Multiple, migrating quasi-zonal jets in the eastern North Pacific

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Abstract

Low-frequency motions in the eastern part of the subtropical North Pacific are characterized by multiple, alternating quasi-zonal jet-like features (striations), which slowly, at a speed of about 0.3 km/day, propagate toward the equator. Their structure and energetics are studied using three data sets: satellite sea level anomaly observations, historical hydrographic data, and output of the Ocean general circulation model For the Earth Simulator (OFES). We find that the striations' energy cycle is dominated by two dynamically distinct components. The first one is attributable to baroclinic instability of the large-scale, weekly-sheared meridional flow in the eastern limb of the subtropical gyre. Potential energy stored in the large-scale flow is accessible for conversion directly to the zonal striations. The latter, therefore, may have a profound effect on the thermohaline structure of the subtropical gyre and the mean circulation. The second component arises from the nonlinear interactions between the zonal striations and eddies and can be put into the context of the geostrophic turbulence theory. While the baroclinic conversion from the mean state to the zonal striations occurs throughout the layer between 200 and 600 m depth, the eddy effects are primarily confined to the upper 200 m.

1. Introduction

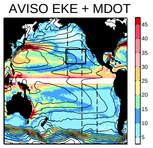


Figure 1. RMS eddy velocity (cm/s; colors) and mean dynamic topography (contours).

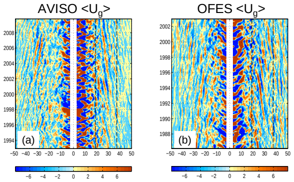


Figure 2. Latitude-time diagram of the zonally averaged zonal surface geostrophic velocity anomaly (cm/s) in the eastern Pacific form (a) satellite SLA data and (b) OFES hindcast. Zonal average is between 150-130°W and 130-110°W in the Northern and Southern Hemispheres, respectively (black dashed lines in Fig. 1).

Questions: (i) What are the primary generation mechanisms for propagating striations? (ii) How do they very with depth? (iii) How do they interact with the mean circulation? (iv) What is their role in the ocean energy cycle?

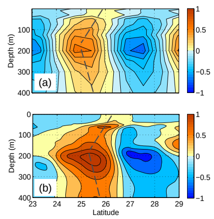


Figure 3. Vertical structure of potential temperature anomaly associated with the propagating striations in the eastern North Pacific:

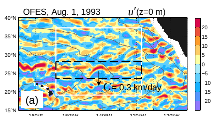
(a) Reconstructed from historical XBT data. The XBT data are used as follows. For each XBT profile and at each depth level the potential temperature anomaly is computed relative to the climatological field from the World Ocean Atlas 2005. At each depth level all data points are averaged within 0.5°-latitude x 6-month spatio-temporal bins in the zonal band between 150-125°W to construct the corresponding latitude-time diagram of zonally averaged potential temperature anomaly. For each latitude-time diagram the lead harmonic is determined by the spectral analysis and the diagram is filtered in the spectral space to retain only the lead harmonic. Note that during this procedure each depth level is treated independently. The composite vertical structure of the striations' thermal field is then reconstructed at any given time by combining structures at all depth levels.

(b) Computed from the August 1993 OFES data. The August 1993 model data are selected for convenience of comparison.

2. Having the correspondence between the model and observations established…proceed with energetics

Each variable is decomposed into the time mean part and deviations from the time-mean. The latter (transient part) is further decomposed into the zonally-averaged part (jets) and deviations from the zonal average (eddies). For instance

$$\mathbf{u} = \overline{\mathbf{u}} + \mathbf{u}' = \underbrace{\overline{\mathbf{u}}}_{\text{Time-mean}} + \underbrace{[\mathbf{u}']}_{\text{Zonal jets}} + \underbrace{\mathbf{u}^*}_{\text{Eddies}}$$



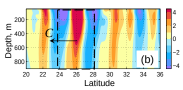
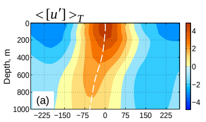
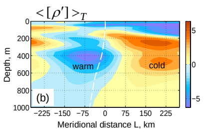


Figure 4. The striations' vertical structure and energetics are analyzed following a volume (~ 500 km-meridional x 2500 km-zonal; H=1000 m) centered at and moving with (C~0.3 km/day) a selected eastward flowing jet. In this illustration, the boundaries of the volume in August 1993 are shown by the black dashed lines on top of **(a)** zonal geostrophic velocity anomaly at the sea surface and **(b)** meridional section of the zonal velocity anomaly averaged between 153-132°W. Units are cm/s.





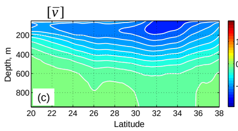


Figure 5. Composite vertical structure of propagating striations in the Eastern North Pacific:

(a) Zonal velocity [cm/s]. Note that the vertical profile of zonal velocity exhibits a clear southward tilt with depth, particularly below 200 m depth.

(b) Potential density [10^{-2} kg/m^3]. The vertical structure of zonally averaged perturbation density follows closely that of zonal velocity, yet with a generally northward tilt with depth and some more complicated structure near the surface Ekman layer.

(c) Meridional section of large-scale, time-mean meridional flow in the eastern limb of the subtropical gyre.

3. Energetics

Vertical structure and energetics of propagating striations in the eastern North Pacific:

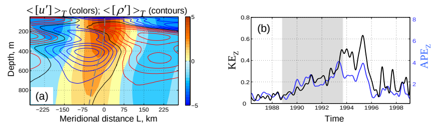


Figure 6. **(a)** Zonal velocity (cm/s; color) and potential density (contours). Blue (red) contours correspond to negative (positive) potential density anomaly. Contour interval is 0.01 kg m^{-3}. **(b)** Time evolution of the volume-averaged KE (black) and APE (blue) of the zonal flow. The gray box indicates the time period, *T*, over which vertical sections of different variable were averaged to construct the composite structures. Note that during the growth phase, both KE and APE of the zonal flow are growing – a signature of baroclinically unstable wave.

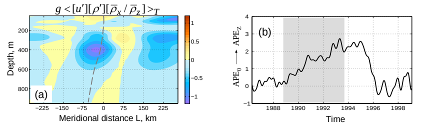


Figure 7. **(a)** Baroclinic energy conversion between the time-mean density field and zonal striations (10^{-7} kg m^{-1} s^{-3}). **(b)** The same as in (a) but averaged over the volume moving with the selected eastward flowing striation. The phase shifts with depth, as seen in Fig. 6a, result in the perturbation density flux down the mean density gradient. There is a net conversion from the mean APE stored in the large-scale meridional flow to the striations' APE, consistent with the baroclinic instability mechanism.

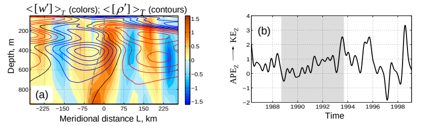


Figure 8. **(a)** Vertical velocity (10^{-4} cm s^{-1}; color) and potential density (contours). **(b)** Time evolution of the volume-averaged baroclinic conversion from the zonal APE to KE (10^{-7} kg m^{-1} s^{-3}). Although zonally averaged vertical velocity looks different from a simple sinusoidal wave, it still demonstrates the required correlations with density perturbations to provide a net release of zonal APE.

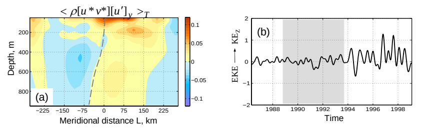


Figure 9. **(a)** The averaged vertical structure of the KE conversion from eddies to the zonal striations due to horizontal Reynolds stresses. **(b)** The volume-averaged eddy term as a function of time. Units are 10^{-7} kg m^{-1} s^{-3}. The eddy term exhibits oscillations between positive and negative values, presumably reflecting periods when eddies gain energy from the zonal striations and vise versa. On average, this term is not zero and provides a net transfer of EKE to the zonal striations.

Scenario: (i) Large-scale, weakly sheared meridional flow ⟶ (ii) Baroclinic instability – perturbations are primarily zonal due to beta (Spall, 2000) ⟶ (iii) Secondary, transverse instability – eddies ⟶ (iv) Feedback

4. Spectral view

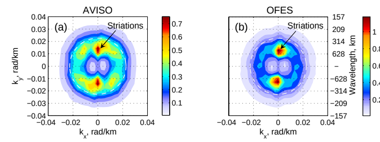


Figure 10. Time-averaged, two-dimensional transient kinetic energy spectra from **(a)** AVISO and **(b)** OFES surface velocity data, evaluated in the sub-region depicted by the white rectangle in Fig. 4a. Unites are 10^6 (cm/s)^4 km^2. Radii of the white dashed circles correspond to the first mode deformation wavelength. The maxima in the spectra, located at k_x=0 rad/km and k_y=0.012 rad/km (the corresponding wavelength =500 km), are due to propagating striations.

For spectral component $n = (\mathbf{k}, \omega)$, the spectral KE budget for the transient motions can be written symbolically as (e.g., Hayashi, 1980)

$$\frac{\partial}{\partial t} KE(n) = \underbrace{\boxed{I_K(n)}}_{\text{Nonlinear}} + \underbrace{G_K(n)}_{\text{Generation}} + \underbrace{C(n)}_{\text{APE} \rightarrow \text{KE}} + \underbrace{D(n)}_{\text{Dissipation}}$$

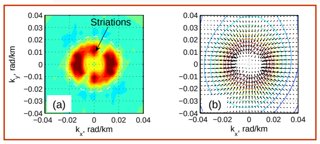


Figure 11. (a) Time-averaged nonlinear KE transfer spectrum, integrated over the upper 1000 m layer, and **(b)** the associated spectral potential function (contours) and the flux of energy through the spectral space (arrows). Nonlinear eddy-eddy interactions produce an upscale KE cascade directed toward the center of the spectral domain (the largest scale).

Spectral APE budget for the transient motions can be written symbolically as

$$\frac{\partial}{\partial t} APE(n) = \underbrace{\boxed{I_A(n)}}_{\text{Nonlinear}} + \underbrace{\boxed{G_A(n)}}_{\text{Generation}} - \underbrace{\boxed{C(n)}}_{\text{APE} \rightarrow \text{KE}}$$

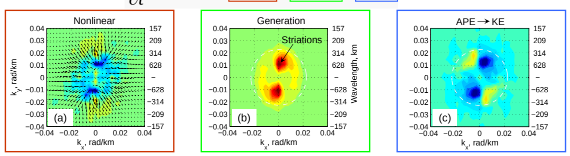


Figure 12. **(a)** Nonlinear interaction term for APE (color) and the associated flux of energy through the spectral space (arrows). Note that the maximum nonlinear transfer of APE occurs out of wavenumbers associated with the striations. **(b)** APE generation by baroclinic instability of the mean state. The maximum generation also takes place at wavenumbers associated with the striations. **(c)** Baroclinic conversion from APE to KE.

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