Met Office

Investigating biophysical feedbacks in a coupled physical-biogeochemical ocean model

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Contents

Executive summary

In the ocean, phytoplankton provide a feedback on the physics by altering the light attenuation, and therefore the distribution of heat uptake in the upper ocean. This feedback could play an important role in the ocean circulation and air-sea interactions, but is not currently included in Met Office forecasting or climate models. This report details a preliminary study to assess the impact of including the feedback in the Met Office's operational FOAM (Forecasting Ocean Assimilation Model) system.

The feedback was implemented in a low-resolution version of FOAM with no physical data assimilation. Four model runs were performed, covering the period 2009-2011, each with the light attenuation coefficient based on chlorophyll concentration from a given source: 1) constant, negligible chlorophyll (the control run); 2) 2D-varying chlorophyll from an ocean colour-based climatology; 3) 2D-varying chlorophyll from a fully coupled biogeochemical model; 4) 3D-varying chlorophyll from the coupled model.

The main results found were:

- Consistent with theory, the feedback resulted in a small increase in sea surface temperature (SST) in most regions, with a corresponding sub-surface cooling.
- The original model had an overall warm SST bias, so the feedback resulted in a slight degradation of SST error statistics compared with observations.
- Conversely, between about 50 m and 200 m depth, temperature bias was reduced.
- The increase in SST increased evaporation and reduced sea surface height. This was beneficial compared with observations, and substantially reduced model drift.
- In the central Tropical Pacific, the feedback enhanced surface warming during El Niño and enhanced surface cooling during La Niña.
- The inclusion of the feedback was found to make a larger difference than whether a model or climatology was used, with similar results in each case. However, using depth-varying chlorophyll did serve to slightly reduce sub-surface temperature errors.

In conclusion, the feedback resulted in changes consistent with theory and observations, and so it is recommended that it should be further tested with a view to including it in the operational FOAM system. Using climatological chlorophyll would be sufficient initially, with a longer-term aim of using a fully coupled biogeochemical model. The investigation of such a coupling in Earth-system climate models is also recommended.

1. Introduction

Whilst often considered to be simply driven by ocean physics, marine phytoplankton can also influence the physics of the ocean and atmosphere in a number of ways. Phytoplankton take up carbon during photosynthesis, affecting global cycling of the greenhouse gas carbon dioxide (Watson and Liss, 1988); sea-air fluxes of biological particles and gases such as dimethyl sulphide can lead to the formation of cloud condensation nuclei (Charlson et al., 1987); the presence of phytoplankton in the upper ocean can alter the ocean surface albedo (Jin et al., 2004); and phytoplankton in the water column affect the light attenuation and therefore the distribution of ocean heat uptake (Morel, 1988). It is this latter process which is the subject of this study.

Solar radiation reaching the sea surface can be split into longwave (wavelengths greater than about 700nm) and shortwave (wavelengths less than about 700nm, mainly visible light). Longwave radiation is absorbed in the upper few centimetres of the ocean, contributing to surface heating. Shortwave radiation penetrates more deeply, causing sub-surface as well as surface heating. In case I (Morel and Prieur, 1977) open ocean waters, the dominant factor controlling the depth over which shortwave radiation is absorbed is the concentration in the water column of chlorophyll-like pigments contained in phytoplankton cells (Smith and Baker, 1978; Sathyendranath et al., 1991). Essentially, the greater the chlorophyll concentration, the greater the absorption of shortwave radiation in the surface layers (see Morel (1988) and Morel and Maritorena (2001) for a more detailed treatment), meaning the associated heating is restricted to the near-surface. This impacts the sea surface temperature (SST), sub-surface temperature, ocean circulation and air-sea interactions.

The impact of spatial and temporal variations in chlorophyll concentration on ocean heat uptake and circulation has been previously studied in observations (e.g. Sathyendranath et al., 1991; Strutton and Chavez, 2004) and in models (e.g. Oschlies, 2004; Manizza et al., 2005; Marzeion et al., 2005; Lengaigne et al., 2007; Jochum et al., 2010; Turner et al., 2012). These studies have often focussed on highly productive and variable regions such as the Tropical Pacific and Arabian Sea, and have found significant effects on both regional and global scales. For instance, Manizza et al. (2005) found a roughly 10% global amplification of the seasonal cycles of temperature, mixed layer depth (MLD) and sea ice cover, whilst Turner et al. (2012) found increased rainfall during the onset of the South Asian summer monsoon. Meanwhile, a number of studies have noted an impact on El Niño Southern Oscillation (ENSO) variability, although with sometimes contradictory results concerning whether ENSO variability is enhanced (Marzeion et al., 2005; Lengaigne et al., 2007) or damped (Jochum et al., 2010).

This biophysical feedback process is not yet routinely included in forecasting or climate models however, including those run at the Met Office. With other processes becoming more accurately represented, this could be an increasingly important omission. For instance, the current generation of climate models typically underestimate SST in tropical regions (Wang et al., 2014), where biophysical feedbacks would largely be expected to increase surface warming.

This report details a preliminary study into the impact of including the feedback in hindcasts of the Met Office's operational global ocean forecasting system, with chlorophyll concentration specified either climatologically, or from a fully coupled biogeochemical model. Section 2 of this report describes the models, data and experiments, the results are presented in section 3, and conclusions are drawn in section 4.

2. Methods

Experiments have been performed using the Met Office's global Forecasting Ocean Assimilation Model (FOAM) system, which is based on the Nucleus for European Modelling of the Ocean (NEMO) hydrodynamic model (Madec, 2008). This study uses FOAM v13, which is as described in Blockley et al. (2014), but including the upgraded GO5.0 configuration of NEMO detailed in Megann et al. (2014). Operationally, FOAM is run globally at 1/4° resolution with assimilation of physical observations, but this study uses a 1° resolution configuration with no physical data assimilation. The reduced horizontal resolution (vertical resolution is unchanged at 75 levels) is for reasons of computational cost due to the coupling with the biogeochemical model. The lack of physical data assimilation is to allow the reaction of the free-running model to the biophysical feedbacks to be assessed. In this study, FOAM is forced at the surface with atmospheric data from the ERA-Interim reanalysis (Dee et al., 2011).

FOAM is coupled here with the Hadley Centre Ocean Carbon Cycle (HadOCC; Palmer and Totterdell, 2001) model, into which chlorophyll data derived from remotely sensed ocean colour are assimilated. The chlorophyll products are provided as part of the GlobColour project (http://www.globcolour.info), and are also available through MyOcean (http://www.myocean.eu). The data assimilation is as described in Ford et al. (2012) and Hemmings et al. (2008), but updated to use the 3D-Var NEMOVAR implementation of Waters et al. (2015) for the generation of surface chlorophyll increments.

In FOAM, the penetration of solar radiation is calculated using the "RGB" scheme of Lengaigne et al. (2007). The scheme splits shortwave radiation into three wavebands, representing red, green and blue light, and is designed as a simplification of the 61 waveband model of Morel and Maritorena (2001). For each of the three wavebands, a chlorophyll-dependent attenuation coefficient is specified at each model grid point. FOAM currently assumes a constant, negligible, chlorophyll concentration of 0.05 mg m^{-3} everywhere. This results in a constant set of attenuation coefficients, meaning that biophysical feedbacks are not considered.

In this study, biophysical feedbacks have been introduced by supplying the light penetration scheme with chlorophyll fields which more realistically represent global variations in phytoplankton distribution. Different sources of chlorophyll fields have been used. Firstly, a monthly-varying climatology of sea surface chlorophyll derived from ten years of GlobColour products (Ford et al., 2012). Values are assumed to be constant throughout the water column, meaning the spatial variation is only two-dimensional (2D). Secondly, the fully online coupled HadOCC model, which allows (sub-)daily and inter-annual variations in chlorophyll concentration to be accounted for. The 2D-varying surface fields can be propagated downwards in the same way as for the climatology, or the full three-dimensional (3D) HadOCC chlorophyll fields can be used, thus accounting for variations in chlorophyll with depth.

To test the impact of including biophysical feedbacks, and the different sources of chlorophyll fields, four hindcasts have been performed with FOAM-HadOCC:

1. A control run with no biophysical feedbacks (hereafter "Control");
2. Biophysical feedbacks based on the satellite climatology ("2D climatology");
3. Biophysical feedbacks based on surface chlorophyll from HadOCC ("2D HadOCC");
4. Biophysical feedbacks based on 3D chlorophyll from HadOCC ("3D HadOCC").

The hindcasts cover the three-year period from 01 January 2009 to 31 December 2011. This period was chosen as it includes a major El Niño period (May 2009 to May 2010) followed by a major La Niña period (June 2010 onwards).

The hindcasts are validated by comparing against satellite observations of sea surface height (SSH) and sea ice concentration, and in situ observations of SST and temperature and salinity profiles. These observations would normally be assimilated by FOAM, and the data sources are described in Blockley et al. (2014).

3. Results

From theory, the most obvious expected impact of introducing biophysical feedbacks would be to increase SST in most regions, as a greater proportion of shortwave radiation is absorbed in the surface layers. Mean SST over the full period of the hindcasts is shown in Fig. 1, with the hindcasts with feedbacks shown as differences from Control. All three feedback runs show a general surface warming, which is largest in regions of high chlorophyll concentration, such as the eastern Tropical Pacific and Brazil-Malvinas confluence. A notable exception is the central Tropical Pacific, which shows an overall cooling – the reasons for this will be discussed later in this report. As well as an increase in mean SST, there is also an increase in standard deviation (not shown). Very similar changes are seen whether chlorophyll from HadOCC or a climatology is used.

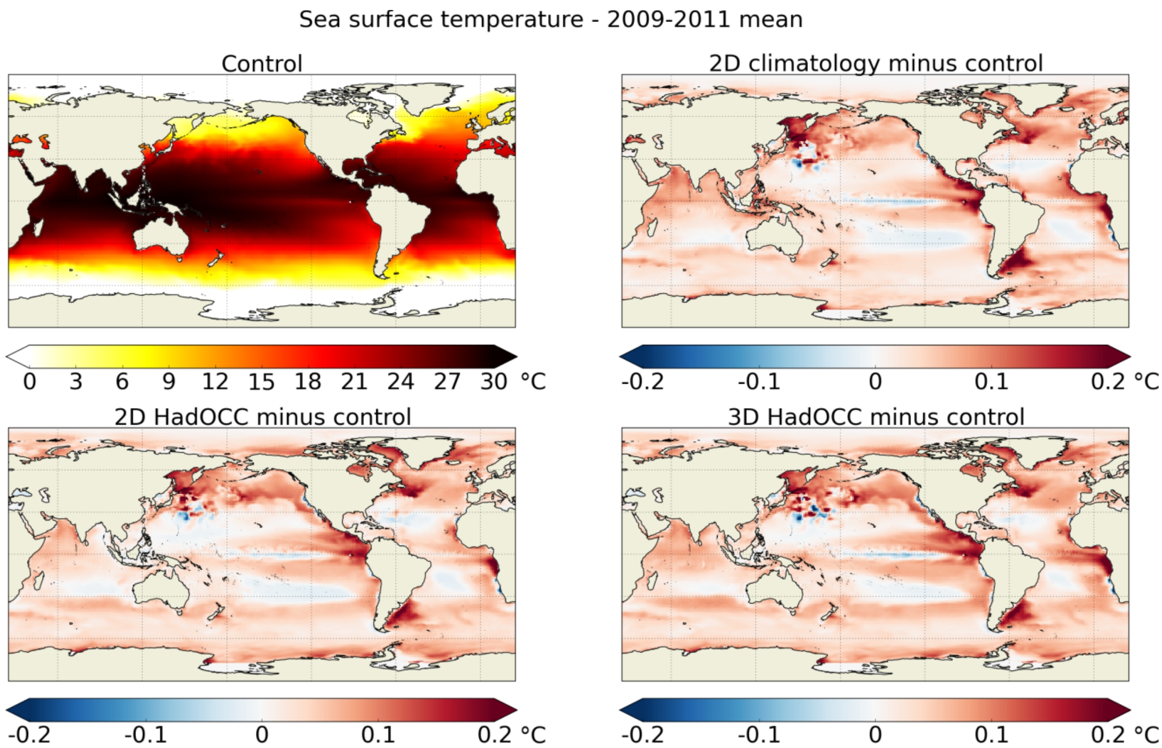

Fig. 1. *Mean SST for 2009-2011 from Control (top left), and the difference between Control and the three hindcasts with biophysical feedbacks (remaining panels, as labelled).*

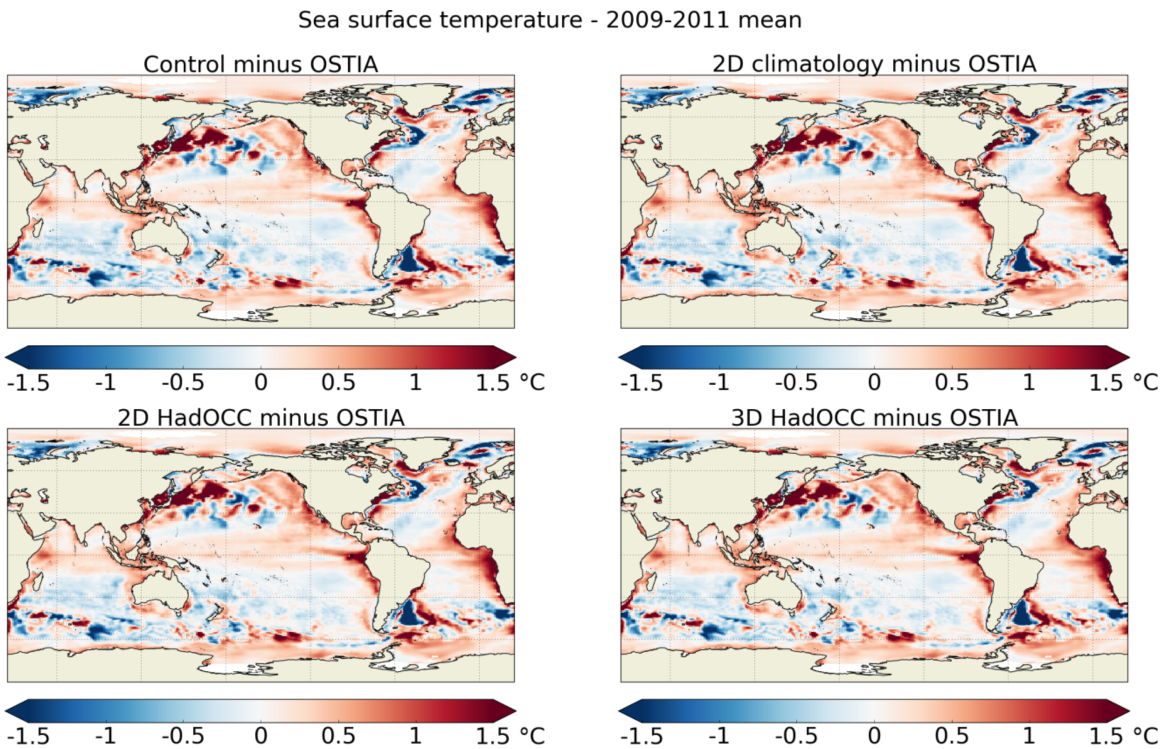

Fig. 2. *SST bias for 2009-2011 for each hindcast (panels as labelled) compared with OSTIA.*

Variable	Statistic	Control	2D climatology	2D HadOCC	3D HadOCC
SST (°C)	RMSE	1.146	1.163	1.159	1.160
	Bias	0.201	0.240	0.237	0.242
SSH (m)	RMSE	0.236	0.226	0.228	0.227
	Bias	0.130	0.112	0.113	0.110
T (°C)	RMSE	1.367	1.366	1.365	1.365
	Bias	0.146	0.127	0.130	0.129
S (psu)	RMSE	0.343	0.342	0.343	0.342
	Bias	0.005	0.006	0.006	0.006
MLD (m)	RMSE	44.472	44.748	44.741	44.712
	Bias	-4.738	-6.183	-6.150	-6.164
Sea ice	RMSE	0.147	0.149	0.150	0.150
	Bias	0.003	0.004	0.003	0.003

Table 1. *Global error statistics for 2009-2011 for each hindcast. All model values were first interpolated to observation locations at the nearest model time step. Bias refers to model minus observations. SST observations used are in situ only. T and S refer to temperature and salinity profiles respectively. MLD has been calculated from T and S matchups using the same method for model and observations. Sea ice observations are of sea ice concentration fraction.*

The difference in mean SST from each hindcast and from the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA; Donlon et al., 2012) is shown in Fig. 2. The biases for all four hindcasts are extremely similar, showing the changes due to the biophysical feedbacks to be small compared with the overall magnitude of SST errors. In some regions the warming from the feedbacks serves to counter cold biases (e.g. Brazil-Malvinas confluence), whereas in other regions warm biases are further increased (e.g. eastern Tropical Pacific). One area where a cold bias is reduced is off Newfoundland in the North Atlantic Current region. This is a common large bias in low-resolution ocean models, and is sometimes referred to as the "blue spot of death" (Gnanadesikan et al., 2007). Overall though, Control has a warm SST bias, which the introduction of biophysical feedbacks serves to increase. This is quantified in Table 1, which shows root mean square error (RMSE) and bias statistics for each hindcast compared with all available in situ SST observations. The global RMSE is increased by 1.5% from 1.146°C for Control to 1.163°C for 2D climatology, and similarly for 2D HadOCC and 3D HadOCC. This could indicate that the formulation of the light penetration scheme needs to be improved. Alternatively, since the changes due to the feedbacks are broadly in line with theoretical expectations, it could just be that there are other, cancelling, errors which should be addressed.

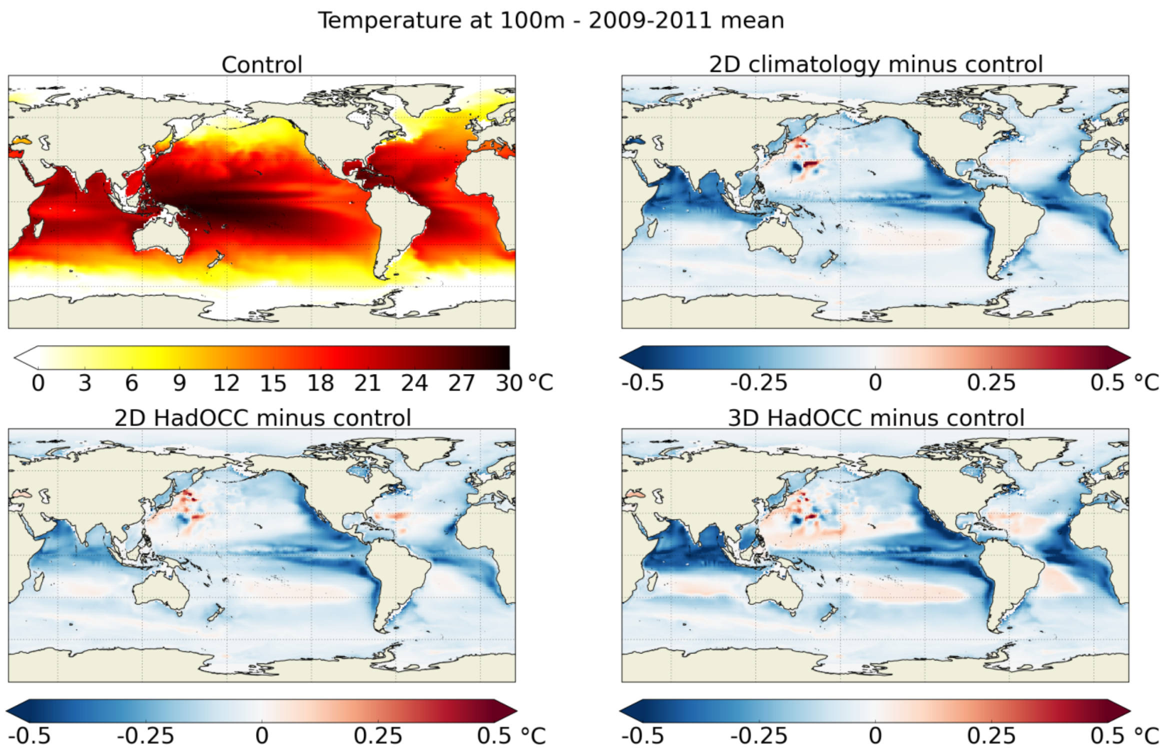

Fig. 3. *Mean temperature at 100m depth for 2009-2011 from Control (top left), and the difference between Control and the hindcasts with biophysical feedbacks (remaining panels, as labelled).*

In conjunction with an increase in SST, the biophysical feedbacks result in a sub-surface cooling in most regions, as demonstrated in Fig. 3, which shows mean temperature at 100m depth. The cooling is greatest in equatorial regions, and larger in magnitude than the surface warming. Overall, there tends to be a warming in the mixed layer and a cooling beneath this, with very little difference deeper than a few hundred metres. In the oligotrophic subtropical gyres however, where chlorophyll concentrations are typically lower even than the 0.05 mg m^{-3} assumed by Control, there is a surface cooling and a sub-surface warming. The sub-surface temperature changes in 3D HadOCC are generally larger than those in 2D HadOCC, demonstrating the impact of considering variations in chlorophyll concentration with depth, including deep chlorophyll maxima. Comparison with observations at different depths is made in Fig. 4, with overall error statistics given in Table 1. Very little change is found in RMSE, but all three hindcasts with biophysical feedbacks show a reduction in temperature bias between about 50m and 200m depth. Results are very similar for all three runs, but 3D HadOCC has a slightly lower bias than 2D HadOCC does, especially at 100m depth.

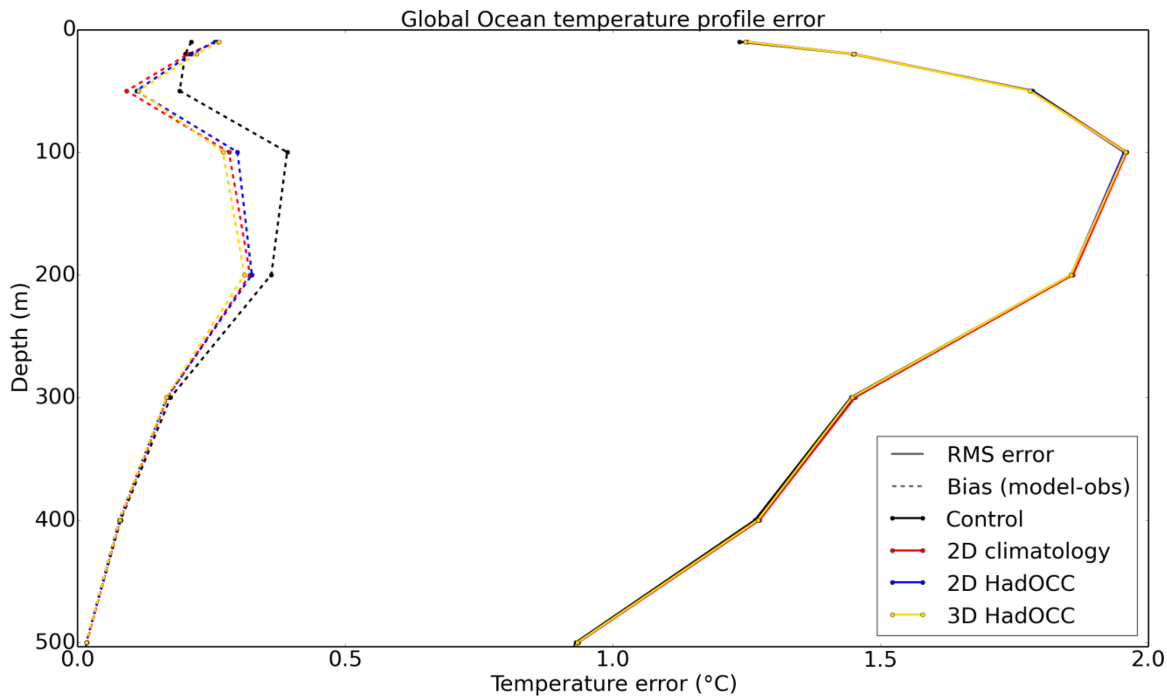

Fig 4. *Global temperature profile error for 2009-2011 for Control (black), 2D climatology (red), 2D HadOCC (blue) and 3D HadOCC (gold). Solid lines are RMSE, dotted lines are bias.*

Apart from on temperature, the largest impact seen due to the biophysical feedbacks is on SSH, with a reduction in mean SSH for 2009-2011 in all regions (not shown). This is primarily because increasing SST increases evaporation. Since the same atmospheric forcing is used for all hindcasts, there are no changes to precipitation, meaning this increased evaporation results in the surface ocean becoming saltier and denser, which reduces SSH. When compared with observations, as in Table 1, this reduction is globally beneficial, with improvements in RMSE and bias for all three runs with biophysical feedbacks. Control has a bias towards too high global mean SSH, and as can be seen in Fig. 5, there is a model drift which means this increases over time. This drift is not apparent in the runs with biophysical feedbacks, and the reduction in SSH error increases over the hindcast period accordingly (not shown).

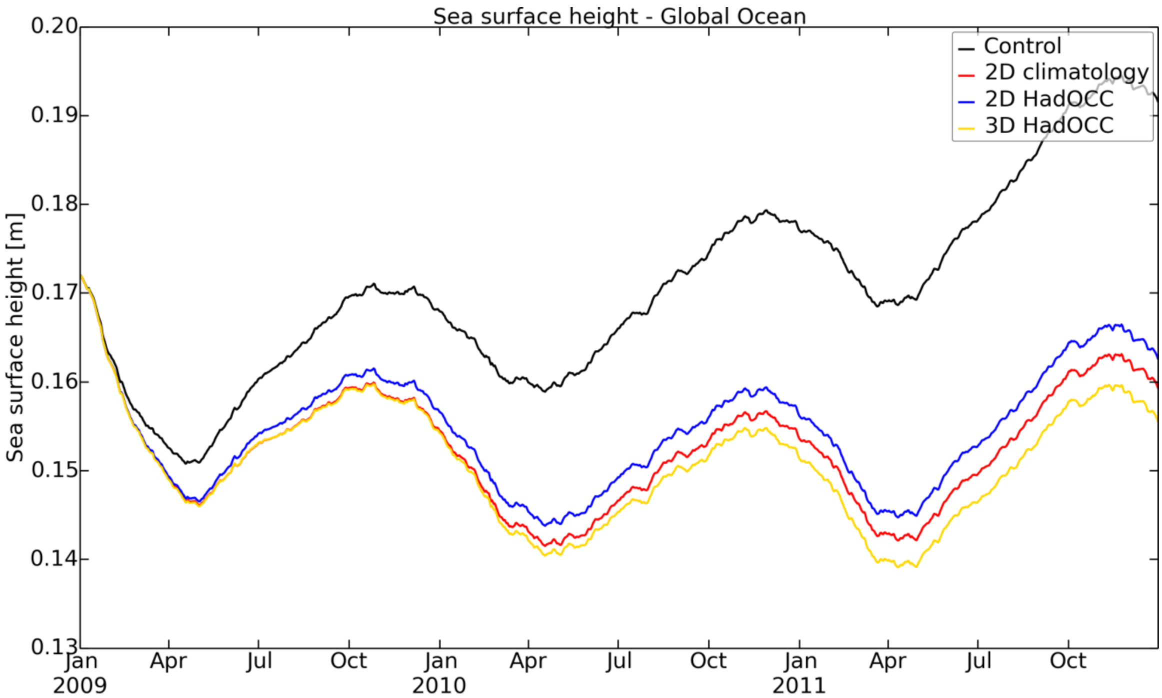

Fig. 5. *Time series of daily global mean SSH for Control (black), 2D climatology (red), 2D HadOCC (blue) and 3D HadOCC (gold).*

The remainder of this section will focus on particular regions where previous studies have suggested the inclusion of biophysical feedbacks might have a significant impact. Firstly, the Tropical Pacific, which is the source of ENSO variability, a major driver of global weather patterns. As noted in the discussion of Fig. 1, the feedbacks resulted here in an overall reduction in SST in the central Tropical Pacific, counter to the patterns seen in other highly productive regions. This is examined in more detail in Fig. 6, which shows depth versus time Hovmöller plots of temperature averaged over the Niño 3.4 box. This is defined as the region bounded by 120°W-170°W, 5°N-5°S. In the first half of the period, when ENSO is predominantly in its warm El Niño phase, the biophysical feedbacks do indeed result in an increase in SST. In the second half of the period, when

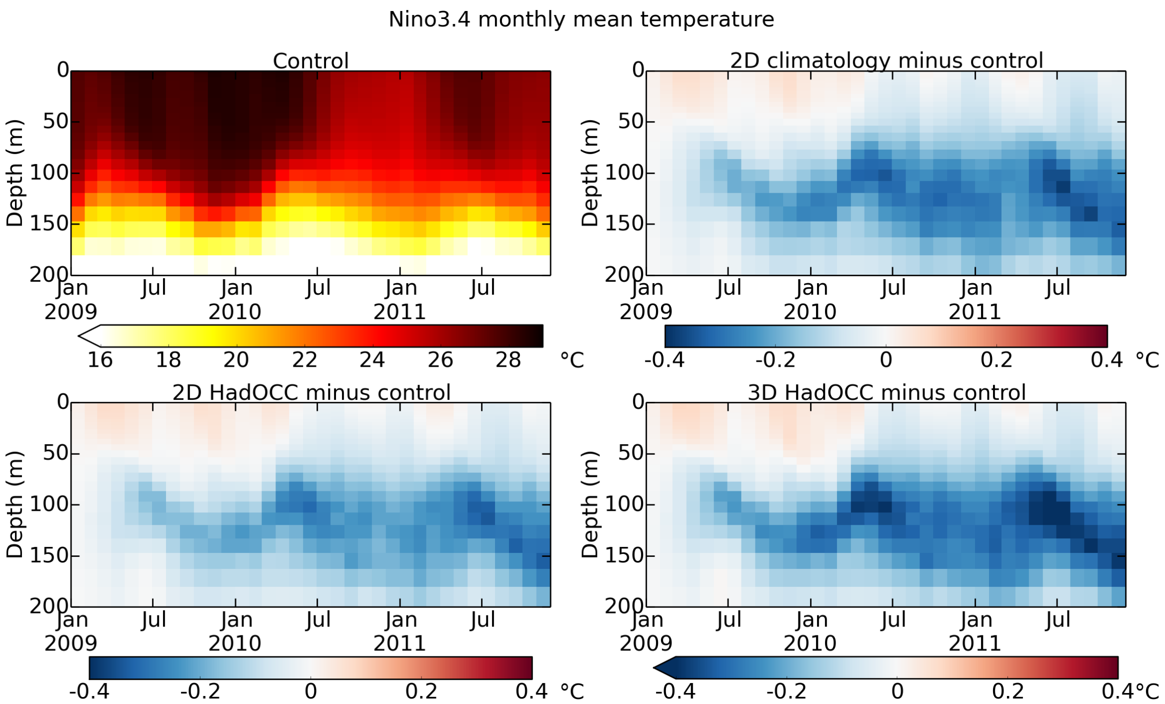

Fig. 6. *Hovmöller plots of monthly mean temperature with depth in the Niño 3.4 region for 2009-2011. The top left panel shows the absolute values for Control, the remaining panels show the difference between Control and each hindcast with biophysical feedbacks (as labelled).*

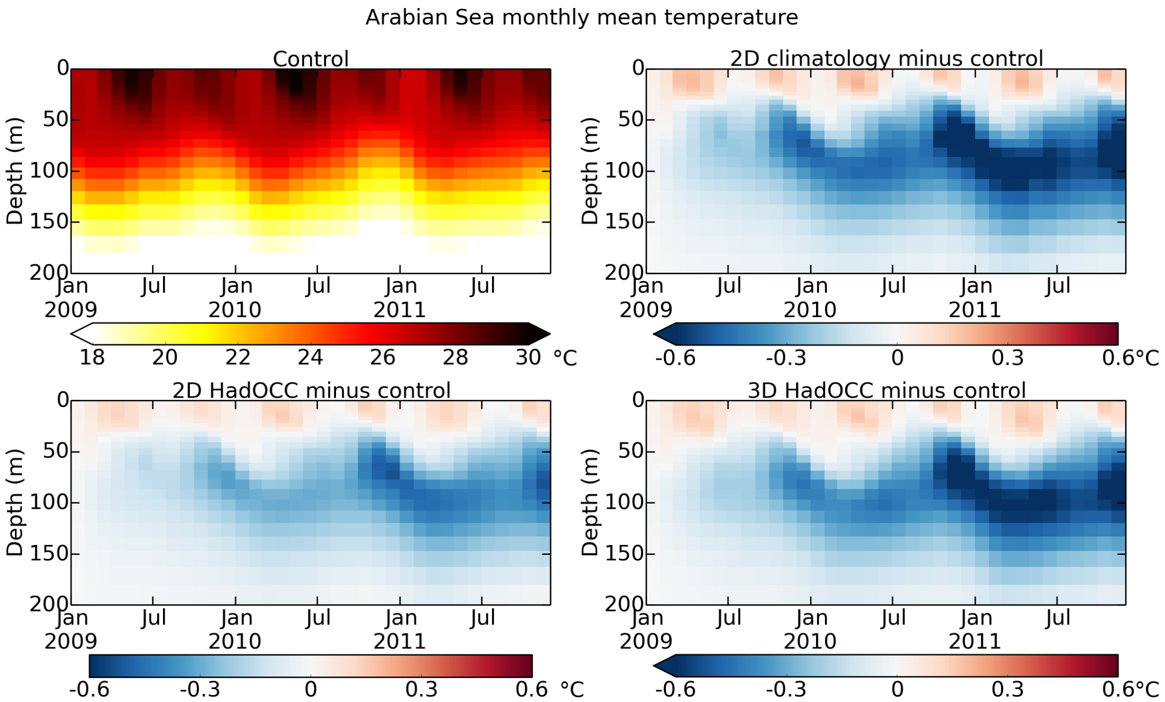

Fig. 7. *Hovmöller plots of monthly mean temperature with depth in the Arabian Sea for 2009-2011. The top left panel shows the absolute values for Control, the remaining panels show the difference between Control and each hindcast with biophysical feedbacks (as labelled).*

ENSO is in its cool La Niña phase, there is a reduction in SST. Overall, the cooling over the period is greater than the warming, hence the results seen in Fig. 1. Previous ocean-only modelling studies have found contradictory results about whether biophysical feedbacks warm (Murtugudde et al., 2002) or cool (Nakamoto et al., 2001; Manizza et al., 2005) the Tropical Pacific. In contrast, most coupled ocean-atmosphere modelling studies have found an overall surface warming (Lengaigne et al., 2007). Interestingly, in this current study, similar results are seen whether chlorophyll is taken from a climatology with no inter-annual or depth variability, or from a fully coupled biogeochemical model. This is contrary to the findings of other studies such as Jochum et al. (2010), and suggests that the physical model response is not dominated by previously documented mechanisms due to inter-annual chlorophyll changes (typically decreases during El Niño and increases during La Niña) or the presence of deep chlorophyll maxima. Instead, it seems to be due to changes in the relative importance of two "competing processes" described by Lengaigne et al. (2007), with these changes driven by physical, rather than biological, variability. Firstly, there is the direct warming effect due to the absorption of shortwave radiation. This will have no inter-annual variability in 2D climatology, and actual be stronger during La Niña than El Niño in 2D HadOCC and 3D HadOCC, because the increase in upwelling during La Niña increases the nutrient supply and therefore productivity. This warming effect is counter-acted by a cooling effect. Off the equator, there is a sub-surface cooling due to the feedbacks. These cooler sub-surface waters are advected towards the equator and upwelled. During La Niña upwelling is strengthened, and since the water being upwelled is even cooler due to the feedbacks, the cooling of surface waters during La Niña periods is enhanced. During El Niño this sub-surface cooling effect still occurs, but because upwelling is decreased, the surface warming due to changes in light attenuation dominates, thus enhancing the surface warming that characterises El Niño.

Another previously studied (e.g. Sathyendranath et al., 1991; Turner et al., 2012) area of interest is the Arabian Sea. This exhibits large seasonal variability in both physics and chlorophyll, and plays a key role in determining Asian monsoon rainfall. Hovmöller plots of temperature in this region are shown in Fig. 7. When biophysical feedbacks are included, an enhancement of the seasonal cycle of SST is seen, with further warming during the clear-sky conditions preceding the monsoon, and a slight cooling effect during the monsoon. These results are very similar to those obtained by Turner et al. (2012), to which the reader is referred for a description of the mechanisms, and so similar changes in monsoon rainfall might be expected if FOAM were coupled to an atmosphere model.

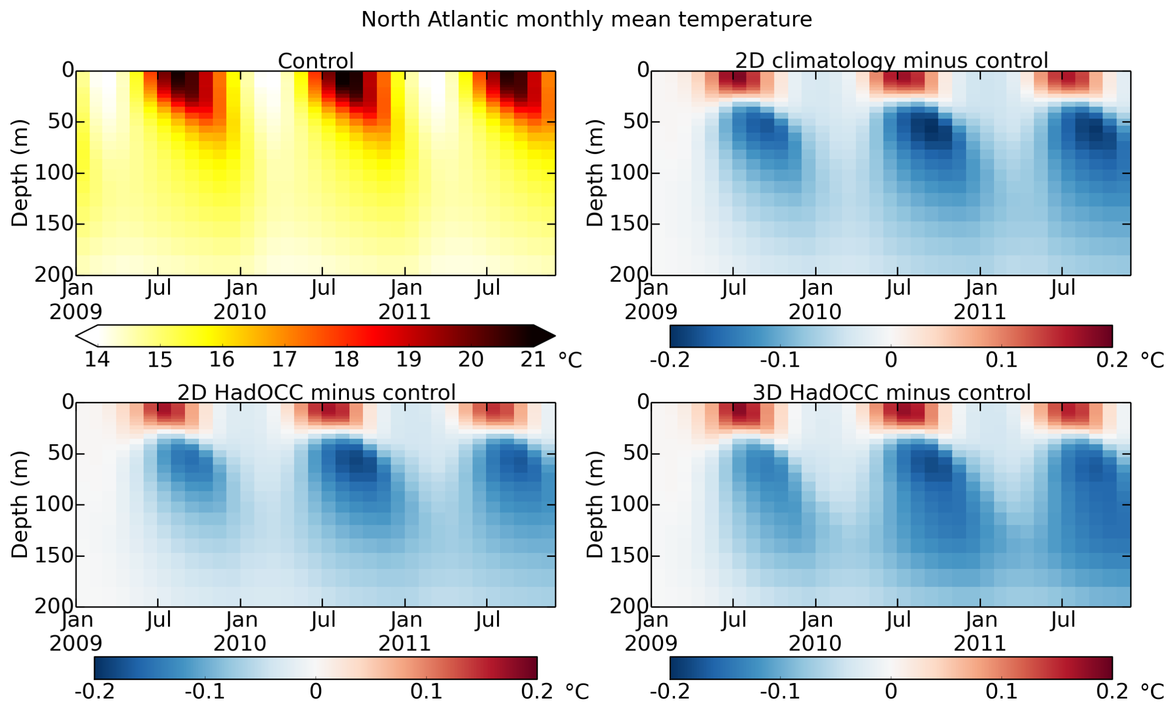

Fig. 8. *Hovmöller plots of monthly mean temperature with depth in the North Atlantic for 2009-2011. The top left panel shows the absolute values for Control, the remaining panels show the difference between Control and each hindcast with biophysical feedbacks (as labelled).*

Finally, a region of particular interest for UK and European climate is the North Atlantic, and Hovmöller plots of temperature averaged over this region are shown in Fig. 8. The biophysical feedbacks result in an amplification of the seasonal cycle of SST, with a warming effect during summer and a cooling effect during winter. The increase in SST during summer months seems to be due to the direct heating effect from the seasonal increase in chlorophyll concentration. In winter, chlorophyll concentrations are much lower, but still typically higher on average than the 0.05 mg m^{-3} assumed by Control, meaning the cooling effect must be an indirect one. It seems to result from the sub-surface cooling introduced by the biophysical feedbacks during summer and autumn. When the mixed layer deepens in winter, the sub-surface waters are colder than they would be otherwise, cooling the entire mixed layer. The feedbacks also result in a slight deepening of the MLD during winter (not shown), but since this is by no greater than 2m on average, it is unlikely to have a substantial impact on a basin scale.

It should be noted that whilst the focus of this study is on the physical impacts of the biophysical feedbacks, impacts would also be expected on the biogeochemical fields, including the carbon cycle. This is largely left as an area of future research, which will be especially relevant in the context of Earth-system models, but some comparison has been performed here between HadOCC fields from Control and 2D climatology, performed without chlorophyll data assimilation. In terms of global error statistics, very similar results were obtained for both runs when comparing surface chlorophyll against GlobColour products, and fugacity of carbon dioxide (fCO_2) against in situ observations from the Surface Ocean Carbon Atlas (SOCAT) database (Bakker et al., 2014). The main regions with notable differences in the mean fields were the eastern Tropical Atlantic, Indian Ocean, eastern Tropical Pacific, and high latitude areas. In the eastern Tropical Atlantic and Indian Ocean the biophysical feedbacks resulted in a decrease in surface chlorophyll and increase in sub-surface chlorophyll, with an overall decrease in depth-integrated primary production. This was combined with a decrease in surface fCO_2 and therefore a reduction in CO_2 outgassing, particularly in the Arabian Sea during the monsoon months. In the eastern Tropical Pacific there was a smaller biological response, but still a decrease in surface fCO_2 and reduction in CO_2 outgassing, particularly during periods of La Niña. In both the Arctic Ocean and Southern Ocean, the feedbacks resulted in an increase in surface chlorophyll in spring and summer months, in regions of seasonal ice melt.

4. Summary and conclusions

Biophysical feedbacks have been implemented in a coupled physical-biogeochemical ocean model by allowing variations in chlorophyll concentration to affect the attenuation of shortwave radiation. The impact of this has been assessed in a set of three-year hindcasts, with chlorophyll concentration taken either from a satellite-derived climatology or from the coupled biogeochemical model. Consistent with theory, there was an overall increase in SST, sub-surface cooling, and decrease in SSH. Biases in sub-surface temperature and SSH were reduced, whilst SST biases were increased. In general, similar results were obtained whether modelled or climatological chlorophyll was used, and the magnitudes of the impacts were small in comparison to total model error. Regional and seasonal variations in impact were found, such as an increase in ENSO variability in the central Tropical Pacific, and enhancement of the seasonal cycle of SST in the North Atlantic and Arabian Sea.

These feedbacks are a well-documented process that is currently omitted from Met Office forecasting and climate models. This study demonstrates that the process can be successfully implemented, albeit with mixed impact on error statistics. Whether the increase in SST error is due to inaccuracies in the formulation of the solar radiation penetration scheme, or simply the reduction in a compensating error, is unclear. Either way, the results are sufficiently encouraging, and the process sufficiently important, that further testing (and if necessary development) should be carried out, with a view to implementing the feedbacks in the operational FOAM system. Since similar results were achieved with climatological chlorophyll as with using HadOCC, and the coupled FOAM-HadOCC system is not yet run operationally, using a chlorophyll climatology should be the first step. In the longer term, the aim should be to include a fully coupled biogeochemical model, in order to account for inter-annual variability, and variations in chlorophyll with depth.

Biophysical feedbacks are also expected to be important in longer-timescale ocean model runs, and in coupled ocean-atmosphere models. Therefore the inclusion and assessment of such feedbacks in climate models (especially Earth-system models), and seasonal-to-decadal forecasting systems, is also recommended. The process should also be considered during development of the Met Office coupled ocean-atmosphere numerical weather prediction system, which is becoming increasingly mature, and in regional shelf seas models.

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