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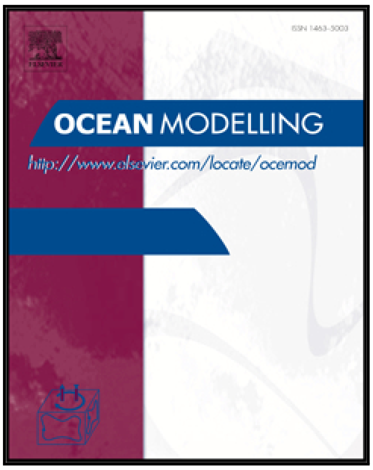

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Highlights

- Tangible benefits from increasing ocean resolution towards mesoscale eddy resolving
- Ocean mesoscale variability in boundary current regions impacts the atmosphere
- Coupled feedbacks are important in western boundary current dynamics
- Sub-gridscale parameterisations remain important for all resolutions
- Future research priorities are identified

Will high-resolution global ocean models benefit coupled predictions on short-range to climate timescales?

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ABSTRACT

As the importance of the ocean in the weather and climate system is increasingly recognised, operational systems are now moving towards coupled prediction not only for seasonal to climate timescales but also for short-range forecasts. A three-way tension exists between the allocation of computing resources to refine model resolution, the expansion of model complexity/capability, and the increase of ensemble size. Here we review evidence for the benefits of increased ocean resolution in global coupled models, where the ocean component explicitly represents transient mesoscale eddies and narrow boundary currents. We consider lessons learned from forced ocean/sea-ice simulations; from studies concerning the SST resolution required to impact atmospheric simulations; and from coupled predictions. Impacts of the mesoscale ocean in western boundary current regions on the large-scale atmospheric state have been identified. Understanding of air-sea feedback in western boundary currents is modifying our view of the dynamics in these key regions. It remains unclear whether variability associated with open ocean mesoscale eddies is equally important to the large-scale atmospheric state. We include a discussion of what processes can presently be parameterised in coupled models with coarse resolution non-eddying ocean models, and where parameterizations may fall short. We discuss the benefits of resolution and identify gaps in the current literature that leave important questions unanswered.

1. Introduction

The ocean is a fundamental part of the climate system through its dominant role in storing heat and carbon, and in modifying climate responses to anthropogenic forcing (e.g., Stocker, 2013). On seasonal and decadal timescales the ocean memory in both the Tropics and Extratropics plays an important role in setting the space and time scales for variability (Kirtman et al., 2013; Latif, 2013).

Coupled ocean-atmosphere-land-ice modelling systems are now being tested for global prediction on short-range timescales (Brassington et al., 2015) and are well established on longer time horizons from seasonal prediction to climate change projections. As such modelling systems evolve, there are significant choices to be made regarding the competing needs for refined resolution to enhance the fidelity of resolved flow features; increased component complexity/capability to allow for the representation of otherwise missing processes and feedbacks; and increased numbers of ensemble members required to extract a signal from the noise (e.g. Ferro et al., 2012; see Figure 1). Further competing needs arise from those associated with data assimilation required for initialisation of forecast/prediction systems.

Resource allocation largely depends on the goals of the research and/or operations. For example, Schneider et al. (2017) argue that climate sensitivity questions are best answered by focusing resources on refining atmospheric resolution, with the aim to reduce uncertainties with cloud processes. For prediction, however, we contend that fine scale transient ocean processes are crucial towards improvements in prediction skill, thus identifying the key use for enhanced ocean resolution. Such discussions take on renewed energy as the advent of exascale computing opens the possibility for significant enhancements to model complexity/capability, refined resolution, and significant increases in ensemble number.

Our focus is motivated by the work of Haarsma et al. (2016), who emphasize the enhanced fidelity for predictions available with increased resolution in all components of global coupled models. Whereas Haarsma et al. (2016) focus largely on atmospheric resolution, we emphasize the potential benefits from enhanced ocean model resolution. In so doing, we hope to enable informed decisions when choosing from among the competing needs and goals of climate system modelling.

In the atmosphere, the first baroclinic mode Rossby radius is approximately 1000 km at mid-latitudes, and this scale sets that of synoptic atmospheric variability (i.e., the day-to-day weather patterns). The atmospheric components in the Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012) typically have a resolution of about 100 km. These models are thus able to realistically capture synoptic scale atmospheric motions, though they are far too coarse to resolve convective motions and clouds (e.g., Schneider et al., 2017). For the ocean, the 1st baroclinic Rossby radius decreases from a few hundred km near the equator to a few km near the poles and on the shallow continental shelves. The smaller scales relative to the atmosphere are associated with differences in vertical stratification and characteristic depth scales. As in the atmosphere, eddy activity is intensified in key locations, i.e. “oceanic storm-track” such as the Western Boundary Currents (WBC) and the Antarctic Circumpolar Current (ACC). However, these eddies are ubiquitous through the global ocean, with, for example, Chelton et al. (2011) identifying 215,000 eddies with lifetimes over 4 weeks in a 20 year period from the AVISO (http://www.aviso.altimetry.fr/) sea-surface height analysis. Like the atmospheric components, many of the ocean components employed in CMIP5 climate models have a resolution of ~100 km or 1°. These models are thus unable to explicitly resolve oceanic mesoscale motions associated with the Rossby radius length scale, such as transient mesoscale eddy fluctuations and baroclinic boundary waves.

When ocean model resolution is refined sufficiently to explicitly capture transient mesoscale motions, the simulations exhibit fine scale boundary currents, jets, meanders, coastal upwelling zones, and transient fluctuations, each of which correspond to the observed ocean. The question we wish to address in this review is whether these fine scale ocean features have an impact on predictions using coupled model systems. One step towards addressing this question is to investigate the impact of fine scale Sea Surface Temperature (SST) forcing on atmosphere models. Such numerical experiments provide an indicator of the importance of resolving ocean mesoscale fronts and eddies to capture atmospheric variability (e.g., Minobe et al., 2008; Chelton and Xie, 2010; Frenger et al., 2013; Ma et al., 2015). While this approach addresses the effect of the surface boundary condition on the large-scale atmospheric response, it clearly neglects any feedbacks which could be crucial to the coupled response. In coupled models, it is important to address the potential mismatch in resolved spatial scales between the atmosphere and the ocean components. In particular, will ocean resolution only impact on the atmospheric response when there is sufficient vertical and horizontal resolution in the atmospheric component?

We have particular interests in identifying where ocean simulations with an active mesoscale eddy field lead to an improved prediction of atmospheric variability over a range of timescales. Questions that form the focus and outline of this paper are the following.

- What are the benefits of increased ocean resolution for global ocean simulations?
- Is there evidence from atmosphere models that increased resolution in oceanic forcing (e.g., SST) enhances the fidelity of atmospheric processes?
- What is the evidence of enhanced realism in coupled model systems resulting from increased ocean resolution?
- Could the benefits of increased resolution be achieved by parameterisation of sub-gridscale processes in coarser resolution models?

In this paper, we first review the benefits from ocean horizontal and vertical resolution that have been seen in forced ocean/sea ice models (section 2). In section 3, we then turn our attention to evidence for the impact of the small-scale ocean features on atmospheric simulations. Section 4 presents the evidence for improved simulations from coupled models with an oceanic mesoscale eddy field and discusses to what extent these impacts can be captured by coarse-resolution ocean components with parameterised eddy effects. We discuss issues raised in this review in section 5. Finally, we summarise the current state of knowledge and propose priorities for future research in section 6.

The number of studies that utilise high resolution ocean components either forced ocean/ice or coupled experiments is still relatively small compared to those at more standard CMIP5 resolutions. In that sense, this review might be viewed as pointing out the emerging consensus and remaining challenges.

2. Impacts of horizontal and vertical resolution in forced ocean models

Increasing ocean model horizontal resolution from a relatively coarse scale of 1° towards resolving the first baroclinic Rossby radius fundamentally changes the character of the simulated ocean. Quite simply, the simulations transition from the relatively smooth laminar flow regime found in coarse models to a chaotic turbulent regime in mesoscale eddying models.

Hallberg (2013) considers the horizontal grid spacing required to admit the first baroclinic Rossby radius with two grid points (Figure 2). Models with resolutions of 1° or coarser do not admit transient eddy features, whereas “eddy-permitting” (or “eddy present”) models (with resolution of ~1/4°) resolve the first baroclinic mode in the low latitudes and exhibit variability similar to that observed by satellite (Penduff et al., 2010). Resolutions of roughly 1/10° or 1/12° are needed to resolve the first baroclinic Rossby radius in the open ocean of the middle to high latitudes (“eddy resolving” or “eddy active” models). Achieving a full resolution globally, including the high latitude continental shelves, requires roughly 1/50° resolution. Furthermore, even finer resolution is needed to capture the second and higher baroclinic modes. Although our focus in this review concerns the mesoscale, recent results point to the importance of the even smaller scale submesocale processes (with typical length scales of a few km or smaller) for upper ocean restratification and associated impacts on air-sea fluxes (e.g., Haine and Marshall, 1998; Boccaletti et al., 2007; Fox-Kemper et al., 2008; Thomas et al., 2013, Naveira Garabato et al., 2017).

While most efforts have focussed on horizontal resolution, it is also relevant to ask about the requirements for vertical resolution. Stewart et al. (2017) propose that vertical grid spacing be set according to the needs of resolving the vertical structure associated with those baroclinic modes admitted by the horizontal grid spacing. They suggest at least three vertical levels are required to resolve the depth between the surface and the first zero crossing (of vertical velocity) of the baroclinic mode and between subsequent zero crossings. This requirement implies that maximum vertical resolution (i.e., minimum vertical grid spacing) is required where either bathymetry is shallow or stratification is strong. For z-coordinate models, vertical resolution of 75 vertical levels (e.g., Megann et al., 2014), is sufficient to globally resolve the first baroclinic mode in the open ocean, with less required in shelf regions with depths shallower than ~100m. Similar arguments applying to sigma-coordinate models, and to a lesser extent to isopycnal coordinate models.

2.1. Representing boundary and frontal currents

The representation of boundary currents is significantly improved as resolution increases and the ocean model becomes less diffusive/viscous. For example, Marzocchi et al. (2015) show a continued improvement in North Atlantic surface circulation patterns as the resolution increases from 1° to 1/4° and 1/12°. In particular, the position of the North Atlantic Current (NAC, the extension of the Gulf Stream into the Atlantic after separation at Cape Hatteras) becomes increasingly realistic when compared with satellite altimetry. The improvements are seen in terms of its mean location and, at 1/12°, in its eddying structure in the North-West corner where the flow takes a general northward deflection around the Grand Banks before returning to a more zonal pathway. Improving the position of the NAC, and in particular the presence of the relatively warm eddies in the Northwest corner, also leads to significantly reduced SST biases in the North Atlantic which imprints on the atmospheric state (e.g., Scaife et al., 2011).

Further improvements in the representation of boundary currents (notably their penetration and associated recirculation gyre) are found when refining beyond 1/12°, as illustrated in Figure 3 with simulations carried out with HYCOM by Chassignet and Xu (2017) (see also Hurlburt and Hogan, 2000; Levy et al., 2010).

This example brings into question the use of observations for model evaluation. At 1/50°, the overall distribution of Eddy Kinetic Energy (EKE) (e.g., RMS) is in good agreement with observations, especially its zonal extent but its amplitude is significantly larger, especially around the New England seamounts. The difference reflects limitations of the altimetry (here AVISO) which only resolves eddies on O(150) km length scales over a 10-day window. When the 1/50° model is subsampled to represent the altimetric processing (with a 150 km spatial bandpass filter and 10-day temporal averaging), the EKE resembles more closely the AVISO-derived EKE. This result suggests that the AVISO-derived EKE underestimates the observed EKE by approximately 30% in the Gulf Stream region (Chassignet and Xu, 2017).

The effect of increased resolution is not limited to the surface. Using a large collection of moored current meter records to assess the ability of three eddying global ocean models (POP, OCCAM, and HYCOM with 1/10° to 1/12° grid spacing), Scott et al. (2010) found that the time-averaged total kinetic energy throughout the water column in the models only agreed within a factor of two above 3500 m, and within a factor of three below 3500 m. Thoppil et al. (2011) did show that increasing the model resolution to 1/25º significantly increased the surface and the abyssal EKE and clearly demonstrated that a better representation of upper ocean EKE is a prerequisite for strong eddy-driven abyssal circulation. In Figure 4, vertical sections of EKE along 55°W for the three HYCOM simulations shown in Figure 3 are compared to sections based on long term observations using drifters, floats, and moored current meters (Richardson, 1985). EKE is very weak at

1/12°, in agreement with the Scott et al. (2010) results. But it does increase significantly as the model resolution is refined and, at 1/50°, the level and vertical pattern of the zonal velocities and EKE are similar to the observations.

In spite of the improvements in simulations beyond ~1/10°, for many coupled applications, the step change associated with a resolution of ~1/10° will be significant for representing most boundary currents. At 1/12°, the Gulf Stream separates realistically at Cape Hatteras as an inertial jet without a spurious deflection to the north immediately after separation (Chassignet and Xu, 2017). Similarly, resolution of this order can be expected to capture the eastward penetration of the Kuroshio (Hurlburt et al., 1996); the retroflection of the Agulhas current and associated shedding of rings which play a key role in the transport of warm, saline water from the Indian Ocean into South Atlantic Ocean and feed the upper limb of the Atlantic meridional overturning circulation (Biastoch et al., 2008; Beal et al., 2011); a realistic West Greenland current (Chanut et al., 2008, Boning et al., 2016) which is associated with freshwater transport into the Labrador Sea; and the watermass structure in coastal regions, critical for ecosystem dynamics and impacts (e.g., Saba et al., 2016).

Boundary and frontal currents have also been shown to be regions of high intrinsic ocean variability; low frequency and large scale chaotic variability has been shown to exist within ocean-only models (Penduff et al., 2010; Serazin et al., 2017) with the largest fraction of the variability concentrated in regions of high eddy kinetic eddy, such as boundary and frontal currents. Intrinsic ocean variability is also extremely resolution-dependent, being very weak in coarse resolution models where eddies are parameterised and strong in eddy resolving models.

2.2. Impact of mesoscale eddies on the vertical heat balance

Increasing ocean model resolution has a key impact on the role eddies play in the ocean heat budget and in turn the climate system. As baroclinic eddies obtain their kinetic energy by releasing the available potential energy of the mean flow, they have a large effect on vertical transport. Namely, when averaged over broad scales, mesoscale eddies act to transport heat upwards within the ocean interior. Conversely, the mean flow generally transports heat downwards (Wolfe et al., 2008; Morrison et al., 2013; Griffies et al., 2015; Kuhlbrodt et al., 2015; von Storch et al., 2016; see Figure 5). In this way, mesoscale eddies act as a barrier or gatekeeper to heat penetration from the surface into the ocean interior. As resolution increases towards ~1/10°, the magnitude of the eddy heat transport increases. The increased upward mesoscale eddy heat transport largely compensates the downward transport from the mean and in turn reduces subsurface temperature warming drifts that otherwise appear in many coarser resolution models, including eddy-permitting models that represent weak transient eddies (Griffies et al., 2015; von Storch et al., 2016). Von Storch et al. (2016) show that a similar pattern also emerges for the vertical salt transport. These two studies indicate that there are two key regions for this vertical heat and salt transport. These regions are 1) the Southern Ocean due to the deep penetration of eddy energy within the water column and 2) the mid-latitude gyres where Ekman pumping brings heat into the ocean interior, with mesoscale eddy activity directly compensating this effect (Griffies et al., 2015, Doddridge et al., 2016). Presumably, the eddy heat and salt transports should numerically converge as the resolution increases, but this convergence has yet to be demonstrated.

2.3. Topographic control and overflows

As well as allowing fronts and eddies to be represented, increased horizontal resolution allows finer details of coastlines and bottom topography to be represented (e.g., Adcroft, 2013). One definition of an eddy resolving model is that it is able to represent the interaction between mesoscale motions and bathymetry sufficiently well for paths of the western boundary currents to be accurate (Hurlburt et al., 1996; Hogan and Hurlburt, 2000; Hurlburt et al., 2008). Hurlburt et al. (2008) suggested that baroclinic eddies flux momentum downward (consistent with their poleward heat flux) and induce an interaction with the bathymetry (see also Rintoul et al. (2001) for a review of vertical momentum transfer in the Southern Ocean). As the mean flow becomes sufficiently large at depth, bathymetric steering along *f/H* contours (due to conservation of potential vorticity) will likely intensify (Greatbatch et al., 1991).

Increased horizontal resolution also opens up the possibility of representing regions otherwise below the grid scale. This includes cavities below the Antarctic ice shelves (e.g., Losch, 2008) where the under ice shelf flow introduces zonal variation in the heat input to the ice shelves, affecting the pattern of ice shelf melt rates (e.g., Goldberg et al, 2012; Spence et al. 2014, 2017; Stewart and Thompson, 2015; Holt et al., 2017).

Grid resolution determines whether channels and straits that control exchange between basins (Whitehead, 1998) are present. Topography is frequently adjusted in models (e.g., Roberts and Wood, 1997; Beismann and Barnier, 2004) to ensure this exchange (an approach which in principle could be improved with the use of objective mapping of topography, such as proposed by Adcroft (2013)). Topographic impacts are particularly significant in overflow regions of the North Atlantic (including the Denmark Strait and Faroe Bank Channel; Legg et al., 2009; Wang et al., 2015) and around much of the Antarctic shelf (e.g., Snow et al., 2016). In both cases, deep water formed in shallower high latitudes is transported over sills or off the shelf into the deep ocean. At resolutions of approximately 1/10°, models have been shown to capture the exchange and downslope flow (Chang et al., 2009; Behrens, 2013) although the simulation may still have large biases in overflow properties (e.g., Marzocchi et al., 2012). Changes in overflow simulations have been cited as the cause of large-scale changes in the Atlantic Meridional Overturning Circulation (AMOC) as resolution increases. Winton et al. (2014) and Hewitt et al. (2016) found that increasing resolution affects the strength of the AMOC in opposite manners (decreasing/increasing respectively). In both cases, the suggestion is that the representation of overflows is implicated either due to their influence being reduced as topography is more realistic and less-tuned (Winton et al., 2014), or being stronger due to the presence of more accurate straits (Hewitt et al., 2016). Further investigation of the sensitivity of overflows and the AMOC to resolution is needed. In addition, investigation into parameterisation approaches (e.g. streamtubes; Danabasoglu et al., 2010 or Lagrangian particle approaches; Bates et al., 2012a,b; Snow et al., 2015) and two-way high resolution nesting to enable improved representation of critical overflows in global models is warranted.

An increase in horizontal resolution may also raise questions about the most appropriate vertical resolution or coordinate to represent interactions with topography. While partial cell representation of bottom levels in z-coordinates (Adcroft et al., 1997, Pacanowski and Gnanadesikan, 1998; Barnier et al., 2006; LeSommer et al., 2009) significantly improves the representation of topography and associated topographic waves, terrain-following (sigma) coordinates are an obvious choice for capturing topographic effects. Downslope flows are particularly sensitive to the choice of vertical resolution and coordinate. Idealised models show that high resolution both horizontally (3-5km) and vertically (30-50m) is required for geopotential coordinate models to capture the downslope flow of deep waters (Winton et al., 1998; Riemenschneider and Legg, 2007). In terms of coordinate choice, isopycnal models perform well in overflow regions due to their limited numerical entrainment (Legg et al., 2006; Wang et al., 2015), with similar behaviour holding in principle for terrain-following sigma models. Terrain-following coordinates are not commonly used for large-scale climate studies (but see Lemarie et al. (2012) for a discussion along with promising methods to resolve these limitations) and have their limitations for capturing near-surface processes, so they are commonly combined with z-coordinates in the near surface (e.g., Griffies et al., 2000).

3. Impacts of SST resolution on simulations of the atmosphere

To anticipate potential benefits of ocean resolution in a coupled model, we first turn to atmospheric simulations forced by SST fields. To what extent is the atmosphere influenced by its response to mesoscale fluctuations in the SST field? Is the mesoscale only important in terms of western boundary currents and their extensions or do transient mesoscale eddies in the open ocean also play a role?

3.1. Response of atmospheric circulation to basin-scale anomalies

In the 1990s and early 2000s, many studies explored the impact of SST anomalies (SSTA) on the atmospheric circulation, as well as the potential predictive skill associated with this impact. The focus was essentially on basin-scale SST anomalies typically forced by low frequency atmospheric variability (e.g. the North Atlantic Oscillation; NAO) or fluctuations in the large-scale ocean circulation (e.g. the AMOC or gyre circulation). A few influential studies (Rodwell et al., 1999; Mehta et al., 2000) showed that the NAO variations could be reproduced when SSTAs were prescribed in an atmospheric GCM. Although the mechanism behind these results was subject to debate (e.g. Bretherton and Battisti, 2000), these results suggested a potential for improved NAO prediction on seasonal timescales (assuming a useful predictability of the SSTA themselves).

How well is the atmospheric response to SSTAs understood? A consensus view, based on studies employing basin scale SSTA and coarse resolution atmospheric models (100km or larger horizontal grid cells), has been that the atmospheric response is relatively small, a few 10s m of geopotential height at 500 mb per K of SSTA (see review by Kushnir et al., 2002). While the primary response of the atmosphere to changes in SSTA is on the large scale, the feedback by transient (atmospheric) eddies (2-10 days band-pass filtered) has a substantial rectifying effect. Notably, the transient eddy feedback would tend to convert the fast baroclinic response (consistent with linear dynamics, see Hoskins and Karoly, 1981) into an equivalent barotropic response (Ferreira and Frankignoul, 2005, 2008; Deser et al. 2007). Despite progress in understanding the processes, the sensitivity of the large-scale atmospheric circulation to SSTA is inconsistent across different studies. For example, the atmospheric response is sensitive to atmospheric resolution (horizontal and vertical), background model climatology, seasonality, and details of the imposed SST patterns. This inconsistency is in part because of the low signal to noise ratio but also because of the complex eddy-mean flow interaction setting the equilibrium response to SSTAs.

An important consequence of this state-of-affairs is that the impact of large-scale SSTAs on atmospheric modes of variability (e.g. NAO) in coarse resolution AGCMs has been found to be rather small although sometimes significant (Saravanan, 1998), especially if the SSTAs have a large enough amplitude (see Woollings et al. (2012) in the context of coupled models). The associated predictability typically represents 10 to 20% of the monthly variance of the atmospheric modes (e.g. Kushnir et al., 2002; Keenlyside et al., 2008; Smith et al., 2010). It seems that such limitations are intrinsic in the use of the coarse resolution atmospheric models and large-scale patterns of SSTAs. This situation is further complicated by the fact that the SSTAs of interest are often themselves forced by the atmospheric variability (Frankignoul, 1985). These findings largely imply that in the extratropics, large scale air-sea interactions are, to first order, dominated by the atmosphere driving the SST variability (Frankignoul, 1985).

3.2. Response of the mid-latitude atmosphere to mesoscale ocean anomalies

New ideas and concepts are emerging that come out of the realisation that vigorous air-sea interactions occur on small (oceanic) space scales; i.e. over fronts and eddies (a few 10s to few 100s of km). Observations (mostly from satellite measurements) reveal a contrasting picture between small-scale and large-scale interactions. A robust signature of this difference is the association, at small scale, between a warm SSTA and increased surface wind stress while on the large-scale, the correlation is of the opposite sign, where increased surface wind stresses are associated with cold SSTA (Xie, 2004). The large-scale behaviour reflects the atmospheric forcing of the ocean, with increased surface wind stress driving increased turbulent fluxes (mainly latent) out of the ocean. The reversed signature appearing on the small-scale is interpreted as evidence for the opposite causality, where SSTAs drive anomalies in surface wind stress. As the resolution of satellite SST products has increased (typically from 1° to 1/2° or 1/4°), the imprint of the oceanic small-scale features into the Atmospheric Boundary Layer (ABL) has become noticeable (Xie, 2004; Small et al., 2008; Kelly et al., 2010).

Although the detailed mechanisms are still debated, a dominant effect is the modulation of the ABL by SSTAs. Over a warm SSTA, the ABL becomes more unstable, resulting in increased mixing, increased momentum flux and decreased shear. This situation results in a more efficient transfer of upper level winds down to the surface (Small et al., 2008). These processes result in a quasi-linear relationship between SSTA and wind-stress anomalies on the small scale (Frenger et al., 2013). The impact of small-scale SST features on the ABL is clearly found in atmospheric re-analysis and free-running AGCM simulations with prescribed SST. Impacts are also seen in coupled atmosphere-ocean models (e.g. Maloney and Chelton, 2006; Bryan et al., 2010), provided an ocean resolution of 1/4° or finer is used (Roberts et al. (2016), see Figure 6).

Importantly, the impact of fine scale SSTAs is not limited to the wind stress. Namely, due to divergence in the ABL, impacts are also found in boundary layer height, precipitation, low levels clouds, air-sea fluxes, and planetary albedos (Bryan et al., 2010; Kirtman et al., 2012; Frenger et al., 2013; Nakamura et al., 2015). A common weakness of the modelled results is that the slope of the linear regression between SSTA and wind stress anomalies is significantly smaller than observed. Recent results (Roberts et al., 2016) suggest that the magnitude of the slope is not strongly sensitive to resolution, provided ocean eddies and fronts are present in the solution, possibly pointing to a deficiency in the physics of ABL parameterizations (Song et al., 2009).

It is unclear whether the same mechanism of atmospheric adjustment applies over open ocean transient mesoscale eddies as it does over SST fronts associated with western boundary currents (WBCs). There are indeed crucial differences between the two cases: eddies are transient features found over the whole ocean while WBC SST fronts are quasi-permanent structures that often sit under storm tracks. It remains to be determined whether the thousands of cyclonic and anti-cyclonic (ocean) eddies that are present globally have a net effect on the atmosphere. SST fronts, however, can efficiently influence the atmospheric surface baroclinicity and recurrent cyclonic development directly, thereby affecting the eddy-driven (atmospheric) jet, and possibly annular modes that capture wobbles of the jet (Hotta and Nakamura, 2011; Sampe et al., 2013).

A central question now emerges: does the influence on the atmosphere from oceanic fronts and mesoscale eddies extend beyond the ABL into the free troposphere? This is a critical question to answer in order to determine the role of the ocean mesoscale on the predictability of larger-scale atmospheric variability. Net effects from the ocean mesoscale beyond the atmospheric boundary layer into the free troposphere are beginning to be seen in modelling studies (e.g., Minobe et al., 2008; Bryan et al., 2010; Ma et al., 2015; Smirnov et al., 2015; Parfitt et al., 2016; Piazza et al., 2016; Ma et al., 2017). Smirnov et al. (2015) recently analyzed the atmospheric response to an SSTA produced by a realistic Kuroshio displacement (e.g. Qiu and Chen, 2005) using two different atmospheric model resolutions (1° and 1/4°). The dynamical adjustment is significantly different between the two resolutions (see also Ma et al., 2017). At low atmospheric resolution, the diabatic heating generated by the SSTA is balanced by horizontal advection driven by a large-scale low-level response. This behaviour bears many similarities to those seen in earlier studies (e.g. Kushnir et al., 2002) and the linear balance discussed by Hoskins and Karoly (1981). In contrast, for the high resolution atmospheric model, vertical advection is a leading term in the heat budget.

Smirnov et al. (2015) point out that vertical motions within synoptic eddies are a key contributor to the net vertical advection.

Minobe et al. (2008) showed that the strong SST front associated with the Gulf Stream provides a sharp precipitation pattern over the front which is associated with parameterised convection (Minobe et al., 2010) rather than vertical motions. Further work by Vanniere et al. (2017) suggested that this reflected the shallow convection occurring in the cold sector of cyclones, which contrasts with the more likely role played by the warm sector of the cyclones and their ascending conveyor belts in Smirnov et al. (2015). However, we can conclude that as atmospheric resolution increases, vertical velocities become more intense as part of better resolving frontal circulations and possibly their instability - see Sheldon et al. (2017).

Simulations by Ma et al. (2015, 2017) showed that the impact of small-scale SST fronts under the storm track is not just local. Namely, comparison of simulations with and without eddy SSTA in the Kuroshio region revealed basin-wide changes in rainfall extending to the West coast of the US, thus suggesting a rectifier effect of mesoscale SST on the net diabatic heating within the storm track. The high resolution results suggest that SST anomalies directly impact synoptic eddies in the atmosphere, as opposed to low resolution results where atmospheric eddies appear as (important) feedbacks modifying the large-scale response.

Despite the limited number of studies, we contend that fundamental characteristics of the atmospheric response to small-scale SST anomalies are starting to emerge. In particular, vertical and horizontal motions are essential, and the impact of SST anomalies is directly felt through synoptic eddies and their embedded frontal circulations in the storm tracks. These are major differences compared to the basin-scale SSTA response to low resolution AGCMs discussed in section 3.1. Figure 7 summarizes possible biases of the latter because of their inability to see SST fronts as well as to represent the vigorous vertical exchanges communicating information between the ABL and the free troposphere.

4. Impact of ocean resolution in coupled AOGCM simulations

In section 2 we reviewed evidence that resolving the first baroclinic Rossby radius, at least in the lower to middle latitudes, makes a major improvement to ocean simulations, providing a degree of realism not possible in lower resolution models. In section 3 we argued that, given sufficient resolution, atmospheric models can respond to mesoscale features in SST fields associated with fronts and eddies that are present in eddy-resolving models (and to a lesser extent in eddy-permitting models). Together, these results suggest that introducing enhanced ocean resolution into coupled models, along with sufficient atmospheric horizontal and vertical resolution, may improve the simulation of the large-scale weather and climate system.

4.1. Improvements in mean state of coupled models with eddy-resolving ocean components

The typical grid spacing of climate models in CMIP5 (Taylor et al., 2012) was ~100 km in the atmosphere and 1° in the ocean. In contrast, coupled models with atmospheric components of 25-50 km and ocean/sea ice components of 1/10° enable the sub-components of the coupled system to interact over a range of hitherto unresolved spatial scales. As discussed in section 2.2, a key feature of coupled models of this resolution is the reduction in subsurface ocean model drift due to vertical eddy fluxes (Griffies et al., 2015). Improved representation of poleward ocean heat transport, AMOC, and ACC transport have also been found at higher resolution (Hewitt et al., 2016) and attributed to increased resolution both in the ocean and atmosphere as well as higher coupling frequency.

Large-scale surface biases in coupled models can be broadly similar at different ocean-resolutions, which might suggest that ocean resolution is not a first order problem. This similarity arises since biases in many regions largely reflect errors in the atmospheric forcing. However, biases can differ considerably between resolutions particularly in frontal regions. The atmosphere and ocean communicate via heat, moisture, freshwater and momentum fluxes and small regions of extremely high exchanges are likely to have an impact on the coupled system which is disproportionate to their geographical size. Heat and moisture fluxes tend to be very large in frontal regions (>200 W/m^2; Figure 8a), making a significant contribution to the global energy balance. Heat loss in frontal regions is caused by very sharp SST gradients (Figure 8b) which allows cold dry air to flow over warm SSTs, for example in the Gulf Stream. The SST gradients are indicative of ocean baroclinicity and hence high ocean eddy activity (Figure 8c). The representation of boundary and frontal currents is highly resolution dependent (section 2.1) and the high SST gradients associated with the fronts influences the overlying atmosphere and the storm tracks downstream (Minobe et al., 2008; section 3.2). In summary, the sensitive frontal regions are extremely resolution-dependent in models with large discrepancies between simulated characteristics and observational estimates. Hence, even if low resolution models are able to capture the large scale global SST distribution fairly well, they are unlikely to adequately capture heat fluxes in the frontal regions which are key to communication between the ocean and atmosphere.

Experiments with coupled models, confirm the improvement in positioning of western boundary currents (and thus SST fronts) at eddy-resolving resolution (Section 2.1) and the expected improvement in the atmospheric state (Section 3.2). Using a 1/10° ocean model Kirtman et al. (2012) found that the better-resolved SST front in the Gulf Stream region led to a more realistically positioned mean precipitation maximum relative to that seen in a coarser resolution model. Roberts et al. (2016) comparing eddy-resolving and eddy-permitting coupled models with hourly coupling showed that North Atlantic SST was better depicted in a 1/12° eddy-resolving simulation than a 1/4° eddy permitting simulation. These improvements largely result from better positioning of the Gulf Stream front. A more accurate Gulf Stream front then leads to a significant increase in latent heat loss to the atmosphere, which removes a persistent bias in lower resolution coupled simulations. Improved representation of western boundary currents and their extensions is also likely to be key to improvements in forecasts. With increasing ocean resolution in their seasonal forecast model from 1° to 1/4°, Scaife et al. (2011) showed that a reduction in SST biases due to a better position and path of the Gulf Stream and the North Atlantic Current gave rise to reduced storm track biases and improvements in blocking frequencies over Western Europe. Lee et al. (submitted) also demonstrate that errors in the SST field due to incorrect positioning of the Gulf Stream can produce large-scale biases in the atmospheric circulation and storm track. Investigating the impact of further improvements from 1/4° to even finer ocean resolution will be an important next step.

Western boundary currents are regulated by the interaction of ocean eddies and the atmosphere (Ma et al., 2016; Renault et al., 2016). In particular, Renault et al. (2016) show that the ocean current feedback to the atmosphere via the surface stress transfers energy from the geostrophic current into the atmosphere, dampening ocean eddies, and consequently stabilizing the Gulf Stream separation, leading to a proper separation and penetration (Özgökmen et al., 1997). The dependence of the energetic Kuroshio Extension (KE) system on the feedback between mesoscale ocean eddies and the atmosphere was investigated by Ma et al. (2016) using coupled models with an eddying ocean component. They found that roughly three-quarters of the eddy potential energy (EPE) generated by the KE jet was dissipated by this feedback mechanism, while the remaining quarter was converted to eddy kinetic energy that drove the eddy circulation. Consequently when the feedback was suppressed, the energy cycle significantly changed such that the EPE dissipation was reduced and the EKE production was increased, resulting in a weaker, more strongly meandering KE jet (Ma et al., 2016; Kang and Curchitser, 2017). These studies modify our understanding of western boundary current dynamics that is built on concepts and models that do not include this air-sea feedback.

In addition to western boundary current regions, eddying simulations have shown reductions in SST biases in Eastern boundary upwelling regions (e.g. Small et al., 2014). The underlying physical cause of these changes is unclear at the present time. However, these regions are important as the upwelling brings nutrient-rich waters to the surface driving important interactions with ocean biogeochemistry. Further research is clearly justified to understand the role of resolution in representing the coupled processes in these regions and this is planned within the CLIVAR research focus on Eastern Boundary Upwelling Systems (http://www.clivar.org/sites/default/files/EBUS-Prospectus.pdf).

Vertical resolution particularly in the near surface ocean may also have a role to play in reducing SST biases. High near-surface vertical resolution (such as 1m at the surface rather than the more common 10 m near surface) allows for the possibility of capturing the diurnal cycle. The diurnal cycle can in turn lead to large-scale warming of SST as well as enhanced seasonality in the Tropics where the diurnal cycle is particularly important (Bernie et al., 2008).

4.2. Resolution requirements to capture variability and responses

There is emerging evidence that the atmosphere and ocean interact to modify climate variability. On interannual time scales, SST variability outside of the tropics is greater when mesoscale eddies are present (Kirtman et al., 2012). As discussed in Section 3.2, strong forcing of the atmosphere by this SST variability (absent in lower resolution coupled simulations) is evident in eddy-resolving models (Bryan et al., 2010; Kirtman et al, 2012; Roberts et al., 2016; Siquera and Kirtman, 2016). In terms of large-scale climate modes, Small et al. (2014) reported improved representation of the El Niño Southern Oscillation (ENSO) variability in fine resolution simulations relative to coarse resolution simulations. Putrasahan et al. (2016) found that high resolution coupled models were able to resolve oceanic teleconnections between ENSO and Agulhas leakage SST. Ocean resolution is particularly key to the simulation of Agulhas eddies with improvements in pathways in coupled simulations (McClean et al., 2011) most likely due to the ocean current feedback to the atmosphere (Renault et al., 2017).

As discussed in section 2, the ocean is a source of low frequency intrinsic variability. Simplified coupled ocean-atmosphere models (based on quasi-geostrophic dynamics) have shown that, when the resolution is sufficient to capture non-linear mesoscale dynamics, decadal timescale coupled modes emerge at mid-latitudes (Kravstov et al., 2007). The coupled modes build on the presence of intrinsic variability in the ocean. To date, coupled modes such as these have not been found in more realistic coupled models. However, as the length of integrations of realistic high resolution coupled models are extended, it should be possible to establish whether such coupled modes are present. If such modes were present, this may have implications for predictability on decadal timescales in the mid-latitudes.

Is resolution likely to affect predictions of the response to future climate forcing? The transient response of the AMOC is key to the large-scale climate response particularly in the Northern hemisphere. He et al. (2017) suggest that the initial state of the AMOC is a leading factor in capturing future response. Do we expect the initial state of the AMOC to improve with eddy-resolving resolution? As described in section 2.3, the response of the AMOC to resolution is unclear and, given the strong control the AMOC exerts on global climate, further research is justified to understand the sensitivity of the present day and future change of the AMOC to resolution (including the associated processes controlling the AMOC).

In addition to the AMOC, there is now strong evidence to suggest that the Southern Ocean response to wind changes depends critically upon eddy dynamics to capture features of eddy saturation of the depth integrated ACC transport, and eddy compensation of the overturning circulation (Hallberg and Ganandesikan, 2006; Farneti et al., 2010; Gent, 2016). With the Southern Ocean being estimated to be responsible for 40% of the net ocean CO_2 uptake and 75% of the heat uptake from the atmosphere (Frolicher et al., 2015), it is critical that the future response of the Southern Ocean is properly represented and this is likely to require eddy-resolving resolution.

In the Southern Ocean, the net (residual-mean) overturning circulation is the sum of the wind-driven (Ekman) circulation and the compensating eddy-induced circulation (Marshall and Radko, 2003). From an energetic point of view, the balance is between the generation of available potential energy by Ekman pumping that steepen isopycnals and the release of this available potential energy (through baroclinic instability that flattens isopycnals) to the mesoscale eddies (eddy kinetic energy). Consequently, with a vigorous mesoscale eddy field, we can expect the ocean’s residual-mean overturning response to wind changes to be partially compensated by eddy processes, i.e. weaker than expected from the Ekman response alone. Additional wind energy input flows into available potential energy and ultimately into the eddy kinetic energy leading to increased eddy activity with weak changes in slopes (Hallberg and Gnanadesikan, 2006).

Complementing the overturning compensation idea, the depth integrated horizontal transport is thought to be in a partially eddy saturated state, whereby increases in winds increase the eddy field but do not alter the net transport (Hogg and Meredith, 2006; Meredith et al., 2012). The net effect is that both the overturning circulation and ACC transport have only a weak dependence on wind strength (e.g. Hallberg and Gnanadesikan, 2006; Abernathey et al., 2011; Munday et al., 2013; Hogg and Munday, 2014; Farneti et al., 2010, 2015; see Figure 9). While the extent of the eddy saturation/compensation in the real world is uncertain, no significant change in the slope of the ACC isopycnals could be detected from observations over the last 40 years (Boning et al., 2008), despite zonal mean winds becoming stronger and shifting to the south (Bindoff et al., 2013), consistent with expectations from eddy compensation/saturation ideas.

Changes in the Southern Ocean may affect both heat uptake and the outgassing of CO_2 from carbon-rich deep waters if the upwelling of the deep waters changes. Newsom et al. (2016) demonstrated that the lower limb of the Southern Ocean circulation extended further equatorward and its circulation was greater in a high resolution model compared to a low resolution case. Differences in the circulation were attributed to larger water mass transformation rates at the surface within the Antarctic sea ice pack and transformation from diapycnal mixing processes as water flowed northward into the abyssal ocean. Bishop et al. (2016) further demonstrated that increasing the zonal wind stress by 50% in the mid- to high-latitudes of the Southern Hemisphere led to enhanced transport in the lower branch of the overturning circulation leading to increased upwelling of Circumpolar Deep Water which, in turn, produced increased sea ice melt. The transient-eddy overturning cell in the upper ocean was little changed although the wind-driven component was partially compensated by the standing-eddy component of the circulation (see also Dufour et al. 2012). The results of Newsom et al. (2016) indicated that heat (and therefore CO_2) uptake in the Southern Ocean could be enhanced at eddy-resolving resolution. The critical role of eddies in the Southern Ocean and the eddy saturation/compensation mechanisms suggest this is an area for further research and model consensus.

4.3. Prospects for resolutions coarser than eddy-resolving

Given pressures on computational resources, it is likely that the majority of coupled models used in the foreseeable future will have ocean resolutions below mesoscale eddy resolving, particularly for applications such as multi-centennial projections. There are essentially two classes of these models: eddy parameterising (~1°) and eddy permitting (~1/4°).

In the first class of models (eddy parameterising; ~1°), the ocean grid spacing is larger than the Rossby radius, so that eddy effects must be parameterised. This parameterisation is achieved by representing the two impacts that ocean mesoscale eddies have on the large-scale tracer distribution. The first effect is a diffusion oriented along isopycnal surfaces (Solomon, 1971; Redi, 1982; McDougall, 1987; Griffies et al., 1998; McDougall et al., 2014). The second effect is an eddy-induced tracer advection (or a quasi-Stokes transport) which is generally parameterized by including an eddy-induced velocity or skew diffusion in the tracer equation designed to reduce the available potential energy of the large-scale flow (Gent and

McWilliams, 1990 (GM90); Greatbatch and Lamb, 1990; Gent et al., 1995; Griffies, 1998). Other approaches such as the Transformed Eulerian Mean (Young, 2012; Maddison and Marshall, 2013) have been tested, where parameterisations aim to emulate the vertical eddy-induced form stress (Ferreira and Marshall 2006).

Eddy-induced diffusion and advection are included in almost every standard ocean component that does not admit mesoscale eddies. These parameterizations have been shown to provide a step-change in the fidelity of simulations (e.g., Danabasoglu et al., 1994). By including GM90, both Gent et al. (1998) and Gordon et al. (2000) were able to make centennial timescale simulations using coupled models without the use of atmosphere/ocean flux-corrections, otherwise common for climate models of that era. In particular, the eddy-advection parameterisation captures the upward heat flux from mesoscale eddies in the mid-latitude gyres, and the neutral diffusion parameterization captures the upward heat transport seen in the high latitude Southern Ocean (Figure 5; Gregory, 2000; Griffies et al., 2015; von Storch et al., 2016).

Nonetheless, eddy-parameterised models are highly deficient in many of the areas we have previously discussed. The resolution is insufficient to properly represent western boundary currents, capture mesoscale atmosphere-ocean interactions (see Figure 6) and fails to simulate intrinsic (or internally generated) variability in the ocean state which drives the atmosphere (Penduff et al., 2011; Hu and Deser, 2013). In terms of the future response of the ocean and climate system, coarse coupled models are unable to represent some of the ocean mechanisms that feedback onto climate such as eddy saturation/compensation.

The second class of models (eddy permitting; ~1/4°), with resolution close to the Rossby radius, can represent eddies to a certain degree and only in low to mid latitudes. They sit in the so-called “grey zone” where it is unclear whether the benefits of almost resolving mesoscale features outweigh the benefits of applying eddy parameterisations. In coupled models with such eddy-permitting ocean resolutions, improvements over the eddy-parameterising class of models have been demonstrated in terms of reduced SST biases (Roberts et al., 2009); and improved representation of ENSO (Shaffrey et al., 2009), stratocumulus in upwelling zones (Toniazzo et al., 2010) and extratropical storms (Catto et al., 2010, 2011). Nevertheless, models of this class are likely to remain deficient in terms of simulating eddy saturation/compensation (Figure 9) and in some regions have less intrinsic variability than mesoscale eddy-resolving models (Gregorio et al., 2015).

Given computational costs of mesoscale eddy-resolving models and the deficiencies of eddy-permitting models, research is currently directed towards considering how to parameterise in the grey zone. One proposed approach is to apply the GM90 scheme at latitudes where the Rossby radius is not resolved (Figure 2) at mid- to high latitudes (Hallberg, 2013). This “resolution function’’ approach can improve the large-scale overturning. However, this approach has yet to be tested extensively in a standard global model. Other research has focussed on scale-aware parameterisations to improve the representation of eddy momentum fluxes via the application of backscatter methods (e.g., Berloff, 2005). These schemes are based on the notion of mechanical energy conservation, whereby energy that would otherwise be dissipated at the grid scale (and thus fully removed from the model system) is reinjected at the large scale. One means for realizing a backscatter parameterization is to introduce a negative Laplacian operator whose strength is set according to the dissipation engendered by a corresponding biharmonic operator (Jansen and Held, 2014). The scale separation between Laplacian and biharmonic operators allows the scheme to retain numerical stability, since the biharmonic operator strongly dissipates energy at the grid scale. Crucially, the negative Laplacian acts at scales slightly larger than the biharmonic operator, with its re-injected energy cascaded to larger scales through the eddies explicitly represented by the eddy-permitting simulation. An alternative approach is to introduce a non-Newtonian stress tensor whose stresses have properties in common with those of the unresolved motions (Mana and Zanna, 2014; Anstey and Zanna, 2017). Another means to increase backscatter is to introduce a stochastic term in the model equations (e.g., Jansen et al., 2015; Zanna et al., 2017). Further applications of stochastic physics have been proposed (Brankart, 2013; Williams et al., 2016) although work is required to address issues such as tracer conservation. Stochastic methods have been successfully implemented in weather and climate models (usually in the atmospheric component) and been shown to improve aspects of their performance (e.g. Berner et al, 2012; Dawson and Palmer, 2015). Evaluating the ability of stochastic methods to enhance low frequency intrinsic variability in coarse resolution models will be an important step.

While there are some promising prospects in parameterisation for both eddy-parameterising and eddy-permitting resolutions, evaluation of the methods in realistic coupled models in order to measure their performance against simulations with eddy-resolving oceans remains to be done. These assessments should include experiments that assess air-sea interaction and its impact on the mean climate, variability and future response. We also note that even eddy-resolving models still need to parameterise sub-gridscale eddies (e.g., submesoscales) and this is likely to be best achieved by implementing scale-aware parameterisations (e.g., Pearson et al., 2017).

Finally we here briefly discuss the atmospheric counterpart to the parameterization of the oceanic mesoscale (in the same range at 10-100km). The research summarized in section 3.2 on the impact of the SST field on the storm track has indeed highlighted the role of frontal circulations embedded in synoptic storms and it would be of great interest if the response of the latter to SST changes could be parameterized. Some attempts have been made in the past at parameterizing shear instabilities of the fronts (e.g., Lindstrom and Nordeng, 1992) in terms of an homogenization of moist potential temperature along absolute momentum surfaces and these could be investigated further in the context of ocean-atmosphere interactions. It must be emphasized though that such parameterizations have to be informed by yet very basic unanswered questions: does the interaction of an extra-tropical cyclone with the underlying ocean always act to enhance its frontal circulation or to damp it? When this interaction occurs over an oceanic front, does the feedback on the ocean tend to maintain or erode the ocean front? Work addressing these questions is only now emerging (e.g., Thomas et al., 2013; Parfitt et al., 2017).

5. Discussion

This review has raised several issues for high-resolution ocean models. What are the limitations on using observations to evaluate high resolution models? What are the associated requirements for vertical resolution or coordinates to match the horizontal resolution both in terms of admitting baroclinic modes and the interactions with bathymetry (including western boundary currents and overflows)? What is the relevant importance of boundary and frontal currents compared with open ocean eddies for air-sea interaction? Are there other areas like Eastern upwelling zones where resolution may be important? Can models that do not fully represent the ocean mesoscale simulate climate change and variability?

In section 2, the issue of numerical convergence was raised. Early studies with coupled models have indicated changes in large-scale climate properties such as drifts in hydrography and ocean heat transports as ocean resolution increases. It is therefore highly relevant to ask at what resolution we might expect the simulations of such large-scale properties to converge and what mechanisms are associated with convergence (e.g., boundary currents, mesoscale eddy processes). This is a more informal approach to convergence than other areas of computational physics. Nevertheless, it is an important step to addressing what resolution is sufficient for a particular application.

There have been many advances in investigating the impact of ocean mesoscale activity on the atmosphere. The emerging consensus is that mesoscale SST anomalies can be expected to impact the atmospheric boundary layer and above, and affect the extra-tropical storm tracks. While at the large-scale the atmosphere primarily drives the ocean, at the small-scale, the surface ocean properties can play a dominant role in driving the atmosphere. It remains unclear whether it is the mesoscale associated with western boundary currents or in the open ocean which are most important for driving the atmospheric response. The results we have reviewed indicate that the atmospheric response may be sensitive to both atmospheric model resolution and the physics in atmospheric boundary layer schemes. Further investigation of the sensitivity of the response to these factors is suggested. Preliminary results suggest that once resolution is sufficient to resolve SST fronts in the ocean and the vertical transport in the atmosphere, there may be limited sensitivity or modest improvements due to further increases in resolution (Small et al., 2014; Roberts et al., 2016; Sheldon et al., 2017). These results suggest that the SST impact on the atmosphere is neither linear nor systematic.

In the last few years, evidence has emerged which demonstrates that coupled models with mesoscale eddy-resolving ocean components offer tangible improvements in terms of their representation of the large-scale climate, particularly in reduction of SST biases associated with western boundary currents and Eastern upwelling zones. Considering the impact of the ocean mesoscale on the atmosphere, it is not surprising that improvements in atmospheric storm-tracks are also found, although again the role of (ocean) mesoscale eddies relative to western boundary currents is less clear. Mesoscale eddies make a significant contribution to the large-scale tracer budgets, reducing large-scale coarse model biases and contributing to the maintenance of a stable climate. Evidence suggests that simulating a realistic state of the ocean is likely to be important to understanding future changes in the Meridional Overturning Circulation. It also appears that the role of transient eddies in the Southern Ocean could be crucial to accurately simulating its response to climate change, which affects global heat and carbon uptake. There is some evidence of changes in ENSO at high resolution but the underlying processes require further investigation.

To fully represent the role of the ocean in coupled models, there are clear deficits that are apparent at coarse resolutions where the effects of eddies are parameterised. Eddy-permitting resolution in coupled models provides tangible benefits, but further work is required to (a) better represent important features such as boundary currents, and (b) consider how to compensate for the lack of upward eddy heat transports in regions where they are neither explicitly represented nor parameterised. In idealised models, scale-selective choices for GM90 and the backscatter parameterisation approach have shown promise for eddy-permitting models in the grey zone, but remain to be demonstrated in global ocean models and coupled models. A more concerning question for parameterisation is whether these approaches will be able to correctly simulate eddy-related effects such as eddy compensation/saturation in the Southern Ocean (but see Mak et al. (2017) for promising results in an idealized set-up), or intrinsic variability of the coupled system that is related to eddy activity in western boundary currents.

Observations indicate that the near-surface atmosphere responds to ocean mesoscale activity. However, Eade et al. (2014) have provided evidence that the signal-to-noise ratio is lower than expected in both seasonal and decadal predictions, prompting the use of large ensembles. Given the role of intrinsic variability in the ocean (Penduff et al., 2011), there is speculation that mesoscale air-sea interactions, which are missing in many predictions due to their low resolutions, might be a source of increased predictability. If that is the case, it opens up the possibility that seasonal prediction models of sufficiently high resolution might be able to capture mechanisms that give increased predictability at mid-high latitudes. This tantalizing prospect drives a great deal of the ongoing research and development of fine resolution coupled climate prediction systems.

We have raised the question of whether the interaction of the atmosphere with mesoscale eddies in the open ocean is as important as the interaction with the western boundary currents. Given that mesoscale eddies are ubiquitous in the ocean, the null hypothesis has to be that high resolution is required globally - in the central part of the gyres as well as western boundary currents. Interactions will clearly be intense over the western boundary currents but we cannot rule out the possibility that the net effect of weak interactions elsewhere in the ocean is important. The use of unstructured meshes that allow the possibility of enhanced resolution locally may offer one approach for testing this hypothesis.

Although we have emphasized western boundary current regions in this review, mesoscale dynamics has relevance to the Southern Ocean not only for heat and carbon uptake but also for ocean-atmosphere coupling. Some studies were mentioned in section 3.2 with respect to interactions between oceanic and atmospheric boundary layers but it is yet unclear whether the type of processes summarized in Fig. 7 apply to the Southern Ocean because of the much colder mean SST and the weaker diabatic heating of the storms there (e.g., see the factor 2-3 reduction in precipitation and hence latent heat release in the ERA40 climatology over the Southern Ocean compared to the Northwest Atlantic and Pacific).

6. Conclusions and Research Priorities

In this review we have addressed emerging evidence for the potential importance of ocean resolution in coupled prediction models. Simulations of the ocean with a prescribed atmospheric state, such as in the CMIP6/OMIP protocol (Griffies et al., 2016), clearly demonstrate that as we move away from an eddy-parameterising regime to a regime where the first baroclinic Rossby radius is resolved, models are able to simulate not just mesoscale eddies but also key frontal regions such as western boundary currents and flow-topography interactions.

Recent studies indicate that both eddies and fronts are likely important for coupled prediction. Resolving eddies modifies the ocean heat budget, with resolved eddies transporting heat upwards more effectively than parameterised eddies leading to more accurate depictions of ocean water masses. Correctly simulating frontal positions improves SST and surface currents which are key to the ocean’s interaction with the atmosphere. As resolution increases, details of bathymetry are also better represented. This improved representation allows for regions of topographic control to be modelled more accurately, including overflows and topographic steering of the large-scale flow. The Greenland-Iceland-Norwegian seas and Antarctic continental shelf and the associated downslope flows to the deep ocean are important for large-scale climate and likely require both high horizontal and vertical resolution to capture the details of the slope current.

In this review we have built a case that ocean resolution is an important factor in the competing requirements for computation. To make further progress in addressing this question we highlight the following research priorities.

1. While the balance of evidence suggests that increased resolution will improve both atmosphere and ocean simulations in coupled models, more systematic studies which make use of a traceable model resolution hierarchy (Griffies et al., 2015; von Storch et al., 2016; Storkey et al., in prep.) are recommended. It is only in carefully constructed model frameworks such as these, that the relative contributions of resolution-related properties and parameterisations can be explored to produce a cross-model consensus. More specifically, the following issues merit further research: the most appropriate vertical resolution and coordinates for representing the effects of the ocean mesoscale and topographic interactions; the use of observations to evaluate simulations at different resolutions (which can be higher in resolution than the observations themselves); the development and assessment of scale-aware sub-gridscale parameterisations suitable for eddy-resolving resolutions and finer; the demonstration of numerical convergence as ocean resolution is increased; and the understanding of drifts, variability and response to forcing at different resolutions.

2. New paradigms in ocean-atmosphere interaction are leading to a greater understanding of the role of air-sea feedback in western boundary current dynamics and the role of vertical motions in the atmosphere allowing mesoscale features in the ocean surface to influence the atmospheric boundary layer and the upper

troposphere. Further exploration of these paradigms and the impact on variability and change associated with large-scale climate modes such as ENSO and the NAO is important. This includes understanding to what extent the variability due to open ocean eddies is important as opposed to that due to western boundary currents. In terms of coupled prediction, a key question which remains unanswered is the relative importance of resolution in the atmosphere and ocean components to capture the essential processes.

3. While coupled models with ocean mesoscale eddying resolution remain expensive computationally, further effort is required to convince operational centres of the benefits of resolution, and to better gauge the relative benefits of resolution versus complexity/capability and ensemble size should be a priority. Development of modelling protocols to better quantify the benefits of resolution in a predictive setting would help to quantify the importance of resolution. An example is the use of instantaneous quadrupling of CO_2 for climate projections - an experiment with a large response but requiring fewer model years to distinguish a signal from noise. Another example would be a re-emergence experiment (e.g., Cassou et al., 2007, Sinha et al., in prep.) to assess the role of resolution for seasonal forecasting. Experimental designs of this type are an important step towards understanding the competing benefits of resolution relative to complexity and ensemble size. With the availability of routine ocean analyses and forecasts, many institutional groups have taken the opportunity to develop high resolution short- to medium-range forecasting systems (Brassington et al., 2015). In many cases, controlled experiments are now performed to obtain statistically significant metrics and operational predictions that will in turn provide additional understanding of the impact of resolution on the coupled system.

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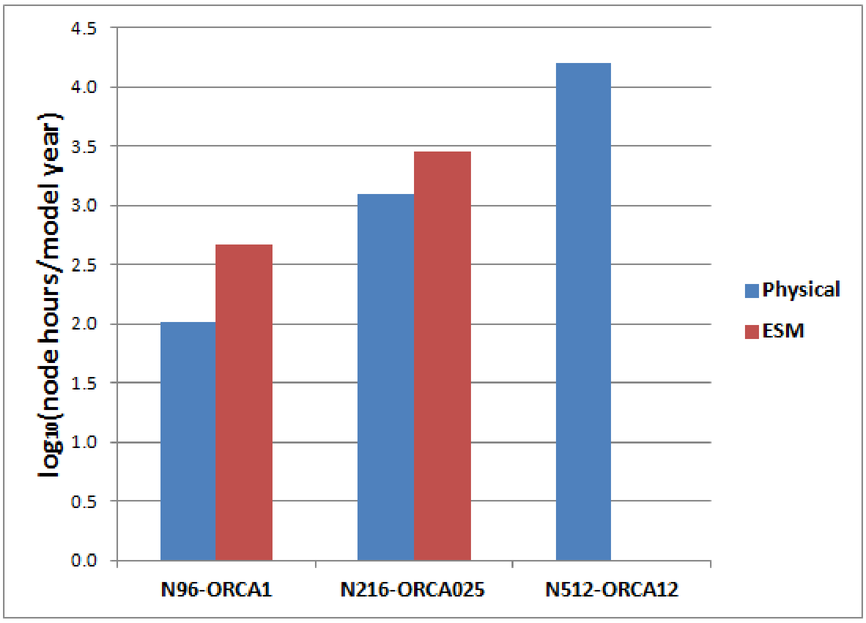

Figure 1: Example of node hours per model year (shown as $\log_{10}$) for coupled configurations of varying resolution and complexity based on the Met Office GC3 climate model (Williams et al., 2017) for the physical model only (blue) and the inclusion of the Earth System Model components (ESM; red-estimated for N216-ORCA025). N96, N216 and N512 are atmosphere resolutions of 150, 60 and 25 km respectively. ORCA1, ORCA025 and ORCA12 are ocean resolutions of nominally 1°, 1/4° and 1/12° respectively. This figure demonstrates that each increase in resolution incurs approximately a factor of 10 increase in computational cost, which is equivalent to a 10 member ensemble at the lower resolution. The cost of increased resolution is greater than that of additional complexity/capability at lower resolution, while both compromise on ensemble size. Our focus concerns the payoffs available from increased resolution in the ocean.

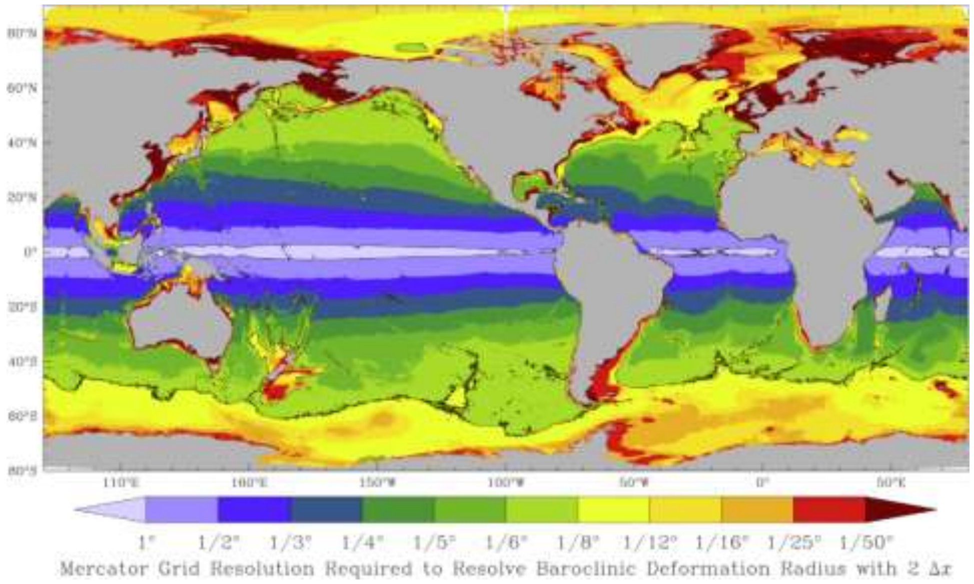

Figure 2: Grid resolution needed to resolve the first baroclinic mode Rossby radius with two model grid points (from Hallberg, 2013). This criteria allows for approximately six grid points within a first-mode baroclinic wave.

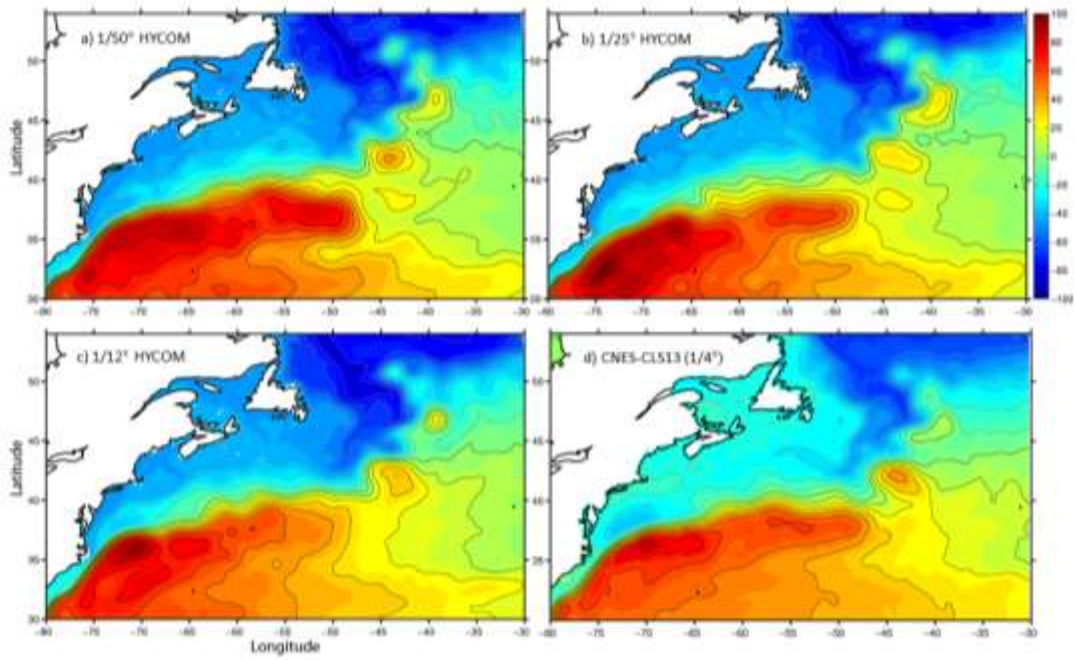

Figure 3: Mean sea surface height fields (cm) from the (a) 1/50°, (b) 1/25°, (c) 1/12° HYCOM simulations and with (d) from the AVISO CNES-CLS13 climatology (Rio et al., 2014). In all three HYCOM simulations, the Gulf Stream separates at the correct location at Cape Hatteras, but its eastward penetration into the interior differs greatly. At 1/12° (panel c), the modelled Gulf Stream does not penetrate far into the interior and the recirculating gyre and highest eddy kinetic energy (not shown) are confined west of the New England seamounts (60°W). The 1/25° simulation (panel b) does not show a lot of improvement over the 1/12° simulation and it is arguably worse since the Gulf Stream in the 1/25° simulation not only does not extend as a coherent feature past the New England seamounts, it exhibits an unrealistically strong recirculating gyre southeast of Cape Hatteras, and has excessive surface variability (not shown) west of 60°W. It is only when the resolution is increased to 1/50° (panel a) that the Gulf Stream system (recirculation gyre and extension) settles in a pattern that compares well with the latest AVISO CNES-CLS mean dynamic topography (panel d). Adapted from Chassignet and Xu (2017).

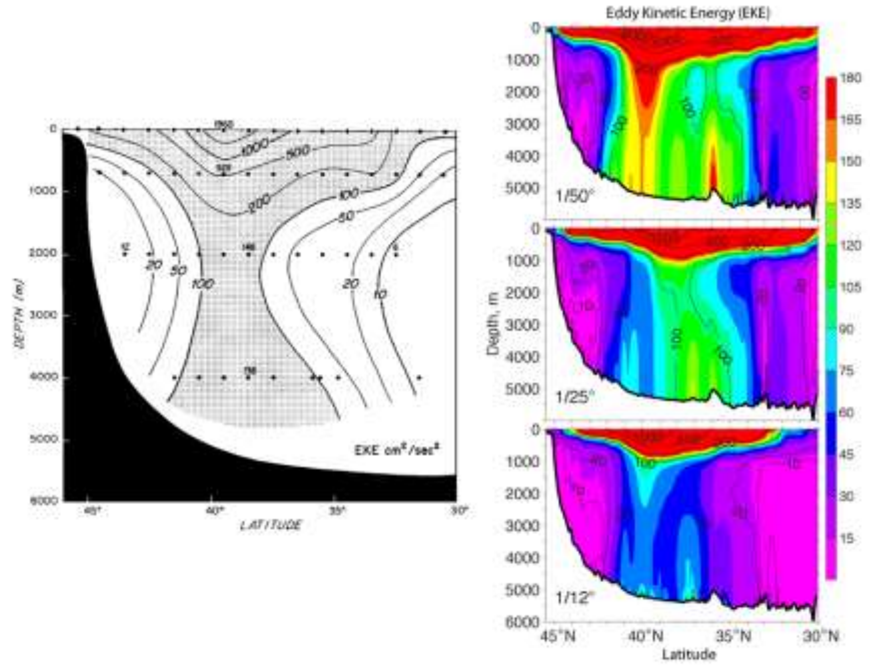

Figure 4: Eddy kinetic energy (cm^{2}s^2) along 55°W in the 3-year long mooring measurements of Richardson (1985) (left panel) and for the 1/50°, 1/25°, and 1/12° HYCOM simulations (right panel). Note the increased penetration of high EKE into the deep ocean with the finer resolution simulation, better reflecting that seen in the mooring data. Adapted from Chassignet and Xu (2017).

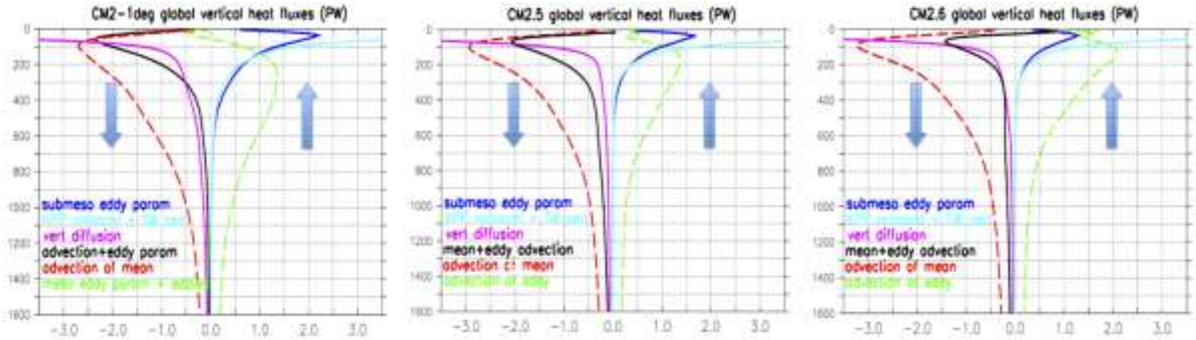

Figure 5: Global horizontal mean vertical heat transport after Griffies et al. (2015). Heat transports are shown in units of PW = 10^{15} Watts. Results are shown for a climate model with a one-degree ocean component (left panel), ¼ degree ocean (middle panel), and 1/10 degree ocean (right panel). Positive (negative) values arise from upward (downward) heat transport. The heat transports are decomposed into various physical processes as indicated by the legend (see Griffies et al. (2015) for details). For our purposes, the main lines to focus on are the dashed red and green, indicating heat transports by the mean (red dashed) and eddy (green dashed). Note that at around 300m depth, the eddy contribution to the ¼ degree model CM2.5 is half that of the 1/10 degree model CM2.6. The one-degree model in the right panel also exhibits an upward, albeit entirely parameterized, eddy transport. Its magnitude better matches the 1/4 degree model rather than the 1/10 degree model, thus suggesting that work remains in refining eddy parameterization.

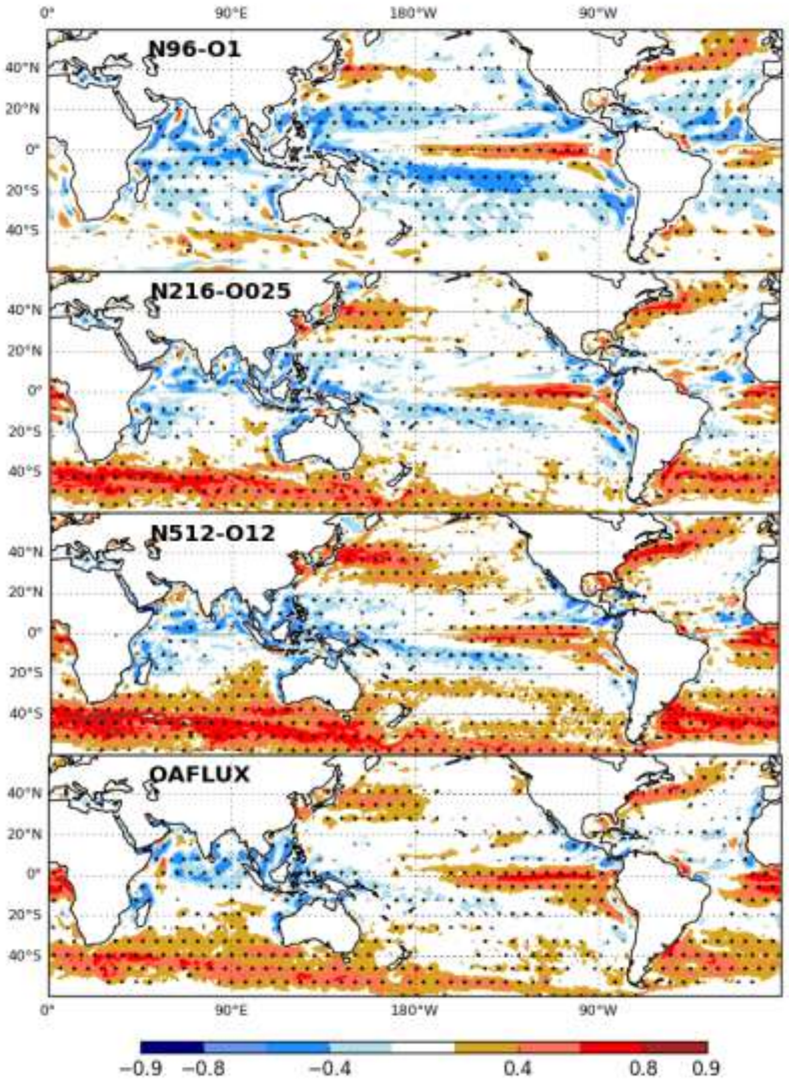

Figure 6: Temporal correlation of the monthly mean of spatially-filtered daily anomalies of SST and windstress from models and observations. Models (atmosphere-ocean resolution) are: N96-O1, 130km-1°; N216-O025, 60km-0.25°; N512-O12, 25km-1/12°; Observations OAFLUX (Yu et al. 2008). The positive correlation suggests that the ocean is forcing the atmosphere. Adapted from Roberts et al. (2016).

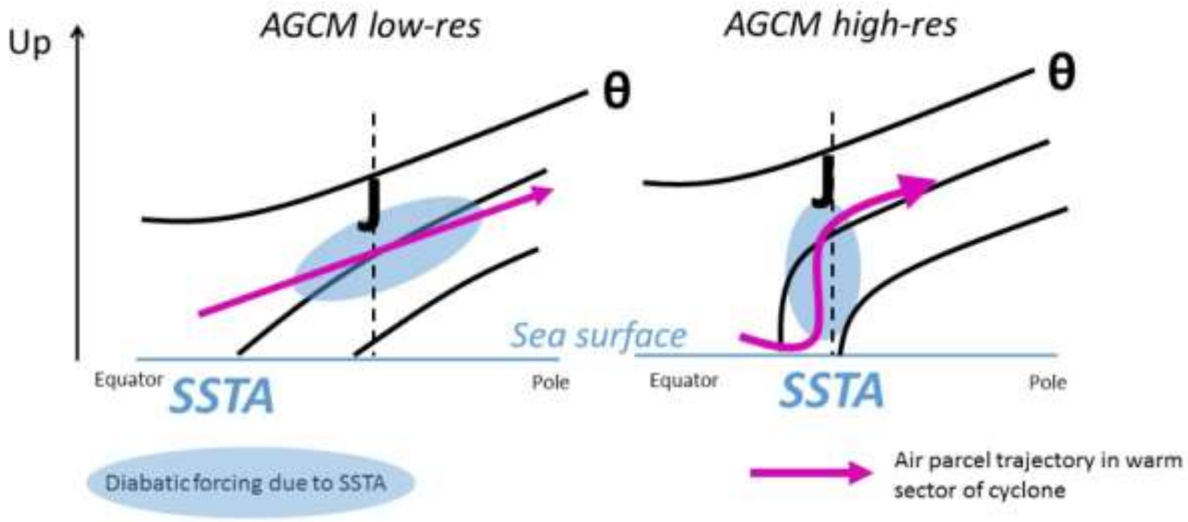

Figure 7: SSTA indicates the location of a sea surface temperature anomaly (defined from either temporal or spatial averaging) and the anomalous diabatic heating (pale blue shading) it induces in the atmosphere is shown in light blue. The trajectory of air parcels in the warm sector of the storm is shown in magenta superimposed on the jet stream (J) and isentropes (black lines). At low resolution, air parcels have a shallow trajectory so the anomalous diabatic heating mostly reflects SSTA further equatorward, possibly explaining the larger sensitivity of coarse AGCMs to subtropical rather than extra-tropical SSTAs. At high resolution, air parcel trajectories have a more pronounced ascent and an "S-shape" which allows the anomalous diabatic heating to be directly related to the underlying extra-tropical SSTA. Adapted from Czaja (2012).

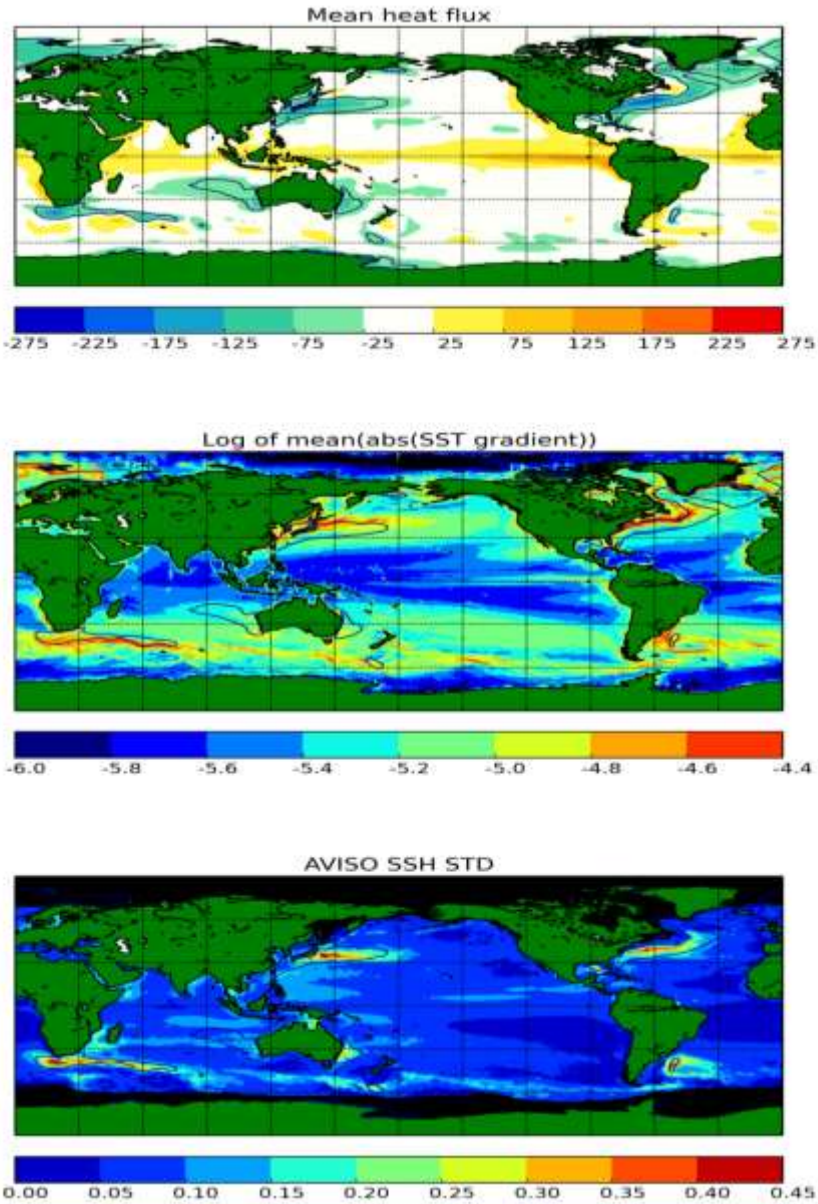

Figure 8: a) Global annual mean surface flux (W/m^2), b) Log10 mean(abs(SST gradient)) (K/m) and c) standard deviation of weekly sea level anomaly (SLA; cm). The surface fluxes are from DEEP-C energy divergence based estimates (195-2004) (Liu et al., 2015), SST gradient from My Ocean AMOR3D v3.1 ¼ SST observational analyses (1994-2013 monthly), standard deviation of SLA from years 1993-2012 of AVISO (Pujol et al., 2016). Standard deviation of SLA is a proxy for eddy kinetic energy (EKE). The co-location of high surface fluxes, SST gradients and EKE highlights the important role that frontal regions (including western boundary currents play in atmosphere-ocean exchange.

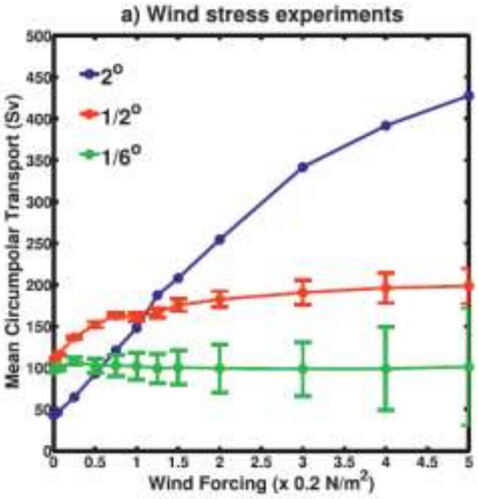

Figure 9: Sensitivity of the circumpolar transport to the wind stress. The ‘‘error bars’’ are two standard deviations around the long-term mean, calculated from instantaneous monthly values throughout the averaging period. The 2° (blue) experiments are averaged over 1000 years, the 1/2° (red) experiments over 100 years, and the 1/ 6° (green) experiments over 10 years. Taken from Munday et al. (2013). ©American Meteorological Society.