Observed Ocean Turbulence Spectra from ARGO Profiling Floats

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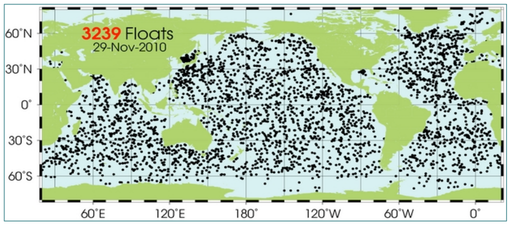
Abstract

While there are many theories predicting the spectral slopes associated with the statistics of ocean macro-turbulence, there have been no observations at depth to guide these discussions. Here, a method developed for estimating the structure function of atmospheric macro-turbulence using rawinsondes is adapted to estimate the structure function and corresponding spectral slope of oceanic macro-turbulence using data collected by ARGO profiling floats. Structure functions were calculated over a range of depths and latitude bands, as well as in eddy-rich and eddy-poor regions. It is shown that the horizontal structure function evaluated at pressure levels differs from that evaluated along potential density surfaces, consistent with the internal wave spectrum. In pressure coordinates below 45m at larger scales, the results follow the Batchelor (1959) theory, with spectral slope of -1, and smaller scales follow the Kolmogorov (1941) theory of spectral slope of -5/3. The potential density coordinate results are consistent with the Batchelor spectrum at large scales over all depths. Eddy-rich regions show the Kolmogorov spectrum at small scales, and Batchelor at larger scales, while eddy-poor regions have a slope shallower than all theories predicted at all scales. The latitude dependence appears as a difference in structure function strength, rather than slope variation, with higher latitudes exhibiting higher energy levels.



Structure Function and Spectral Slope

The structure function estimates the difference in temperature, velocity, or salinity between two locations a distance, *s*, apart, using the isotropic kinetic energy:

$$\overline{u^2} = \int_0^\infty E(k)dk.$$

For velocity, the autocorrelation function, R(s), and structure function, D(s), are calculated by

$$R(s) = \overline{u(x)u(x+s)},$$

$$D(s) = \overline{(u(x)-u(x+s))^2} = 2(\overline{u^2} - R(s)).$$

The autocorrelation and structure function are represented spectrally by

$$R(s) = \int_0^\infty E(k)\cos(ks)dk,$$

$$D(s) = 2\int_0^\infty E(k)(1-\cos(ks))dk,$$

For a given spectral slope, $E(k)=\alpha_E k^{\beta_E}$ and a given structure function $D(s)=\alpha_D k^{\beta_D}$ a change of variables $(ks \to \xi)$ yields

$$D(s) = 2\int_0^\infty \alpha_E k^{\beta_E}(1-\cos(ks))dk,$$

$$= 2\alpha_E s^{-\beta_E -1}\int_0^\infty \xi^{\beta_E}(1-\cos(\xi))d\xi$$

This shows that $\beta_D = -\beta_E - 1$. Similarly for potential temperature, the structure function is related to the spectral slope, $D_\theta(s) \propto s^{\gamma_D}$.

The primary goal of this project will be to estimate γ_D from ARGO data over length scales where an inertial range is apparent, and compare to theories that predict γ_D.

Theoretical Predictions

Different theories predict the spectral slope for energy, enstrophy, and temperature cascades at inertial scales, in 3-dimensional, 2-dimensional, quasi-geostrophic and surface quasi-geostrophic cases. Kolmogorov's (1941) 3D energy-cascade and Blumen's (1978) SQG temperature cascade both predict a spectral slope of 2/3, and at the surface and in the mixed layer, Capet et al (2008) and Klein et al (2008) both find $\beta = \gamma = 2$. We expect to see the spectral slopes equal to either 2/3 or 2 at the macro scale ($s \sim 10^2$).

For passive tracers, Batchelor (1959) predicts a spectral slope of -1, corresponding to a structure function slope of 0. This is the prediction for the temperature structure function on potential density surfaces.

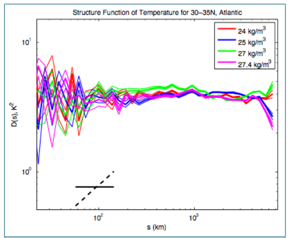


Figure 2: Structure function along 30-35N in the Atlantic Ocean for 4 different depths, in and below the mixed layer. Also included are two black lines showing spectral slopes of 2/3 (dashed) and 0 (solid).

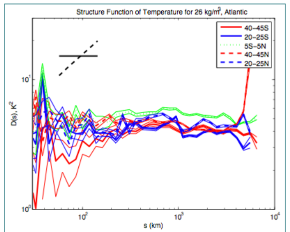


Figure 3: Structure function at a constant depth of 26 kg/m³ along latitude bands of 40-45 (red; N-dashed, S-solid), 20-25 (blue; N-dashed, S-solid) and 5N-5S. Spectral slopes of 2/3 (dashed) and 0 (solid) are shown in black.

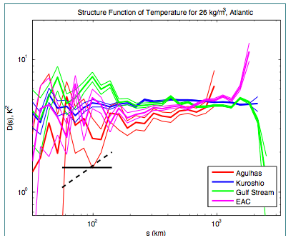


Figure 4: Structure function on an isopycnal of 26 kg/m³ in the eddy-rich regions of the Agulhas (red), Kuroshio (blue), Gulf Stream (green) and East Australian (purple) currents. Spectral slopes of 0 (solid) and 2/3 (dashed) are shown in black.

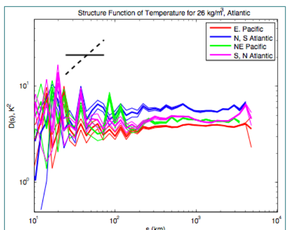


Figure 5: Structure function on an isopycnal of 26 kg/m³ in the eddy-poor regions of the East Pacific (red), northern South Atlantic (blue), Northeast Pacific (green) and the southern North Atlantic (purple).

Structure Function Results

Depth Dependence

Figure 2 shows the structure function in the Atlantic Ocean at 30-35N at several depths. It was expected that the overall strength of the structure function would be lower at depth, since there is more turbulence in the mixed layer, but the structure function is approximately the same at all depths. Theory predicted that the spectral slope would be 2 at the surface, and this is clearly not the case. The structure function slope of 0 is equivalent to a spectral slope of -1, as was achieved by Batchelor's theory of tracer spectra. A forcing scale below which the slope is steeper is not visible in these structure functions because the lacking data provides noisy and imprecise structure functions (note larger confidence intervals).

Latitude Dependence

As seen in Figure 3, latitude does not have a strong impact on the structure function, in either strength or spectral slope. Overall, turbulence is slightly greater at the equator, possibly because it is the northern and southern boundary of the mid-latitude gyres of the South and North Atlantic, respectively, with the addition of Equatorial Kelvin waves. The spectral slopes at all latitudes are close to 0. Taking into account the confidence interval, the structure function for 40-45S appears to have a steeper slope below approximately 200km. This slope could be indicative of the forcing scale of 200km where the inverse energy cascade begins and moves to larger scales, and where the enstrophy cascade goes to smaller scales.

Eddy-Rich vs Eddy-Poor Regions

Since all turbulent theory assumes homogeneity, the structure function of regions with high eddy-kinetic energy (EKE) were compared to those with low EKE. Interesting and less-explainable results have been obtained for eddy-rich and eddy-poor regions. The slopes in the eddy-poor regions (Figure 5) are 0, and extend to scales around 50 km. The four regions (chosen subjectively from an EKE map of the world's oceans) each have slightly different strengths apparent in their structure functions, but have the same overall behavior. The eddy-rich regions' structure functions pose a problem. In one region (around the Agulhas Current), there is close to a 2/3 slope, while the region around the Kuroshio has a very steady slope of 1. Note: The confidence intervals are much smaller for the Kuroshio, since there are many more data points available from the large number of ARGO floats in the area. In the Gulf Stream, there is an unusual *increase* in structure function strength at scales around 100 km, and then a decrease and a leveling-off to a slope of 0 at larger scales. The Easy Australian Current has a structure function slope between 0 and 2/3.

Questions to consider

In future work, the assumptions that are made in turbulent theory must be addressed, most importantly the assumptions of homogeneity and isotropy. Especially when looking at latitude bands that extend across both eddy-rich and eddy-poor regions like in Figures 2 and 3, neither of the assumptions are accurate. The eddy-rich and –poor regions were chosen to maximize homogeneity, but in future work, sections will be chosen to match the direction of the flow so that isotropy can safely be assumed. With confidence intervals on the structure functions, error bounds for slope are also possible, and will be calculated soon.

Acknowledgements

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