Seasonality in dominant upper-ocean dynamics at submesoscales

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Key Points.

- Submesoscale (10-100 km) vertical vorticity and lateral strain peaks in late Winter/early Spring; divergence and stratification peaks in late Summer/early Fall.
- Quasi-balanced eddies dominate the variability in late Winter/early Spring; inertia-gravity waves dominate in late Summer/early Fall.
- These results have implications for the diagnosis of surface velocity from high-resolution altimeters.

(Type abstract here)

1. Introduction

1.1. Motivation

Recent studies have suggested that submesoscale upper-ocean flows undergo strong seasonal cycle [*Sasaki et al.*, 2014; *Qiu et al.*, 2014; *Callies et al.*, 2015; *Thompson et al.*, 2016; *Buckingham et al.*, 2016].

Observations at submesoscales are limited.

SWOT and COMPIRA will provide submesoscale-resolving SSH measurements with global coverage.

1.2. This paper

Using the output of a 1/24° state estimate, we show that (vertical) vorticity and (horizontal) divergence undergo strong seasonal cycle that are out of phase. This seasonal cycle is associated with changes in the upper-ocean stratification. As previously argued, in late Winter/early Spring, deep mixed-layers are prone to shallow baroclinic instabilities that are roughly in geostrophic balance and flux energy upscale [*Sasaki et al.*, 2014; *Callies et al.*, 2016], driving a mild seasonal modulation at mesoscales [*Sasaki et al.*, 2014; *Qiu et al.*, 2014]. The divergence part of the flow, however, peaks in late Summer/early Fall, when the upper-ocean is strongly stratified. Hence these results suggest a strong seasonal modulation of the dominant upper-ocean submesoscale dynamics with the dominance quasi-balanced turbulence in late Winter/early Spring and quasi-linear inertia-gravity waves in late Summer/early Fall.

2. The LLC2160 model output

We use the output of the latitude-longitude polar cap (LLC) MITgcm numerical simulation. The output analyzed here, the LLC2160, is the 1/24° — 90-vertical-levels simulation from a hierarchy of global forward numerical solutions on a LLC grid [*Forget et al.*, 2015] that were spun up from a ECCO2 adjoint-method state estimate. The LLC2160 was forced by tides and high-resolution surface fluxes similarly to the LLC4320 simulation used by *Rocha et al.* [2016] — see their appendix D. We chose the second-higher resolution simulation (LLC2160) of the LLC hierarchy because it was run for longer: the LLC2160 output spans two years form March 2011 to April 2013. The model time-step was 45s and the model variables were saved hourly. LLC hierarchy setup and control files are available online (at `http://mitgcm.org/viewvc/MITgcm/MITgcm_contrib/llc_hires`). For the LLC hierarchy, the sea-surface height is calculated using a linearized equation. The model output was provided by D. Menemenlis (JPL/NASA).

A key aspect of the simulation analyzed here is that it is forced by the 16 most significant tidal components. Barotropic tides interact with topography and generate internal tides that project on mesoscales to submesoscales [*Rocha et al.*, 2016]. Hence, tidal forcing fundamentally differentiates our analysis from other modeling studies that investigated upper dynamics and its seasonality [*Sasaki et al.*, 2014; *Qiu et al.*, 2014].

The region of focus is the northwest Pacific, in the vicinities of the Kuroshio Extension, where previous studies have shown strong seasonality in the quasi-gesotrophic surface velocity field. We analyze a sub-domain of the LLC2160 simulation of about 2000 km^2 spanning 155-175°E; 25-40°N. We focus on the surface velocity field and near-surface stratification.

3. Seasonality in surface velocity and near-surface stratification

We calculate the vertical vorticity, horizontal divergence, and the magnitude of the lateral rate of strain:

$$\zeta \equiv v_x - u_y \,, \tag{1}$$

$$\delta \equiv u_x + v_y \,, \tag{2}$$

and

$$S \equiv \left[(v_x + u_y)^2 + (u_x - v_y)^2\right]^{1/2} \,, \tag{3}$$

The velocity gradients are calculated using a centered second-order finite differences scheme.

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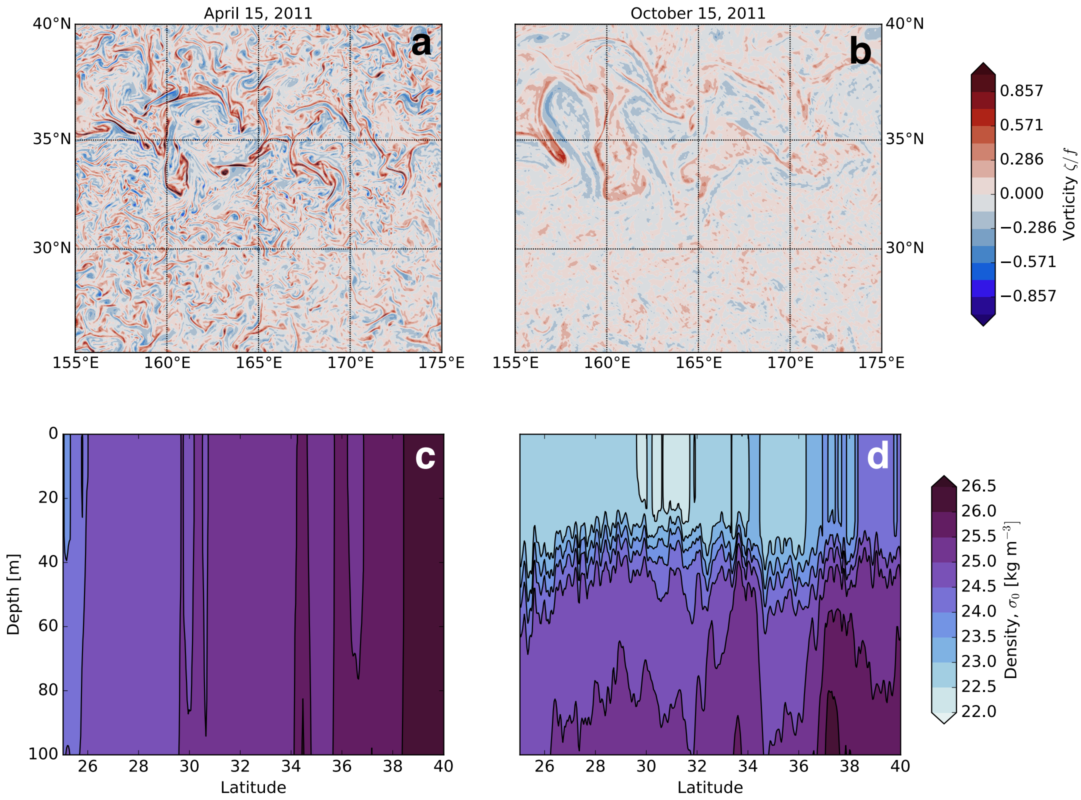

Figure 1. Snapshots of surface vorticity (a and b) and a transect of potential density at 165°E (c and d). The snapshots were taken at 00:00 UTC.

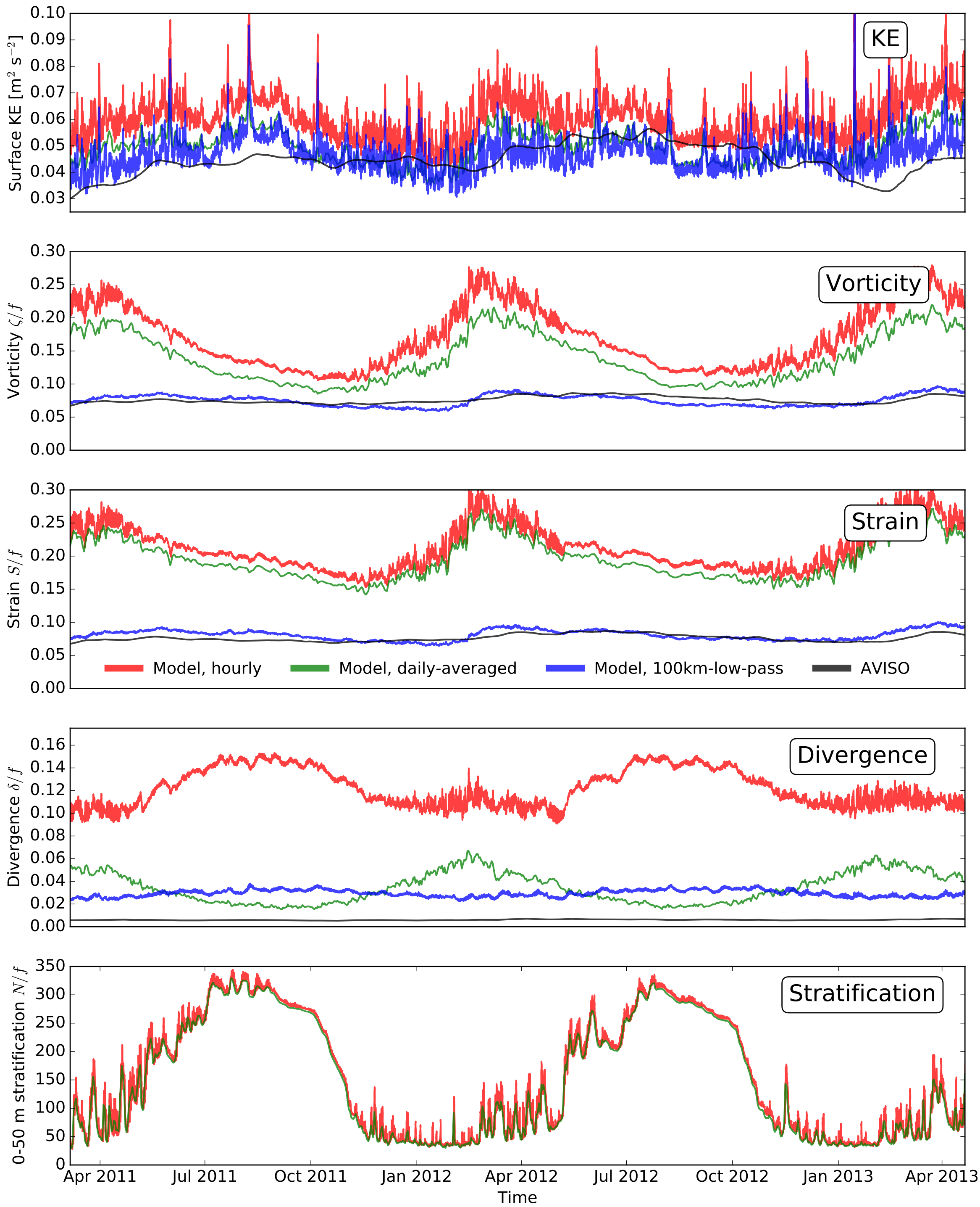

Figure 2. Time series of horizontal velocity diagnostics at the surface (a through d) and stratification in the upper 50 m (e).

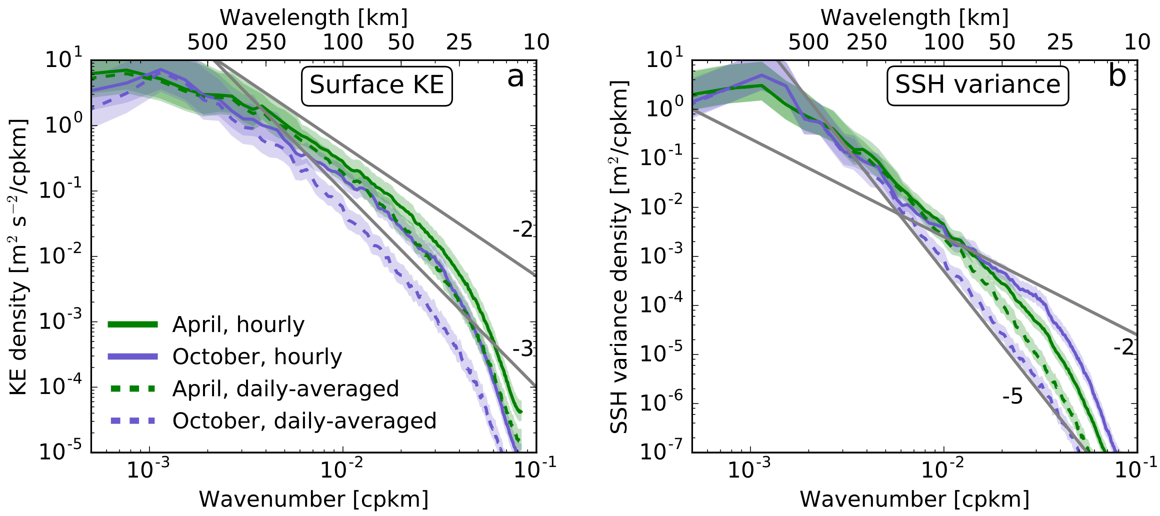

Figure 3. Surface (horizontal) KE and SSH variance wavenumber spectra. Solid lines are spectra based on hourly snapshots, dashed lines are spectra based on daily-averaged fields.

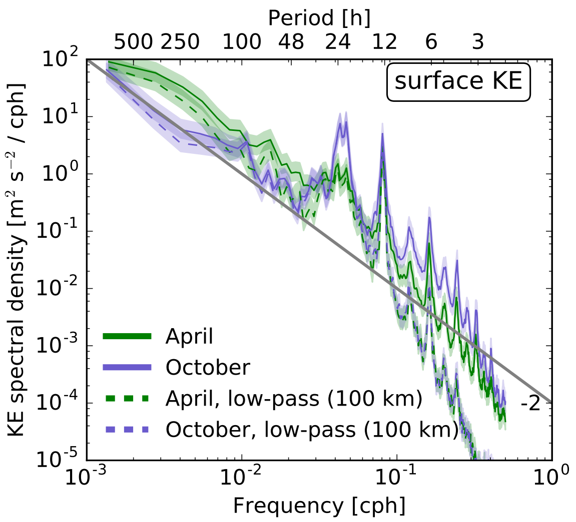

Figure 4. Surface (horizontal) KE frequency spectra. Solid lines are spectra based on the 1/24° fields, dashed line are spectra based on 100-km-low-pass smoothed fields.

3.1. The high-frequency signal

Here we argue that those divergent motions are likely inertia-gravity waves. We can show a couple of spectra and argue that they roughly satisfy polarization relations.

We can also try and show some observations here. Any cruises with ADCP data. While it may be hard to have enough data for the errorbars to be small, a rough consistency may be better than nothing.

Perhaps a mooring data should show strong seasonal modulation at high-frequencies?

We must be able to present some observational evidence that the model is not misleading at high-frequencies.

3.2. Geostrophic velocities from SSH

Here we argue that high-frequency (supra-daily) flows significantly project on the sea-surface, and thus estimation of submesoscale (10-100 km) geostrophic velocity from sea-surface height (SSH) is not warranted. Calculating spectral KE fluxes from both velocity and geostrophic velocity (from SSH) would contrast with the results in Sasaki et al.

4. Summary and Discussion

Our main finding is that upper-ocean divergent flows, dominated by inertia-gravity waves, undergo a strong seasonal cycle that is out-of-phase with the seasonal cycle of the quasi-balanced flows. Therefore, the present results suggest significant seasonal modulation of the dominant upper-ocean dynamics at submesoscales (10-100 km): Quasi-balanced turbulence driven by shallow baroclinic instabilities in late Winter/early Spring and inertia-gravity waves dominate in late Summer/early Fall.

That the surface velocity and SSH submesoscale (10-100 km) variability may be dominated by ageostrophic flows in Summer/Fall has consequences for the interpretation of data from the future SWOT and COMPIRA altimeter missions, which will deliver SSH measurements at submesoscales. To the extent that high-frequency flows are dominated by incoherent internal tides and other internal waves, it may be very difficult (if not impossible) to separate submesoscale SSH variability associated with geostrophic motions from high-frequency, ageostrophic flows. Thus, previous claims that one will be able to easily obtain submesoscale surface geostrophic velocities and monitor such seasonal cycle on global scales [*Sasaki et al.*, 2014; *Qiu et al.*, 2014] are overstated.

The present analysis focuses on a single patch of ocean in the vicinities of the Kuroshio Extension, not representative of other regions such as eastern boundary currents and the middle of the subtropical gyre: care must be taken in overgeneralizing these results with care. The effects of smaller-scale/higher-frequency "sub-submesoscale" flows on the submesoscale surface velocity and SSH variability are presently unknown.

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