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Seasonality of eddy kinetic energy in an eddy permitting global climate model

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ABSTRACT

We examine the seasonal cycle of upper-ocean mesoscale turbulence in a high resolution CESM climate simulation. The ocean model component (POP) has 0.1° resolution, mesoscale resolving at low and middle latitudes. Seasonally and regionally resolved wavenumber power spectra are calculated for sea-surface eddy kinetic energy (EKE). Although the interpretation of the spectral slopes in terms of turbulence theory is complicated by the strong presence of dissipation and the narrow inertial range, the EKE spectra consistently show higher power at small scales during winter throughout the ocean. Potential hypotheses for this seasonality are investigated. Diagnostics of baroclinc energy conversion rates and evidence from linear quasigeostrophic stability analysis indicate that seasonally varying mixed-layer instability is responsible for the seasonality in EKE. The ability of this climate model, which is not considered submesoscale resolving, to produce mixed layer instability although damped by dissipation, demonstrates the ubiquity and robustness of this process for modulating upper ocean EKE.

1. Introduction

Mesoscale turbulence is ubiquitous in the ocean and has significant impacts on the large-scale ocean circulation and its interaction with the climate (e.g. Jayne and Marotzke, 2002; Volkov et al., 2008; Lévy et al., 2010; Griffies et al., 2015). Ocean currents are most energetic in the mesoscale range, on the order of tens to a few hundred kilometers. Mesoscale turbulence is driven by baroclinic instability of the main thermocline (Gill et al., 1974; Smith, 2007), and is relatively well described by quasi-geostrophic (QG) models (Rhines, 1979; Held et al., 1995), in which enstrophy and energy conservation lead to the inverse cascade of energy from small to large scales (Charney, 1971). Below the mesoscale lies the submesoscale, which feeds off of the available potential energy (APE) in the mesoscale fronts, particularly in the mixed layer (Boccaletti et al., 2007).

A number of recent observational and modeling papers have demonstrated a pronounced seasonality in surface EKE in the submesoscale range, roughly 10–100 km (Mensa et al., 2013; Qiu et al., 2014; Sasaki et al., 2014; Callies et al., 2015; Brannigan et al., 2015; Rocha et al., 2016b; Buckingham et al., 2016). Most of the studies cited are regional or from idealized models, thus global patterns have not yet been established. Moreover, there are at least four main hypotheses proposed to explain this seasonality: (i) variation in internal gravity wave energy due to seasonality in upper ocean stratification (Rocha et al., 2016b); (ii) variation in frontogenesis (FG) due to seasonality in lateral strain and convergence in horizontal density gradients (Mensa et al., 2013); (iii) variation in the interior baroclinic instability (BCI) due to seasonality in the vertical shear of the full-depth background state (Qiu et al., 2014); and (iv) variation in the mixed-layer (ML) BCI due to seasonality in ML stratification, depth and vertical shear in the mixed layer (Boccaletti et al., 2007; Qiu et al., 2014; Callies et al., 2016). There is as yet no strong consensus about the relative roles of these mechanisms on a global scale.

Current generation satellite altimetry products provide global observations of sea surface height (SSH), and thus geostrophic velocity, but the spread of the tracks and instrument noise limit the effective resolution to about 100 km (Xu and Fu, 2012), which is just sufficient to see the peak of the mesoscale. The almost-submesoscale-resolving Surface Water Ocean Topography (SWOT) satellite (Fu and Ferrari, 2008) is expected to launch in 2021, and until then, investigations of submesoscale and submesoscale-driven seasonality in EKE must rely on models.

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In this paper, we investigate seasonal variability of eddy kinetic energy (EKE) in a state-of-the-art global climate model; specifically the 0.1°-resolution configuration of the Parallel Ocean Program (POP) model, run within the fully-coupled Community Earth System Model (CESM) simulation described in Small et al. (2014). To our knowledge, the seasonality of ocean turbulence has not been examined in a coupled model on a global scale. According to the criteria of Hallberg (2013), this configuration ranges from mesoscale-resolving at low latitudes to mesoscale-permitting at high latitudes. Although this is very fine resolution for a climate model — finer than resolved by current generation altimeters — it is coarse compared to recent numerical studies of submesoscale seasonality, some of which have used a spatial resolution of 1 km or even higher (Mensa et al., 2013; Sasaki et al., 2014; Gula et al., 2014; Brannigan et al., 2015; Rocha et al., 2016a; 2016b). The lack of resolution is a necessary trade-off for a global analysis. Moreover, analysis of such a model should provide a useful test bed for future work on SWOT observations.

Driven by this connection to altimetric observations, we focus on the analysis of surface fields, especially on wavenumber power spectra, which provide a practical way to characterize scale-dependent variance and have been widely used in related studies (e.g. Stammer, 1997; Thomas et al., 2008; Capet et al., 2008b; Xu and Fu, 2011; 2012). An oft-cited motivation for spectral analysis is its connection to inertial-range turbulence theories, which provide specific predictions for spectral power law scalings that vary with the nature of the turbulence, suggesting a tempting way to test ideas. For example, Xu and Fu (2012) made a global estimate of two-dimensional (2D) along-track spectral slopes of SSH observed by satellite altimeters on *Jason-1* and *Jason-2*. They found that in regions of high eddy activity, the SSH spectral slopes had values between k^{-5} and $k^{-11/3}$, which are consistent with predictions by QG (Charney, 1971) and surface-QG (SQG) theory (Blumen, 1978; Held et al., 1995; Lapeyre and Klein, 2006), respectively. However, such theories formally only apply to scales that are neither directly forced nor dissipated, are stationary in time, and reflect only one underlying dynamics. Callies et al. (2016) points out that the submesoscale range is likely directly forced, violating the inertial assumption, and Dufau et al. (2016) argues that previous estimates of spectral slopes from altimetry which do not properly account for the spatial and temporal variability of significant wave height (e.g. Xu and Fu, 2012) may be contaminated by observational noise even in the mesoscale range. Moreover, the very temporal variability we seek to study implies temporal non-stationarity. Consequently, our study does not emphasize specific values of the spectral slopes; rather, we simply use spectra as one of many tools to characterize energy variations in a scale-dependent way.

Despite the limitations imposed by the model resolution and strong damping due to dissipation, we show that the POP simulation resolves some submesoscale generated energy cascading up to the mesoscale. Moreover, many lines of evidence — including linear stability analysis, predictions for energy transfer rates, and phase correlations — point to an inverse cascade of submesoscale energy generation by mixed-layer instability as the primary driver of this seasonality.

The paper is organized as follows. In Section 2, we give a brief description of the POP model. The results of spectral analysis and comparison of the spectral slopes among seasons are shown in Section 3. In Section 4 we discuss baroclinic instability at the mesoscale and submesoscale, and detail our evidence for MLI as a main source of seasonality in EKE. In Section 5, we examine two other possible drivers of seasonality in small-scale EKE: intertia-gravity waves and frontogenesis. We summarize and conclude in Section 6. The details of our spectral analysis and linear stability analysis are given in the appendix.

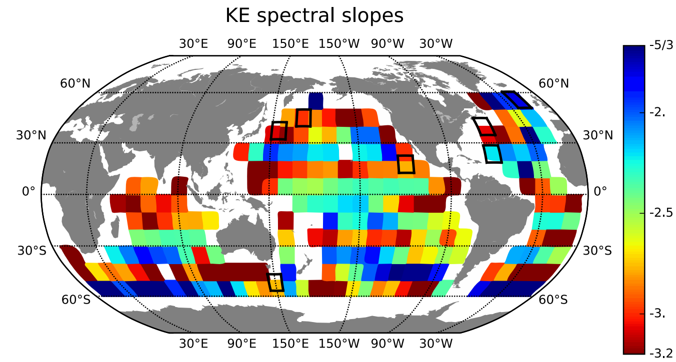

Fig. 1. Annual mean of spectral slopes at scales above 200–250 km (4×10^{-3} – 5×10^{-3} cpkm). The black boxes indicate the seven regions (Kuroshio, north of Kuroshio, east Pacific, Gulf Stream, Sargasso Sea, northeast Atlantic and the ACC) we consider in detail.

2. Description of the numerical model

The ocean simulation we examine is a part of the fully-coupled global simulation using the CESM described in Small et al. (2014), which was run under present-day greenhouse gas conditions for 100 years, similar to McClean et al. (2011). The POP model, which is the ocean component, is a level-coordinate ocean general circulation model that solves the three-dimensional primitive equations for ocean dynamics. The hydrostatic and Boussinesq approximations are prescribed, and the model employs a B-grid (scalars at cell centers, vectors at cell corners) for the horizontal discretization scheme. The time discretization scheme uses a three-time-level second-order-accurate modified leap-frog scheme for stepping forward in time. The diffusive terms are evaluated using a forward step.

Subgrid scale horizontal mixing is parameterized using biharmonic diffusivity and viscosity, with the coefficients spatially varying with the equatorial values of $A_H = -3.0 \times 10^9$ m^4/s and $A_M = -2.7 \times 10^{10}$ m^4/s respectively. The vertical diffusion depends on the K-profile parameterization (KPP) of Large et al. (1994). Further details about the discretization and advection schemes of the primitive equations and parameterization methods are described in the Parallel Ocean Program Reference Manual (Smith et al., 2010). The horizontal grid spacing in the POP simulation is approximately 0.1° in latitude/longitude. Each component of the coupled model exchanges information at different time intervals, with the atmosphere, sea ice, and land models coupling every time step (15 min), and the ocean every 6 h. The simulation outputs at the ocean surface were saved as daily averages, while interior information was saved as monthly averages. The available model output constrains the scope of our analysis; since the monthly averaging filters out lots of small-scale variance, we focus our spectral analysis at the surface. More details of the model setup can be found in Small et al. (2014).

A video of the sea surface temperature in the Kuroshio region is available online at https://vimeo.com/channels/oceandynamics/99933667. This video clearly shows the formation of secondary instabilities on the fronts of mesoscale eddies; this process appears to be much more active in winter, when mixed layers are deep. Although the spatial resolution of this model (0.1°) is not considered submesoscale resolving, the video suggests that some submesoscale processes are captured by the model. This visualization provided the motivation for our subsequent quantitative analysis of seasonality.