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Nonlinear Processes in Geophysics
Discussions
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Interactive comment on "Theoretical comparison of subgrid turbulence in the atmosphere and ocean" *by* V. Kitsios et al.

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GENERAL COMMENTS:

We appreciate the reviewer's efforts and comments on our paper. As mentioned in the response to the other reviewers, we further emphasise the new and novel aspects at the end of the introduction in the revised manuscript, by including the following points

1. We believe that this is the first ever study to systematically compare subgrid models of quasigeostrophic (QG) turbulence in the atmosphere and ocean. In particular it is the first study were simple unified scaling laws have been presented that apply to both media.

2. The study uses a much larger set of simulations covering a much broader range of flow parameters, including an order of magnitude change in the Rossby radius of deformation and the energy containing scale, compared with previous studies.
3. By focussing on the enstrophy cascading inertial range in both media, the large number of simulations and wide parameter range has enabled the establishment of robust scaling laws.
4. The scaling laws presented here are particularly simple with eddy viscosity magnitudes that are proportional to T_R^{-1} and power exponents that are approximately proportional to T_R. These results, and the fact that $\nu_{\mathbf{d}} \approx 2\nu_{\mathbf{b}}$, are suggestive of robust fundamental properties of QG turbulence.

We reviewer's specific comments are addressed below. Associated changes to the manuscript are marked in blue text.

The updated manuscript can be found in the supplementary material.

SPECIFIC COMMENTS:

- *The scaling laws for the inverse energy cascade range are not included*

The scaling law behaviour within the inverse energy cascade is different to that within the forward enstrophy cascading inertial range, with different resolution dependence. The subgrid dissipation matrices in the inverse energy cascade are in fact more complex as they are non-diagonal in level space, while the matrices are diagonal in the enstrophy cascading inertial range.

Within the enstrophy cascading inertial range the resolution dependence of the scaling laws also suggests something more fundamental about turbulence in general. The scaling laws illustrated in figure 4, indicate that the magnitude of the eddy viscosity is

proportional to T_R^{-1}, which means that as resolution doubles the eddy viscosity halves. The power exponents are approximately proportional to T_R. These exponents indicate that the wavenumber extent that the subgrid interactions can span is fixed and equal to k_E. This concept is discuss further on page 1691 of the previous (and current) version of the manuscript, and is restated below.

It is the extent of the energy containing scales (k_E) that defines how far nonlinear interactions can span in wavenumber space (Kraichnan, 1976), which effectively sets the size of the largest eddy that can interact with the subgrid scales. This wavenumber distance is inversely proportional to the power exponents, and is represented by the span of wavenumbers over which the eddy viscosity profiles are non-zero in Fig. 3(c) and Fig. 3(d).

- *The title is a bit misleading.*

Your point is duly noted. Perhaps the following title would be more appropriate:

Theoretical comparison of subgrid turbulence in atmospheric and oceanic quasi-geostrophic models

- *Justification for drag in atmospheric and oceanic regimes.*

As discussed with reference to a comment by reviewer 2, the drag applied in both the atmospheric and oceanic cases is used to control the extent of the energy containing scales of wavenumber, k_E. In the atmospheric case the a constant drag is applied from the first wavenumber to the Rossby wavenumber, k_R, to ensure that the enstrophy cascade starts at the end of the energy containing range, consistent with observations of the real atmosphere. As mentioned in response to the comments of reviewer 2, in

the oceanic case a more complex wavenumber dependent drag is used to control the position of k_E. Using this approach we are able to study the influence of k_E on the subgrid coefficients, and in the manuscript we develop scaling laws to represent the variability in both k_R and k_E. The updated version of the manuscript now includes the following sentence after the definition of the functional form of the oceanic drag:

This functional form allows us to control the location of the energy containing wavenumber.

- *Why does the benchmark calculation have a viscosity that is determined from the scaling laws obtained using the benchmark calculation.*

There are theoretically two ways to ensure that the benchmark simulations accurately represent the associated physics. The first is to resolves all scales of turbulence down to the Kolmogorov scale, such that no subgrid model is required. However, this is obviously not possible since the Kolmogorov scale in the atmosphere and ocean is approximately 1mm and 1cm respectively. The second and chosen approach, is as you say, to employ benchmark simulations that use a subgrid model obtained consistent with the scaling laws determined from it and other benchmark simulations. This has required that the entire exercise to be undertaken twice. The first time an estimate of the subgrid model in the initial benchmark simulations was used. The subgrid coefficients, and hence scaling laws were determined from these initial benchmark simulations. The subgrid model used in the benchmark simulations were then replaced with a subgrid model consistent with the scale laws, and the process repeated again. Minimal changes to the scaling laws were observed, however, this exercise ensured that the subgrid model used in the benchmark simulation is self-consistent with the subgrid models determined from it.

- *What is the physical justification for the power law? How can you apply the spec-*

tral power law to grid-point models?

As mentioned in response to the comments of reviewer 2, we would first like to reiterate that the focus of this manuscript is to accentuate the similarities between the properties of subgrid turbulence in the atmosphere and ocean, and not on addressing issues associated with specific numerical implementations. Having said that, as you request, we have addressed the issues associated with the implementation of such scaling laws into grid point models.

Firstly the cusp-like nature of subgrid turbulence was first discussed in the seminal works of Kraichnan (1976), and in many articles on fundamental turbulence since. There are two possible approaches to implementing these scaling laws in grid point models, which are now outlined in the following new paragraph in the conclusions.

The scaling laws developed here can be implemented directly into spectral simulations, and are expected to improve the efficiency and accuracy of numerical weather and climate simulations (Frederiksen et al., 2003, 2015). There are also two possible approaches to implement these scaling laws into grid point codes. The simplest approach is to apply the subgrid model directly in grid-point space via a Laplacian operator of the appropriate power, as outlined in Table 1. More generally it is also possible to employ grid to spectral transforms, where the subgrid model is calculated in spectral space, and then applied in physical space.

- *p1692, line 16-18: If the enstrophy flux is required to determine the eddy viscosity, how would this parameterization be used in a coarse resolution ocean model where the enstrophy flux is not known a priori?*

The enstrophy flux could be estimated from either previous oceanic GCMs or from measurements of ocean spectrum as those in Stammer (1997). In either case, this

is arguably a more sophisticated and self-consistent approach than subgrid model parameter tuning that is typically undertaken in both atmospheric and oceanic GCM, to attain numerical stability and produce desirable results (Griffies et al., 2005). The efforts taken to get appropriate measures of the enstrophy flux is a judgement call that the modeller themselves need to make.

- *Figure 4: what is the dashed line in b and d?*

The dashed lines in figures 4b and 4d and the same as the solid lines in figures 4a and 4c respectively, to serve as a direct comparisons. The following sentence has been added to the caption of figure 4.

The dashed lines in figures **b** and **d** represent the drain scaling laws to serve as a direct comparison to the backscatter scaling laws represented by the solid lines.

References

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Please also note the supplement to this comment:
http://www.nonlin-processes-geophys-discuss.net/2/C715/2016/npgd-2-C715-2016-supplement.pdf

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Interactive comment on Nonlin. Processes Geophys. Discuss., 2, 1675, 2015.