

Dear Bob, we have revised the manuscript to comprehensively address the reviewers' comments, within limits of what is practical and to maintain the original scope and aim of the paper. We hope it is now acceptable for publication,

Best wishes,

Jason

## ***Prospects for improving the representation of coastal and shelf seas in global ocean models***

### ***Response to referee: RC1***

*These estimates are of interest, but they are insufficiently deep.... I would be happy to see more substance. The manuscript presents a view, but does not formulate solutions which respect of numerics of physics....*

It was never our intention to provide a comprehensive solution to this question with specific numerical options. This would essentially require the description of a new model. Instead we aim in this revision to better articulate the challenge, and so offer more 'substance'. To this end, we now include a new comparison of CMIP5 models with an observed profile data set and the NNA and ORCA12 high resolution NEMO models, which we believe is novel, robust and informative. This now clearly demonstrates some of the benefits of improved resolution and process representation. P6 L25 and Section 3.2. Figs 4, 5, 6.

*The technical side of the problem of matching coastal and global scales in a single setup is addressed from the side of mesh resolutions. Many physical aspects are mentioned, but without practical recommendations.*

We have developed section 3.2 with a list of specific recommendations and issues, drawing on the literature.

*While it is true that a precise boundary between coastal and global scales does not exist and a lot will be possible as resolution is further refined, there are even smaller scales or physical processes resolving which in a global setup will make the global approach strongly suboptimal (for example, regimes with wetting and drying). So I see the technologies based on two-way nesting or unstructured meshes much more promising and requiring much less computational resources in many coastal tasks. I would recommend to define more precisely the context of global coastal modeling.*

We agree regional models with both structured and unstructured mesh approaches remain the optimal solution for many coastal-ocean questions. To this end we better articulate the drivers for using global models in the coastal-ocean in a revised section 1.1, which ends with a list of the specific types/uses of global model this work is aimed at (P3 L28). One practical point that should not be neglected, but was not made in the original submission is the cost (e.g. in scientists time) of configuring and testing a new regional model for each area of interest. If readily available global information had improved coastal-ocean representation then this could substantially aid a diverse range of activities, albeit often sub-optimally to setting up a new region configuration for each case, but particularly useful for the research community who are not experts in coastal ocean modelling (P3 L20-27).

*I would also recommend to put more focus on specific issues such as the reduction of spurious mixing on terrain following meshes as suggested by Lemarie et al. (2012, Ocean*

*Modelling), the Arbitrary Lagrangian–Eulerian vertical coordinate (MPAS and MOM6), scale-aware mixing and eddy parameterizations, measures influencing numerical stability if the intention is to really discuss the prospects.*

We agree these are very important issues and have developed the discussion of these, section 3 (P8 L25 onwards). But we are not in a position to offer new solutions here or further test existing ones.

*The analysis of future perspectives based on the evolution laws for the available computational power is a bit superficial. The point is not only the computational power on its own, but also time step limitations.*

And..

*However, if the scalability stays as its present level, the codes will become slower in terms of simulated years per day of computations. The key question is which technologies can improve scalability and how, and without answering it the rest is just an exercise.*

Given the many uncertainties of the evolution of computing we do not feel it appropriate to consider this in more detail than simply extrapolating the current trend in peak performance (e.g. to look at projections of future chip technology).

The time step question is a crucial point and we have added a section on this (P13 L34-P14 L2). We have also added a section on ocean model performance and scalability (section 4.4 P15), and identified one practical way to re-code ocean models to make optimization on new computer architectures much more straightforward. This has the potential to substantially improve ocean model scalability (P16 L24 onwards).

We now make the important distinction between resource and turn-around time and provide some specific re-world examples of realised SYPD (P15 L35; Table 3). Some ocean modelling activities will be resource limited, others SYPD limited. Including scalability into the simple cost model we use is not straightforward and would complicate this beyond what is warranted, given the other uncertainties. So we leave it as a simple estimate of resource needed, but make clear the SYPD may decrease even if more resource is available.

*The view on unstructured meshes proposed in the manuscript seems to be outdated and is based on just arbitrary comparison for a particular model (FVCOM). Here, the point is better parallel scalability of current unstructured-mesh codes on large meshes which warrants comparable throughput (but with somewhat larger demand to computer resources per degree of freedom).*

Agreed and we have revised section 3.4 accordingly, reducing the discussion on unstructured meshes to fit with the original assertion that we would not try and review these here. We have added a discussion on the relative performance of structured and unstructured meshes (P15 L35), related to the real-world examples in Table 3. On this basis we now give a range of figures allowing for the resource-use of unstructured mesh models to vary from about 3 to 1 (parity with structured mesh models). In this way we feel we now present a more balanced view.

*Furthermore, unstructured-mesh codes deal only with wet nodes, which creates noticeable economy in coastal areas.*

This maybe important for coastal models with complicated topography (e.g. estuaries) but is a marginal issue for global models run on many 1000's of processors and where land-only processors are excluded (P15 L41).

*If the coastal area occupies less than 10%, running an unstructured-mesh model or model with two-way nests on a mesh that is three times coarser in the global ocean than in the coastal part is 5 times less expensive (in terms of computational resources) than running this model on a global fine mesh. Such arithmetic is trivial and hardly tells in favor of global fine meshes; devoting a significant place in the manuscript to all the would be issues is not very appropriate (for it depends on the slowness factor of 5 that the authors took for unstructured meshes).*

The arithmetic may be simple but providing an objective basis for the 'ocean area occupies less than 10%' and the global ocean is 'three times coarser' is far from straightforward, and this is central to the question we are trying to address. We could add other layers of complexity to the calculation – e.g. by assuming a maximum gradient of grid-refinement, but we do not feel these would helpfully inform the overall message. We do agree the 'factor of 5' needed to be addressed and have modified as described above.

Other points

*The contents of 1.2 and 1.3 are a bit shallow to warrant their publication. 1.3 fails to convey a message that downscaling cannot be done with nesting, for one just needs to take a (two-way) nest of appropriate size. Page 3, lines 3-5: The sills between the Nordic seas and the North Atlantic are not as deep as 1500-3000 m. So the NADW is very indirectly connected to what is said.*

These sections have been substantially edited and reduced in size to now just convey the overall motivation with some brief examples.

*Page 4, bottom, the first and third issues are rather close. Page 5: top, rivers are also accounted for in global models Fast ice is accounted (through parameterization) in some large-scale models; it is not a strong point of most coastal models.*

True, but this section refers to properties of these regions, irrespective of how they are treated in the current generation of models (P4 L11).

*The beginning of 2.1: To compute the scales one does not need a NEMO grid and can use the original data instead. So you need it to put the scales into the context of particular model. There is no issue of North Pole singularity for scalar data.*

True – data here originated on the NEMO grid (apart from TPX) so it is appropriate to use this grid. An area-weighted mean is used, so the results are not dependent on this choice of grid (P5 L30). The mention of a NP singularity has been removed.

*Page 6: If  $L_1=c/f$ , where  $c$  is the speed of the first mode, then for the Eady instability wave the wavelength of most unstable wave is approx.  $3.9 \pi L_1$ , giving different size of eddies.*

We have changed to use this measure of eddy scale and re-drawn fig 2 accordingly.

*Page 8, top: Mentioning barotropic tidal models is hardly relevant in the context of 3D modeling. Instead of reviewing who did what it would be much more appropriate to formulate what is the essence of difficulties and only then discuss the current status.*

Agreed and the text on barotropic tidal models has been removed.

*Discussion of spurious mixing in the context of tides sounds strange to me—according to Ilicak et al (2013) it is the grid scale motions that have the largest impact. The point of spurious mixing deserves much more attention, for it is also related to terrain following coordinates which intersect isopycnals at some angle and introduce spurious mixing*

*precisely where they are most needed (the continental break boundary). The manuscript mentions it, but not the measures needed to overcome the difficulties.*

Spurious mixing in the context of tides is likely to arise when large amplitude internal tides are generated. Without special treatment coordinate surfaces will only move with the barotropic tide, so the baroclinic tide will lead to high frequency isopycnal displacement across the coordinate surface. This is likely to lead to spurious vertical mixing. It is the motivation for the development of the z-tilda coordinate in NEMO. The discussion on this has been expanded (P7 L37), although we are not in a position to offer novel solutions here.

*Page 9: Transition to terrain-following coordinates in shallow water: This option is available in some other models (SELFE, FESOM) from much earlier date.*

This has been noted (P9 L4).

*The message of Figure 5 is not very clear. It does not show why or which technology should be selected.*

This figure has been replaced with a quantitative comparison with CMIP5 models and observations, in both the overall (Fig 4) and seasonal cycle (Fig 6) cases, along with a qualitative comparison between NNA and ORCA12 (Fig 5). This provides a much clearer message on the benefits of improved resolution and process representation.

*Page 10: "Mixing of temperature and salinity usually takes place along isoneutral, rather than geopotential, surfaces and this requires careful implementation in the case of sloping vertical coordinates." What about transport algorithms with upwinding or limiters? Most coastal applications will need upwinding and limiters.*

It not clear what is being suggested here. The NEMO model uses the same transport algorithms in coastal and open-ocean applications, which is appropriate.

*Line 20: The simplest is of course scaling with the horizontal mesh cell size for harmonic and cube of that for biharmonic operators as is routinely done in most codes.*

Agreed

*Discussion mixes horizontal (Smagorinsky) and vertical aspects.*

This has been clarified with section headings

*Scale-selective approaches deserve more attention.*

They do deserve more attention, but we are not in a position to provide any further developments on this here and are not aware of any other published work in this area.

*In most cases the horizontal subgrid operators just aim to remove the grid-scale variance, which is far from physically motivated solutions.*

Agreed and noted (P9 L35)

*Line 25: "Quadrilateral meshes approximate coastlines by imposing zero-normal flow condition on specific edges of the mesh and masking the landward solution." — I think all meshes do the same in this respect.*

Agreed and corrected P10 L13.

*The representation of coastlines should not be a big issue on terrain following quadrilateral meshes if the depth tends to zero. On the other hand, on triangular meshes smooth coastlines do not really help unless terrain-following meshes are used, for boundary of any layer should be smooth. If wetting and drying is present, then again it is the bottom representation. So there is general problem of bottom representation, and the example of Kelvin wave is in essence related to it. The representation of coastlines is a part of this general problem, and cannot be considered separately.*

This may be true, but the depth does not generally tend to zero in terrain following coordinate models due to the combatively coarse resolution considered (compared with coastal models of 100m's meter resolution; P10 L25), particularly when wetting-drying has not been implemented and a minimum depth is required. This implies that Kelvin-wave retardation remains a potential issue for the barotropic solution of structured mesh models where the coast is not aligned with the coordinate system. The relation between this and the underlying topography is now discussed (P10 L18).

*Section 3.2. ORCA meshes assume certain scaling (largely with latitude), so together with calculations for them it would be of interest to present a mesh-independent calculations: you have your pattern of the smaller of the baroclinic, barotropic, and topographic scales and can compute distribution of mesh nodes over scales for just resolving and for resolving with two points per scale. This is more informative for unstructured meshes.*

Agreed it would be possible and maybe interesting to reproduce this refinement process with other underlying mesh structures, but we're not sure this significant added complication (e.g. extra figures and description) would add much to the paper.

*A delicate question is the behavior of time step with resolution, which needs some extra discussion. ORCA meshes partly account for the reduction of the phase speed of internal waves with latitude, but other processes may be (locally) limiting at fine scales.*

*And...*

*The discussion of the number of mesh points looks unsatisfactory (it is elementary) to me if not augmented by time step analysis, at least on a qualitative level.*

*And...*

*Scale  $L_{min}$  may imply different time step selection at different locations, so the question is what is the optimal strategy.*

Agree and we have added a section on timestepping (P13 L34). In all the resource estimates we have assumed a single global time step and this scales with the inverse of the minimum length scale, now explicitly stated: P17 L9. An exception is the block refined case, where we assume each refined block can have a different time step and appropriate load balancing is in place (P17 L18). We mention the possibility of locally varying timesteps in discussion (P14 L1) but do not include this possibility in our resource estimates for unstructured mesh models.

*Page 11, line 40: In reality hybrid approach is used by all these models as concerns the computation of pressure gradients. It is also true for many other models.*

Noted – this has been deleted.

*Page 12: Line 1: I think the authors derived a wrong message. There is no point with formal accuracy on unstructured meshes, in fact smooth triangular meshes are more isotropic than quadrilateral and will be more accurate. Computational modes indeed require attention, but there are solutions how to handle them. The technology is mature enough, it requires more caution*

Noted and no longer included

*Line 3: Wave propagation on quadrilateral meshes has no advantages. Quadrilateral meshes are simply cheaper for there are less edges, which is crucial for finite-volume codes.*

Noted and no longer included.

*Line 10: "The former ....but have not yet reached ...." Please be careful, for the statement is wrong. FESOM, for example, was a part of CORE-II intercomparison (see the virtual special issue of Ocean Modelling), it is a component of AWI climate model (see Sidorenko 2015, Clim. Dyn), and in this way participates in CMIP6. I think that the unstructured-mesh part of this section is weak and does not convey a correct message to community.*

Section 3.4 has been re-written to address these concerns.

*The discussion proposed in this section misses some important points. If the clock speed peak is already reached, the throughput of codes on fine meshes will decrease on mesh refinement. This aspect is not less practical than the availability of computational power and has to be mentioned. The authors state "This requires at least threeway nested parallelism ..." Are there solutions allowing to efficiently work with smaller mesh pieces per core? A perspective in this direction should be addressed. The other aspect is structured vs unstructured codes. In finite-volume unstructured-mesh codes the neighborhood information is two-dimensional, so it is related to the vertical column of computational points and accessing it is not expensive. Computations of high-order advection or gradients are more expensive than on sttuctured meshes, but if memory bandwidth is a limiting factor, the need in more computations will be less apparent.*

*Furthermore, mesh partitioning is easier (it is derived from the connectivity pattern and involves only wet nodes). I am not sure whether discussing all this is possible in this manuscript, but proposing some discussion would provide a much more valuable message to the community.*

We now provide a section discussing the efficiency and scalability of ocean models (section 4.4) and provide a practical suggestion on how they can be coded to accommodate this three-way nested parallelism (P16 L24).

*The statement on page 15 "Hence, unless very efficient methods of multiscale modelling are developed ....." can be critisized, and the extent of this depends on what we define as efficiency and what oceanographic task we are considering. I would not do here, but only note that multiscale modeling methods can be (and are) much more efficient than assumed in the manuscript.*

This has been corrected both in the text and resource estimations.

*I think Fig. 10 is not really necessary, for much more work is needed to explore functioning of such meshes for eddy-rich dynamics. There is no substance at present. It is in contrast to numerous other efforts on triangular meshes which are barely addressed.*

Agreed and this has been removed.

## **Response to RC2**

*Most of the introductory theory is well-known to modellers in both ocean and shelf communities, and could be truncated, keeping the informative figure 1 and reducing figures 2*

and 3 since there is no discussion of 1/24 and 1/48 degree resolution. The same can be said for figure 7 as 1/36 degree resolution is only briefly discussed.

Sections 1.2 and 1.3 have been substantially edited. Figs 2, 3 and 7 and table 4 have been simplified to only include the resolutions discussed in the text. We retain 1/36 as a likely next step from the current 1/12 model (P6 L17).

*I also feel that figures 4,5 and 6 contribute little enhancement over the given text and can easily be omitted.*

Figures 4 and 5 have been replaced with the comparison between CMIP5, NNA and ORCA4 models and EN4 observations (F4, 5, 6). Old Fig 6 (new fig 7) has been retained as we feel it important include an illustration of the refinement process to help explain fig 8.

*However the treatment of other numerical schematisations is given only cursory consideration and selects, what seems to me, to be a totally arbitrary scaling factor (5) for the performance of unstructured models (in this case FVCOM is chosen) against NEMO in a limited shelf region (without any detail of these simulations), which is then applied on a global scale.*

*A more considered view of alternative numerical representations is warranted, and the authors are aware of some of these (e.g. FESOM, MPAS) and there are others (e.g. SELFE, SCHISM), and what about adaptive grid schemas?*

It is not our intention to go into the details of numerical approaches as this would require a much more comprehensive review. We now briefly describe a wider range of models (P12 L34-39) and provide some more detailed discussion on the relative efficiency of structured and unstructured mesh models (P15 L35), and also provide a more detailed consideration of what an appropriate range of scaling factors might be (P16 L5-18).

*Also, there is no discussion of the efficiency of NEMO against other comparable models which are global (e.g. MOM, HYCOM, ROMS).*

We aim at the discussion here to be model independent – the simple cost model makes no assumptions on actual model used. We now include some anecdotal estimates of present day global model turn-around time (Table 3).

*some of the processes discussed e.g. tides, sea ice, etc. will need to be included to properly represent the physical processes in these regions at this scale, so some estimates of their inclusion ought to form part of the discussion.*

We include an estimate of efficiency of a shelf sea model in Table 3. Efficiency of sea ice modelling can be a particular issues (e.g. around load balancing), but is not pertinent to the discussion here (P1 L34).

*Minor points*

Corrected

*Page 5, line 17 “: : tides are ubiquitous in the coastal-ocean”. Well, no they are not an important process to resolve everywhere, some coastal ocean regions have extremely small tides.*

Agree – we have replaced this statement with a quantification of how important tides are (by area) P4 L15

*Page 6, line 34. Please better explain the factor E*

This has been clarified P5 L23-25,

*Page 9, line 20+. Worth adding further detail regarding the sophistication of the hpg calculation and explanation of its impact on the energy cascade*

Discussion on this has been developed: P8 L37-

*Page 10, line 12. “: : : but is not generally used : : :” is it ‘used’ or ‘required’?*

Agreed and changed P9 L34.

*Page 12, line 5. States Figure 9, should be Figure 10*

*Page 12, line 8. Need a reference for the statement “serious numerical issues”*

*Page 12, lines 13-16. Sentence badly constructed*

This has now been removed

*Page 13, line 30. What are the implications of this energy figure?*

A comment has been added P14 L29

*Page 13, line 31. The projections of compute power in Figure 9 appear to be based on extrapolations of existing architecture, how realistic is this assumption?*

It is based on an extrapolation: this is the best information we have to judge future evolution of computer resources – there are of course many unknowns. But even this uncertain information is much better than the common unquantified assertions of ‘increasing computer power’.



# Prospects for improving the representation of coastal and shelf seas in global ocean models

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**Abstract.** Accurately representing coastal and shelf seas in global ocean models represents one of the grand challenges of Earth System science. They are regions of immense societal importance, through the goods and services they provide, hazards they pose and through their role in global scale processes and cycles, e.g. carbon fluxes and dense water formation. However, they are poorly represented in the current generation of global ocean models. In this contribution we aim to briefly characterise the problem, and then to identify the important physical processes, and their scales, needed to address this issue in the context of the options available to resolve these scales globally and the evolving computational landscape.

We find barotropic and topographic scales are well resolved by the current state-of-the-art model resolutions, e.g. nominal 1/12°, and still reasonably well resolved at 1/4°, here the focus is on process representation. We identify tides, vertical coordinates, river inflows and mixing schemes as four areas where modelling approaches can readily be transferred from regional to global modelling with substantial benefit. In terms of finer scale processes, we find that a 1/12° global model resolves the 1<sup>st</sup> baroclinic Rossby Radius for only ~8% of regions <500m deep, but this increases to ~70% for a 1/72° model, so resolving scales globally requires substantially finer resolution than the current state-of-the-art.

We quantify the benefit of improved resolution and process representation using 1/12° global and basin scale northern North Atlantic NEMO simulations; the latter includes tides and a k-ε vertical mixing scheme. These are compared with global stratification observations and 19 models from CMIP5. In terms of correlation and basin wide RMS error, the high resolution models out perform all these CMIP5 models. The model with tides shows improve seasonal cycles compared to the high resolution model without tides. The benefits of resolution are particularly apparent in Eastern Boundary upwelling zones.

To explore the balance between the size of a globally refined model and that of multiscale modelling options (e.g. finite element, finite volume or a 2-way nesting approach) we consider a simple scale analysis and a conceptual grid refining approach. We put this analysis in the context of evolving computer systems, discussing model turn-around time, scalability and resource costs. Using a simple cost-model compared to a reference configuration (taken to be a 1/4° global model in 2011) and the increasing performance of the UK Research Councils' computer facility, we estimate an unstructured mesh multiscale approach resolving process scales down to 1.5km would use a comparable share of the computer resource by 2021, the 2-way nested multiscale approach by 2022, and a 1/72° global model by 2026. However, we also note that a 1/12° global model would not have a comparable computational cost to a 1° global model today until 2027. Hence, we conclude that for computationally expensive models (e.g. for oceanographic research or operational oceanography), resolving scales to ~1.5km would be routinely practical in about a decade given substantial effort on numerical and computational development. For complex Earth System Models this extends to about two decades, suggesting the focus here needs to be on improved process parameterisation to meet these challenges.

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## 1. Introduction

Improving the representation of coastal and shelf seas in global models is one of the grand challenges in ocean modelling and Earth System science. Global ocean models often have poor representation of coastal and shelf seas (Renner et al., 2009; Holt et al., 2010), further quantified below, due to both their coarse resolution and their lack of coastal-ocean process representation.

5 See Griffies and Treguier (2013) for a recent review of the state of the art in global ocean modelling. In this paper we aim to identify the relevant physical processes, quantify the horizontal scales needed to resolve these processes and explore the approaches that could be employed to realise an improvement. In particular we compare the relative merits of a continued refinement of quasi-uniform structured grids with multiscale approaches, which would allow increased resolution where required. The multiscale approach could, for example, use unstructured meshes or multiple two-way nested grids. There have  
10 been other previous explorations of the scales important in shelf sea models (Greenberg et al., 2007; Legrand et al., 2007). These have tended to focus on specific numerical methods and approaches, largely around triangular unstructured meshes. Here we step back from a detailed analysis of the numerics and consider, in general terms, what is likely to be practical to achieve improved coastal and shelf sea modelling on a global scale, on what time scales and what the ways forward may be. We primarily draw on experience with the NEMO model (Nucleus for a European Model of the Ocean; Madec, 2008) to provide a specific context, but expect the conclusions drawn to be generic.

The remainder of this section describes the background and motivation. Coastal-ocean processes and scales and their relation to global quasi-uniform model grids are described in section 2. Section 3 considers modelling approaches that might address coastal-ocean process representation and resolution, drawing on the CMIP5 coupled ocean-atmosphere climate models (Taylor et al., 2012) and two 1/12° NEMO configurations in comparison with EN4 profile observations (Good et al., 2013) to provide  
20 quantitative examples. These considerations are related to changing computer architectures and issues of model performance, in section 4, to estimate when they may be practical. The paper ends with conclusions in section 5.

### 1.1 Background and Motivation

Coastal and shelf seas represent a small fraction of the area of the global ocean (9.7% of the global ocean is <500m deep and 7.6% <200m), but have a disproportionately large impact on many aspects of the marine environment and human activities.

25 While, our focus here is on modelling physical-ocean processes, facets of marine biogeochemistry and ecosystems, and the climate system often provide the underlying motivation. These seas are the most highly productive regions of the world ocean, providing a diverse range of resources (e.g. food, renewable energy, transport) and services (e.g. carbon and nutrient cycling and biodiversity), and also expose human activity to hazards such as flooding and coastal erosion.

The geography of these seas is very varied including semi-enclosed seas, broad open shelves, narrow shelves exposed to the  
30 open ocean, and coastal seas behind barrier islands. Rather than adopt a typological approach (e.g. Liu et al., 2010) we focus on generic physical processes described by some straightforward spatially-varying properties, as is appropriate for the global case; regional model studies would go beyond this to consider the detailed conditions specific to the region and tailor the model accordingly. While many of the largest shelf seas are in polar regions, we limit our investigation here to liquid water modelling and leave considerations of sea-ice modelling in this context to further work.

35 The study of coastal and shelf seas in a global context involves both upscaling (small scales influencing large) and downscaling (large scales influencing small) considerations, alongside the internal dynamics. Both dynamics and biogeochemistry provide motivations to studying the influence of coastal-ocean processes on a global scale. A particularly important dynamical feature is the formation of dense water on Arctic and Antarctic (Orsi, 2010; Orsi et al., 1999) shelves and its subsequent downslope transport and mixing to form deep water masses through the “cascading” process, thereby contributing to the global thermohaline circulation. Similarly coastal-upwelling is both an important control of air-sea heat flux with implications for regional climate (e.g. in the southeast Pacific; Lin, 2007) and a key process in global marine ecosystems. The coastal-ocean plays a key role in global biogeochemical cycles, for example through the drawdown of carbon in highly productive shelf seas

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and its transport either to on-shelf sediments or off-shelf to the deep ocean, where it is isolated from atmospheric exchange (Bauer et al., 2013; Chen and Borges, 2009). Shelf seas are also a source of potent greenhouse gases, such as nitrous oxide (Seitzinger and Kroeze, 1998) and methane release from hydrates (Shakhova et al., 2010). The coastal-ocean is the first point of entry for all material of terrestrial origin entering the marine environment, for example freshwater from rivers and ice sheets/shelves, inorganic nutrients, organic material and anthropogenic pollutants and this material can be substantially modified as it is transported across the coastal-ocean (Barrón and Duarte, 2015). Hence the coastal- and open-ocean biogeochemical cycles are intimately coupled. There is still substantial uncertainty in their role and feedbacks with the wider climate system, and making progress on this is largely dependent on the accurate simulation of the physical environment in the coupled coastal-open-ocean system.

Investigating the large scale impacts on smaller scale processes in the coastal-ocean can often be successfully treated by (one-way or two-way) nested regional studies, focusing on an area of interest ranging from local (e.g. Zhang et al., 2009) to regional (e.g. Wakelin et al., 2009) to basin (e.g. Holt et al., 2014; Curchitser et al., 2005) scale. There are, however, occasions where a global or quasi-global approach is appropriate. These relate to cases where it is important to consider impacts on human systems of global relevance. Examples include global food security and the role of Living Marine Resources in ensuring this (Merino et al., 2012; Barange et al., 2014), and quantifying global vulnerability to sea level rise and coastal-flooding (e.g. Nicholls, 2004). Moreover, cases where basin scale oceanic processes directly influence the coastal-ocean are best considered on a global scale (Popova et al., 2016), as regional simulations may be compromised by errors propagating from simplified boundary condition approaches (see below). Coastal upwelling (Popova et al., 2016; Hobday and Pecl, 2014) and impacts of changes in western boundary currents (Wu et al., 2012) are notable examples.

While regional or local models often provide the optimal solution for many coastal-ocean questions there is a significant overhead in their deployment. A global model with improved representation of the coastal-ocean opens up the opportunity to provide rapid and cost effective information in a particular region for either scientific or operational use, without needing to configure a new domain. A particular example, here is the European Copernicus Service (marine.copernicus.eu). In this multi-~~in~~ investment, operational forecast and reanalysis products are provided to a range of users, from bespoke models of several European regions. If the global model in this service had improved coastal-ocean representation then a similar, but not optimal, range of information could be provided for a much wider range applications around the world, notably where this level of investment is not available.

Hence we define the context of the present study to be the improvement of the representation of the coastal-oceans in four classes/uses of global ocean models: i. global climate models, ii. global earth systems models, iii global models used as a resource for regional scientific studies, and iv. global models providing regional operational information.

## 2. Coastal-Ocean processes and scales

The distinct physical characteristics of the coastal-ocean, in comparison to other oceanic regions, are largely determined by their shallow depth and proximity to land. This has several implications for the dynamics:

- The water depth is generally similar to or not much greater than the surface or seabed boundary layers, so turbulence and mixing is invariably important.
- Extreme variations in topography (compared with the water depth) are a defining feature.
- Incident waves grow in amplitude in shoaling water to conserve energy flux, so, for example, these can be regions of large tides.
- The inertia (thermal and mechanical) of shelf seas is small, so they are highly constrained by external forcing.
- The horizontal length scales of the dominant physical processes decrease with decreasing depth (see below) and so are generally much smaller than in the deep ocean.

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A particularly important dynamical feature is the formation of dense water on Arctic and Antarctic shelves and its subsequent downslope transport and mixing to form deep water masses through the "cascading" process, thereby contributing to the global thermohaline circulation.¶

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There are three key motivations to studying the influence of coastal-ocean processes on the global scale: dynamics, biogeochemical cycles and anthropogenic impacts (i.e. the large scale impact of small scale human activity). Here we consider some examples, without attempting to be exhaustive.¶  
A particularly important dynamical feature is the formation of dense water on Arctic and Antarctic shelves and its subsequent downslope transport and mixing to form deep water masses through the "cascading" process, thereby contributing to the global thermohaline circulation.¶  
Two key water masses in the global ocean circulation are Antarctic Bottom Water (AABW) forming the densest water masses in all the major ocean basins, and North Atlantic Deep Water (NADW) found predominantly in the North Atlantic, lying above the AABW. Both these water masses are key components of the climate system, e.g. the NADW forms the lower limb of the Atlantic Meridional Ocean Circulation, responsible for the northward transport of large quantities of heat.¶  
The AABW typically forms on the Antarctic shelves (primarily in the Weddell and Ross Seas, Adelle Land and near Cape Darnley) and subsequently cascades downslope into the deeper Southern Ocean (Orsi, 2010; Orsi et al., 1999). The source waters for the deeper component of NADW are mainly located in the extensive shelf seas of the Arctic and Greenland-Norwegian Basins, e.g. Deep Barents Sea Water forms through winter buoyancy loss west of Novaya Zemlya and cascades down through the St Anna Trough to reach depths of 1500-3000 m (Aksenov et al., 2011). ¶

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- Rivers and glacial melt provide a source of buoyant fresher water that forms coastal currents and impacts stratification and mixing near the coast.
- In Polar Regions, land provides both a point of attachment (land fast ice) and a source of divergence (polynias) for sea ice.

5 Alongside these internal dynamics, coastal-open-ocean coupling is of critical importance to the considerations here. At ocean margins currents tend to follow contours of the Coriolis parameter divided by water depth ( $f/h$ ), and so coastal regions are largely isolated from the large scale geostrophic circulation. Physical processes at the shelf break mediate the transfer of material across this barrier (Huthnance, 1995), e.g. the Ekman drain within the bottom boundary layer, eddies and internal waves; these tend to be fine scale and high frequency.

10 While there are numerous physical processes at work in shelf and coastal seas the underlying principles and equations are the same as in the open ocean, and many features noted above are represented in the current generation of global models. Their relative importance and scale differ significantly in the two cases, and so does how they are treated in numerical models. The processes are reviewed by Robinson and Brink (1998), Huthnance (1995) and Holt et al (In Press), so we do not discuss the dynamics in any detail here; we are primarily concerned with their characteristic horizontal scales (Table 1).

15 Ocean tides make a substantial contribution to the mixing and transport in most coastal-ocean regions. For example, the mean  $M_2$  semi-major axis tidal current speed is  $0.29\text{ms}^{-1}$  for water shallower than 500m, compared with a global mean of  $0.06\text{ms}^{-1}$  (based on TPX data; Egbert and Erofeeva 2002). Only 8% by area of these shallow regions have tides  $<0.12\text{ms}^{-1}$  (i.e. weak tides). The barotropic tide propagates on-shelf as a coastal-trapped wave (CTW), amplifying, and transferring energy to higher harmonics as the water depth shoals; the scale ( $L_{bt}$ ) is characterised by either their wave length or Kelvin wave scale. The (substantially finer) scale of rectification of tidal currents around topography and the periodic mixing and stratification at fronts is set by the tidal excursion ( $L_e$ , e.g. Polton, 2014). Topographic steering of currents is a characteristic feature of shelf seas and ocean margins (e.g. the Dooley Current in the North Sea), with a barotropic scale of the water depth divided by the slope ( $L_T$ ) (Greenberg et al., 2007). Other topographic scales, such as the size of individual features, will be locally relevant, but are not considered here.

25 The annual stratification cycle is a key feature of many shelf seas that are shallower than the winter ambient open-ocean mixed-layer depth. This is well described by a balance between surface heating and mixing (Simpson and Hunter, 1974) and the general spatial pattern is then set by the propagation of tides across the shelf and the topography (i.e. the barotropic scales;  $L_{bt}$ ,  $L_T$ ). Mixed and seasonally stratified waters are bounded by sharp mixing fronts. These provide effective barriers to lateral transport, and drive baroclinic frontal jets (Hill et al., 2008), at a scale characterised by the 1<sup>st</sup> baroclinic Rossby Radius ( $L_1$ ;

30 Table 1). While mesoscale eddies are present in shelf seas (e.g. Badin et al., 2009) their importance in dynamics and transport on-shelf is much less clear than in the open-ocean (Hecht and Smith, 2008) or for ocean-shelf transport (e.g. Zhang and Gawarkiewicz, 2015). Coastal upwelling, and consequent frontal jets and filaments (Peliz et al., 2002) also scale with the Rossby Radius.

Tidal flow over topography in a density stratified ocean excites internal waves at tidal frequencies (Baines, 1982), and their

35 role in mixing at the shelf break (Rippeth and Inall, 2002) and in the vicinity of banks (Palmer et al., 2013) is now well established. Much of the energy resides (at least initially) in the 1<sup>st</sup> mode, so their scale ( $L_{iw}$ ; Table 1) is closely related to  $L_1$ . Hence, we see that resolving  $L_{bt}$ ,  $L_T$  and  $L_{iw}$  is crucial for a wide range of coastal-process representation.

Riverine and glacial freshwater inputs form buoyant coastal currents that can form a substantial part of the coastal-ocean circulation and an important control mediating the transport of terrestrial material, notably by inhibiting its direct off-shore

40 transport. Their scale is difficult to quantify in general terms on a theoretical basis. To characterise how well riverine coastal currents are modelled, we consider the minimum of two scales ( $L_r$ ): the horizontal scale characteristic of seabed frontal

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Since they are regions of strong bathymetric variation, t
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- Deleted: Yanklovsky and Chapman (1997) estimate the scale of a cyclotropic plume, but this is highly dependent on detailed conditions at the river mouth, specifically the in-flow velocity (rather than transport) and the depth at the river mouth. Moreover, the flow then evolves as a 'bottom trapped', or 'surface advected' plume depending on prevailing conditions; these are difficult to evaluate in a global context. So instead,
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trapping, defined as the depth of trapping (Yankovsky and Chapman, 1997) divided by the local slope and the inflow Rossby Radius (Avicola and Huq, 2002) (Table 1).

## 2.1 Coastal-ocean process scales in a global context

To put the scales described above and listed in Table 1 into a global context we calculate values using the global ORCA12 NEMO model (set up by the DRAKKAR group e.g. Marzocchi et al., 2015; Duchez et al., 2014) as a reference grid and bathymetry. This is a tri-polar grid with a coarsest resolution of 9.3km, but decreasing to minimum values of 1.8km in the southern ocean and 1.3km in the Canadian archipelago. The median scale is 6.3km. The bathymetry is a combination of GEBCO and ETOPO2. The process scales are themselves very much dependent on the scale of the information used to calculate them (e.g. the level of detail in topographic roughness used in calculating  $L_T$ ), so a high resolution model grid used in practice is a good starting point, although the results presented below are not generally dependent on this grid choice. Figure 1 shows values of the barotropic ( $L_{bt}$ ) and 1<sup>st</sup> baroclinic Rossby Radii ( $L_1$ ), the topographic length scale ( $L_T$ ) and the tidal excursion ( $L_e$ ); see figure caption for further details of the calculation.

The barotropic Rossby radius is, as expected, large (>1000km) even at high latitudes, except in shelf seas and near the coast e.g. in 20m water depth at mid-latitudes,  $L_{bt}$ ~100km. For  $L_T$ , values <100km are widely distributed across the ocean, reflecting features such as ridges and sills. Values <10km are, however, restricted to the slopes at the ocean margins between the deep ocean and either the continents or the continental shelves. For the baroclinic Rossby radius ( $L_1$ ), values <10km occur in high latitude oceans, whereas values <6km are limited to continental shelves. The tidal excursion ( $L_e$ ) is much smaller, generally <10km. It shows an opposite pattern to the baroclinic Rossby radius, being largest at the coast. Where it is very small (e.g. in the open ocean) so is the tidal velocity and it is of minimal importance. Where it is large, however, it can make a significant contribution to local water column mixing/stability and fine scale residual transport.

To assess how model resolution compares with these scales we define a parameter:

$$e = L_x / (\max(\Delta x, \Delta y) \cdot E) \quad (1)$$

at each model grid cell (size  $\Delta x, \Delta y$ ) of the ORCA12 mesh, i.e. the number of cells per length scale for process 'x'. We multiply the size of each cell of the original grid ( $\Delta x, \Delta y$ ) by a factor,  $E$ , to approximate other grid resolutions (without needing to generate the grids; e.g.  $E=3$  for a nominal  $1/4^\circ$  resolution). We focus on the barotropic and baroclinic Rossby radii and the topographic scale. We do not consider the tidal excursion further in this context, as resolving it is only beneficial in regions where the tide is large. Here we consider the nominal model resolutions listed in Table 2, along with example applications for the global and coastal-ocean cases. It is worth noting the current generation of forced, high resolution global models are of similar resolution to many historic and on-going shelf sea simulations (see references in Table 2). The cumulative distributions of  $e$  (Figure 2), weighted by the area of each grid cell, then show the fraction of the model area at a particular resolution that resolves scale  $L_x$  with  $e$  or more grid cells. This figure also shows the distribution calculated just for water depth <500m i.e. the coastal-ocean. What constitutes adequate resolution then depends on the process in question. Hallberg et al (2013) suggest 2 grid cells per baroclinic Rossby radius gives a good representation of eddy fluxes, so we take  $e > 2$  to be eddy resolving. If eddies have a characteristic size of  $\sim 2L_1$  (i.e.  $1/2$  the wavelength of the fast growing baroclinically unstable mode; Pedlosky, 1987) then we take  $e < 1$  to be eddy excluding (i.e., a full parameterisation of eddy effects would need to be included in the model) and between these to be eddy permitting. For the barotropic Rossby radius ( $L_{bt}$ ) we take the limits on excluding and resolving to be  $e < 2$  and  $e > 10$ , on the basis that this scale needs to be well resolved to capture many coastal-ocean processes (as discussed above). For the topographic scale we set the limits at 1 and 3 respectively, since at least three cells are required to represent a topographically constrained jet.

We can therefore demonstrate that a  $1/4^\circ$  global model is eddy resolving for 27% of the globe; this increases to 52% for  $1/12^\circ$ , 77% for  $1/36^\circ$  and 91% for  $1/72^\circ$ . The fraction of the coastal-ocean that is eddy resolving is significantly less: ~8% at  $1/12^\circ$ ; 34% at  $1/36^\circ$ ; a  $1/72^\circ$  resolution is needed to be eddy resolving over ~70% of the coastal-ocean. The topographic scale is much

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more promising. A  $1/12^\circ$  model has  $e > 3$  for ~90% of the global and ~70% coastal-ocean case. Resolving the barotropic Rossby radius is a somewhat more stringent criterion than resolving the topographic scale in the coastal-ocean at  $1/4^\circ$  or coarser resolution.

To explore the ability of models of different resolution to represent river plumes on a global scale, Figure 3 shows the cumulative distribution of the number of rivers (out of the 925 largest by volume flux; Dai et al., 2009) where the scale,  $L_r$ , is resolved to level  $e$ . This suggests modelling riverine coastal currents is an extreme challenge for structured grid global models. Using the same criteria limits as for  $L_T$ , at  $1/12^\circ$  only 38 of the largest 925 rivers meet the ‘permitting’ criteria. This implies that, while the fresh water balance is correct, its dispersion and transport properties will be limited. This number increases to 165 at  $1/72^\circ$ .

We see from this scale analysis that  $1/72^\circ$  (~1.5km) might be taken as a good target for resolving many small scale coastal-ocean processes such as eddies, upwelling and the largest river plumes. We would also expect it to be adequate for resolving tidal excursions (where important) and internal tides. However, it is important to consider these results in the context of coastal-ocean dynamics and previous modelling experience. Very few regional coastal-ocean modelling studies have been conducted at eddy permitting resolution, yet significant progress in our understanding of the dynamics of these regions has still been achieved. Hence, while 1.5km might be seen as an aspiration, the practicalities of being eddy resolving on-shelf (when/how this can be reached are discussed below) should not be seen as a particular obstacle to making shorter term progress in modelling the coastal-ocean on a global scale, for example by using  $1/36^\circ$  as a compromise resolution (as in many coastal-ocean studies: e.g. Maraldi et al 2012) or focusing on process representation (e.g. Luneva et al., 2015). Some features with scales of the Rossby radius, such as coastal upwelling, river plumes and frontal jets will still be present in models that do not resolve this scale, they will just not be particularly well represented. For example, continuity will lead to upwelling in a model of any resolution; its horizontal scale will be determined by the grid and numerics rather than the physics. Internal waves and eddies, in contrast, will simply be absent, and so need to be parameterised. The barotropic and topographic scales are vitally important for the accurate modelling of coastal-ocean dynamics, but can be reached at more modest global resolutions.

### 3. The Modelling Approaches

Here we consider, in general terms, how the processes considered above are represented by the model dynamical equations or specific parameterisations, and those that are resolved by the model grid. The inadequacy of global climate models in the coastal-ocean is frequently quoted but rarely quantified. So we start this section with a consideration of how well the CMIP5 generation of climate models (Taylor et al., 2012) performs in these regions. We focus on the potential energy anomaly (PEA) as a useful measure of water column stratification. The PEA is defined by:

$$\phi = -\frac{g}{h} \int_{z=-h}^0 z(\rho(T, S) - \overline{\rho(T, S)}) dz \quad (2)$$

where  $h$  is the water depth (here the integration is limited to 200m),  $g$  is the gravitational acceleration,  $\rho$  the density and  $z$  the (positive up-wards) vertical coordinate. An overbar indicates an average over the same depth as the integration. This represents the energy (per depth) needed to mix the water column. It is a commonly used metric for stratification since it is an integral quantity that does not relate to a particular vertical structure or threshold and connects with simple theories of stratification evolution (Sharples and Simpson, 1996; Simpson and Hunter, 1974). Using the historical period (1970-2005) of 19 CMIP5 models, we calculate mean PEA for each month and average over these 36 years to give a mean annual cycle, interpolated onto the Northern North Atlantic  $1/12^\circ$  NEMO Model grid (see below). These models were selected because they all simulate aspects of marine biogeochemistry. We also calculate the PEA for each profile in the EN4 CTD profile dataset (Good et al., 2013), and average these onto the same model grid to give an observed mean annual cycle on a common grid. The model and observed values are then compared to give RMS error (RMSE) and correlation statistics, here mixing spatial and seasonal

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variability. Figure 4 shows these values calculated for the whole northern North Atlantic and only where depths are less than 500m (approximately the coastal ocean). This shows the general picture that the performance of these models is degraded in the coastal-ocean (RMS errors are higher, correlations are lower). This is the case for all models for RMSE except one (marginally), and 11 out of 19 for correlation; for the models lying above the line, the correlations are either small or they sit very close to the line. This figure also shows that all the higher resolution models (0.5° or finer) perform well, but there is not a clear resolution dependence, e.g. some coarser resolution model perform similarly well.

### 3.1 Process representation

The representation of coastal processes in global ocean models is straightforward, at least in concept. For example, the NEMO model, from V3.2 onwards has the capability of simulating both open ocean and shelf sea cases (O'Dea et al., 2012; Maraldi et al., 2012), with capability improving in later versions. This essentially allows these processes to be included by configuration selection as the global model resolution is refined. The open question is whether features pertinent to the coastal-ocean can be introduced into global models without degrading the solution in the open ocean or significantly increasing their computational cost. The model development process is largely focussed around reconciling the differences between coastal-ocean and global ocean approaches; a good guiding principle could well be to minimise the changes needed in the global modelling approach, on the basis that these choices are well suited for the majority of open ocean processes.

#### 3.1.1 Tides

The representation of tides in global models is the natural starting point. There are two approaches that can be considered: direct simulation and parameterisation. Along with tide generating forces, self-attraction, loading and solid earth tides need to be represented to achieve an accurate tidal simulation (e.g. Stepanov and Hughes, 2004). In addition the correct energy dissipation through bottom friction and internal tide generation is required. Baroclinic global tidal models with prognostic temperature and salinity (e.g. HYCOM; Arbic et al., 2012) can directly simulate the internal tide field. However, low mode internal tides can propagate large distances from their generation region, making their impact (e.g. on mixing) hard to adequately parameterise (Simmons et al., 2004). As identified above, global models at resolutions finer than  $\sim 1/4^\circ$  permit low mode internal tides in the open ocean, but not higher modes or wave numbers or internal tides in the coastal-ocean. For example, Niwa and Hibiya (2011) find a strong resolution dependence of barotropic to baroclinic tidal energy conversion with no convergence even at  $1/15^\circ$ . Hence, some form of wave drag parameterisation may be required. Arbic et al (2012) found a carefully tuned wave drag parameterisation is necessary to accurately simulate tides in the isopycnal HYCOM model, whereas Muller et al (2010) found that a wave drag scheme was not required in the geopotential ( $z$ -) level MPI model.

Introducing tides into a global models requires changes to a number of model formulations. For example, The accurate representation of the bottom boundary layer by fine near bed vertical resolution, e.g. through terrain ( $s$ -) following or Arbitrary Lagrangian Eulerian coordinates (Petersen et al., 2015); turbulence models suited for multiple boundary layers (Burchard et al., 2008); a sophisticated representation of bottom friction, e.g. quadratic friction with log layer formulation (Blumberg and Mellor, 1987) and a semi-implicit bed stress implementation for numerical stability, given the large stresses and thin vertical layers. For conservation reasons (Campin et al., 2004), most global ocean models are now moving towards using a non-linear free surface, as is also required to represent large tidal amplitudes. Tidal dynamics are most accurately represented with a mode-split time stepping approach (e.g. Shchepetkin and McWilliams, 2005), rather than a fully implicit solution; this is also a trend in recent global ocean model development.

The high frequency cross-coordinate surface vertical displacement of isopycnals arising from an energetic internal tide field in a  $s$ - or  $z$ - coordinate model, but not in an isopycnal model, might be expected to lead to increased spurious mixing, unless accompanied by methods to control it. For example, this motivated the development of the  $z$ -tilde coordinate in NEMO (Leclair and Madec, 2011). A recent review of spurious numerical mixing, focusing on global ocean models with energetic ocean

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eddies, is provided by Griffies and Treguier (2013). With energetic eddying or tidal flow, the non-linear advection of momentum becomes more important, which poses a challenge for the numerical methods of momentum advection. This ultimately results in spurious diapycnal tracer transports since, even with very accurate tracer advection schemes (Colella and Woodward, 1984; Prather, 1986), or adaptive vertical coordinate systems (Leclair and Madec, 2011; Gräwe et al., 2015), this will produce spurious transport and/or dispersion errors if the velocity field contains too much energy near the grid scale (Ilicak et al., 2012). They show the spurious diapycnal transport is proportional to the 'Grid-scale Reynolds number', defined as  $Re_A = \min(\Delta x, \Delta y) U / K_H$ , where  $K_H$  is the Laplacian viscosity that dissipates the mechanical energy.  $Re_A$  should be maintained below a value of 2 to minimise this spurious transport (Griffies and Treguier, 2013; Ilicak et al., 2012). As  $U$  increases with the inclusion of tides and other high frequency processes, then maintaining  $Re_A$  below this limit becomes more problematic. Beyond this simple criteria, quantifying spurious numerical mixing remains challenging, with a number of different methods having been proposed, each with different assumptions and applicability (Griffies and Treguier, 2013 and references therein; Burchard, 2012; Klingbeil et al., 2014).

When changes to the underlying numerics or refining the grid to at least resolve the barotropic and topographic scales is not practical (e.g. for an Earth System Model), or if numerical mixing remains an issue, making direct tidal modelling undesirable, then the alternative is to use tidal mixing parameterisations, which can be adjusted not to overmix in the deep ocean. These make use of the increasingly fine resolution tidal information available from altimetry constrained models, e.g. TBX08 at  $1/30^\circ$  (Egbert and Erofeeva, 2002). The parameterisations should include benthic and under-ice mixing (Luneva et al., 2015), and mixing by baroclinic tides (St. Laurent et al., 2002). Simmons et al (2004) consider the application of an internal tide energy flux parameterisation, driven by a barotropic tidal model (St. Laurent et al., 2002; Jayne and St. Laurent, 2001), and how to translate this to an interior vertical diffusivity for implementation in a coarse resolution ocean circulation model (Simmons et al., 2004a). In contrast, Allen et al (2010) explore using a 1D mixing model (GOTM) driven at each horizontal grid cell by imposed sea-surface slopes to estimate the vertical profiles of tidal shear. This has the advantage that it can accurately account for the interaction of tidal boundary layers and stratification, which is seen to be important, for example, in the Arctic (Luneva et al., 2015), but does not account for internal tide mixing. Transport by tidal rectification is less easy to parameterise, but is expected to be secondary to the mixing effects on a global scale.

### 3.1.2 Vertical coordinates

Vertical coordinates are a key consideration when modelling the coastal-ocean; the bathymetry necessarily varies substantially at the transition from open-ocean to shelf sea and from coastal seas to the land. As noted above, mixing processes require the accurate resolution of the benthic boundary layer, as do downslope flows such as cascades and Ekman drains. Moreover, bottom boundary mixing and freshwater input lead to exceptionally sharp pycnoclines. For example, an analysis of CMIP5 models by Heuzé et al. (2013) showed that those (few) models that correctly produced Antarctic Bottom Water on the shelves were unable to cascade this water down-slope to the deeper ocean.

This need to increase resolution in shoaling water, alongside the need for smoothly represented across-isobath flows has led to a prevalence of  $s$ -coordinates in coastal-ocean models, accepting some exceptions (Maraldi et al., 2012; Daewel and Schrum, 2013) that have used  $z$ -coordinates. The large majority of global ocean models use  $z$ - or isopycnal coordinates. The reasons behind the lack of global  $s$ -coordinate models are the well documented issues of calculating horizontal pressure gradient and diffusion terms on sloping coordinate surfaces.

The requirement for tidal simulations to employ a non-linear free surface and sophisticated vertical grid leads to time-varying vertical coordinates with large slopes. This requires the use of complex schemes to derive the horizontal pressure gradient term in order to avoid spurious currents at steep topography (e.g. Shchepetkin and McWilliams, 2003) and an unrealistically energetic inverse energy cascade (e.g. Holt and James, 2006). As with numerical diffusion, accurately diagnosing this issue in realistic model simulations is problematic, so recourse is usually made to theoretical constraints such as the hydrostatic

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Vertical coordinates are a key consideration when modelling the coastal-ocean; the bathymetry necessarily varies substantially at the transition from open-ocean to shelf sea and from coastal seas to the land. As noted above, mixing processes (notably tides)... require the accurate resolution of the benthic boundary layer, as do downslope flows such as cascades and Ekman drains. Moreover, bottom boundary mixing and freshwater input lead to exceptionally sharp pycnoclines. For example, How vertical density structure changes on the transition from open- to coastal-ocean is clearly illustrated by two parameters: the pycnocline depth ( $Z_D$ ) and thickness ( $Z_T$ ). Here we use integral definitions:¶

$$Z_D = \frac{1}{I} \int_{-H}^0 N^2 dz$$

$$Z_T = \left[ \frac{1}{I} \int_{-H}^0 N^2 (z - z_D)^2 dz \right]^{1/2} \dots \dots \dots (2)¶$$

$$I = \int_{-H}^0 N^2 dz \quad N^2 = \frac{g}{\rho} \frac{\partial \rho}{\partial z}$$

where  $z$  is the positive upwards vertical coordinate,  $\rho$  the potential density,  $H$  the water depth and  $g$  the gravitational acceleration. These are readily calculated from observed profiles (here we use the EN4 data set; Good et al., 2013) and the global distribution of these parameters with water depth (Figure 4) shows a distinct pattern. The median pycnocline thickness increases steadily with water depth from ~2m (limited by resolution of the data) at 10m water depth to ~8m at ~300m, and plateaus at this value, only slowly increasing. The pycnocline depth shows similar behaviour, but does not plateau until ~500m. While EN4 is a very unevenly distributed data set, it c...

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consistency condition to define limits on the steepness of coordinate surfaces. Substantial progress has been made in addressing this issue through advanced numerics (e.g. Shchepetkin and McWilliams, 2003) or hybrid coordinate approaches (e.g. Siddorn and Furner, 2013); bathymetric smoothing is the last resort, but is still required in some cases. Given the principle of minimising the changes to the model in the open-ocean, the natural choice (for a z-coordinate model) is to move to a hybrid system with z-coordinates in waters greater than a certain depth, transitioning to terrain-following coordinates in shallower water (Shapiro et al., 2013; Luneva et al., 2015; Zhang and Baptista, 2008). These can be formulated to match the original model's vertical coordinate system at the transition depth. Such an approach does require the use of a sophisticated horizontal pressure gradient calculation, but minimises the effect of any residual error from this term in the low dissipative open-ocean region where it is likely to be most harmful (e.g. in feeding spurious energy into the inverse energy cascade). This approach has potentially substantial benefits for mixing and downslope flows. For example, Wobus et al (2013) have shown some success with a mixed z-s coordinate model to facilitate the cascading downslope near Svalbard. It could also be used to facilitate accurate cross-basin transports at deep sills.

The issues with using s-coordinates in climate models are described by Lemarié et al (2012). These include spurious mixing through diffusion associated with the advection scheme. This is particularly problematic as it occurs on steep slopes where physical mixing from (e.g.) internal tides may be prevalent. A solution to this is to use a non-diffusive advection scheme coupled with a rotated biharmonic diffusion scheme (Marchesiello et al., 2009). Another issue is the need for vertical mixing schemes that can accommodate wide variations in layer thickness and still retain low mixing in the ocean interior.

### 3.1.3 Vertical and horizontal mixing parameterisations

Surface mixing processes of wind stress, convection and wave effects are common to open and coastal-oceans, and so the primary consideration for vertical mixing schemes in the coastal-ocean that differ from the open ocean is the need to accurately model mixing at the benthic boundary layer. Two equation turbulence models (e.g. k-ε) readily accommodate this and by using the Generic Length Scale approach (Umlauf and Burchard, 2003) these can be flexibly incorporated in a global model. While these approaches give good results in shelf seas (Holt and Umlauf, 2008), they differ substantially from schemes used in global models (e.g. the TKE scheme in NEMO and KPP scheme in MOM5). The implications for global ocean simulations, e.g. deep water mass preservation properties and maintenance of the meridional over turning circulation, have yet to be established. Particularly the issue of the k-ε model's performance at low vertical resolution, needs to be established. With the length scale limiter that is usually used with this model, it reduces to a background value inversely proportional to the buoyancy frequency in strongly stratified, weakly turbulent regimes (Holt and Umlauf, 2008; eqn 6 therein). This is broadly consistent with the behaviour of ocean interior internal wave mixing (e.g. Gargett, 1984), so might be expected to give good results with careful parameter selection. This issue has been explored for the KPP model with terrain following coordinates by Lemarié et al (2012) and modifications proposed in the context of these coordinates.

Quasi-horizontal mixing approaches suitable for both open and coastal-ocean require careful consideration. These schemes play two distinct roles: first to represent the effect of unresolved eddies in transport and second to complete the cascade of energy to unresolved scales. The former is particularly important in non-eddy open ocean models (Gent and McWilliams, 1990), but is not generally required in coastal-ocean models. The latter is common across both types of model, and is often treated as a stabilisation term without reference to specific physical principles. Both shelf and global ocean models tend to employ a combination of Laplacian and/or bi-Laplacian mixing for momentum and tracers. Mixing of temperature and salinity usually takes place along isoneutral, rather than geopotential, surfaces and this requires careful implementation in the case of sloping vertical coordinates and at fronts where isopycnals intersect the sea surface and bed. The sloping coordinate systems requires the use of rotation operators for lateral tracer mixing and this can prove less accurate or more challenging for time-varying and highly sloping coordinates (compared to z-level models since isopycnal slopes tend to be fairly close to horizontal), owing to the small-slope approximation (Beckers et al., 2000). This issue has received significantly less attention than similar

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considerations with regard to the horizontal pressure gradient calculation, but is explored in this context by Lemarié et al (2012).

As we see above global models span a wide range of dynamic scales and this is exacerbated when shelf seas are considered in detail; a quasi-uniform resolution model generally includes both eddying and non-eddying regions. Hence any model that aims to accurately cross these scales needs to account for the qualitatively and quantitatively changing nature of sub-grid-scale processes. This requires scale-selective approaches to determining sub-grid-scale diffusivities and viscosities (or other forms of closure). The simplest are just depth dependence (Wakelin et al., 2009) or based on horizontal shear (Smagorinsky, 1963). Combination of these with water column density structure (Hallberg, 2013) are likely to be most appropriate, but have not yet been tested in both the open and coastal-ocean contexts.

### 3.1.4 Coastal boundary conditions and rivers

A key feature of the coastal-ocean that needs to be considered is coastlines and related bathymetry (e.g. restricting exchange between regional basins). The treatment of the coastal topology is very much dependent on the horizontal gridding approach.

Quadrilateral meshes approximate coastlines by a blocked mask and the resulting representation of the coast is highly resolution-dependent and leads to two specific issues. First the detailed representation of coastal features, e.g. at an inlet or a strait, is limited by this resolution; there is some limited scope to alleviate this through mesh distortion. Second, the staircase representation of a straight coastline impacts the fundamental numerical properties of the model, notably the propagation of Kelvin waves is retarded (Greenberg et al., 2007) and the accuracy of solution is reduced (e.g. from second to first order; Griffiths, 2013), even for coasts very closely aligned with the mesh, with only an occasional step. This can be seen as a special cases of the stepped representation of topography by z-coordinates models; the issue of bottom topography representation is alleviated by using terrain following coordinates.

Available solutions at the coast-line for quadrilateral meshes are through shaved cell (Adcroft et al., 1997; Ingram et al., 2003) or immersed boundary (Tseng and Ferziger, 2003) approaches for high resolution models, or porous barriers (Adcroft, 2013) for coarser resolution models. Triangular mesh models, when paired with terrain following coordinates, do not encounter these issues: they can fit the coastline with an arbitrary degree of accuracy limited by the minimum acceptable scale and accuracy of the geographic information. The representation of the details of the coastline is key advantage of triangular mesh models. However, even with highest resolution models being considered the accurate details of coastlines will not be well represented, particularly in bays, estuaries, fjords, etc and these must be left to local scale models (often of a few 100m's resolution), include more detailed processes such as the capability to wet and dry with the tide. Similarly for the resolutions considered here, parameterisation of riverine effects are still required for an accurate representation of their transport processes. This can be achieved by, for example box modelling approaches, as currently being tested in the Community Earth System Model (Bryan et al., 2015).

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## 3.2 An example of improved resolution and process representation in comparison with CMIP5 models

To illustrate what might be achieved through higher resolution, introducing tides and sophisticated mixing schemes in the context of the coastal-ocean we consider runs of the global ORCA12 (Marzocchi et al., 2015; Ducheux et al., 2014) and the Northern North Atlantic (NNA; Holt et al., 2014) NEMO models. Both use the same NEMO code base (V3.5) and have 75 z-partial step layers in the vertical. The ORCA12 model uses a TKE vertical mixing scheme, a filtered free surface formulation and does not include tides. The NNA model is an extraction of the grid and bathymetry from ORCA12 that includes tides, a k-ε vertical mixing scheme (implemented by the GLS approach; Umlauf and Burchard, 2003), with log-layer bottom friction and a mode-split explicit free surface with variable volume. Both use DFS surface forcing (Brodeau et al., 2010) and NNA takes lateral boundary conditions from ORCA12. For brevity, here we focus on the Potential Energy Anomaly (PEA; Eqn 2) as a measure of upper ocean stratification and Figure 4 shows both these models perform substantially better than the CMIP5 models in both RMSE and correlation across the whole domain. The same is true for the correlation in the coastal-ocean, but

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there are two 0.5° CMIP5 models (NorESM-ME and CNRM-CM5) of comparable performance in terms of RMSE. No significant difference between NNA and ORCA12 is apparent in these overall statistics.

Figure 5 shows the mean July PEA for these two models to examine the differences in stratification in more detail. It shows that while the differences across the whole region are comparatively minor, the differences in some localised regions are very marked. A particular example is in the southern North Sea, English Channel and Irish Sea, where the expected well mixed regions are much clearer in NNA than ORCA12, and more in accord with observations (Holt and Umlauf, 2008).

To explore how well these models reproduce the seasonal cycle in stratification, the mean annual cycles of PEA for 10 regions (see Figure 5) are shown in Figure 6; this is limited to water depth <500m to focus the comparison on the coastal ocean. Each region is selected to cover sufficient data to give a reasonably smooth mean seasonal cycle in the observations, but the results are inevitably dependent on the details of this choice. Moreover, because EN4 is not a systematic data set, deriving a mean annual cycle in this way potentially mixes inter-annual and spatial variability (for further discussion on this see Holt et al., 2012). Nonetheless, it provides a useful guide to model performance. Alongside NNA and ORCA12, results are shown for the same 19 CMIP5 model as in Figure 4 and the overall RMSE, the median and minimum RMSE values for CMIP5 and which model is the lowest. We see that NNA has a lower RMSE than ORCA12 in all regions except 1 and 9 (Norwegian Sea and Georges Bank, where both models exhibit no significant improvement on CMIP5) and 4 (southern North Sea, where both have small errors). This demonstrates a clear advantage of this combination of process representation (i.e. including tides and a two-equation turbulence closure scheme). Apart from in regions 1 and 9, the NNA and ORCA12 models improve on the median error from the CMIP5 models; this is not a remarkable result and it would be worrying if it were not the case that high resolution, reanalysis forced models could not out-perform coarser resolution coupled models. However, what is more interesting is that in most regions the best of these CMIP5 models out-performs or is very close to either NNA or ORCA12. This may well happen by chance: there is a broad spread of CMIP5 models results here and 6 different models are the highest performers. However, some of the higher resolution models (CNRM-CM5, 0.5°; MPI-ESM-MR, 0.3°; NorESM1-ME, 0.45°) lead (among this CMIP5 ensemble) in 6 out of 10 regions, which deserves further investigation. For example the CNRM-CM5 (Voldoire et al., 2013) and NorESM1-ME (Bentsen et al., 2013) both include the tidal mixing parameterisation of Simmons et al. (2004).

Some other aspects are clear from this comparison. These CMIP5 models generally over-estimate the PEA and its annual cycle. This is particularly apparent in the eastern boundary up-welling regions (5 and 6) where the observed annual cycle is very small. Such biases are not apparent in NNA or ORCA12.

While a much more comprehensive assessment is required to inform the appropriate aspects of model development, this does demonstrate some clear advantages to improved resolution and process representation. It also identifies some areas for further investigation, notably the biases on the eastern U.S. coast.

### 3.3 Resolving the pertinent scales

The most significant challenge in representing the coastal-ocean in global models relates to the small scales needed to represent the processes and geography (coastline, bathymetry, straits) of these seas. There are essentially two options for achieving a refined horizontal resolution: either increase the quasi-uniform resolution of the whole grid or introduce a multiscale capability that allows refinement in specific locations. We consider briefly what these capabilities might be below, but first explore the balance between these two options if we desire to resolve a particular set of processes globally, refining the model locally to achieve this. We quantify this conceptually, with no consideration of mesh structure, by building on the scale analysis above and define:

$$N_{\text{eq}} = \sum_{R^2} \sum (n/e)^2 = \sum (n \max(\Delta X, \Delta Y) E/L_x)^2 \quad (3)$$

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to define the global sum of the number of cells needed in each global model grid cell to resolve a process, characterised by length scale  $L_x$  at a particular level ( $n$ ). Following the discussion in section 2.1 we take  $n=10, 3, 2$  for  $L_{10}, L_3$  and  $L_2$  respectively. A constraint is imposed on this:

$$L_{\min} < L_x/n < \max(\Delta X, \Delta Y) \cdot E \quad (4)$$

The upper limit specifies a 'base' resolution, i.e. a multiple ( $E$ ) of the global ORCA12 grid (resolution:  $\Delta X, \Delta Y$ ) that is being refined. The lower limit,  $L_{\min}$ , acknowledges that there are limits to how fine a resolution is desirable, particularly in the case of scales that tend to zero with the water depth, and with respect to timestep constraints.

As an example, Figure 6 shows how a  $1/12^\circ$  ORCA tripolar grid might be refined to a minimum scale of 1.5km ( $\sim 1/72^\circ$ ) as required by the above criterion, with  $L_x$  being the smaller of the baroclinic, barotropic, and topographic scales. Values at each cell range from  $F^2=(n/e)^2=1$  (no refinement) to  $(\max(\Delta X, \Delta Y) \cdot E / L_{\min})^2 = 36$  in this case. Mid-latitude and arctic shelves require modest refinement ( $\times 10-15$  extra cells); the reduced based mesh size of the ORCA grid counters the reduced Rossby radius here (noting the absolute values of  $F$  are dependent on this grid structure). In some very shallow tropical regions the number is at or close to the maximum value, indicating that the desired level of process resolution is not always achieved. The accuracy of this estimate is limited by the underlying information (notably the bathymetry and the Rossby radius) and no consideration of the refinement needed to resolve the coastline is made. Nonetheless this still provides a useful guide in terms of the relative cost of multiscale and globally-refined resolution approaches. Here we compare this calculation with the total number of grid cells in the globally-refined case (at  $L_{\min}$ ). Because the minimum scale is the same for both no timescale factor is needed. This approach takes no account of the mesh structure needed. In particular there will be limits on how quickly scales can be allowed to vary on an unstructured mesh (see for example Figure 6 lower panels, show the change in resolution needed can be locally very abrupt) and so this puts a lower bound on the number of cells needed in the multiscale case.

We consider three values of  $L_{\min}$ : 9.3km ( $\sim 1/12^\circ$ ), 3.5km ( $\sim 1/36^\circ$ ) and 1.5km ( $\sim 1/72^\circ$ ) (c.f. Table 2) in Figure 8. So for example, a  $1/4^\circ$  global model refined where necessary to resolve the smallest of these scales down to a minimum scale of 9.3 km (left pannel) requires about 0.25 the number of grid-points of a full  $1/12^\circ$  grid, or a saving of about a factor of 4. As the minimum scale decreases to 3.1km (middle panel) and 1.5 km (right panel), the saving increases to 0.095 (10 times fewer points) and 0.046 (factor 22), compared to the full global grid at the minimum resolution. Similarly, a  $1/12^\circ$  model refined to a minimum scale of 1.5km has 0.06 (factor 17) times fewer cells than a  $1/72^\circ$  global model. The limiting behaviour evident from these plots arises because at coarse base resolution most of the grid is refined to meet the criteria (i.e. the base resolution becomes irrelevant), while at a fine base resolution this meets the criteria in many regions anyway and the refinement becomes less relevant. These results are considered in terms of what may be computationally practical in section 4.

### 3.4 Options for multiscale modelling

There is already a substantial literature on multiscale modelling and we do not attempt to review this here. Unstructured mesh approaches generally focus on triangular mesh models using a finite volume approach e.g. FVCOM (Chen et al., 2003); FESOM2 (Danilov et al., 2016) or a finite element approach, e.g. FESOM1.4 (Wang et al., 2014), SELFE (Zhang and Baptista, 2008) and SCHISM (Zhang et al., 2016). In contrast MPAS (Ringler et al., 2013) is based on hexagonal meshes using a finite volume approach. Danilov (2013) provides an account of the issues of unstructured mesh modelling, and what is clear from that review is that selecting a solution approach or grid arrangement, for example, on the basis of a lack of computational modes or formal accuracy is far from straightforward, and must be left to detailed investigations in idealised and realistic cases. Structured grid models have scope for multiscale capability by distorting their horizontal coordinates and through nesting. Coordinate transformations generally limit the refinement to a single region of interest. An example to facilitate regional impact

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A particular caveat of these results is that no account is made of the overhead in achieving this refinement (e.g. using a finite volume or finite element approach), which would be expected to be considerable and some estimate of this is made below.

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studies is the use of a rotated polar grid (Gröger et al., 2012) to focus resolution on European seas. While this can address the downscaling issue for a single region, it does not help with the upscaling question.

Nesting is the most common approach to multiscale modelling. In its simplest form boundary conditions for a fine resolution regional model are taken from a previous run of a larger area ocean model. It has the significant advantage that the global model does not have to be rerun for each regional simulation. There is, however, the practical consideration of the effort required to setup and test a new regional configuration for each new area of interest. Nesting remains an important approach for investigations of regional systems, and providing fine scale information, e.g. for operational or research purposes. The general downside to nesting is the accuracy at which information can be exchanged between the two domains and the degradation of the solution at the boundary; it is usual to linearise the boundary conditions and to only exchange a limited subset of information at lower frequency than the model timestep. That said, there has been extensive work on regional model boundary conditions (e.g. Marsaleix et al., 2006; Mason et al., 2010) and by using a careful combination of active and passive approaches good solutions can be obtained. One-way nesting can be straightforwardly extended to a global scale using multiple regional nests (Holt et al., 2009). The problem is simply one of standardising the configuration procedure and of managing workflow. However, one of the key advantages of regional models, that they can be tailored to the specific conditions of a region, is generally lost in automatically configured domains. The underlying assumption to such one-way nesting is that feedbacks between the regional and global simulations are small, at least on the timescales of interest and again it only addresses the downscaling question.

A natural extension of the nesting approach, which allows for upscaling, is two-way global scale nesting. The AGRIF tool (Debreu et al., 2012) provides a capability to automatically generate nests, which has been utilised in both the ROMS and NEMO systems (e.g. Biastoch et al., 2008), generally with individual regions being refined with one or more nests. In theory this is extendable to the global scale, with multiple nests placed to locally resolve coastal-ocean processes. Several approaches exist to couple the two grids, reviewed by Debreu and Blayo (2008). Because this occurs 'in memory', these can be substantially more sophisticated than off-line nesting by file exchange, and essentially aim to link solution approaches in the two grids, coupling at the time steps of the respective grid. This means that as well as having two-way interaction, many of the issues associated with off-line boundary conditions noted above are alleviated, although noise and wave reflection are two issues that require particular attention. An issue with this approach in the global context is the restriction (for AGRIF) to rectangular domains (in model coordinate space; see below). This is somewhat inefficient and inflexible, and the coupling between neighbouring refined regions, with potentially different levels of refinement needs to be considered. Large irregularly shaped nests (e.g. Holt et al., 2009) would be good option, not over-refining in the open ocean and limiting the number of grids and connections between them. This would require substantial development to AGRIF or an alternative approach. An approach that has yet to be thoroughly explored is using model couplers (e.g. OASIS3-MCT) as a 2-way downscaling tool. This would allow complete flexibility between nests, e.g. a different executable can be run in each nest, but whether the coupling system is sufficiently efficient to permit coupling at the model time-steps is unclear.

A key limitation to multiscale models is time stepping, which is closely related to the scalability of the models, discussed below. The trade-off is between explicit models, which are computationally efficient with MPI parallelism, but have a time step limited by the CFL condition and implicit models, which are not limited by the CFL condition, but are less computationally efficient with MPI parallelism, due to the need for global matrix inversions. Currently the balance is towards explicit time-stepping models (e.g. with time splitting between barotropic and baroclinic modes), given the use of global models on many thousands of processor cores. This has implications for multiscale approaches: the approach must either accept the limitation of the smallest scale in the grid, introduce some level of implicit time stepping, with consequent implications for scalability, or else introduce a locally refined time-stepping approach, whereby different timesteps are used in different regions. The latter is natural for the multi-blocking approach (and is assumed in the analysis below), but is highly complex for unstructured mesh

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multiscale approaches (e.g. Dawson et al., 2013). A move to implicit timestepping, aside from any accuracy/diffusion issues, requires the development/use of very efficient numerical solvers.

To put global nesting in the same context as the above scale analysis, we consider a multi-block approach (accepting the limitation to rectangular domains for now), and consider the global ORCA12 grid divided into  $\sim 15^{\circ} \times 15^{\circ}$  blocks. Each of these is then given a refinement level  $F_2$  ranging from 1 to 36, as above. To provide a representative maximum value (but not set by a very few large grid point values), this is taken to be the 95<sup>th</sup> percentile of the grid cells in each block. To mimic the AGRIF refinement process each block takes an integer value:  $(\text{int}(F))^2$ . This example leads to 194 out of 344 cells requiring refinement (Figure 9). Such a setup would be a challenging computational engineering effort and certainly less elegant than an unstructured mesh approach, but maybe be more efficient (quantified below) and is available as an evolution of the structured mesh approach, common to most of the current climate scale global modelling effort (and so building on the expertise therein), rather than a move to a radically different approach. Whether it is more or less accurate than a comparable finite volume or element unstructured mesh approach must be left for future investigation.

#### 4 Utilising the computational resources

##### 4.3 Trends in High Performance Computing

Ocean modelling has benefited from the general exponential growth in High Performance Computing (HPC) capability, with the largest machines approximately doubling in performance every 18 months since 1993 (TOP500<sup>1</sup> list). There are two technology drivers for this: firstly increases in clock speed and improvements in architecture (particularly Instruction Level Parallelism) and secondly massive increases in parallelism. In 1993 the TOP500 list still contained machines with only one processor, in June 2016 the smallest system had 5310 cores and the largest had over 10 million cores. The first of these drivers has largely stalled as clock speeds have peaked at around 2-3 GHz due to power density limitations. Instruction level parallelism has also peaked at around 4-8 instructions per clock cycle; memories are not fast enough to provide enough operands to justify greater values. Further performance increase into the future is therefore expected to be driven solely by an increase in parallelism, through larger and larger number of processor cores.

Continuing the current exponential growth towards exaflop performance ( $10^{18}$  operations per second), specifically requires a substantial reduction in power consumption (by  $\sim 100$ -fold) to keep the power costs of HPC systems within reasonable limits. If these power efficiency constraints are lifted to achieve exascale systems there are two major impacts for ocean modelling. First is the prospect of a single ocean model running at exascale performance levels on e.g. 100 million cores. Alongside this there would be a knock-on impact of smaller systems as petascale systems become available with about 100,000 cores in a single rack, consuming only  $\sim 100$  kW, and so accessible by the modelling community at an institutional level.

To use the UK research community perspective as a practical example, Figure 10 shows the increase in the peak performance of the UK Research Councils' (RCUK) HPC facility, from HPCx in 2006, through the four phases of Hector to the current machine Archer<sup>2</sup>. The peak performance of this facility has increased exponentially over the past  $\sim 10$  years, although the general trend has flattened off since the rapid increase between HPCx and Hector Phase 2a. A conservative estimate is to extrapolate the trend from Phase 2a to Archer Phase 2. This gives a peak performance of  $\sim 13$  times Archer Phase 2 by 2019 (32Pflop/s) and  $\sim 745$  times by 2023 (610Pflop/s). This closely follows the TOP500 trends, and predicts the UK maintains a performance about a factor of ten lower than the US at any one time (or lags by 3-4 years). There are of course many unknowns in this projection such as the size of the overall research community and share of the resource which the marine science sector may receive. Nonetheless, this usefully quantifies the often quoted remarks around continually increasing computer power and puts bounds on what may be expected.

<sup>1</sup> <http://www.top500.org/>

<sup>2</sup> [www.archer.ac.uk](http://www.archer.ac.uk)

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In terms of ocean model design, to effectively utilise large numbers of cores, codes will have to extract very high degrees of parallelism from the underlying numerical algorithms. This requires at least three-way nested parallelism with high-level coarse-grained parallelism at the node level probably using MPI, multi-threading on a node using OpenMP or OpenAcc, and fine-grained parallelism within a core, e.g. vectorisation at the loop level. Memory management will become increasingly important. The size of memory cannot increase to match the numbers of cores, on ground of cost and power, and the amount of memory per core is expected to reduce significantly (although memory per core is still relatively stable in the example presented here; Figure 10). Memory bandwidth per core and interconnect speed per core is also expected to drop. Algorithm design must therefore focus on management and movement of data in memory and between nodes.

#### 4.4 Scalability and efficiency of ocean models

An important distinction needs to be made between computational resource (CPU hours) and model simulation time (Simulated Years per Day; SYPD). The available computer resource is generally increasing through increased parallelism (more cores per chips, more CPUs and novel, accelerator-based architectures), and is what is metered and limited by computer centres. It is, however, the SYPD that limits the science that can be done with a particular model (assuming the resource is available). For example, Table 3 lists anecdotal reports of turn-around time (SYPD) for three global ocean models (MOM6 GFDL CM2.6; NEMO ORCA12 and FESOMV2 Glob15) and a high resolution coastal-ocean model (NEMO AMM60), also shown is this valued scaled with the grid cells (horizontal and vertical) per core and the time step to give a rough comparison of the efficiency. The two structured grid global models have a comparable efficiency (2.35 and 3.5 SYPD; 207 and 223 kTimestep gridcells/sec; kTGPS), whereas the unstructured mesh model is somewhat more efficient (17 SYPD and 396 kTGPS; discussed further below), but is run on considerably fewer processors.

Currently the minimum efficient size of model run by each MPI process is about 20x20 or 400 grid cells per core. As the resolution reduces, then, for an explicit time-stepping model the CFL stability criteria requires the time step to reduce and the model runs more slowly (reduced SYPD), irrespective of the increased resource. For example, the  $1/60^{\text{th}}$  resolution NEMO model of NW European continental shelf achieves only ~1 SYPD, but is somewhat more efficient at 245 kTGPS than the global NEMO model. For large scale climate and earth system model simulations, with substantial resource available, but a requirement to complete many centuries of simulation in a restricted time period, this is the key limitation. When running large numbers of shorter simulations in research mode (e.g. by a whole research community), the resource (CPU hours) itself provides the limit. Given static CPU speeds there are two options to mitigate this reduction in SYPD: modify the model numerics (with respect to time-stepping; see above) and/or improve the parallel scalability. The latter can occur in two ways. Firstly, by reducing the size of the sub-domain within an MPI process that can be used efficiently, essentially by reducing the ratio of communication costs to computation costs, e.g. by using larger halos to increase message size and reduce latency effects. Secondly, by introducing alternative levels of parallelism, so that more cores can be used efficiently by a single MPI process, e.g. using multi-threading (loop-level parallelism) with OpenMP or OpenACC. Another possibility which is being explored is parallelization of the time-domain, especially attractive for long time duration low-resolution climate runs. Parallel-in-time methods offer the prospect of another two orders of magnitude in concurrency (Haut and Wingate, 2014), but are still at the early research stage.

An important and complex question is whether unstructured mesh models are inherently more computationally expensive than structured grid ones. They are certainly more complex, with more floating point operations required per degree of freedom and also require indirect memory addressing (only in the horizontal, assuming a structured vertical data structure). However, we are moving to a computational situation where 'flops' form a minor part of the cost, and the cost of indirect addressing can be effectively 'hidden' by sufficient vertical computation. Triangular meshes require more edges to span a particular domain with comparable resolution to quadrilaterals, but equally can have fewer edges if areas can be identified where reduced resolution is required. They have an advantage over structured mesh models in that computation is only over 'sea'-points, but this is a

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marginal advantage with a large number of cores when land-only cores are excluded and/or sophisticated load-balancing algorithms for domain decomposition are used (e.g. k-partitioning; Ashworth et al., 2004). There is no *a-priori* reason why either class of model is more or less scalable than the other, simply on the basis of grid and data structure: the answer in practice lies in the details of numerics, e.g. choice between implicit and explicit time-stepping and the number of halo-exchanges needed for high-order advection schemes, and the success of the optimisation in a specific context. The higher computation per degree of freedom may weigh in favour of unstructured grid models in terms of relative scalability. Historically, there has been a substantially computational penalty e.g. the finite element model FESOM1.4 was reported to be ~10 times slower than comparable structured grid models (Wang et al., 2014) and experience with the FVCOM in the NW European shelf suggest this model is ~5 times slower than NEMO. More recent work suggests a very different picture: MPAS quotes a penalty of 3.4 compared with POP (Ringler et al., 2013) and the finite volume FESOM2 (Danilov et al., 2016) code reports a through-put 5 times faster than FESOM1.4. The comparison of this model with two finer resolution structured grid models in Table 3 suggests this model is, if anything more efficient. This may be because the time step ratio (of 3) between this model and the NEMO and MOM6 cases is substantially larger than the ratio of nominal grid resolution resolutions (15/km9.3km = 1.6; c.f. the ratio of efficiencies in Table 3: 1.6); i.e. the unstructured mesh model achieves a longer time step maybe because it can have a more uniform grid (recalling the finest cell in the ORCA12 grid is 1.3km). So these anecdotal results (accepting different problem sizes, runs with different processor counts, on different computers are being compared here) suggests parity in resource cost and turn-around time between present day structured and unstructured mesh models is a realistic prospect. However, the structured grid models are themselves being continually and extensively optimised (e.g. for openMP parallelisation) so there is also the possibility that a gap similar to the MPAS-POP comparison persists. ▼

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#### 4.5 Exploiting Future HPC Architectures

Exploiting Petascale or Exascale levels of performance will require substantial algorithmic development to achieve the required level of concurrency. Many researchers have been looking at ways to improve the parallel scalability of ocean models on massively parallel architectures. Within the context of NEMO there has been work looking at hybrid MPI/OpenMP parallelisation strategies (Epicoco et al., 2016) and a port of the code using OpenACC directives targeting accelerator-based architectures (Milakov et al., 2013). The layered approach to software design (Ford et al., In Press) provides one way to achieve this, while retaining code that can still be straightforwardly developed by an ocean modeller. The key idea in this approach is the PSyKAI (Parallel System, Kernel, and Algorithm) Separation of Concerns. The ocean modeller should not have to be concerned about the (ever-increasing) complexity of the underlying computer and the computational scientist who optimises the code should not have to understand ocean processes. In practice, the separation is achieved by using domain-specific knowledge about the type of problem being solved; in particular, the fact that the majority of the available parallelism comes about through performing the same computations at each point in the model mesh. In PSyKAI, the ocean modeller is responsible for writing the Algorithm and Kernel layers while all performance optimisation (including all code related to parallelism) is restricted to the PSy layer. The Algorithm describes the model computation in terms of logically-global fields (e.g. add field1 to field2) while Kernels implement the actual computation to be performed at a grid point, and the PSy layer distributes this across the model domain with a particular parallel optimisation approach.

This approach is in use for the new, finite-element LFRic atmosphere model being developed by the UK Met Office. It has also been applied to two different, finite-difference shallow water models. The first, 'shallow', is a benchmark code originally developed by Paul Swarztrauber of NCAR. The second consists of (only) the free-surface component of NEMO and is therefore named 'NEMOLite2D'. It has been demonstrated that any loss in performance resulting from the PSyKAI re-structuring of these codes can be regained by optimising the PSy layer (Porter et al., 2016). The middle, PSy, layer of such models can be automatically generated from a knowledge of the Kernels (as described in meta-data) and the Algorithm. Since this generation can be tuned to match a particular computer architecture (e.g. CPU or GPU) as well as being used to support different forms



of parallel execution (e.g. distributed versus shared memory), the aim is that the model as a whole will be performance portable while requiring no changes to the natural-science parts of the code. There are also substantial software engineering benefits to this approach in that scientists no longer have to worry about writing correct parallel code (e.g. the “Do I need to do a halo-swap?” problem) and optimisation experts are protected from introducing errors in the science.

#### 4.6 The comparative cost of ocean models

To link the scale analysis and the computational issues, Table 4 lists a set of possible future model configurations, and an estimate of their relative resource cost with and without a timestep penalty. The relative resource cost is calculated by:

$$C = \frac{N}{N_{25}} \frac{L_{\min 25}}{L_{\min}} S, \quad (5)$$

where  $N$  is the total number of grid cells in a configuration defined by  $L_{\min}$ , and  $N_{25}$  and  $L_{\min 25}$  are the reference values for nominal  $1/4^\circ$  global NEMO configuration, ORCA025. The inverse ratio of lengths scales is included in Eqn 5 to introduce a global time-stepping penalty on the assumption that local time-stepping approaches have not been implemented (except in the block-refined approach).  $S$  is a factor for models that need unstructured meshes, which following the discussion above we take to range from 3.4 (e.g. Ringler et al., 2013) to 1 (parity between structured and unstructured cases). Here we focus on resource rather than turn-around time (SYPD) and, without the scalability and timestepping improvements identified above, an increased resource may only be utilisable by waiting longer for a finer resolution model to finish. Moreover, this simplistic cost-model ignores all the real-world issues that would have to be faced, notably the changing balance between computation, memory access and communication, and also all arising data handling and storage issues.

Three quasi-uniform structured meshes, three unstructured mesh multiscale options and an example of a block-refined multiscale case are considered. For the block-refined approach, we assume a variable timestep and assign a step penalty (reducing it by  $1/F$ ) for each block independently. This assumes the model is load-balanced and optimised for the finest meshes, so again the measure here is resource used rather than time to completion. To estimate when these could become routine models, an exponential fit to the growth of RCUK computer peak performance (Figure 10) is used so:

$$Y = \text{int}(\log_0(C)/P + Y_0), \quad (6)$$

taking the  $1/4^\circ$  model in 2011 as a base line ( $Y_0$ ) for a ‘routine’ high performance global physical oceanography research model. From Figure 10,  $P=0.258 \text{ yr}^{-1}$  (i.e. doubling every  $\sim 1.2$  years). So, for example in 2017, a  $1/12^\circ$  model uses a comparable fraction of the total computer resource available as a  $1/4^\circ$  model in 2011. There are many caveats to these estimates, not least the scientific development time needed to achieve the various stages, but they do serve as a reasonable guide to either encourage or constrain aspirations.

A key milestone in this growth is a  $1/12^\circ$  global model refined to  $1/72^\circ$  to resolve coastal-ocean processes. This represents the amalgamation of the current state of the art of global and regional scale coastal-ocean modelling. When this would be comparable to a  $1/4^\circ$  model in 2011 for an unstructured mesh multiscale approach depends critically on the efficiency in the unstructured modelling technology. If these achieve parity with present day structured grid models ( $S=1$ ) then this point is reached at 2021, if factors similar to the present day MPAS experience persists then this date becomes 2023. The estimate for the block refined multiscale approach is 2022. All of these are sufficiently ahead of the figure of 2026 for a  $1/72^\circ$  global model, assuming static computational efficiency for the structured grid model (i.e. the development effort is primarily toward scalability and reducing SYPD rather than reducing resource requirement). This sets a clear challenge for ocean model developers and computer scientists to develop an efficient and accurate multiscale approach by this date.

The considerations above have focused on high resolution physical ocean models, e.g. as part of a coupled climate model or an operational forecast system. For Earth System Models with complex marine and land surface ecosystem and atmospheric chemistry components, we must accept that the ‘routine’ model of today (2016) is a  $1^\circ$  resolution ocean. The scaling then

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suggests that a 1/12° global and a 1/12° global model refined to 1/72° would not have a comparable computational cost to a nominal 1° ocean model until 2027 and 2035 respectively. This suggests options to improve the coastal-ocean in centennial scale ESM simulations (e.g. for fully coupled carbon cycle simulations) will remain highly parameterised for at least the next decade, and for fine scale processes, two decades.

## 5. Conclusions

The analysis and investigation presented here suggest the prospects for improving the representation of the coastal-ocean in global models are now promising. We can identify three concurrent avenues of development to achieve this. Firstly, global models are now routinely run at the horizontal resolution of past shelf sea model simulations that capture many of the pertinent scales, and with dynamics that allow the representation of relevant processes, such as split-explicit time stepping rather than long wave-filtered or implicit approaches. In this case some (comparatively) straightforward developments can be included in the simulations to significantly improve the representation of the coastal-ocean. These are: i) including tides, their generating forces, self-attraction and loading and wave drag effects; ii) using vertical coordinate systems that retain resolution in shallow water, resolve the benthic boundary and allow smooth flow over steep topography; iii) adopting vertical mixing schemes that represent mixing at the surface, pycnocline and benthic boundary layers. These are all existing features of regional ocean models and the general challenge here is ensuring the introduction of these features does not compromise the deep and open ocean simulation, or significantly increase the computational costs; the single example in Table 3 suggests this would not be the case. Further developments to achieve this are likely, for example through non-diffusive advection schemes and quasi-isopycnal vertical coordinates. We quantify the benefit of improved process representation within the context of the current state-of the art in global resolution. This shows substantial benefits in including tides in terms of reproducing the seasonal stratification cycle, although interestingly two of the CMIP5 models (including tidal mixing parameterisations) perform particularly well.

The second area of development is the continued refinement of horizontal resolution to the point that the pertinent scales are well resolved (estimated to be ~1.5km). This is the case in the current generation of region models, and the analysis presented here suggests it would be computationally practical in about a decade's time. The options considered here, in very general terms are: a continued refinement of the quasi-uniform structured mesh, some form of unstructured mesh (presumed to be either finite element or volume), or else a multi-blocking refinement (whereby rectangular regions are refined to a fraction of the parent mesh and two-way coupled to it). The block refinement and unstructured mesh approaches show significant advantages over the refined structured mesh using the objective refinement criteria and very simple cost model considered here. The BL approach using ~13 times less computational resource. The resources needed for the unstructured mesh approach depends critically on the relative performance of this class of model, here we estimate 5-17 times less resource depending on how close to parity with structured grid models the unstructured models achieve.

These results need to be seen alongside the needs of the open-ocean model. For example, Griffies et al (2009) note (in the context of mesoscale eddies): "There is no obvious place where grid resolution is unimportant". The refinement criteria we have considered here, while chosen for coastal ocean processes, have been applied globally. It is apparent that modest resolution refined to the level of current high resolution global models have only marginal benefits when an objective refinement approach is used. For example, a ¼ degree model refined to 1/12° only differs from a 1/12° global model by a factor of 4 times few grid cells: much of the ocean is refined to meet (e.g.) the Rossby Radius criteria globally. If the criteria was extended to include additional aspects, e.g. ocean variability, (Sein et al., 2016) then this factor will reduce, and the benefits of the multiscale approach become less apparent. If, however, fine resolution process representation is desirable then the scaling clearly favours multiscale modelling, and if we are sufficiently confident in the refinement criteria to use a coarser base

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resolution than would be otherwise be chosen (i.e. to allow a degree of coarsening from a contemporary high resolution model) then the multiscale approach can achieve a substantial reduction in the resource needed.

The final area of development, and by no means the least important, is the improved representation of the coastal-oceans through improved process parameterisation. This essentially uses fundamental theoretical and empirical understanding to make up for deficiencies in the dynamical approach and the computational resource. This covers both processes that would not be resolved by any scales considered here and the cases where significant horizontal refinement is not practical (e.g. centennial scale ESM's). Particular areas that deserve attention are: tidal mixing, topography and coastlines, horizontal mixing schemes that account for the large change in scales at the ocean margins, and river plumes. Given that the scale analysis presented here suggests we may be one or two decades away from a well-resolved coastal-ocean routinely run in fully coupled complex ESM's, then these parameterisations are paramount.

This conclusion describes three complementary strands of work, which together have the potential to make substantial progress on our ability to model the coastal-ocean at a global scale, and so our ability to simulate global change and its impact on the societally pressing questions.

### 1. Code and data availability

NEMO model code used to run the Northern North Atlantic Model configuration can be obtained from:

[forge.ipsl.jussieu.fr/ipsl/forge/projets/nemo/svn/branches/NERC/dev\\_r3874\\_FASTNet](http://forge.ipsl.jussieu.fr/ipsl/forge/projets/nemo/svn/branches/NERC/dev_r3874_FASTNet)

Data used to prepare Figures 1a-c, 2, 4, 5, 6, 7, 8 is provided at

[ftp://ftp.nerc-liv.ac.uk/pub/general/jth/GMD\\_Holt\\_GlobalCoasts/](http://ftp.nerc-liv.ac.uk/pub/general/jth/GMD_Holt_GlobalCoasts/)

CMIP5 data is available from [pcmdi.llnl.gov/search/cmip5/](http://pcmdi.llnl.gov/search/cmip5/)

Data used for Figure 1d from: [volkov.oce.orst.edu/tides/TPXO7.2.html](http://volkov.oce.orst.edu/tides/TPXO7.2.html), and for Figure 3 from:

[www.cgd.ucar.edu/cas/catalog/surface/dai-runoff/coastal-stns-Vol-monthly.Constructed.wateryr-v2-updated-oct2007.nc](http://www.cgd.ucar.edu/cas/catalog/surface/dai-runoff/coastal-stns-Vol-monthly.Constructed.wateryr-v2-updated-oct2007.nc)

Figure 4 and 6 uses EN4.0.2 profile data from [www.metoffice.gov.uk/hadobs/en4/download-en4-0-2.html](http://www.metoffice.gov.uk/hadobs/en4/download-en4-0-2.html).

Information for Figure 10 was obtained from [www.hpcx.ac.uk/services/hardware/](http://www.hpcx.ac.uk/services/hardware/), [www.hector.ac.uk/service/hardware/](http://www.hector.ac.uk/service/hardware/) and [www.archer.ac.uk/](http://www.archer.ac.uk/).

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Table 1: Physical process horizontal scales in coastal and shelf seas

Process		Horizontal scale	Reference
Barotropic Tide	$L_B$	$\sqrt{gH} / \max(f, \omega)$	(Huthnance, 1995)
Tidal excursion	$L_e$	$U_T / \omega$	(Polton, 2014)
Topographic steered barotropic current	$L_T$	$H.(\nabla H)^{-1}$	(Greenberg et al., 2007)
Front/frontal jet, coastal upwelling	$L_1$	$C_{iw}/f$	(Huthnance, 1995)
Baroclinic eddy	$L_E$	$\pi L_1$	(Griffiths and Linden, 1982)
Internal wave/tide	$L_{iw}$	$C_{iw}/\omega$	(Huthnance, 1995)
Coastal current/river plume	$L_c$	$(2Qf/g)^{1/2} (\nabla H)^{-1}$ $(2Qg')^{0.25}/f^{0.75}$	(Yankovsky and Chapman, 1997) (Avicola and Huq, 2002)

Here:  $U_T$  tidal current,  $\omega$  frequency,  $H$  water depth,  $g$  gravitational acceleration,  $f$  Coriolis parameter,  $C_{iw}$  internal wave phase speed,  $Q$  riverine volume flux.

Table 2 A selection of current model grids

Nominal resolution	Scale at equator (km)	Global application	Coastal-ocean application	Examples
1°	111	Typical of Earth Systems Models CMIP4 and 5	NA	HadGEM3; (Hewitt et al., 2011), HadCM3; (Gordon et al., 2000)
1/4°	25	CMIP6 ESMs	Historical	HadGEM3(Williams et al., 2015)
1/12°	9.3	Next generation coupled	Shelf scale/ocean margin	ORCA12; (Marzocchi et al., 2015) AMM7; (O'Dea et al., 2012) AMM12; (Wakelin et al., 2009)
1/36°	3.5	Next generation forced	Shelf Scale	IBI (Maraldi et al., 2012) ECOSMO (Daewel and Schrum, 2013)
1/72°	1.5	NA	High res. shelf/coastal	HRCs (Holt and Proctor, 2008) AMM60 (Guihou et al In Prep.)

5 Table 3 Reported turn-around time of three global models: the MOM6 and NEMO structured grid and the FESOM fine volume triangular mesh model; and a coastal-ocean NEMO model of the Northwest European shelf, AMM60, shown as Sumulated Years Per Day (SYPD). Also shown is an over-all efficiency scaling factor in kTimestep. Gridcells per second (kTGPS).

Model/ Config.	Nominal resolution	Vertical Levels	Cores for simulation	Grid-cells/core	Time step	SYPD	kTGPS	Reference
MOM6 CM2.6	1/10°	50	10,000	972	300	3.5	207	Dr M. Ward, Australian Natl University; Per Comms
NEMO ORCA12	1/12°	50	8972	1040	300	2.3	223	Dr A. Coward, NOC; Per Comms
NEMO AMM60	1/60°	75	2000	806	60	1.0	245	Dr J. Polton, NOC; Per Comms
FESOM V2 Glob15	15km	46	1728	1150	900	17	364	Danilov et al., 2016

10 Table 4 Possible model grids, their costs (Eqn 5) and when they might be computationally equivalent to ORCA025 model (nominal 1/4°) in 2011 based on Eqn 6, from Figure 10. Unstructured grids are refined to resolve the minimum of  $L_1$ ,  $L_{bt}$ ,  $L_T$  according to Eqns. 3 and 4. The blocked refined approaches allows timestep to vary between block, other cases it is limited by the global minimum scale. S is cost penalty for unstructured grid models.

Global Scale	S/US	Vertical	Size (k cells)	Cost v's ORCA25		When routine physics model	
				No time step, S=1	S=1	S=1	S=3,4
1/4	S	75	905	1	1	2011	
1/12	S	75	8149	9	27	2017	
1/36	S	100	73342	108	972	2023	
1/72	S	100	293370	432	7776	2026	
1/4+1/12	US	100	2037	3	9	2015	2017
1/12+36	US	100	10910	16	145	2019	2021
1/12+1/72	US	100	17409	26	461	2021	2023
1/12+1/72	BL	100	45558	50	593	2022	

S= structured, US = unstructured, BL= blocked refined, e.g. using AGRIF

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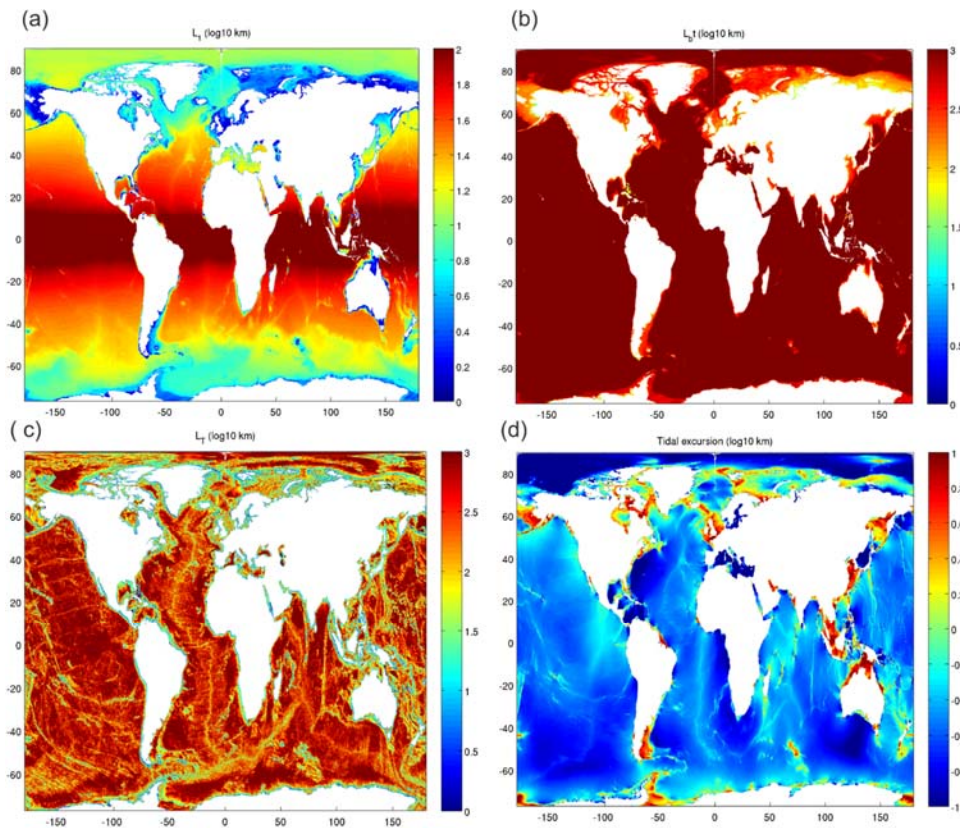


Figure 1 Global scales: a) 1<sup>st</sup> Baroclinic Rossby Radius; the maximum value calculated from monthly ORCA12 density profiles (each month being an average from 1981 to 2010) following Nurser and Bacon (2014), using the model run described by Marzocchi et al (2015) ; c) Barotropic Rossby Radius calculated from ORCA12 bathymetry; c) Topographic scale calculated from ORCA12 bathymetry and mesh; d) Tidal excursion, calculated from TPX barotropic tidal currents (Egbert and Erofeeva, 2002).

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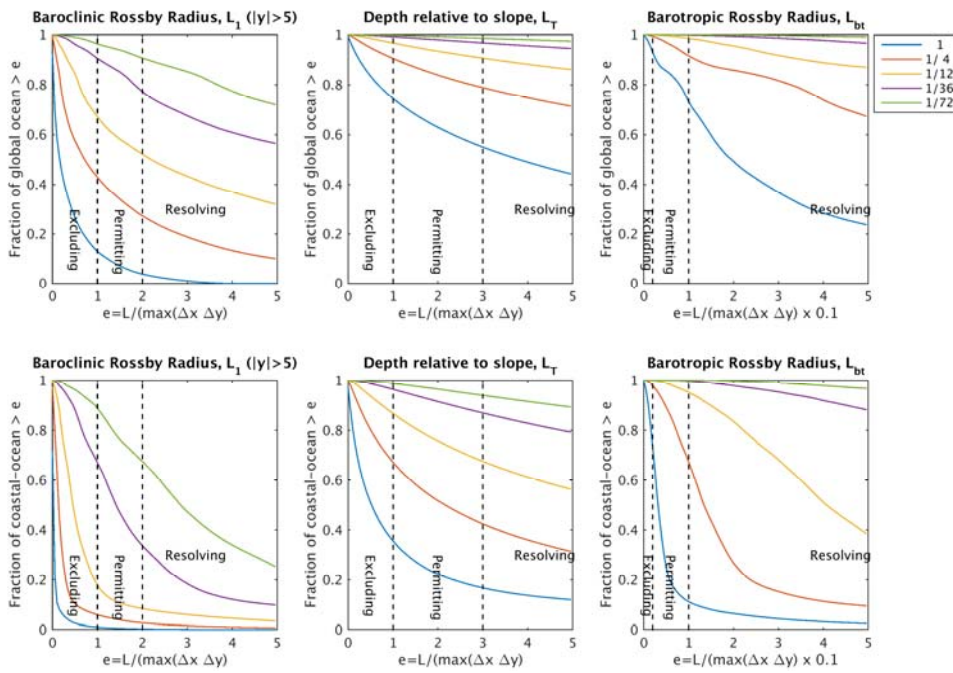


Figure 2 Cumulative distribution of the fraction of global (top) and coastal (bottom) ocean resolving  $L_1$ ,  $L_T$ ,  $L_{bt}$  for different global model resolutions.

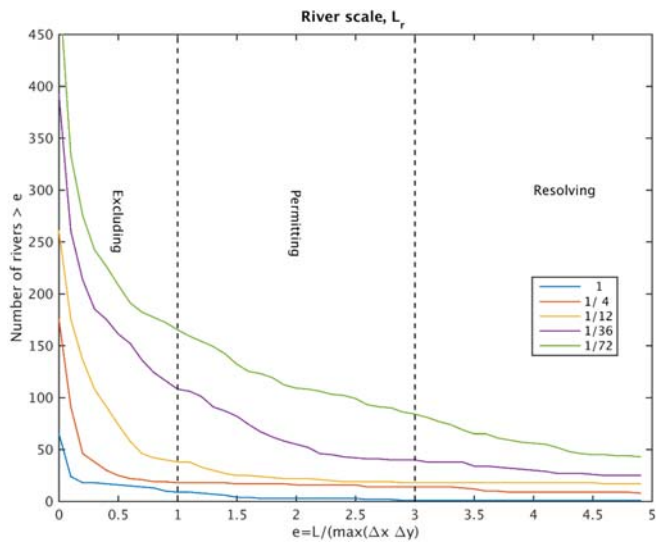


Figure 3 Cumulative distribution of number of rivers where the scale  $L_r$  is resolved at a particular level ( $e$ ). Based on flow data from the 925 largest ocean-flowing rivers globally (Dai et al., 2009).

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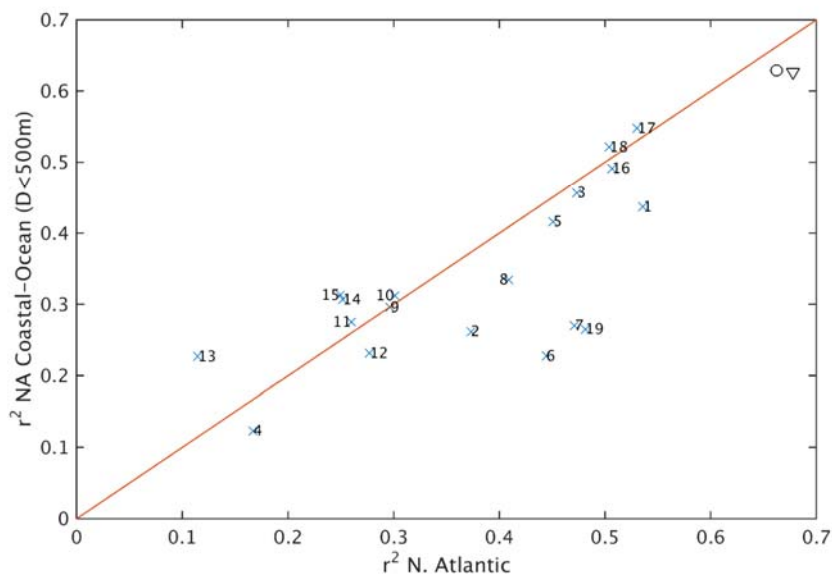
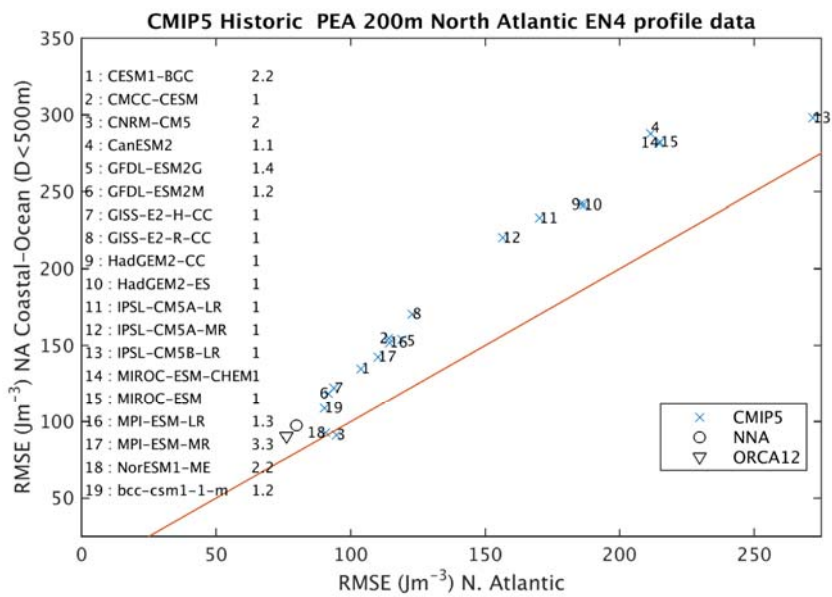


Figure 4 The RMS error and correlation for PEA of 19 CMIP5 models compared with PEA calculated from EN4 profile data (1970-2014) in the North Atlantic. In both model and observations a mean annual cycle is calculated, and error statistics calculated, with both being interpolated onto the 1/12° Northern North Atlantic (NNA) model grid. Values for full region are compared with data only at water depths <500m. Values listed by the model names are the inverse mean meridional resolutions of each model. Also shown are results from the global ORCA12 model and from NNA NEMO model (a regional extraction from the ORCA12 grid, with identical vertical coordinates and forced by this at the boundaries) including tides and k-ε (GLS) mixing (both for 1985-2003, DFS

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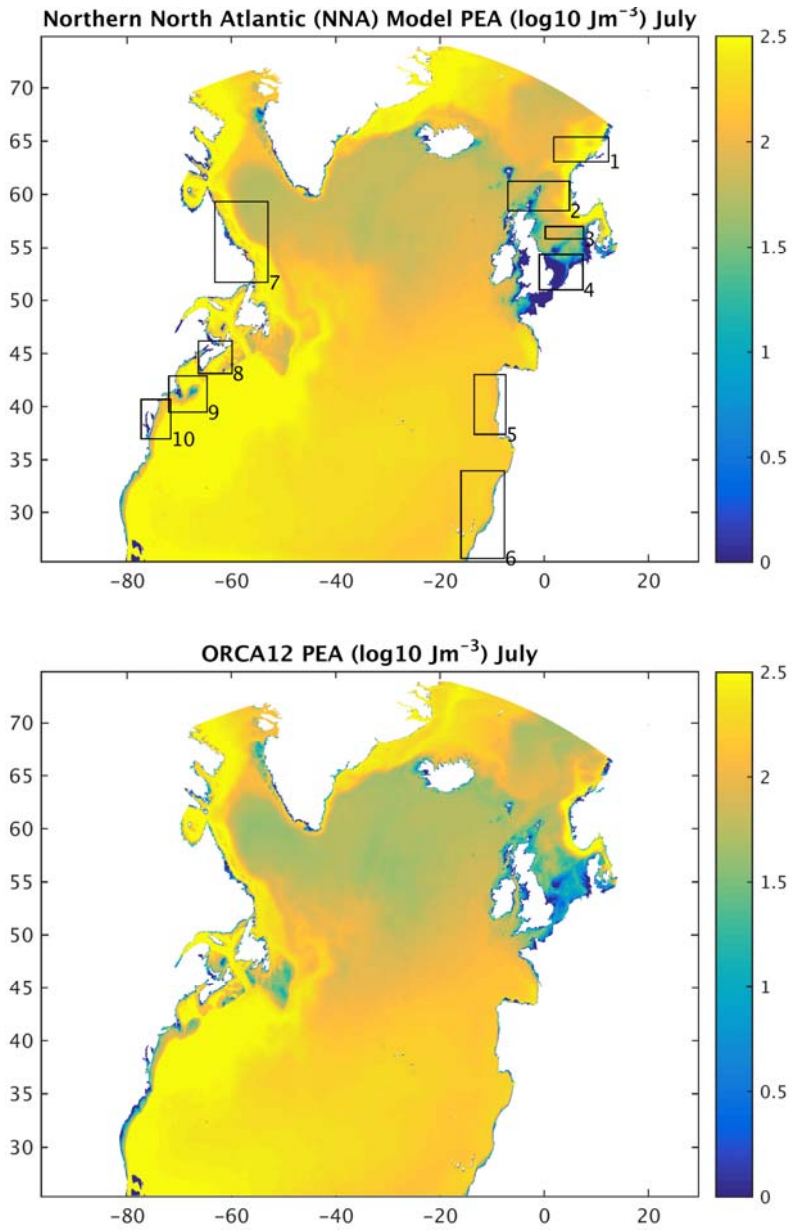


Figure 5 Potential energy anomaly (PEA; Eq1.2) for July (mean 1985-2003; note log scale) for the Northern North Atlantic (NNA) NEMO configuration (TOP; including tides and k-ε (GLS) mixing) and global ORCA12 model (BOTTOM; with the TKE mixing scheme and no tides). Also shown are regions 1-10 used for a seasonal analysis (Figure 6).

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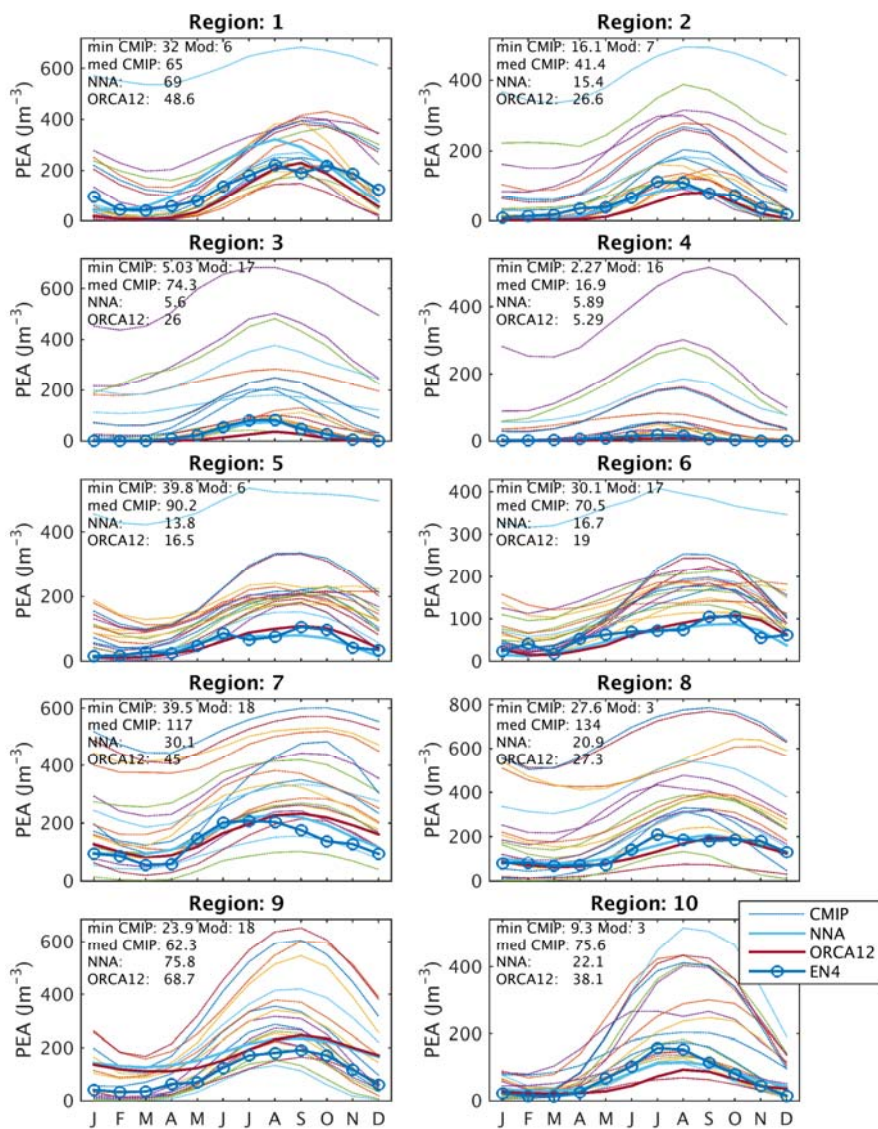


Figure 6 Mean seasonal cycle of PEA averaged over the 10 regions shown on Figure 5, for water depth <500m. Results for 19 CMIP5 models (light lines) are shown along with the ORCA12, NNA (heavy lines) and EN4 observation (lines and circles). The numbers refer to RMSE compared with EN4 showing the minimum of all these CMIP5 model (and the corresponding model number from the list on Figure 4), the median CMIP5 value and the values for NNA and ORCA12.



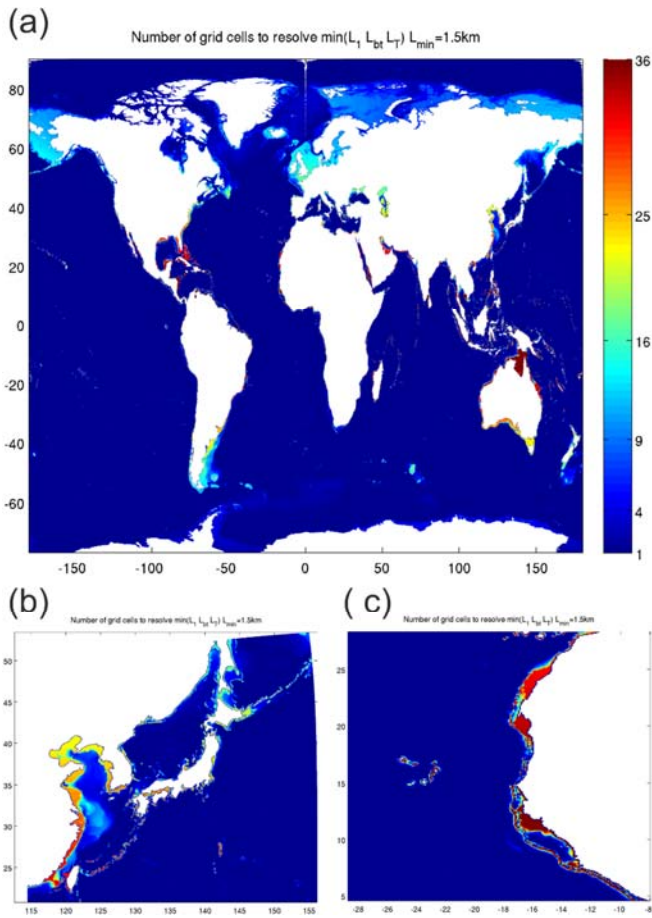


Figure 7 An example of how a  $1/12^\circ$  global grid (a) might conceptually be refined to resolve the dominant scales. Parameter shown is number of cells needed in each global grid cell to resolve these scales down to a minimum scale of 1.5km, so ranges from 1 (no refinement) to  $(72/12)^2=36$ . Below are two example in more detail for (b) East Asia and (c) NW Africa.

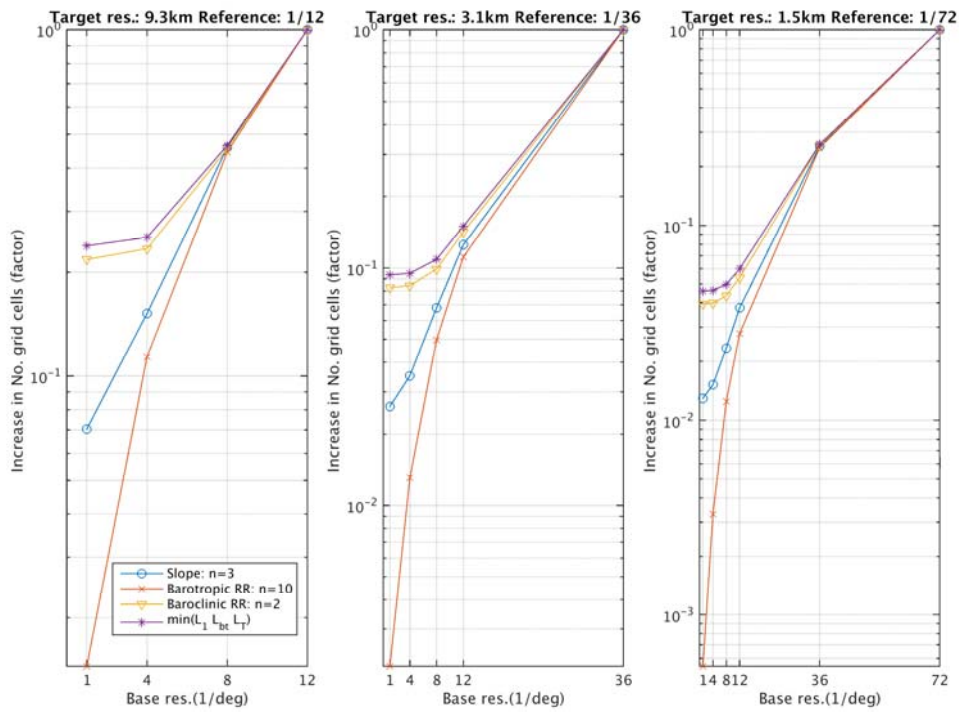


Figure 8 Number of grid cells to achieve process representation in shelf seas with a multiscale approach, relative to a refining global reference resolution of 1/12°, 1/36° and 1/72° and down to a minimum scale set by this global reference.

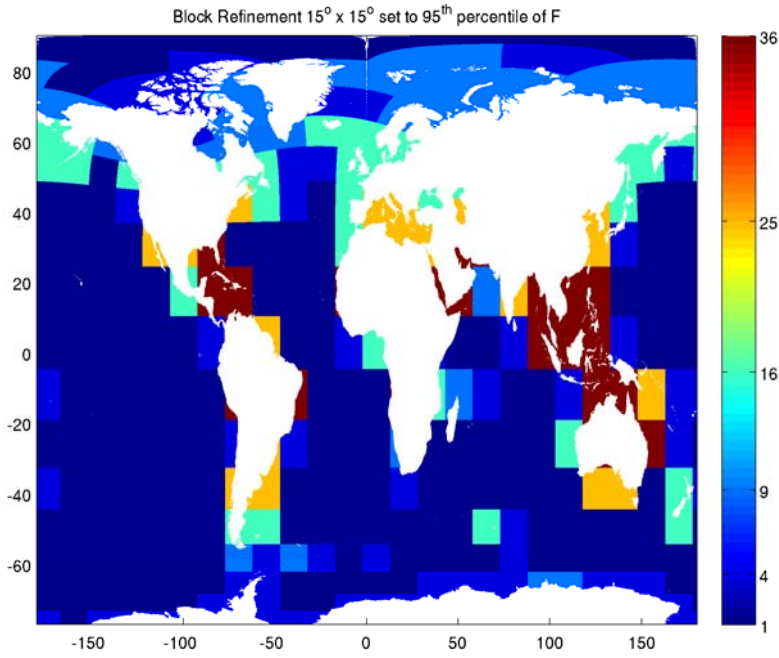
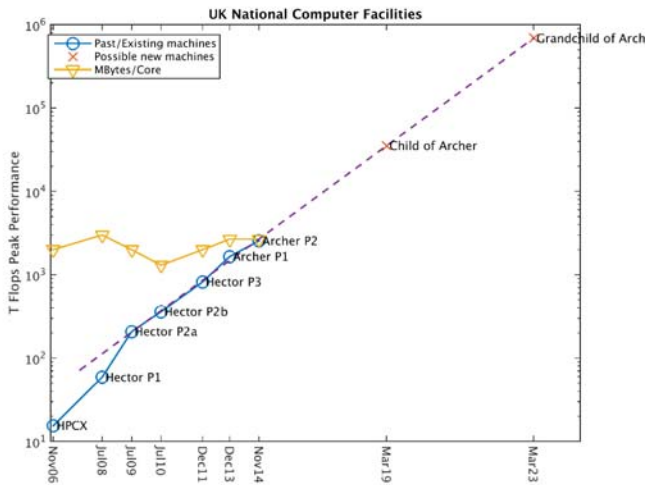


Figure 9 Refinement of  $15^\circ \times 15^\circ$  blocks to the 95<sup>th</sup> percentile of the distribution of  $F^2$  in each block. Set to  $(\text{int}(F))^2$  to approximate refinement by an approach such as AGRIF.



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Figure 10 The UK research computer facility peak performance and memory per core. Also shown are two-projected possible future machines.

les. The motivation for these is now considered.

## 1.2 Upscaling[HJT1]

There are three key motivations to studying the influence of coastal-ocean processes on the global scale: dynamics, biogeochemical cycles and anthropogenic impacts (i.e. the large scale impact of small scale human activity). Here we consider some examples, without attempting to be exhaustive.

A particularly important dynamical feature is the formation of dense water on Arctic and Antarctic shelves and its subsequent downslope transport and mixing to form deep water masses through the “cascading” process, thereby contributing to the global thermohaline circulation.

Two key water masses in the global ocean circulation are Antarctic Bottom Water (AABW) forming the densest water masses in all the major ocean basins, and North Atlantic Deep Water (NADW) found predominantly in the North Atlantic, lying above the AABW. Both these water masses are key components of the climate system, e.g. the NADW forms the lower limb of the Atlantic Meridional Ocean Circulation, responsible for the northward transport of large quantities of heat.

The AABW typically forms on the Antarctic shelves (primarily in the Weddell and Ross Seas, Adelie Land and near Cape Darnley) and subsequently cascades downslope into the deeper Southern Ocean (Orsi, 2010; Orsi et al., 1999). The source waters for the deeper component of NADW are mainly located in the extensive shelf seas of the Arctic and Greenland-Norwegian Basins, e.g. Deep Barents Sea Water forms through winter buoyancy loss west of Novaya Zemlya and cascades down through the St Anna Trough to reach depths of 1500-3000 m (Aksenov et al., 2011).

While these water masses are of key importance in the global ocean circulation, it is presently difficult for models to represent the formation and cascading processes adequately. It is well known, for instance, that geopotential (z-coordinate) models will tend to mix too strongly (and spuriously) dense water masses cascading down shelf slopes, and models using isopycnic coordinates typically do not mix enough, through uncertainty about the specification of the actual mixing processes involved (Roberts et al., 1996; Willebrand et al., 2001). This issue is also apparent in an analysis of CMIP5 coupled ocean-atmosphere climate models by Heuzé et al. (2013). This work showed that those (few) models that correctly produced AABW on the shelves were unable to cascade this water down-slope to the deeper ocean. Wobus et al (2013), however, have shown some success with a mixed z-s coordinate model (see below) in which s- (terrain-following coordinates) are applied over the shelf slope and facilitate the cascading downslope near Svalbard.

In terms of dynamical interaction with the atmosphere, coastal-upwelling (discussed further below) is seen as an important control of air-sea heat flux with implications for regional climate (e.g. in the southeast Pacific; Lin, 2007). On a smaller scale, coastal sea surface temperatures are a key influence on local weather (e.g. coastal fog and sea breezes).

A key role of the coastal-ocean in global biogeochemical cycles is the drawdown of carbon in highly productive shelf seas through photosynthesis (the ‘soft tissue carbon pump’) and its transport either to on-shelf sediments or off-shelf to the deep ocean, where it is isolated from atmospheric exchange (Bauer et al., 2013; Chen and Borges, 2009). Alongside this export, nutrient rich waters are transported on-shelf, carrying properties reflecting the greater depths and longer timescales of recycling experienced by this water. This occurs either by an upwelling circulation or a combination of deep winter mixing and a downwelling circulation (Holt et al., 2009b), and helps

support the coastal-ocean production and carbon drawdown. In addition the fixation of carbon through biogenic calcification (the 'hard tissue carbon pump'), while largely unquantified, would be expected to be particularly active in the benthic ecosystems of the coastal-ocean. Shelf seas are also a source of potent greenhouse gases, such as nitrous oxide (Seitzinger and Kroeze, 1998) and methane release from hydrates (Shakhova et al., 2010). Benthic processes and the resulting benthic-pelagic fluxes are highly significant in the shallower shelf seas water column. Many physical processes influence benthic-pelagic exchange, relating to both the seabed characteristics (e.g. bed material, presence of ripples) and the wave and current dynamics of the bottom boundary layer. The extent to which these influence coastal-ocean nutrient and carbon budgets on a global scale is largely unknown, but estimates (Bauer et al., 2013) suggest coastal-ocean sediments are a substantial carbon sink.

The coastal-ocean is the first point of entry for all material of terrestrial origin entering the marine environment, for example freshwater from rivers and ice sheets/shelves, inorganic nutrients, organic material and anthropogenic pollutants. This material can be substantially modified as it is transported across the coastal-ocean. These transformations (ranging from simple mixing to complex biogeochemical interactions) influence the material's ultimate fate. For example, whether the carbon and nutrients entering the marine environment from rivers (Seitzinger et al., 2005) reach the open-ocean depends on both the biogeochemical cycling on-shelf and the dynamics of the transit (Barrón and Duarte, 2015).

Hence the coastal- and open-ocean biogeochemical cycles are intimately coupled. There is still substantial uncertainty in their role and feedbacks with the wider climate system, and making progress on this is largely dependent on the accurate simulation of the physical environment in the coupled coastal-open-ocean system.

### 1.3 Downscaling

Investigating the large scale impacts on smaller scale processes in the coastal-ocean can often be successfully treated by nested regional studies, focusing on an area of interest ranging from local (e.g. Zhang et al., 2009) to regional (e.g. Wakelin et al., 2009) to basin (e.g. Holt et al., 2014; Curchitser et al., 2005) scales. There are, however, occasions where a global or quasi-global approach is appropriate. These relate to cases where it is important to consider impacts on human systems of global relevance. Examples include food security and the role of Living Marine Resources in ensuring this. Fish and fish meal production are both connected via the global economy (Merino et al., 2012), so considering how climate change might impact them and hence food security requires at least a quasi-global approach (e.g. Barange et al., 2014).

Moreover, cases where basin scale oceanic processes directly influence the coastal-ocean are best considered on a global scale (Popova et al., 2016), as regional simulations may be compromised by errors propagating from simplified boundary condition approaches (see below). Coastal upwelling is a notable example. This is one of the crucial processes influencing shelf ecosystems, acting as an important source of nutrients and also supplying low oxygen and low carbonate saturation state waters (with consequences for oxygen sat and acidification). Coastal upwelling driven by local wind stress (e.g. in eastern boundary upwelling zones) is amenable to regional modelling, accepting the need for accurate boundary conditions of larger scale nutrient distributions (Ryckaczewski and Dunne, 2010). However coastal upwelling that occurs in response to the variations in strength of the boundary currents lying outside of the shelf areas requires a basin scale or global modelling approach. Western boundary currents are shifting polewards and intensifying, and their waters are warming two to three times faster than the global mean (Wu et al., 2012). A reorganisation of the coastal upwelling regimes is expected in these areas leading

to the modification of the large-scale surface distribution of inorganic carbon and with significant consequences for living marine resources (Popova et al., 2016;Hobday and Pecl, 2014).

Another area that would benefit from a well resolved global approach is assessing the impacts of coastal-ocean sea level rise on a global scale; previous studies that have attempted to quantify the global cost of and vulnerability of coastal regions to sea level rise (e.g. Nicholls, 2004) have used coarse resolution global models and are limited in their ability to account for the regional variations in sea level rise that will strongly modulate its impact. Moreover,

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Specifically, users of model-based services (e.g. reanalysis and forecast information) would be expected to benefit. Presently global or basin scale models are typically used to provide boundary conditions for bespoke regional/shelf systems that provide these reanalyses and forecasts. This may remain the best way to provide these services, given that local tuning and high resolution meteorological forcing would be expected to give improvements to model skill. However, it may be the case that acceptable if not optimal information could be provided from one global modelling service and this might satisfy user requirements in many cases, without the additional overhead presently required to provide regionally specific information.

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If it turns out that addressing these issues is problematic or computationally prohibitive

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Quadrilaterals in contrast have good numerical properties (particularly for wave propagation), so a conceptually attractive option would be a mixed element grid, with quadrilaterals covering the majority of the ocean and triangles used to refine the grid where needed (Figure 9). The finite volume method is readily generalised to this approach, which would have the advantage of only requiring stabilisation of numerical modes in the triangular mesh region. However, the best choice of grid arrangement (Figure 9B shows some options) is uncertain. The C-grid type arrangement is the optimal choice for wave propagation in quadrilaterals, but has serious numerical issues for the triangular mesh. Hence, any choice will be a compromise and require careful evaluation. Currently Danilov and Androsov (2015) have investigated the B-grid and Holt et al (2013) the A1 grid cases. Alternative approaches for this are global triangular or hexagonal mesh models. The former have been available for many years, but have not yet reached a level of maturity where they form the ocean component of CMIP models, whereas the latter is an emerging capability (Ringler et al., 2013).

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and requires considerable investment in model configurations (a new global model must be configured and tested); so this region must be likely to endure as a focus of interest.