as stronger) NADW outflow in GC2-N512O12~~this model~~ (Figure 10) and ~~is almost certainly~~ we suggest that this is likely to be associated with the increased resolution of the topography in the region of the overflows.

The Antarctic Circumpolar Current (ACC) usually drifts in the ORCA025 GC models from an initial value of approximately 150 Sv to below 100 Sv (Figure 1~~0~~b). Increased ocean resolution counteracts that, with the ACC stabilising close to 130 Sv in GC2-N512O12~~ this 20 year experiment~~. This value is close to the observations which~~that~~ suggest an ACC transport of 137 ± 8 Sv (Cunningham et al., 2003; Meredith et al., 2011)~~)~~. The increase in the transport in the ACC can be explained by changes in the density field; the meridional density gradients across the ACC (not shown) are increased in GC2.1-N512O12 (with steeper isopycnals) than in GC2. ~~ which~~This result is consistent with increased southward flow, and stronger upwelling, of NADW to the north of the ACC (Allison et al., 2011) and increased convection to the south of the ACC in the Weddell Sea (Hirabara et al., 2012). The Southern Ocean winds (not shown) respond differently across the four simulations (including a small increase in GC2.1-N512O12 and a decrease in GC2.1). Jones et al. (2011) have shown that the transient response of the ACC to changes in winds can be seen within 10 years, suggesting that it is not surprising that we are able to detect changes in the ACC in this set of experiments. ~~and investigating these changes, how they relate to the model internal variability and their impact on the simulation will be a topic of future research.~~

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f. Heat transport

As described in Gordon et al. (2000), drifts in volume averaged ocean temperature can be related to discrepancies between the actual heat transports by the ocean and the heat transport implied by the surface fluxes, i.e.

$$\frac{\partial \rho c_p <\theta>}{\partial t} + \oint \rho c_p (\bar{v}\bar{\theta} + \overline{v'\theta'}) dS + \oint \rho c_p A_{iso} \nabla_\rho \theta \, dS = \int F \, dA, \quad (1)$$

where <θ> is the volume integrated temperature, $\bar{v}\bar{\theta}$ and $\overline{v'\theta'}$ are the time mean and time varying components of the ocean meridional heat transports, ρc_p is density multiplied by specific heat capacity, A_{iso} is the isoneutral diffusivity~~pyncnal diffusion~~, $\nabla_\rho \theta$ is the isoneutral gradients of temperature, ~~and~~ F is the surface heat flux, dS (=dx*dz) is the cross sectional area (x and z denote the zonal and vertical directions) and dA is the surface area of the region. For our purposes here, we make the assumption that the isoneutral fluxes are generally smaller than the other terms (~~dia~~isoneutral diffusive fluxes are very small when integrated over full depth).

Figure 12~~1~~a shows the global northward heat transport in all four simulations. There are some changes in the northern hemisphere in the GC2.1 simulation with the change to hourly coupling, while changes in the southern hemisphere are only seen in GC2.1-N512O12 suggesting that these changes are driven by the increase in ocean resolution. The reduction in southward heat transport in GC2.1-N512O12 centred at 45°S is highly unusual; although the change does not lie outside interannual variability, a change of this magnitude in the multi-year mean heat transport has not been seen in any other development runs of the GC series. The modelled changes in the heat transports suggest that ocean processes are important in this region, which is particularly relevant given the uncertainty in surface heat fluxes in the Southern Ocean (Cerovecki et al., 2011). The increas~~chang~~e in total heat transport comes primarily from the time mean heat transport (not shown). This suggests that increased ~~changes in~~ resolution has~~ve led to a change in~~ either changed the mean circulation or the temperature profile. In contrast, if the ~~(as opposed to a~~ increased heat transport was~~change~~ due to~~in~~ the time varying heat transport, this~~which~~ would imply a direct role for~~of the~~ mesoscale eddies~~)~~. As seen in previous sections, GC2.1-N512O12 shows changes in both the circulation and the temperature profiles. The decreased southward heat transport in the Southern Ocean of GC2.1-N512O12 could – at least partly - explain the reduced warm bias.

By comparing actual ocean heat transports with those implied by surface fluxes (i.e., the second term of the left-hand side of Eqn. 1 with the right-hand side of Eqn. 1), this gives an indication of the volume averaged drift in temperature (first term on the left-hand side of Eqn. 1). To remove the effect of the net radiative imbalance, the implied ocean heat transport is calculated by subtracting the globally averaged imbalance from the surface fluxes before integrating zonally and meridionally. This is equivalent to removing a globally integrated temperature drift from the left-hand side of Eqn. 1. This can be described as:

$$\frac{\partial \rho c_p(<\theta>-\bar{\theta})}{\partial t} + \oint \rho c_p(\bar{v}\bar{\theta} + \overline{v'\theta'})dS = \int (F - \bar{F})dA, \quad (2)$$

where $\bar{\theta}$ and $\bar{F}$ are the global mean temperature and surface flux respectively. Eqn. 2 shows that a residual imbalance between the implied and actual ocean heat transports is indicative of local temperature drifts. Both g~~G~~lobally and in the Atlantic basin (Figure 12~~1~~a,b) GC2.1-N512O12 can be seen to be as close to local balance as any of the other models, suggesting that the net drifts will be of a similar magnitude (in agreement with Figure 5).

Ocean resolution is the driving factor in a 0.2PW increase in the northward heat transport in the Atlantic; the modelled heat transports in GC2.1-N512O12 are generally within the error bars of the observations (Ganachaud and Wunsch, 2003; Figure 12~~1~~b) in contrast to the other models with the lower resolution ocean component. The change in heat transport is linked to an increase in the overturning circulation (previous section), which is unsurprising given the dominant role of the meridional overturning circulation in the Atlantic heat transport (Hall and Bryden, 1982).

4 Summary and Discussion

In this paper we have shown results from a coupled climate model with an eddy resolving (1/12°) ocean component coupled to a high resolution (25 km) atmosphere component. When the SST bias from this climate simulation is compared to that from the Met Office standard resolution climate model, with eddy permitting (1/4°) ocean component and 60km atmosphere component, it is apparent that major SST biases in the Southern Ocean and North Atlantic and North Pacific have been reduced. Comparable experiments increasing only the atmosphere resolution or the coupling frequency, demonstrate that increased ocean resolution is the key driver for this change.

At the enhanced ocean resolution, the ocean circulation leads to increased poleward ocean heat transport in the Northern hemisphere and reduced poleward ocean heat transport in the Southern hemisphere. The change in the northward heat transport is driven at least in part by an enhanced NADW cell ~~which also contributes to maintaining the ACC front~~. The stronger ACC ~~front is maintained in spite of the expectation that improved representation of eddies in the Southern Ocean could lead to slumping of the front, this is at least in part associated with~~ at high resolution may be associated with a number of factors: enhanced windstresses, increased ~~at high resolution~~deep water formation in the Weddell Sea due to the presence of a

polynya, enhanced southward transport of NADW and eddy fluxes. Changes in the global heat transports produce a shift in the large-scale biases, cooling the Southern Ocean and warming the North Atlantic and North Pacific. We have shown that heat penetrates deeper in our 1/12° model; Griffies et al. (2015) have demonstrated that mesoscale eddies transport heat upwards so it is likely that the increased transport of heat to depth is achieved by the time-mean as seen in transient experiments such as Banks and Gregory (2006). Future work will be focused on understanding the relative roles of resolving overflow topography (Behrens, 2013), eddy processes within the ocean including compensation and saturation (e.g., Munday et al., 2013) and air-sea interaction on the eddy scale (Roberts et al., in prep.) in driving the large-scale changes.

Relative to the recent high resolution results of Small et al. (2014) and Griffies et al. (2015), our results emphasise the importance of increasing both ~~atmosphere and~~ ocean resolution and coupling frequency. Griffies et al. (2015) show smaller reductions in SST biases than seen here when moving from 1/4° to 1/10° resolution presumably related to keeping the atmosphere resolution unchanged. Enhanced coupling frequency along with enhanced vertical resolution near the air-sea interface both in the ocean (Megann et al., 2014) and atmosphere (Walters et al., in prep) is one feature of our model setup that is missing in Small et al. (2014). These aspects of the model setup may be especially important in regions of strong air-sea interaction including the stratocumulus regions where we see large improvements in the GC2.1-N512O12 simulation. ~~Overall, the improvements seen in this paper~~ Further work is required to quantify whether~~a combination of~~ high resolution in the~~both~~ atmosphere component is necessary in combination with~~and~~ the high resolution ocean components and~~as well as~~ high frequency coupling to produce the results described in this paper.

As described in ~~the previous~~ section 2, one of the changes to the ocean model at higher resolution was a reduction in the isoneutral diffusivity~~on~~. Pradal and Gnanadesikan (2014) show that a reduction in the isoneutral diffusivity~~ion~~ from 800 m^2s^{-1} to 400 m^2s^{-1} in a coarse resolution climate model is associated with cooling of order 1°C at high latitudes after 500 years. Given ~~While~~that the results here ~~may~~ exhibit some consistency with those of Pradal and Gnanadesikan (2014) in the Southern Ocean, further work is required to quantify the role of isoneutral diffusivity in producing~~the change in isopycnal diffusion is believed to be a secondary effect due to the fact that we are seeing a comparable or larger~~ changes in SST on decadal timescales ~~in a short 20 year run~~.

One caveat of these results is that the parallel simulations lasted only 20 years. However, ~~the close agreement between implied and actual meridional heat transports, suggests that the models are close to quasi-equilibrium. Additionally,~~ the broad similarity of the results presented here compared with those of Small et al. (2014) from over 100 years of simulation suggest that the results are reasonably robust. In terms of model drift, climate models typically have a fast adjustment within the first five years (Sanchez-Gomez et al., 2016). Large adjustments over the first 20 years are generally followed by a multi-centennial drift towards equilibrium between ocean properties and the net TOA flux (Banks et al., 2007). Longer simulations and further analyses will enable the robustness of the results presented here (including wind-SST feedbacks) to be more fully understood.

In the results presented here, the 1/12° ocean model, which has a resolution of approximately 7 km at mid-latitudes, is coupled to an N512 atmosphere model, which has a resolution of 25 km. The relative importance of the atmosphere and ocean resolution remains a question which will continue to be addressed in the community. We suggest that an~~An~~ atmosphere:ocean ratio of 4:1 may be too high for the atmosphere to fully respond to~~capture~~ the details of the ocean mesoscale. Future work will investigate the impact of coupling to even higher resolution atmosphere models to investigate the role of the atmosphere:ocean ratio.

As we move towards ~~seamless coupled prediction,~~ using coupled models for prediction on timescales from days to centuries, the results presented here are highly relevant to prediction up to decadal timescales where data assimilation is employed. A coupled model that more faithfully produces the current state of the ocean will rely less on data assimilation for correcting large-scale biases and ~~be more able to include the representation of~~ better represent spatial anomalies that control the large-scale variability. While there are many regions where subsurface drifts are improved at ORCA12~~this~~ resolution, reducing the drifts seen in mid-depth salinity will be important.

The ocean data assimilation scheme used in Met Office systems is called NEMOVAR, employed in a 3DVar first-guess-at-appropriate-time (FGAT) mode (Waters et al., 2015). A new version of NEMOVAR has recently been developed (Weaver et al. 2016) which uses a 2D implicit diffusion operator to model the horizontal background error covariances, one of the most computationally expensive aspects of the scheme. This new version has been developed in such a way that the number of costly global communications are minimised and is therefore expected to scale well with resolution. Preliminary implementations of this

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scheme in the ORCA12 configuration indicate that it will be feasible to implement it for operational ocean forecasting applications.

A key question for these timescales is whether employing enhanced resolution will address the known problem of low signal-to-noise ratios (Eade et al., 2014) that has led to the need for large ensembles for seasonal to decadal forecasting in lower resolution systems. Future work to understand the drivers of large-scale bias reduction will support targeted experiments to address the relative roles of resolution and ensemble size at these timescales. That said, ocean resolution is clearly not going to solve all the issues in climate models; atmosphere errors often dominate surface biases and, even at high resolution, ocean models need improved representation of sub-gridscale processes.

Code availability

The MetUM is available for use under licence. A number of research organizations and national meteorological services use the MetUM in collaboration with the Met Office to undertake basic atmospheric process research, produce forecasts, develop the MetUM code and build and evaluate Earth system models. For further information on how to apply for a licence see http://www.metoffice.gov.uk/research/collaboration/um-collaboration. JULES is available under licence free of charge. For further information on how to gain permission to use JULES for research purposes see https://jules.jchmr.org/software-and-documentation. The model code for NEMO v3.4 and v3.5 is available from the NEMO website (www.nemo-ocean.eu). On registering, individuals can access the code using the open source subversion software (http://subversion.apache.org/). The model code for CICE is freely available (http://oceans11.lanl.gov/trac/CICE/wiki/SourceCode) from the United States Los Alamos National Laboratory. In order to implement the scientific configuration of GC2/GC2.1 and to allow the components to work together, a number of branches (code changes) are applied to the above codes. Please contact the authors for more information on these branches and how to obtain them.

Appendix A: Model vertical levels

The sensitivity to vertical resolution is not explored in this paper. However, a reduced description of the vertical levels in GA6 (Table A1) and GO5 (Table A2) are included to

allow comparison with other models. For the full vertical levels, see Walters et al. (in prep.) and Megann et al. (2014), respectively.

Level	Rho_height (m)
1	10.00
10	730.00
20	2796.67
30	6196.67
40	10930.12
50	17012.40
60	24710.70
70	35927.89
80	58978.35
85	82050.01

Table A1: Reduced list of level in GA6 which has 85 vertical levels

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Level	Depth (m)	Thickness (m)
1	0.51	1.02
10	13.99	2.37
20	61.11	7.58
30	180.55	18.27
40	508.64	53.76
50	1387.38	125.29
60	2955.57	181.33
65	3897.98	194.29
70	4888.07	200.97
75	5902.06	204.23

Table A2: Reduced list of levels and layer thicknesses in GO5 which has 75 vertical levels

Appendix B: Model performance and technical aspects

The GC2.1 configuration was the first in which several further technical components of the coupled system were considered essential to make the simulation manageable. The coupler was upgraded from OASIS3 to OASIS3-MCT (Valcke et al, 2015) in order to improve parallelisation of the coupling, particularly given the increased coupling frequency.

ORCA025 files are typically written as one file per processor by standard GC2 configurations and combined into a single file prior to analysis as a post processing step. However, as HPC parallel file systems are generally tuned for high bandwidth on large files and as GC2.1-N512O12 configurations allocate 50 of the 80 nodes used by the full coupled system to the ocean, this led to performance and functional issues when running on 1600 or more cores. The NEMO XIOS diagnostic server (Madec, 2014) provides an asynchronous IO server capability that allows the diagnostic files to be output as fewer larger files (although the restart files are still written as one file per processor). Its introduction in the model allowed us to overcome the limitations of the file system.

Land suppression was used for the NEMO and CICE models, so that processors are only assigned to regions with active ocean points. This leads to a significant gain in core count, although it meant that the automated large-scale diagnostics usually produced by NEMO (zonal mean heat transports, meridional overturning) could not be generated.

Data volumes from this experiment were particularly large due to the output of additional hourly and 3-hourly fluxes in order to examine the coupling processes in more detail. Each month of model output comprised: ocean monthly mean files (netCDF) of 87GB together with 6GB of daily files, sea-ice output (netCDF) of 57GB per month (with an additional 48GB of hourly output), and atmosphere output (PP format) of 100 GB per month. In total, the 20 years of simulation produced 85 TB of data.

Little optimisation of the model was attempted since GC2.1 is not intended to be supported in the long-term. Its successor, GC3, will be used for CMIP6. The GC2.1-N512O12 model used 80 full nodes (each of 32 cores) of an IBM Power 7 HPC, of which 55 were allocated to the ocean/sea ice component (including 5 for the IO servers) and 25 for the atmosphere/land component. The model throughput was 4 months per wall-clock day.

For previous model resolutions, the SCRIP utility (Jones, 1998) was used to generate the conservative remapping files used to regrid coupling data between the ocean and atmosphere

grids (for temperature and fluxes), with bilinear interpolation used for the winds and surface currents. However, due to the size of the high resolution grids used here, and the serial nature of SCRIP, a different method was required. ESMF (ESMF, 2014; a package of parallelised tools that use the same input grid descriptions as SCRIP, but can be run in parallel) was therefore used to generate the remapping weights.

Acknowledgements

We thank the Editor and the two reviewers (Stephen Griffies and Andy Hogg) for their constructive comments. Matt Martin provided useful input on data assimilation for ORCA12. This work was primarily supported by the Joint DECC/Defra Met Office Hadley Centre Climate Programme (GA01101). Part of the work was undertaken with National Capability funding from NERC for ocean modelling. We acknowledge use of the MONSooN system, a collaborative facility supplied under the Met Office-NERC Joint Weather and Climate Research Programme (JWCRP). Met Office authors were supported by the joint UK DECC/DEFRA Met Office Hadley Centre Climate Programme (GA01101). MR acknowledges support from the EU FP7 IS-ENES2 project for work on ESMF and regridding tools. We acknowledge the considerable effort on development and evaluation of ORCA12 by the DRAKKAR community. HH thanks IH.

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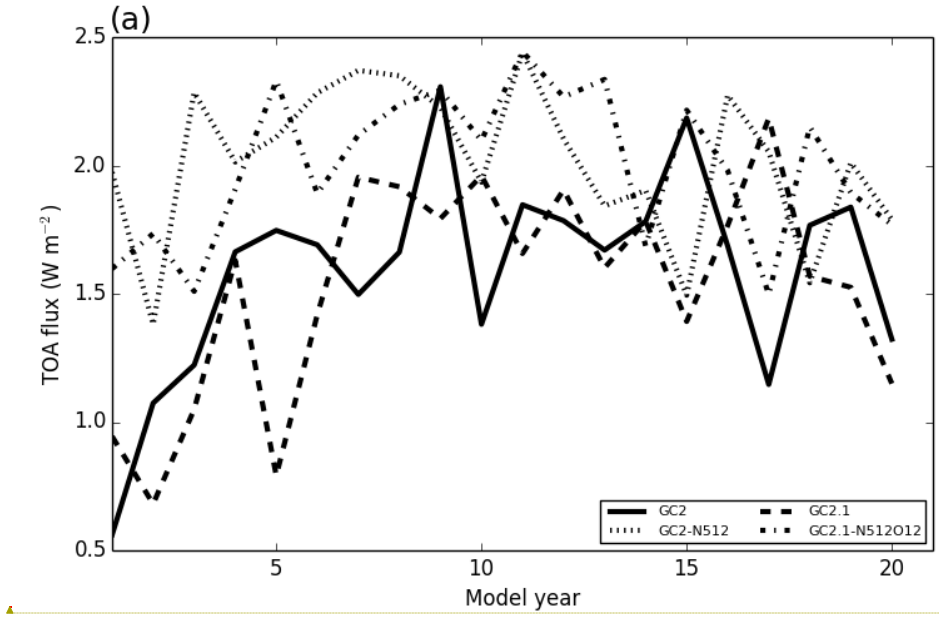
Table 1. Coupled models used in this paper

Model	Horizontal Resolution	Coupling frequency
GC2 (Williams et al., 2015)	N216-ORCA025	3-hourly
GC2-N512	N512-ORCA025	3-hourly
GC2.1 (this paper)	N216-ORCA025	1-hourly
GC2.1-N512O12	N512-ORCA12	1-hourly

Table 2. Key metrics from years 11-20 of the experiments and observations. TOA observations from CERES/EBAF for years 2000-2010. Global mean SST error (compared to Reynolds OI). Overflows are calculated as southward flow across the Greenland-Iceland-Scotland ridge below density of 27.8 kg m^{-3} and have standard deviation shown in brackets.

Model	Net TOA (W/m^2)	Global mean SST error (K)	Maximum overturning at 30°S (Sv)	Maximum overturning at 24°N (Sv)	Net transport from overflows (Sv)
Observations	0.85				
GC2	1.61	0.25	13.7	14.6	4.0 (0.24)
GC2-N512	1.79	0.60	14.3	14.9	3.9 (0.28)
GC2.1	1.64	0.29	14.3	16.4	4.7 (0.26)
GC2.1-N512O12	2.02	0.44	17.5	17.7	5.9 (0.42)



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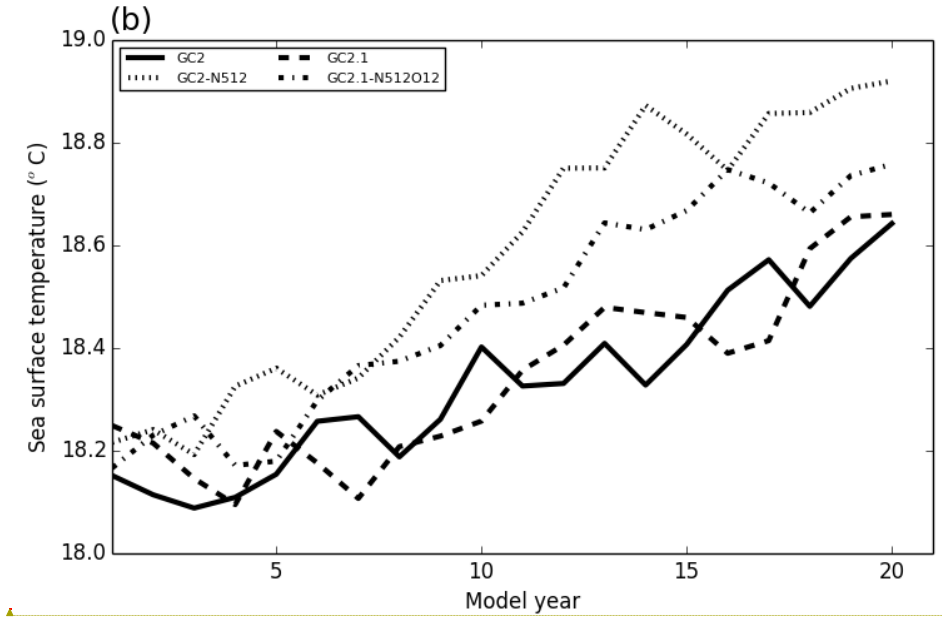

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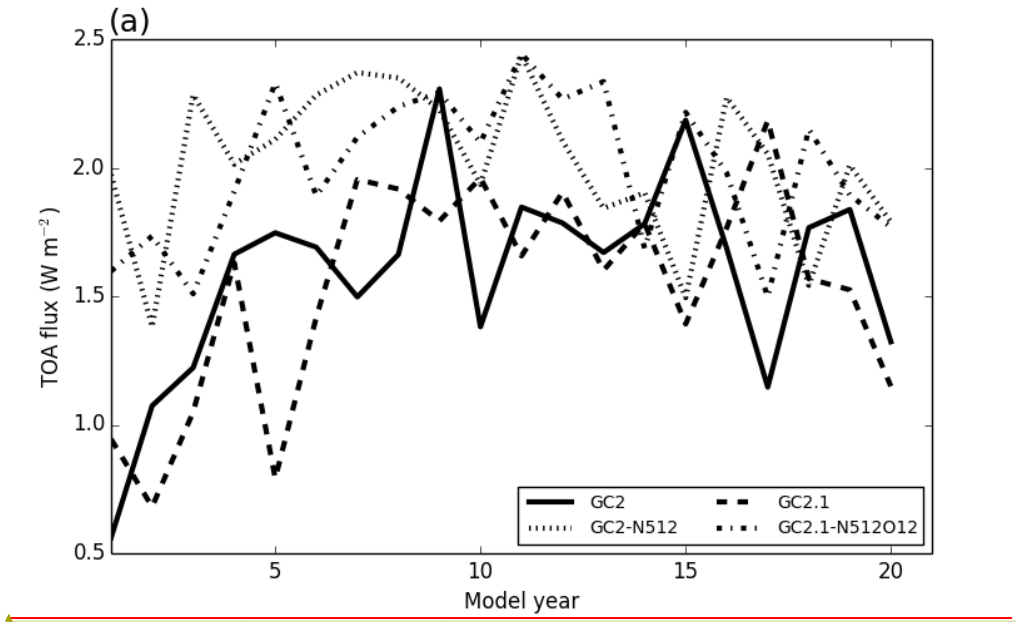

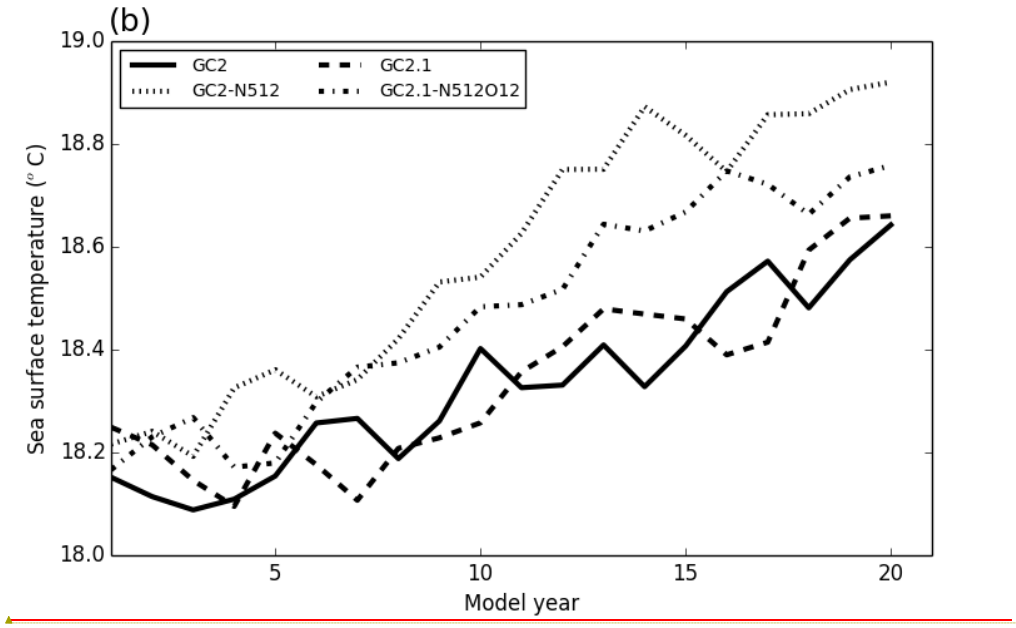

Figure 1: Timeseries of a) net TOA and b) global mean SST from GC2, GC2-N512, GC2.1 and GC2.1-N512O12.

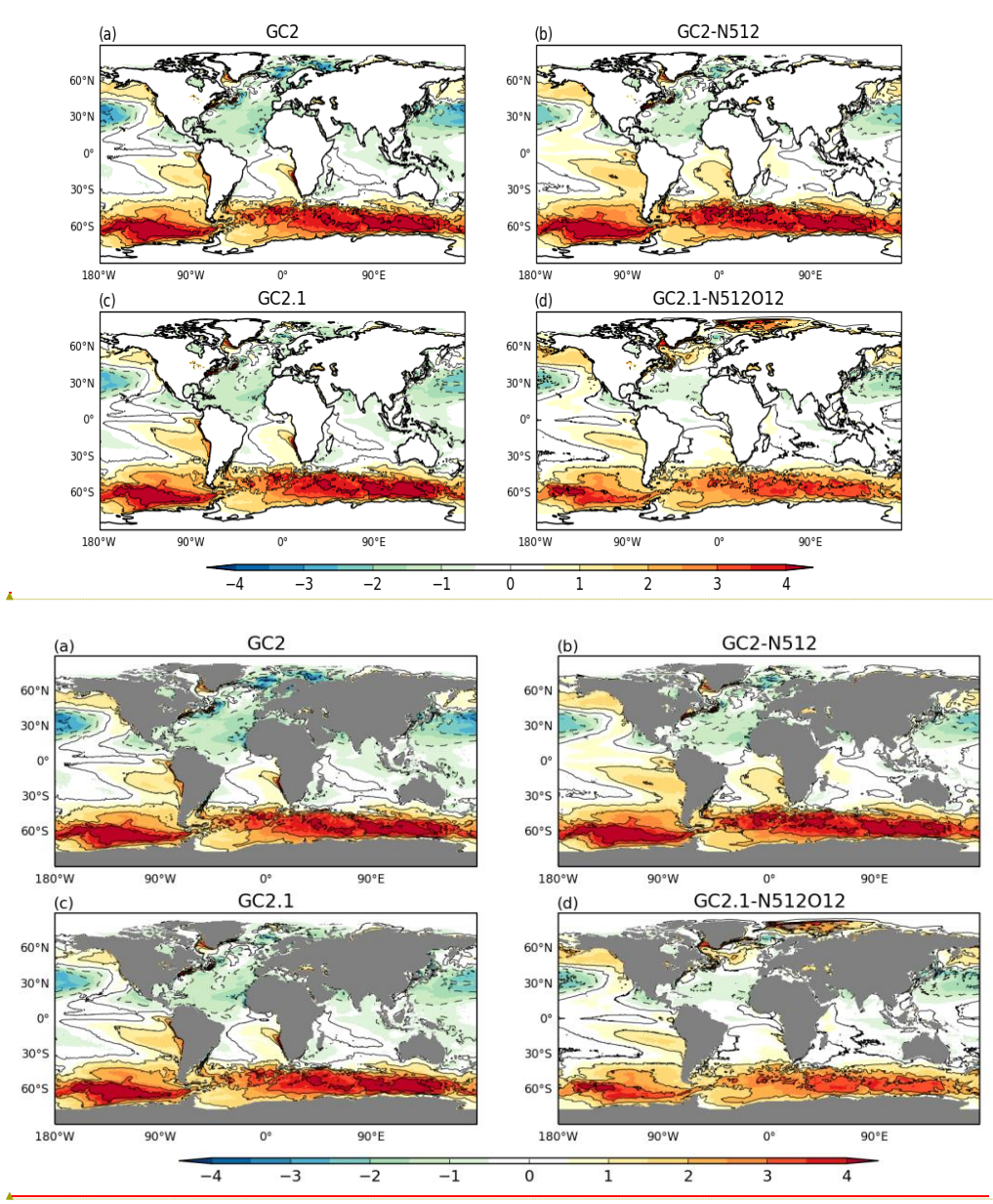

Figure 2: Differences between modelled SST from years 11-20 and observed SST from HadISST (°C) for a) GC2, b) GC2-N512, c) GC2.1 and d) GC2.1-N512O12.

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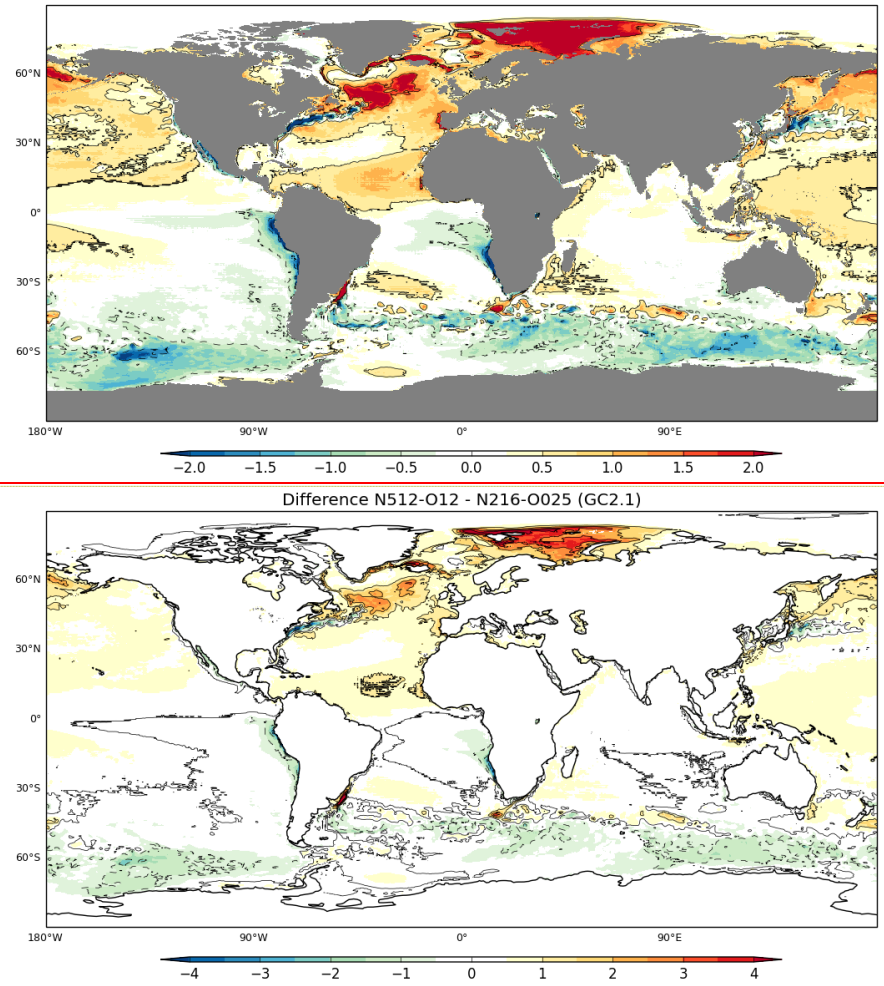

Figure 3: SST difference (°C) for years 11-20 between GC2.1-N512O12 and GC2.1

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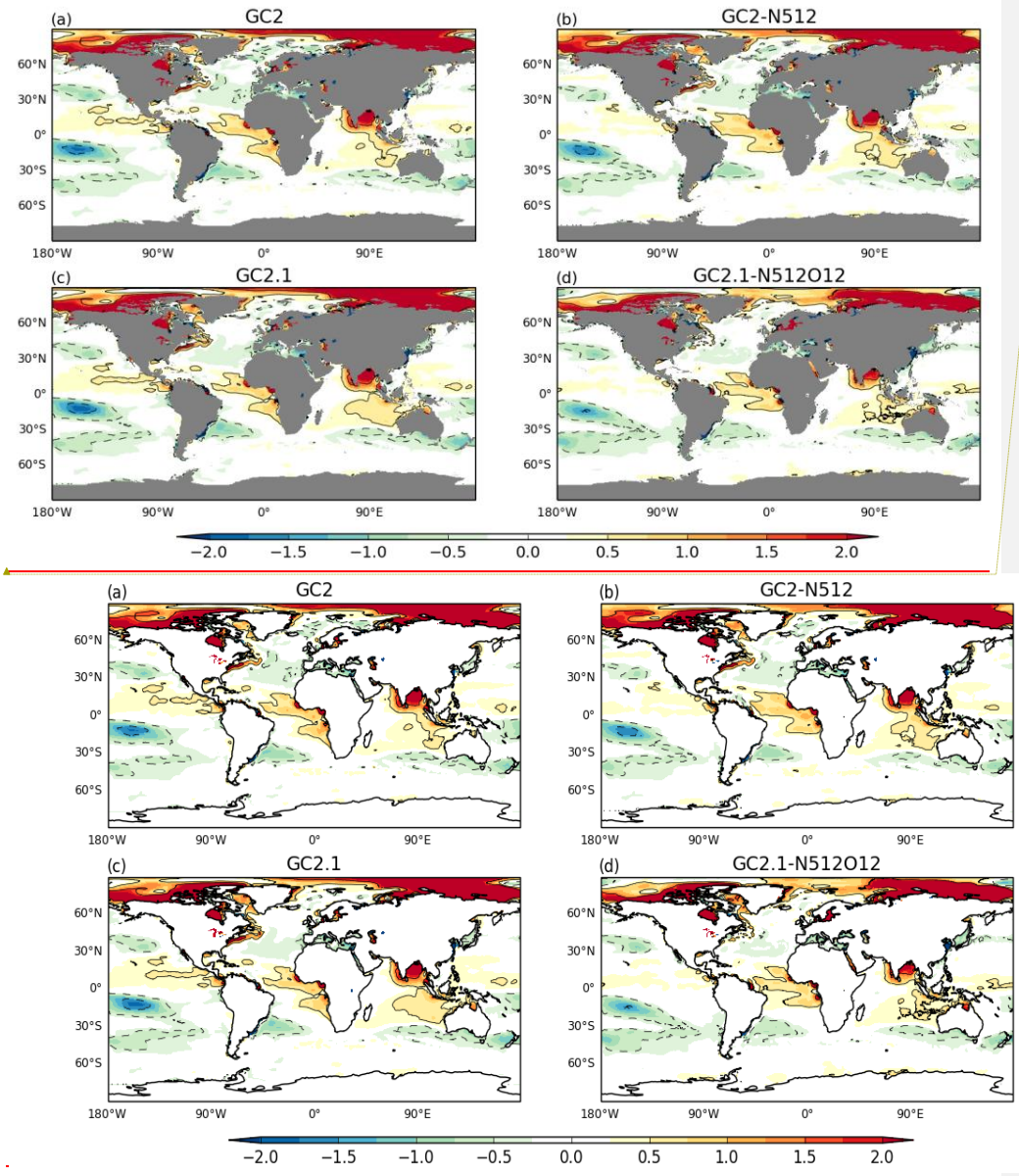

Figure 4: Differences between modelled SSS from years 11-20 and observed SSS from EN4 (psu) for a) GC2, b) GC2-N512, c) GC2.1 and d) GC2.1-N512O12.

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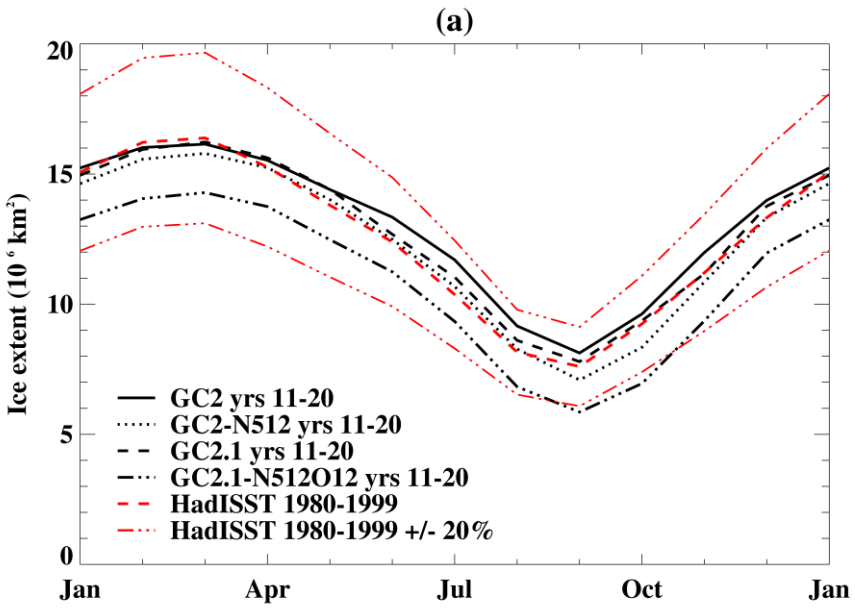

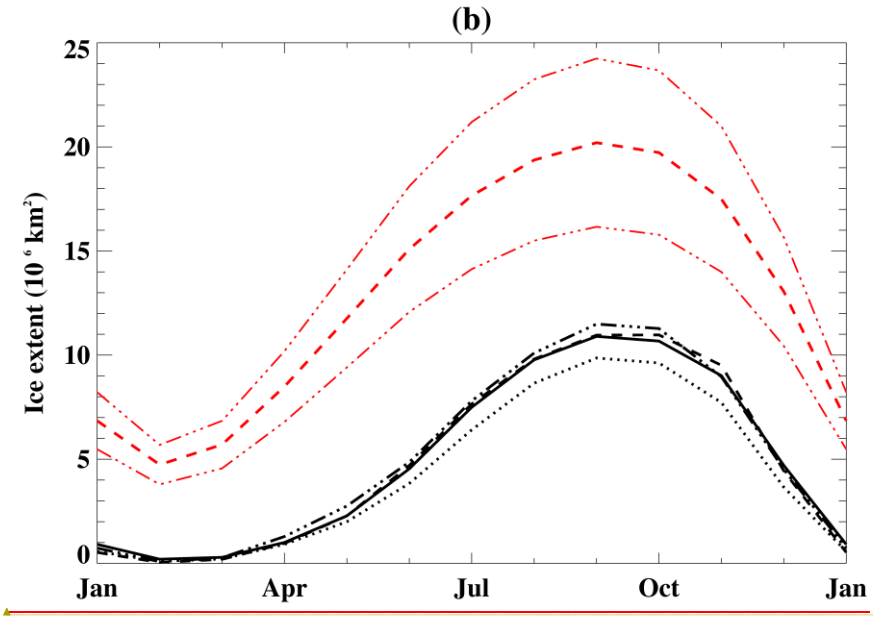

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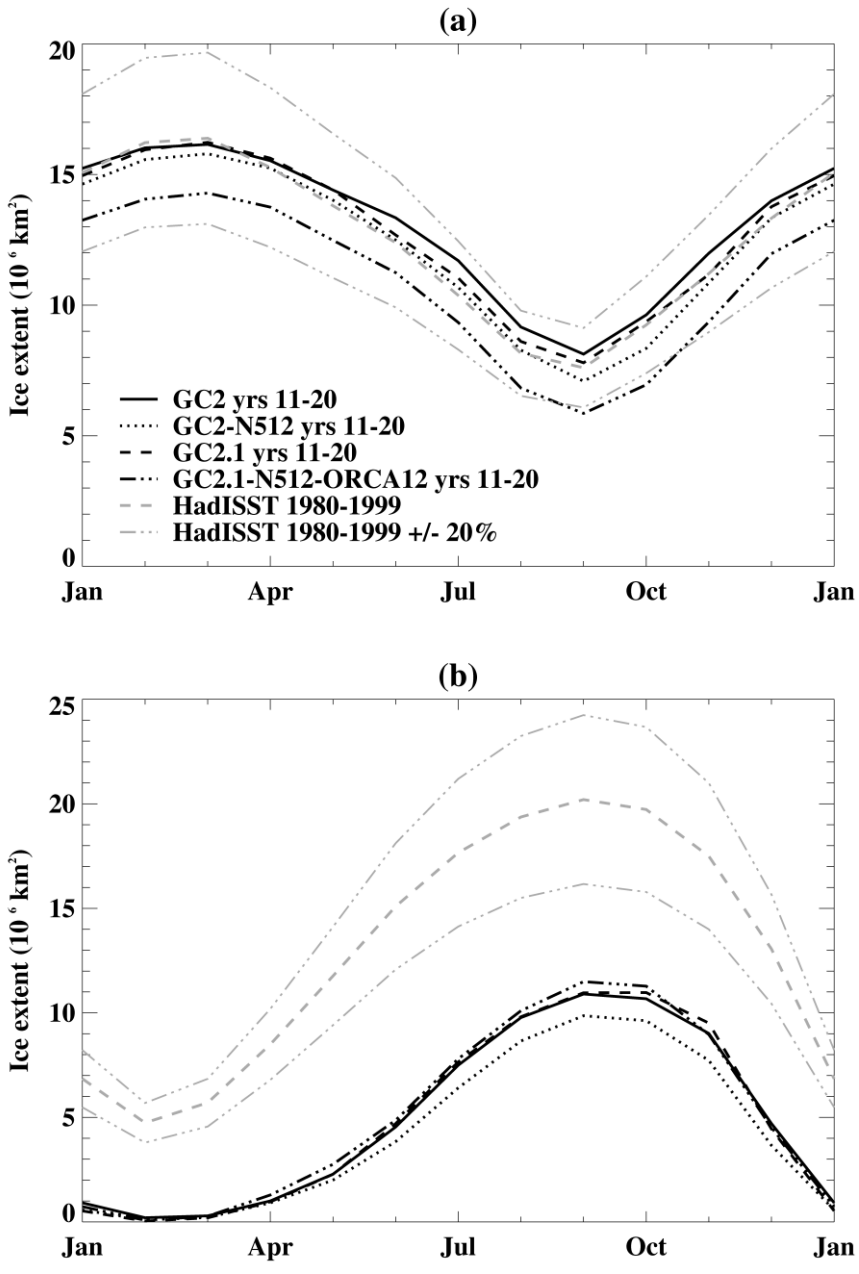

Figure 5: Seasonal cycle of sea ice extent in a) Northern and b) Southern hemisphere for years 11-20 compared against HadISST 1980-99 and with +/- 20% error bars denoted.

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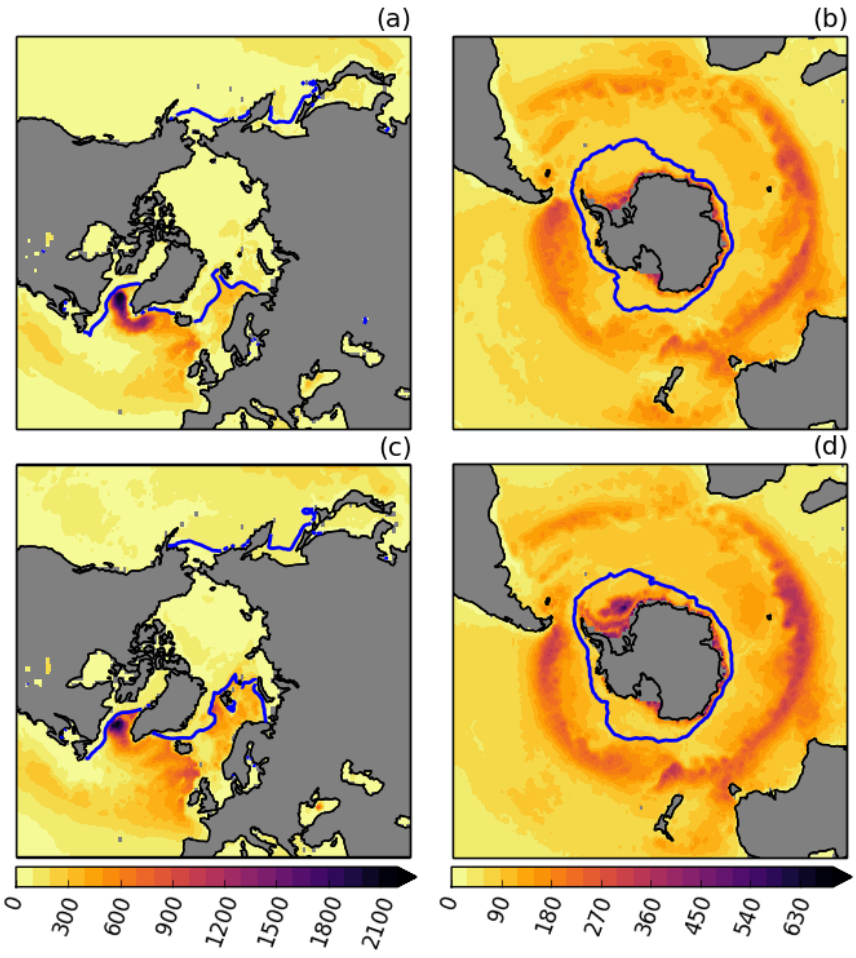

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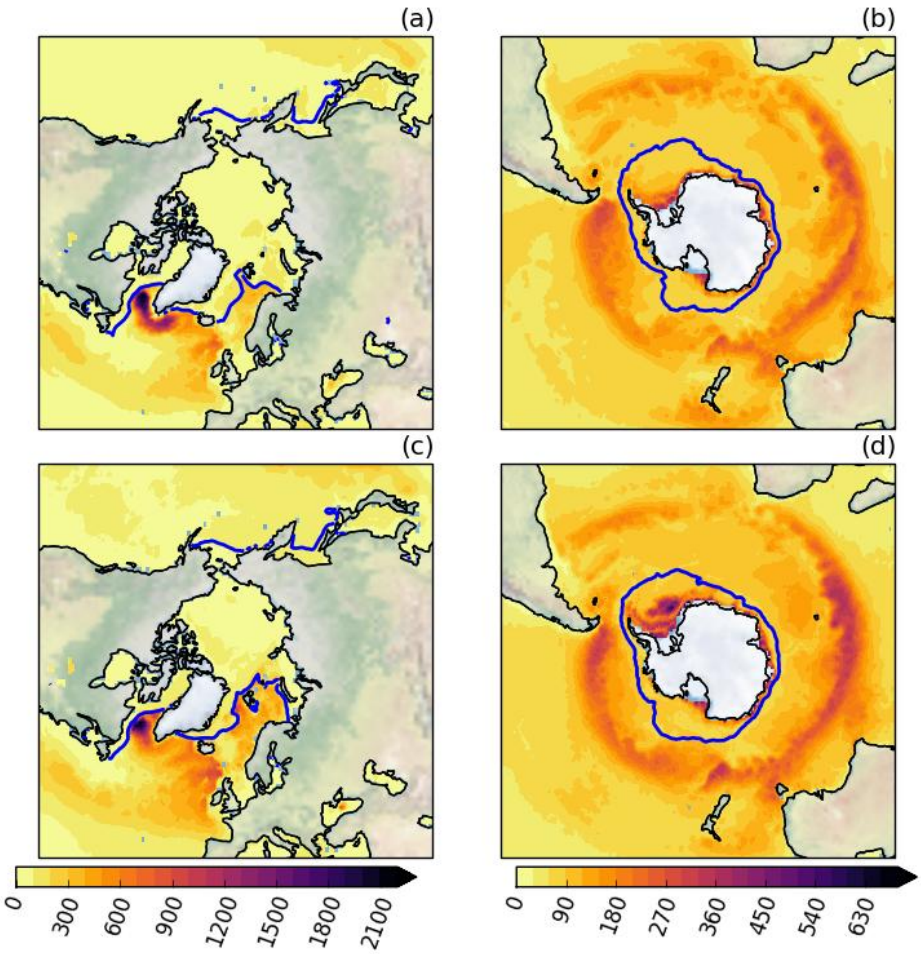
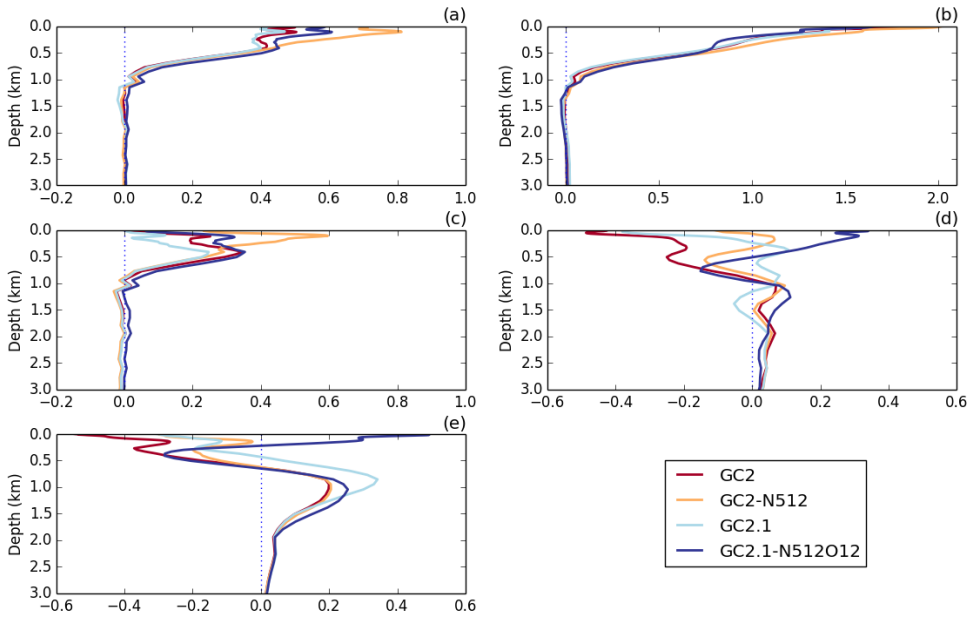


Figure 6: Mean March Northern hemisphere winter mixed layer depth (m) and ~~Arctic~~ sea ice edge and mean September Southern hemisphere winter mixed layer depth (m) and sea ice edge for years 11-20 for GC2 (a,b) and GC2.1-N512O12 (c,d). The sea ice edge (marked in blue) is based on a threshold of 15% ice concentration.



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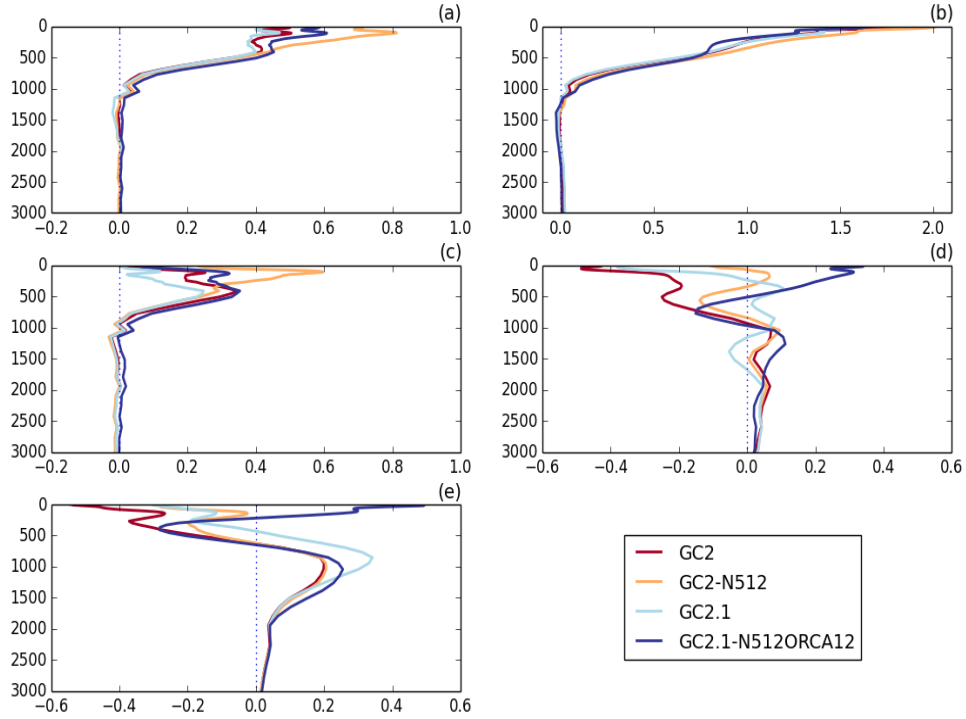
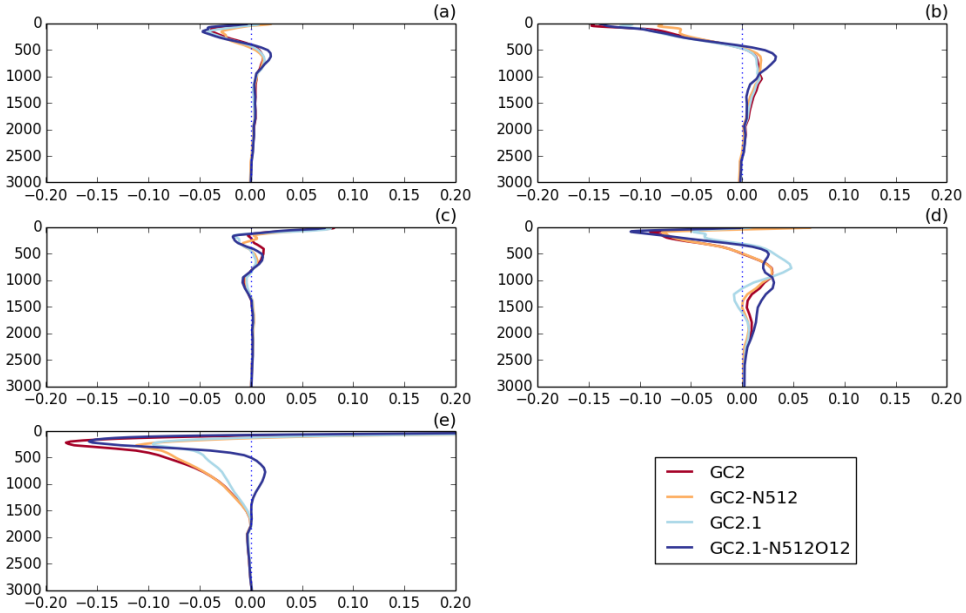


Figure 7~~7~~: Area-weighted mean temperature difference (years 11-20 minus year 1; °C) for GC2, GC2-N512, GC2.1 and GC2.1-N512O12 for a) global, b) 90S-30S, c) 30S-30N, d) 30N-90N, e) 65N-90N. Note the range on the x-axis is equal in all panels except (b). The vertical axis denotes depth (m).



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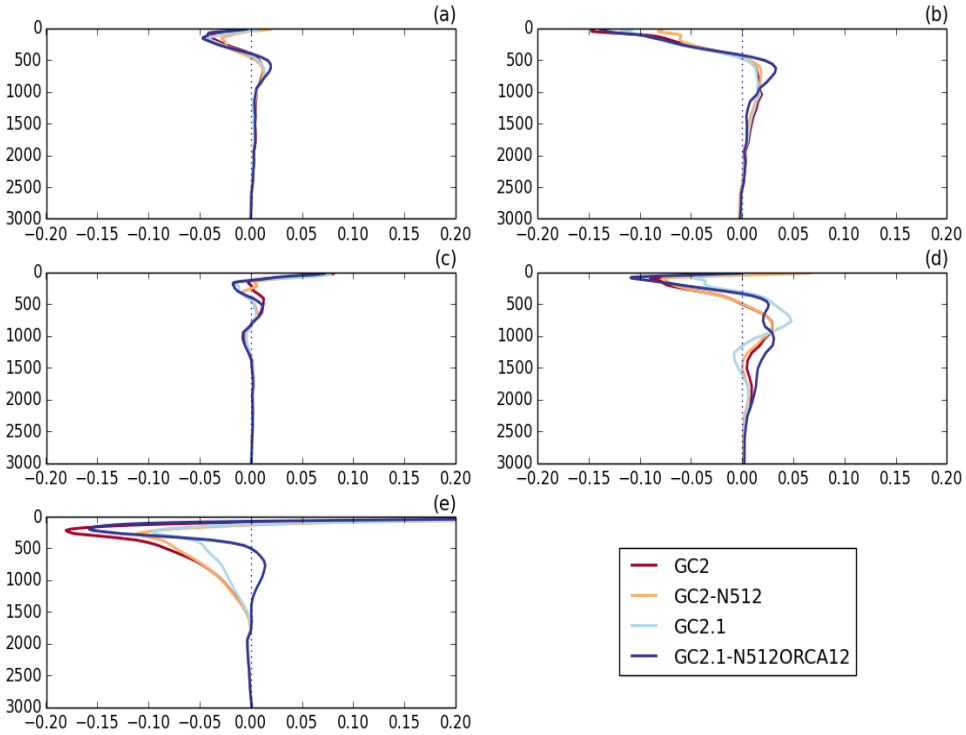

Figure ~~8~~8: Area-weighted mean salinity difference (years 11-20 minus year 1; psu) for GC2, GC2-N512, GC2.1 and GC2.1-N512O12 for a) global, b) 90S-30S, c) 30S-30N, d) 30N-90N, e) 65N-90N. The vertical axis denotes depth (m).

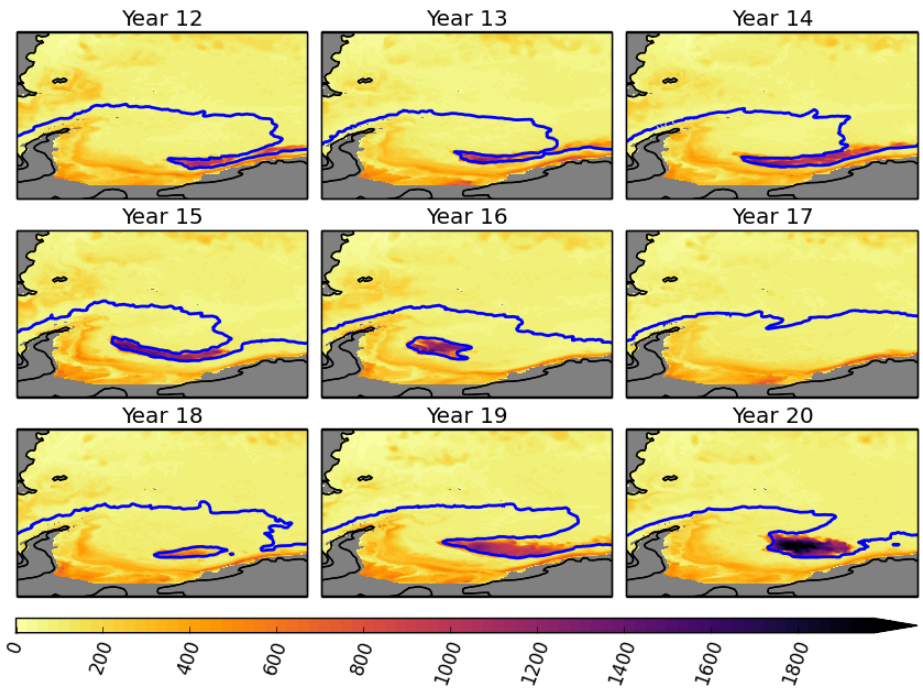

Figure 9: September mixed layer depth (m) and sea ice edge in GC2.1-N512O12 for years 12-20 indicating the presence of a Weddell Sea polynya. The sea ice edge (marked in blue) is based on a threshold of 15% ice concentration.

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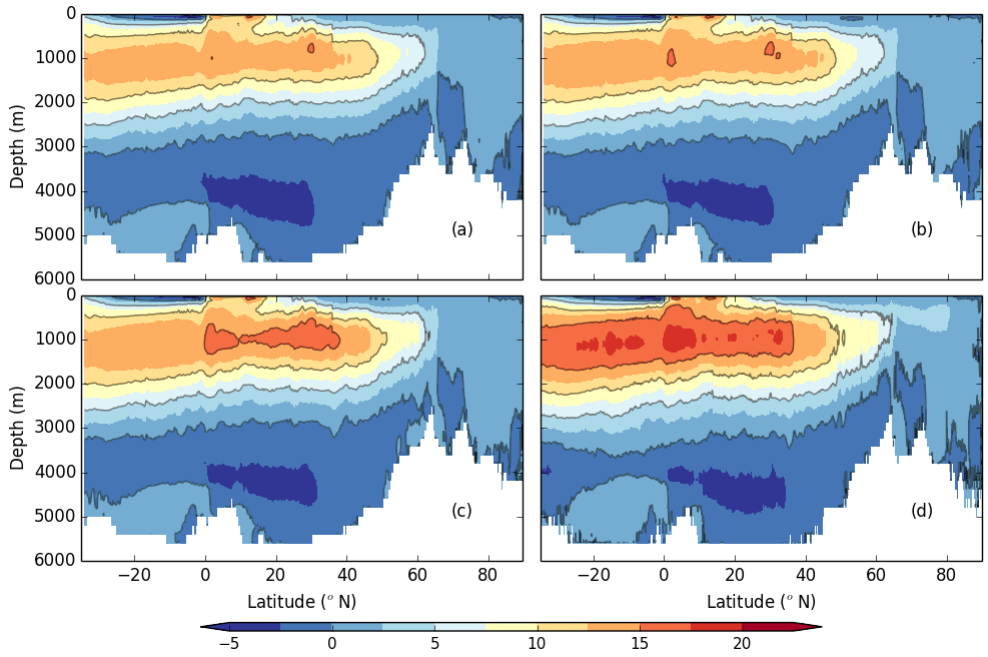

Figure 10~~9~~: Atlantic Meridional overturning for (a) GC2, (b) GC2-N512, (c) GC2.1 and (d) GC2.1-N512O12, meaned over years 11-20. Contours in Sverdrups (10^6 m^3s^{-1}), with line contour spacing of 5 Sv.

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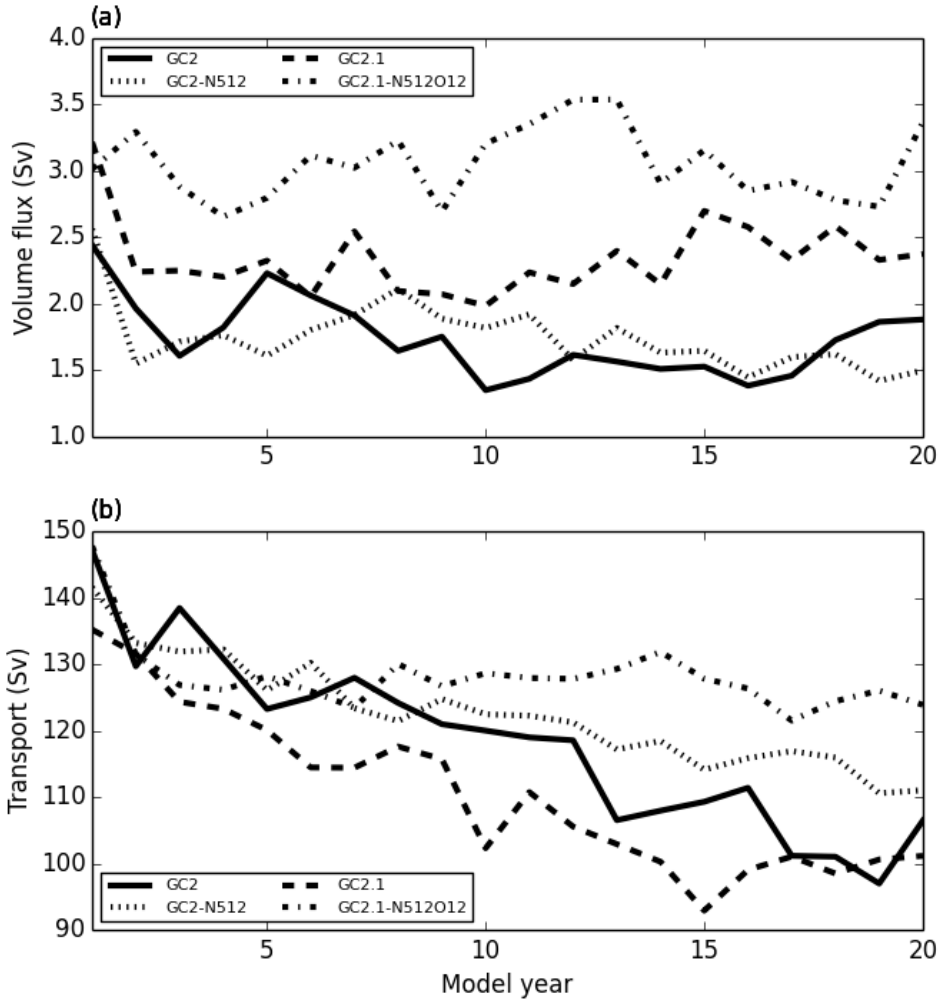

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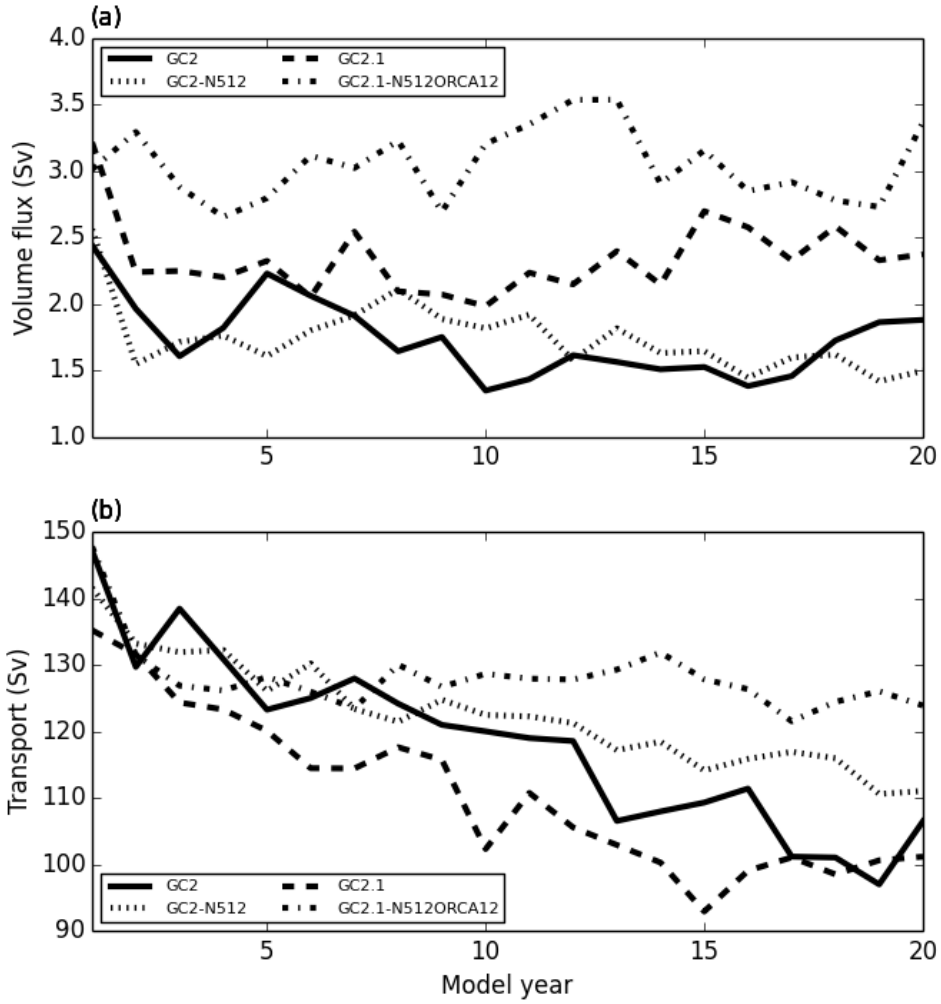
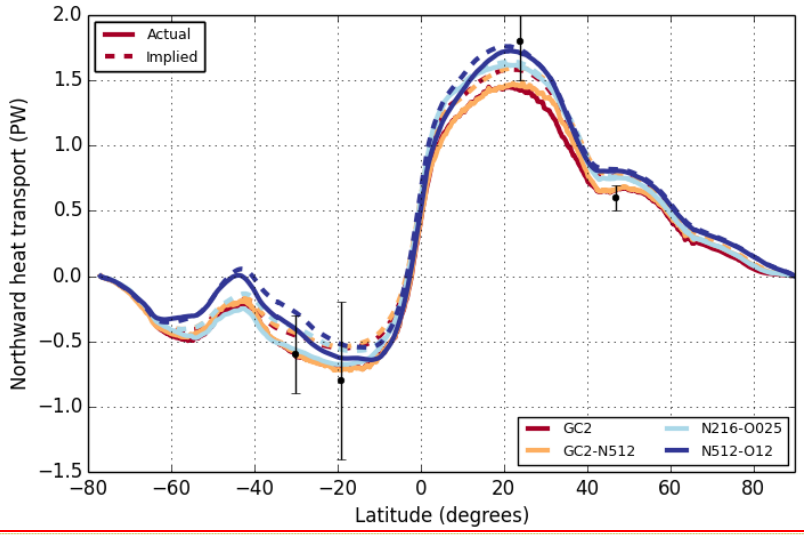
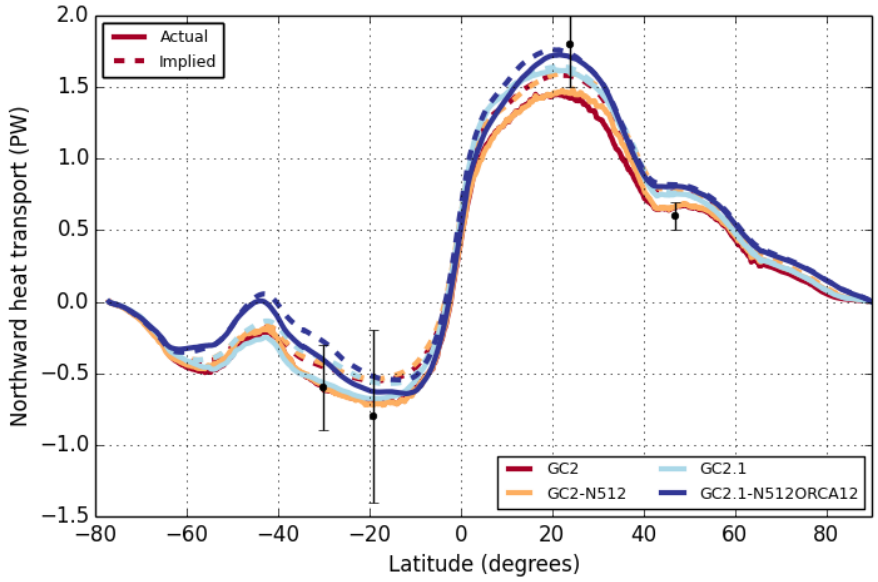


Figure 1~~0~~: a) Denmark Straits volume flux (Sv) (calculated as southward flow across the Greenland-Iceland-Scotland ridge below density of 27.8 kg m^{-3}) and b) Antarctic Circumpolar Current transport (Sv) from GC2, GC2-N512, GC2.1 and GC2.1-N512O12





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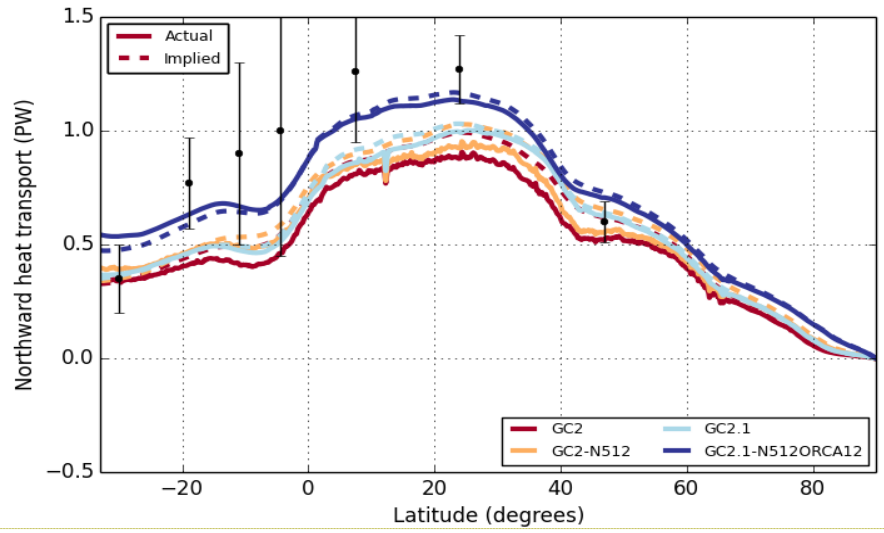

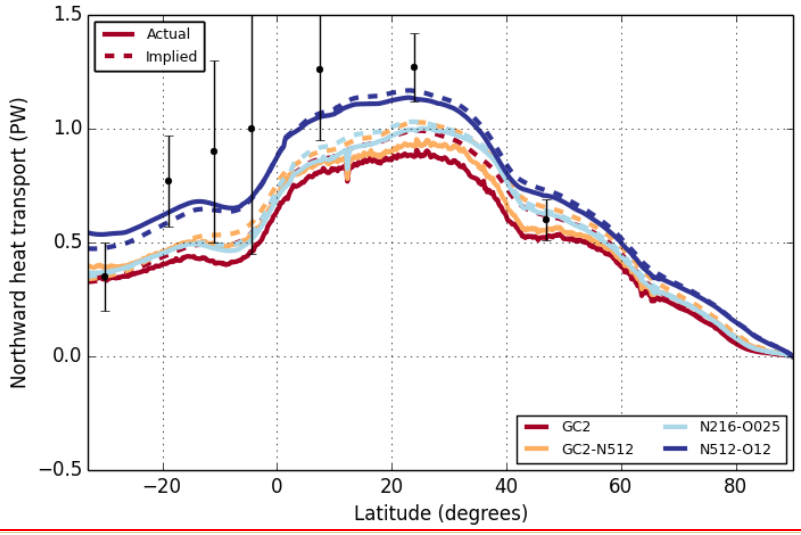

Figure 12~~4~~: Actual (bold) and implied (dashed) northward heat transports from GC2, GC2-N512, GC2.1 and GC2.1-N512O12 for (a) global and (b) Atlantic basins. The implied transport (integrated southwards from the North P~~p~~ole using the ocean surface heat flux) uses heat fluxes in which the global mean imbalance has been removed at every point. Observational estimates and associated error bars from Ganachaud and Wunsch (2003) are shown.

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