Multiple, migrating quasi-zonal jet-like structures in the ocean: descriptive view from satellite data and a global ocean general circulation model

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OSTST2011

19-21 October 2011

San Diego, CA

1. Data

(a) Aviso gridded SSH anomaly: 17 years of satellite observations from November 1992 through October 2009.

(b) Output of the Ocean general circulation model For the Earth Simulator (OFES). OFES is a near-global model with 0.1º horizontal resolution. There are 54 vertical levels with varying distance between levels from 5 m at the surface to 330 m near the bottom. Following the spin-up, hindcast integration from 1950 to 2004 was conducted forced by daily fluxes from the NCEP/NCAR reanalysis.

2. Method

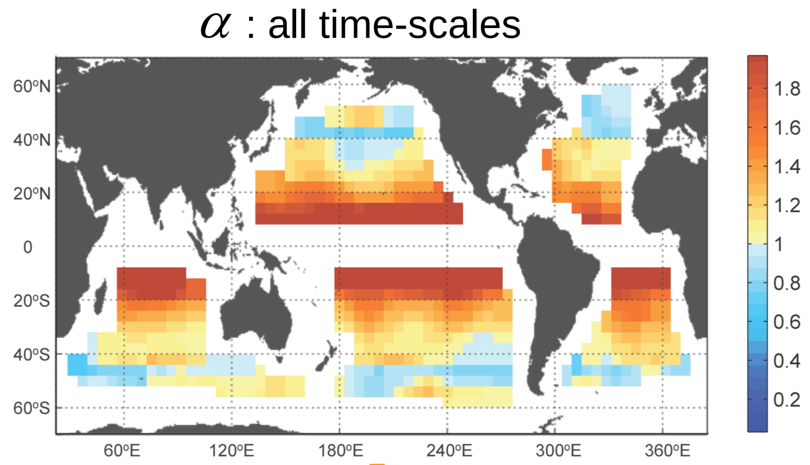
Three-dimensional (wavenumber-frequency) spectral analysis of velocity variability at the sea surface:

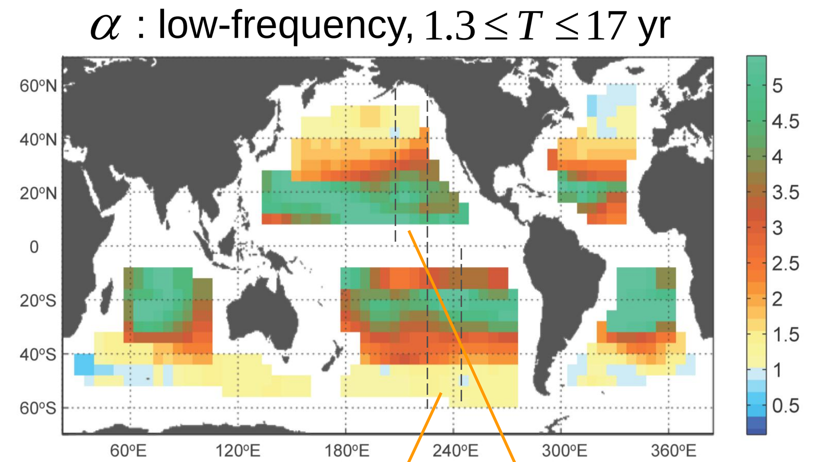
$$KE(k_x,k_y,\omega)=|\tilde{u}(k_x,k_y,\omega)|^2+|\tilde{v}(k_x,k_y,\omega)|^2,$$

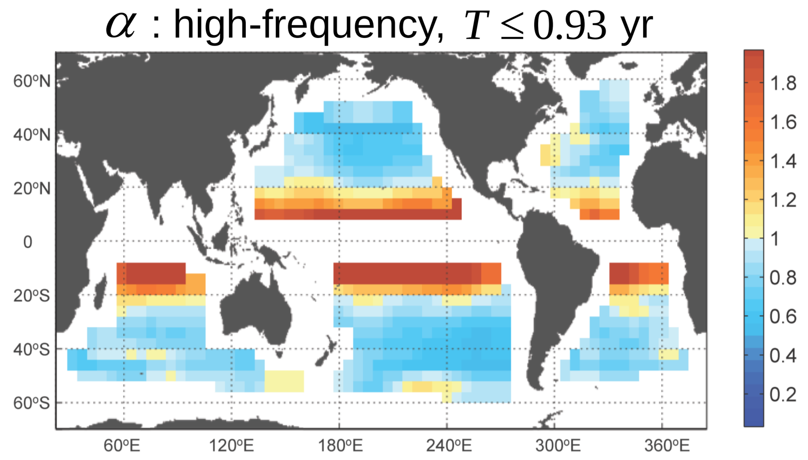
3D transient kinetic energy spectra are evaluated in 22º longitude by 16º latitude bins, centered on a global grid with steps of 11º in the zonal direction and 8º in the meridional direction. The size of the bin is chosen as a trade off between the necessity to resolve spatial scales associated with the dominant variability and the requirement for spatial homogeneity. We have also tried different sizes of the bin and found the results not to be very sensitive.

3. Introduction

Figure 1. The degree of anisotropy, $\alpha=\dfrac{KE_z}{KE_m}$; where $KE_z=\iiint\limits_{k_y>k_x} KE(k_x,k_y,\omega)dk_x dk_y d\omega$, $KE_m=\iiint\limits_{k_y\le k_x} KE(k_x,k_y,\omega)dk_x dk_y d\omega$







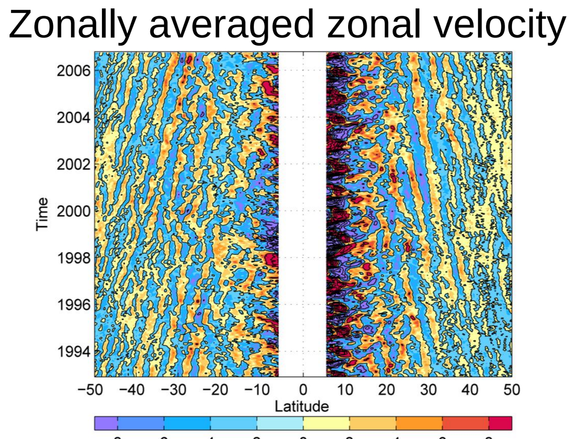


Figure 2. Latitude time plot of zonally averaged zonal surface geostrophic velocity anomaly in the eastern Pacific. Units are cm/sec.

3.1 Regional example

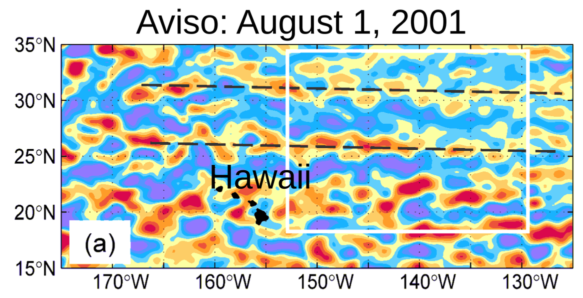
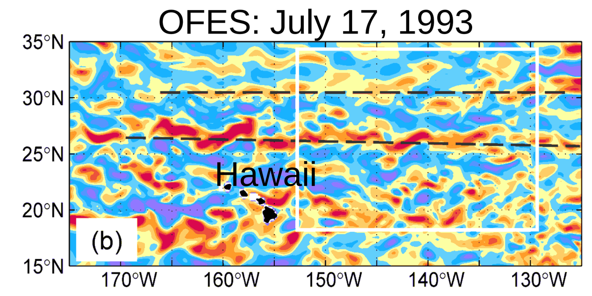


Figure 3. Snapshots of zonal surface geostrophic velocity anomaly: **(a)** Aviso map centered on August 1, 2001 and **(b)** from the OFES hindcast on July 17, 1993. Color scale is from -25 cm/s (magenta) to 25 cm/s (dark red). The white rectangle shows the domain, selected to illustrate the eddy kinetic energy spectrum.

Contrary to the view that some time-averaging is absolutely necessary to reveal the striations, they are apparent in zonal velocity snapshots. The features, shown here, propagate southward at a speed of ~0.3 km/day.



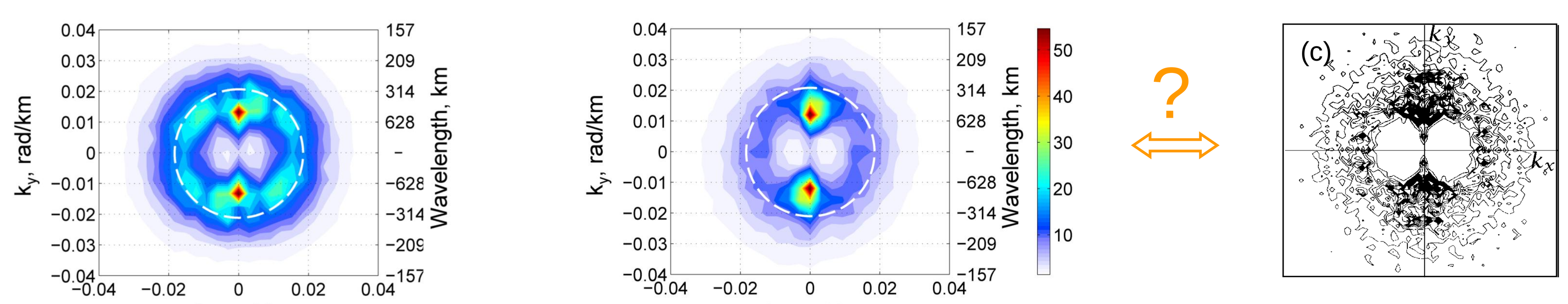


Figure 4. Time-averaged two-dimensional surface kinetic energy spectra from **(a)** Aviso and **(b)** OFES data, both evaluated in the region marked by the white rectangular in Fig. 3. Local maxima in the spectra, located at $k_x=0$ rad/km and $k_y=\pm 0.012$ rad/km correspond to migrating jets. Gray dashed circles show the first mode deformation wavelength. The observed spectra qualitatively resemble those obtained in idealized simulations of freely evolving two-dimensional beta-plane turbulence. An example of such a spectrum, reproduced from *Vallis* [2006], is shown in **(c)**.

4. Multiple, migrating quasi-zonal jets (striations)

A search for propagating striations: (1) moving 3D FFT window; (2) a search for isolated spectral peaks, corresponding to the zonally elongated structures, in the low-frequency part of the KE spectrum; (3) check for asymmetry between negative and positive frequencies (should be clear propagation, no standing or shifting back and forth features); (6) estimation of parameters

Aviso

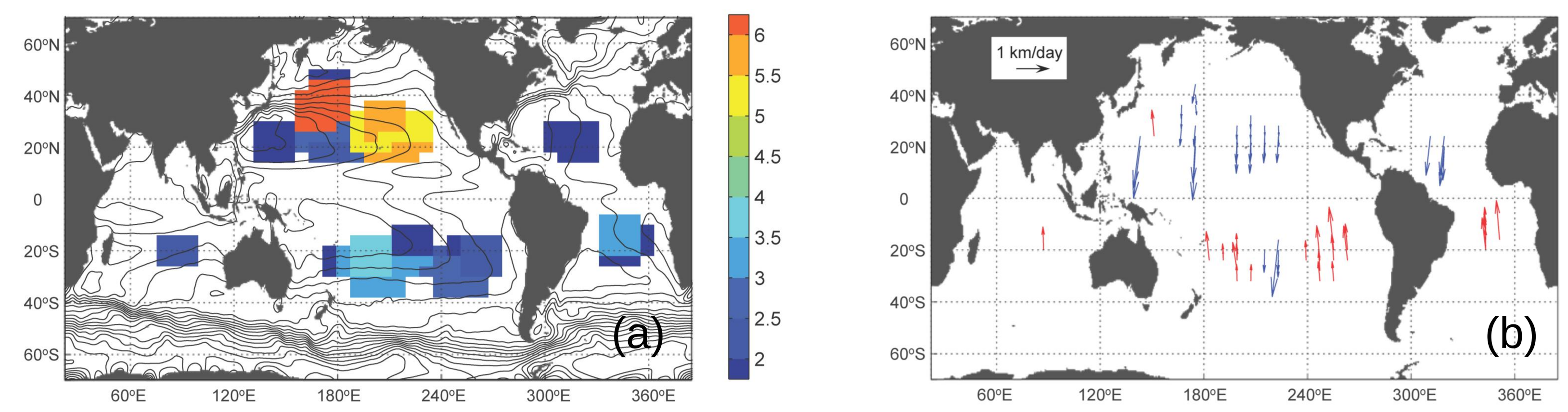


Figure 5. Striations in the satellite altimetry data. **(a)** Regions, where propagating striations were identified in the KE spectra. Periods [yr] of the striations are shown in color. Superimposed are Contours of the time-mean SSH field. **(b)** The striations' propagation speeds and directions. Blue (red) arrows indicate southward (northward) propagation.

OFES

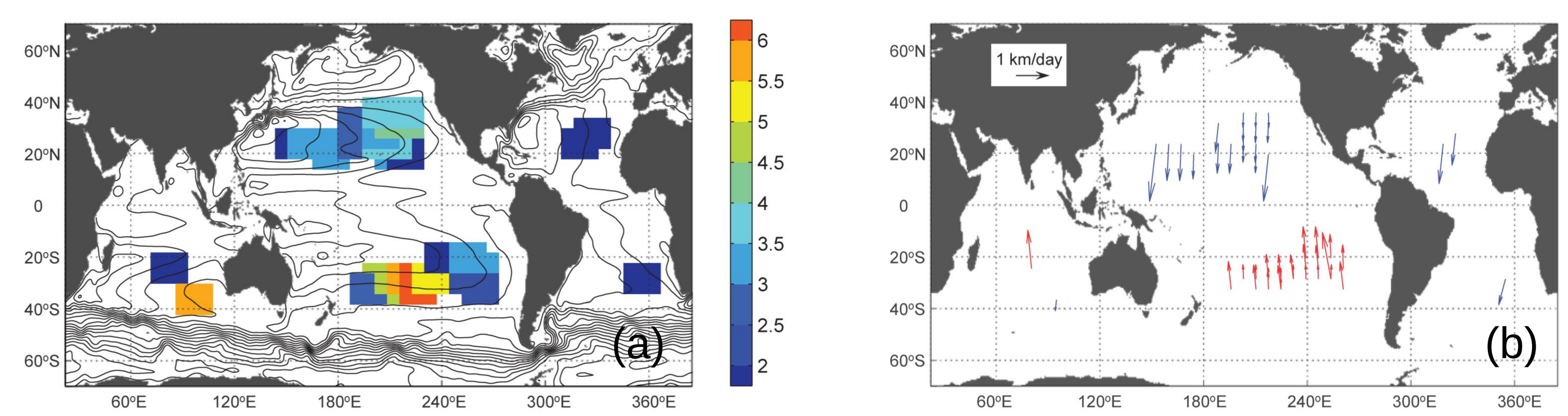


Figure 6. Striations in the OFES hindcast data for the period from 1988 to 2004. **(a)** Regions, where propagating striations were identified in the KE spectra. Periods [yr] of the striations are shown in color. Superimposed are Contours of the time-mean SSH field. **(b)** The striations' propagation speeds and directions. Blue (red) arrows indicate southward (northward) propagation.

Figs 5, 6 show that propagating striations exhibit a broad range of characteristic time scales and seem to be highly intermittent. The propagation directions of the observed striations are predominantly towards the equator in both hemispheres, yet with small (less than 15º) deflection due west, qualitatively in agreement with their interpretation as Rossby waves.

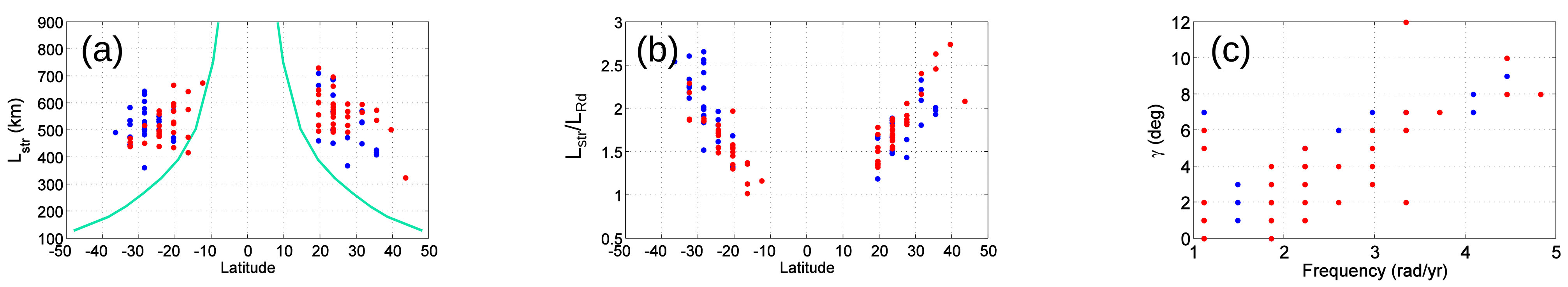


Figure 7. (a) Striations' wavelengths estimated from Aviso (red dots) and OFES (blue dots) data. For the reference, the global zonal average of the first mode deformation wavelength is shown by green curve. **(b)** The ratio of the striations' wavelengths to the local first mode deformation wavelengths. Red dots refer to the altimetry observations, blue dots indicate striations found in OFES. Remarkably, the striations meridional scales agree well with the eddy length scales, reported in the literature [e.g. Chelton et al., 2007, Eden, 2007, Chelton et al., 2011]. **(c)** Scatter plot of the striations tilts versus frequency. The striations' tilts are systematically increasing with frequency.

Rossby waves or eddies?

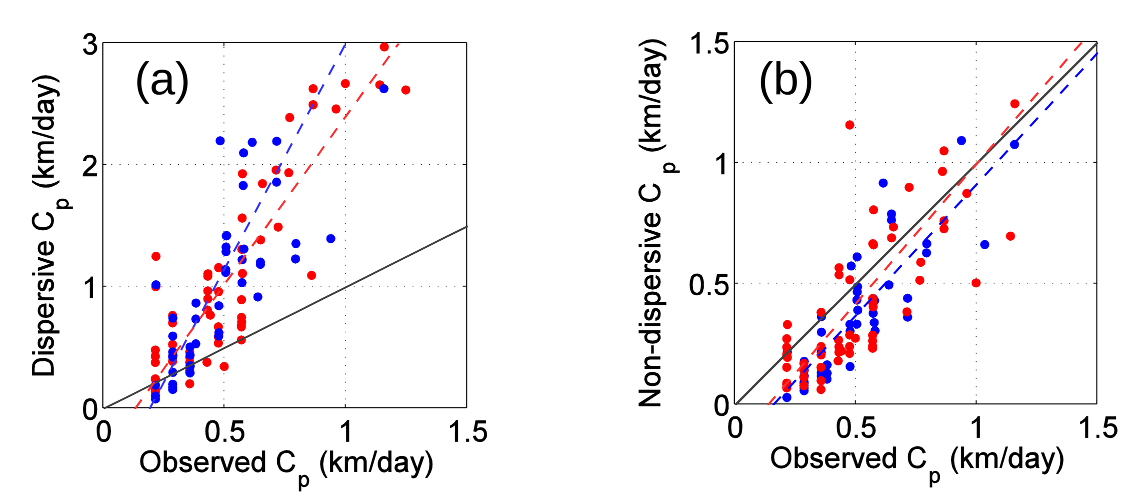


Figure 8. (a) Compare the observed striations' phase speeds with phase speeds of classic, dispersive Rossby waves. We find that the observed phase speeds are systematically slower than those of dispersive Rossby waves with the same **k**. This discrepancy can not be explained by the large-scale advection. Propagating striations populate subtropical latitudes, where Sverdrup dynamics dictate equatorward integral flow. Because the striations movements are predominantly toward the equator (Figs 5,6), the large-scale Sverdrup transport would increase, not decrease the observed phase speeds, if the striations behaved as dispersive Rossby waves [e.g. Glazman and Weichman, 2005]. **(b)** However, the striations' phase speeds can be explained if we assume that they tend to propagate westward at local long Rossby wave phase speeds, independently of the magnitude of the wave vector. The same property is observed for large, nonlinear eddies [e.g. Chelton, 2007, 2011]

4. Summary

In this study we investigate the dynamics of multiple, migrating quasi-zonal jet-like structures (striations), persisting in the large-scale circulation of the ocean. Sea level anomaly from the global satellite altimetry data set is used to estimate the striations' amplitudes, length scales, and propagation speeds.

a) Migrating striations with periods longer than one year are found to populate all subtropical gyres.

b) The propagation directions of the observed striations are predominantly towards the equator in both hemispheres, yet with small (less than 15º) deflection due west, qualitatively in agreement with their interpretation as Rossby waves. The striations' propagation speeds, however, are not consistent with the speeds of dispersive Rossby waves, as one might expect for waves with a near-meridional orientation of the wave vector. Instead, they are close to the local phase speeds of long, non-dispersive baroclinic Rossby waves, characteristic of non-linear mesoscale eddies.

c) Besides, the striations' meridional scales are found to agree well with the eddy length scales, reported in the literature, suggesting that striations and eddies may be two components of the same system, ultimately related to the dynamics of ocean gyres.

d) The observational study is complemented by the analysis of a high-resolution numerical simulation with the global Ocean general circulation model For the Earth Simulator (OFES). General properties of the model striations agree remarkably well with the properties of the striations, detected in the satellite altimetry data, adding significantly to the credibility of both data sets.

We thank NASA for financial support of this study. IPRC is partly supported by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). We acknowledge the use of freely available data from Aviso. We thank Jan Hafner and Sharon DeCarlo (IPRC) for technical help with the data. The OFES runs were conducted on the Earth Simulator under the sponsorship of JAMSTEC.