The Global Seasonal Cycle of Mixed Layer Instability in a GCM

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Objectives

We examine the seasonal cycle of upper-ocean mesoscale turbulence in a high resolution CESM climate simulation. Seasonally and regionally resolved wavenumber power spectra are calculated for sea-surface eddy kinetic energy (EKE). The EKE spectra consistently show higher power at small scales during winter throughout the ocean. Our study looks into:

- A global picture of ocean EKE seasonality in a high-resolution GCM
- The potential mechanisms responsible for seasonality in EKE

Introduction

In this study, we investigate seasonal variability in wavenumber power spectra for eddy kinetic energy (EKE) in an ocean model. SSH and velocity fields through geostrophic balance are observable through remote sensing, albeit with significant noise and sampling issues, and a global climate model (GCM) study provides a useful test bed for future work on satellite observations. Additionally, because of its resolution and dynamical limitations, the analysis of such a GCM serves as an experiment into the mechanisms which can drive seasonality.

According to the criteria of [1], 0.1°-resolution configuration of the Parallel Ocean Program (POP) model, run within the fully-coupled Community Earth System Model (CESM) simulation 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

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. Considering that it is still impractically computationally expensive to run submesoscale-resolving global climate models, our study provides insights into how mesoscale-resolving models reproduce seasonal variations.

Moreover, analysis of such a model should provide a useful test bed for future work on observations by the Surface Water Ocean Topography (SWOT) satellite [2], expected to launch in 2021.

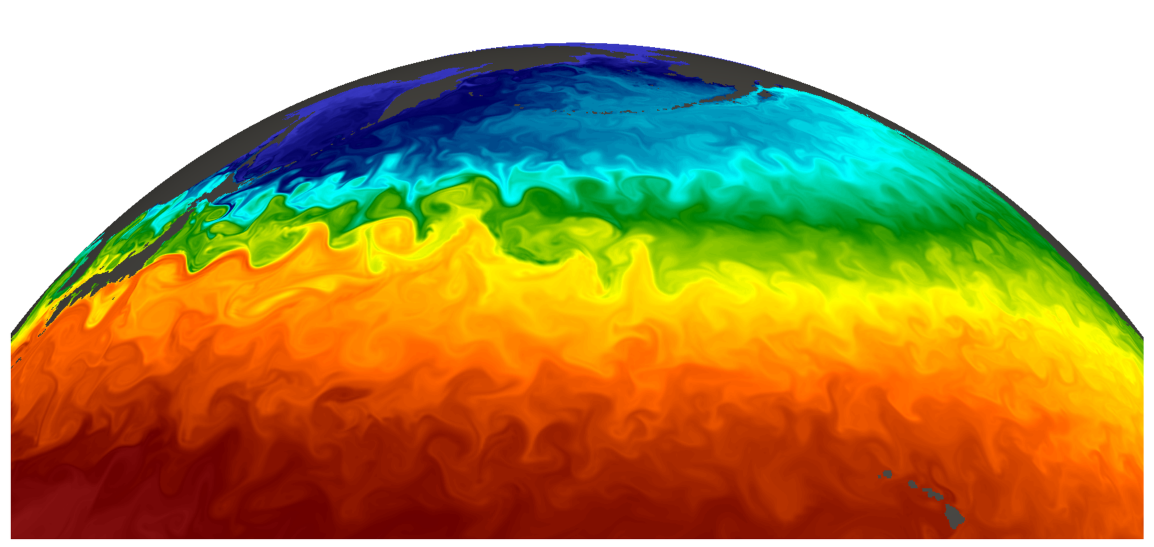

Figure 1: Snapshot of sea-surface temperature (SST) in the Kuroshio region.

Model description

The ocean simulation we examine is a part of the fully-coupled global simulation using the CESM described in [3], which was run under present-day greenhouse gas conditions for 100 years. The POP model had:

- Level-coordinate ocean GCM with three-dimensional primitive equations
- Hydrostatic and Boussinesq approximations are prescribed
- Subgrid scale horizontal mixing is parameterized using biharmonic diffusivity and viscosity
- The vertical diffusion depends on the K-profile parameterization (KPP) of [4]
- Horizontal grid spacing is approximately 0.1° in latitude/longitude
- Each component was coupled at different time intervals, with the atmosphere, sea ice, and land models coupling every time step (15 min), and the ocean every 6 hours.

The simulation outputs at the ocean surface were saved as daily averages, while interior information was saved as monthly average.

Global picture of EKE seasonality

Figure 2 shows the isotropic wavenumber EKE spectra in the Kuroshio and ACC domain for each season (JFM, AMJ, JAS, OND) and seasonality of EKE at scales below 30km. EKE is consistently higher during wintertime compared to summertime in both hemispheres.

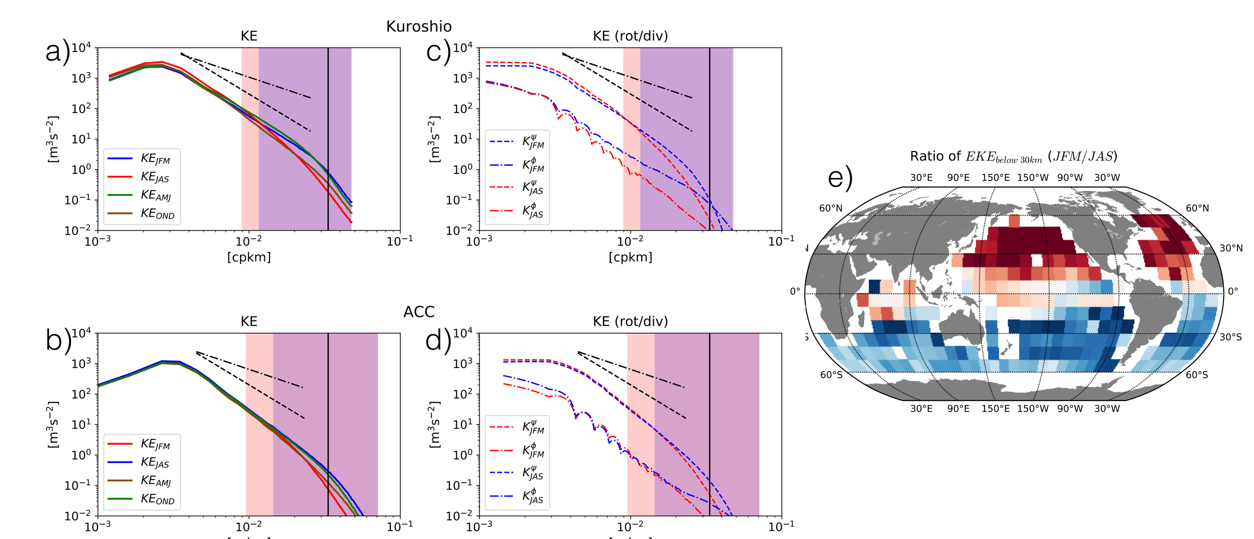

Figure 2: Isotropic wavenumber EKE spectra and its Helmholtz decomposition in the Kuroshio (lon: 150.0E∼160.0E, lat: 31.5N∼41.5N) (a), (c) and ACC (lon: 145.0E∼155.0E, lat: 56.5S∼46.5S) region (b), (d). The shading shows the dissipation range defined as where 80% of the dissipation due to bihamonic diffusion occurs. The black dashed and dotted lines show the spectral slope of -3 and -5/3 respectively. The black vertical line indicates the 30 km scale. (e) Ratio of EKE in scales smaller than 30km .

Important Result

EKE at scales smaller than 30km showed coherent seasonality in both hemispheres, consistent with the seasonality of **baroclinic conversion rates** ($\overline{w''b''}$).

Baroclinic instability

The seasonality of baroclinic conversion rates averaged over the top 100m are shown in Fig. 3.

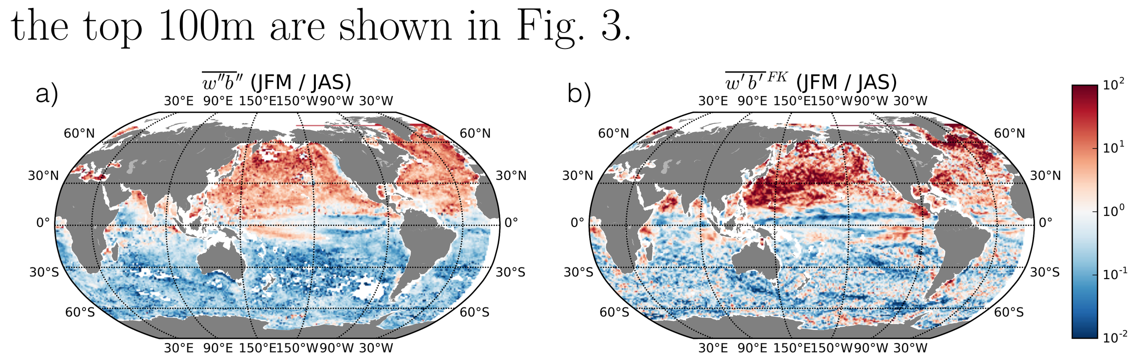

Figure 3: APE energy conversion rate derived using the submonthly variability (a) and parametrization of [5].

We show the seasonality of baroclinic instability growth rates at the Nyquist wavelength of the model in Fig. 4. The large growth rates during winter were due to the reduced stratification in the mixed layer.

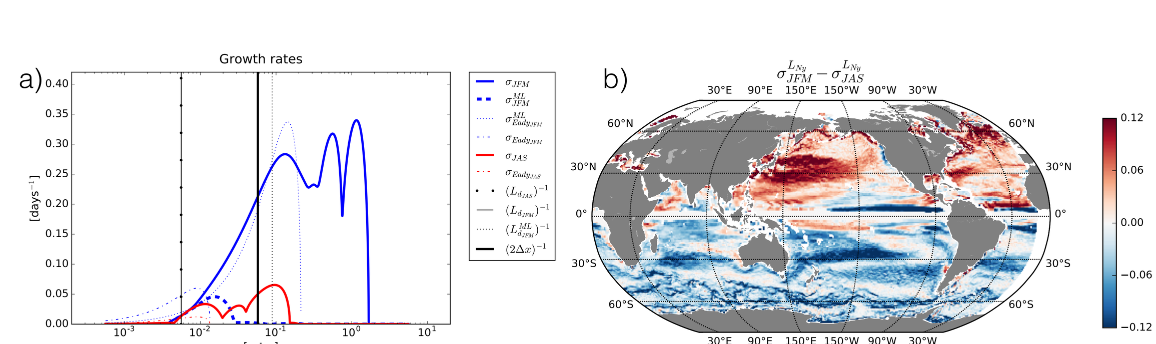

Figure 4: Growth rate of baroclinic instability in the Kuroshio region plotted against inverse wavelength (a) and global picture at the Nyquist wavelength (b).

Frontogenesis (FG)

The relevance of strain-induced FG in producing seasonality at submesoscales can be quantified via the frontogenesis function, defined as

$$F_s = \boldsymbol{Q_s} \cdot \boldsymbol{\nabla}_z b$$

where $\boldsymbol{\nabla}_z b$ is the horizontal buoyancy gradient and

$$\boldsymbol{Q_s} = -\Big(\frac{\partial u}{\partial x}\frac{\partial b}{\partial x} + \frac{\partial v}{\partial x}\frac{\partial b}{\partial y}, \frac{\partial u}{\partial y}\frac{\partial b}{\partial x} + \frac{\partial v}{\partial y}\frac{\partial b}{\partial y}\Big).$$

F_s represents the instantaneous rate of increase of the horizontal buoyancy gradient variance arising from the straining by the horizontal velocity field [6].

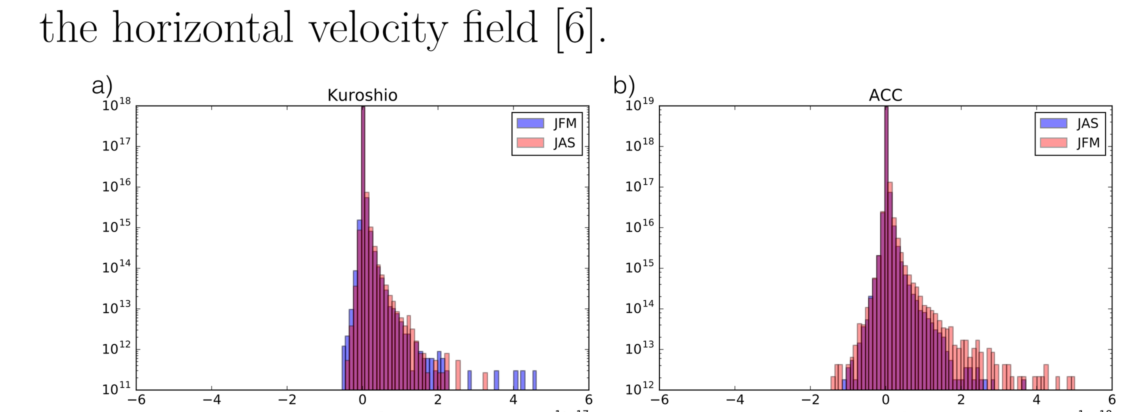

Figure 5: Histogram of Fs for the Kuroshio (a) and ACC (b) domain.

We see that the seasonality of F_s is generally weak and except for the Kuroshio and Gulf Stream (not shown) domain, the seasonality was out of phase with the EKE seasonality, consistent with the findings by [7] (i.e. EKE peaks during winter but FG during summer).

Internal gravity waves

The POP simulation does not include tidal forcings [3] so the main mechanism for generation of subinterial energy is high-frequency wind forcing.

Figure 2 c,d show that, except for the highest wavenumbers, the rotational component dominates for both seasons. The seasonality seen in the POP simulation at scales larger than 50km, therefore, is mostly due to the rotational component of the velocity field, i.e. geostrophic turbulence, which is non-divergent to its first order. The divergent component at the highest wavenumbers is likely due to dissipation acting most strongly on the smallest scales.

Conclusion

Evidence from diagnostics of baroclinic energy conversion rates and linear quasigeostrophic stability analysis indicate that seasonally varying **mixed-layer instability** [8] is responsible for the seasonality in EKE. The ability of this climate model, which is not considered submesoscale resolving, to produce mixed layer instability demonstrates the ubiquity and robustness of this process for modulating upper ocean EKE.

The implications of this seasonality for air-sea interaction, ocean ecosystems, and eddy fluxes are important questions for future research.

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