Dynamics of multiple, migrating quasi-zonal jets in the ocean

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I would like first to acknowledge my collaborators:

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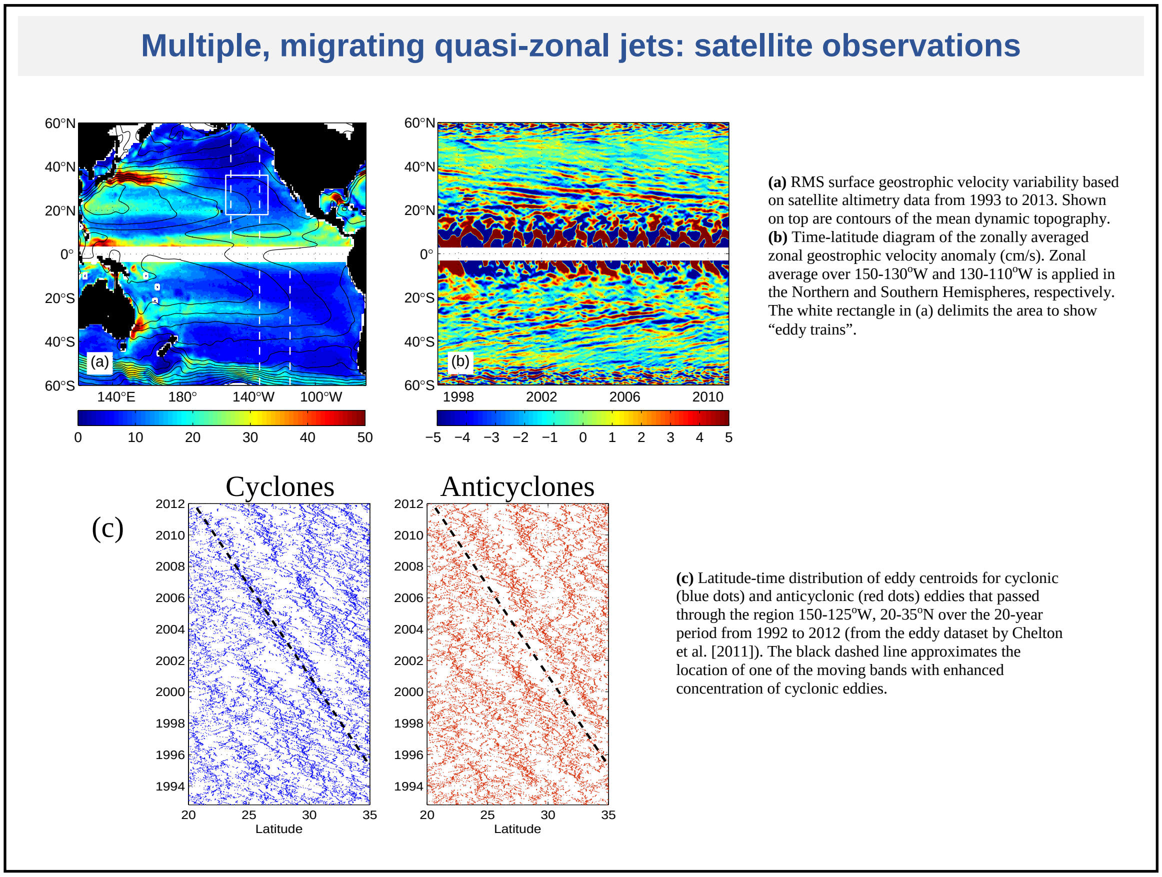
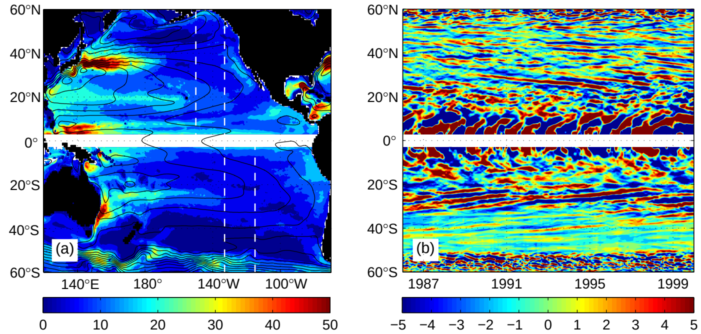


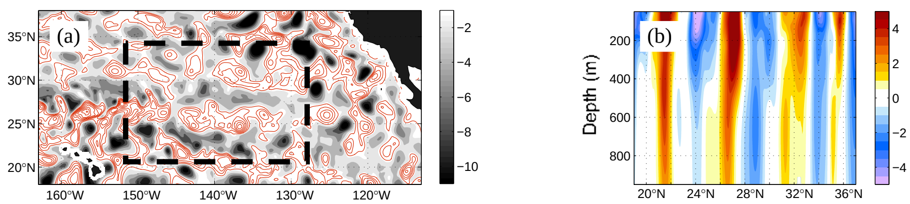
The latitude-time diagram of the zonally averaged zonal velocity anomaly in the Pacific Ocean (this slide) illustrates the phenomenon. Evidently, the zonally averaged zonal flow in the subtropics is characterized by long-lived mesoscale features that systematically and coherently propagate toward the equator. Some of the long-lasting stripes in the figure remain coherent over 5- to 10-year time intervals and thus cannot be a residual effect of random eddies averaged zonally. (To produce such coherent stripes, randomly distributed eddies would have to be very slow propagating (speeds<1 cm/s) and long-lived (lifetimes>2.5 yr), inconsistent with observations [Chelton et al., 2011]).

What about the mesoscale eddies then? Figure (c) shows trajectories of all the cyclonic (blue dots) and anticyclonic (red dots) eddies from the eddy dataset by Chelton et al. [2011] that passed through the region 150-125°W, 20-35°N (white rectangle in Figure (a)) over the ~20-year period from 1993 to 2012. We can see that the distribution of cyclonic and anticyclonic eddies is not completely random but alternates between "troughs" of enhanced concentration of cyclonic eddies (negative SLA) and "crests" of enhanced concentration of anticyclonic eddies (positive SLA). These "crests" and "troughs" coherently propagate equatorward at a speed of about 0.3 cm/s, consistent with the stripes in Figure (b).

OGCM validated against observations



(a) RMS surface geostrophic velocity variability in the OFES hindcast simulation from 1985 to 2000. Shown on top are contours of the mean SSH. **(b)** Time-latitude diagram of the zonally averaged zonal geostrophic velocity anomaly (cm/s). Zonal average over 150-130^{o}W and 130-110^{o}W is applied in the Northern and Southern Hemispheres, respectively.



(a) SSH anomaly in the eastern North Pacific from the OFES hindcast on July 7, 1992 (positive values are red contours (C.I.=1 cm); negative values are gray shade), and **(b)** the corresponding profile of the zonally averaged zonal velocity anomaly (cm/s). The averaging interval is 150-125^{o}W. The jets' vertical structure and energetics are analyzed in a domain (150-130^{o}W, 20-35^{o}N) in the eastern North Pacific. The boundaries of the domain are shown by the black dashed lines.

Because high-resolution satellite data are limited to the sea surface, the vertical structure and energetics of the transient zonal jets will be examined by analyzing output from a high-resolution Ocean general circulation model For the Earth Simulator (OFES). In this regard, the highly complex model will serve as a representation of reality.

The jets' energetics is investigated in the wavenumber-frequency space using a spectral representation of the transient KE and available potential energy (APE) budgets [Hayshi, 1980; Hayashi and Golder, 1983]

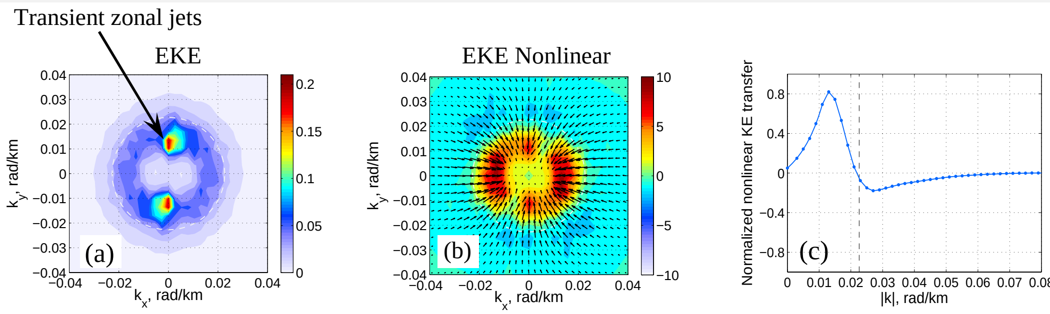
Nonlinear Generation APE→KE Dissipation

$$\frac{\partial}{\partial t}KE(n) = I_K(n) + G_K(n) + C(n) + D(n)$$

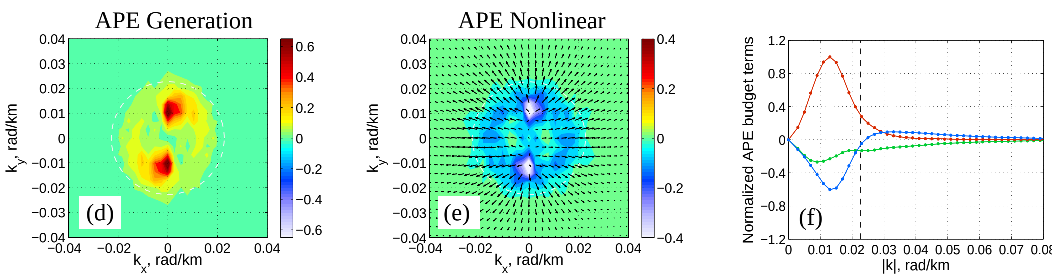
Nonlinear Generation APE→KE

$$\frac{\partial}{\partial t}APE(n) = I_A(n) + G_A(n) - C(n)$$

The jets' energetics



(a) Time-averaged EKE spectrum evaluated using OFES data (1986-2000) in the sub-region depicted by the white rectangle in Fig. 1a. Units are cm^2/s^2. Radius of the white dashed circle corresponds to the first mode deformation wavelength. **(b)** Nonlinear interaction term for the EKE (color) and the associated flux of kinetic energy through the spectral space (arrows). **(c)** Nonlinear transfer term normalized by peak-to-peak amplitude as a function of total wavenumber |k|.



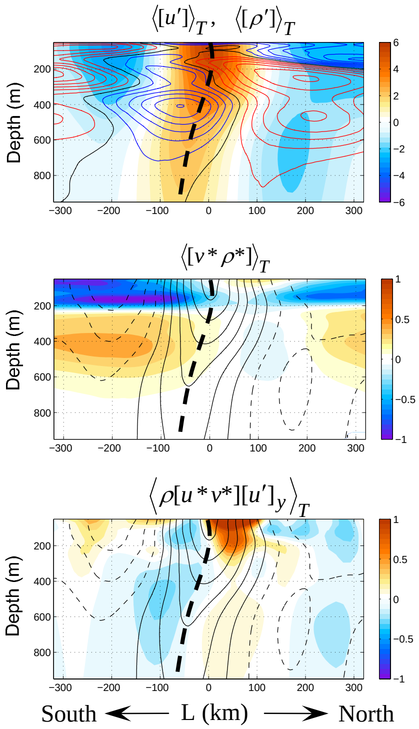
(d) APE generation by baroclinic instability of the mean state. The maximum generation occurs at wavenumbers associated with the transient zonal jets. **(e)** Nonlinear interaction for APE (color) and the associated flux of energy through the spectral space (arrows). The maximum nonlinear transfer of APE occurs out of wavenumbers associated with the transient zonal jets, which can be interpreted as secondary instability. **(f)** Normalized APE generation (red), nonlinear (blue) and APE-KE conversion (green) terms versus total wavenumber |k|. The curves were smoothed with a 3-point Daniell window. The vertical dashed line denotes the first mode deformation wavelength.

The time-averaged, depth-averaged (0-1000 m) EKE spectrum (panel (a)) shows local peaks at $k_x = 0$ rad/km, $k_y = \pm 0.012$ rad/km (wavelength ~500 km) corresponding to the transient zonal jets. The nonlinear KE transfer spectrum, integrated over the upper 1000 m layer, is shown in panel (b). A significant portion of KE is transferred into wavenumber (0, 0.012) rad/km which corresponds to the transient zonal jets (the direction of the energy flux is shown by arrows). The KE cascade slows down dramatically at some wavenumber around |k|=0.012 rad/km (L=530 km). The nonlinear transfer term as a function of total wavenumber |k| has a well recognizable shape, consistent with previous studies of oceanic energetics [e.g., Scott and Wang, 2005; Arbic et al., 2014]. From the analysis of EKE alone, one would probably conclude that the jets are produced by eddy-eddy interactions and are the end result of inverse KE cascade, similar to the "Rhines jets".

Yet, the analysis of APE budget shows that the transient jets are able to tap APE from the time-mean flow. The time-averaged, vertically integrated spectrum of APE generation is shown in panel (d). The maximum generation takes place near wavenumber (0, 0.012) rad/km, indicating that the jets are able to gain energy directly from the mean state. The nonlinear transfer spectrum is displayed in panel (e). In general, the nonlinear interaction term transfers APE from low to high wavenumbers. Yet, the maximum transfer occurs out of wavenumbers associated with the jets, indicative of a secondary instability, presumably producing eddies. A significant part of APE at these scales also serves as the source of KE (panel (f)).

Zonal jets and eddies: vertical structure

Composite analysis in the reference frame commoving with the jets



Composite vertical structure of the transient zonal jets in the eastern North Pacific: zonal velocity (cm/s, color) and potential density (contours; C.I.=0.01 kg m^{-3}). Blue (red) contours correspond to negative (positive) potential density anomaly. The composite is based on 3-day zonal averages (152-125^{o}W) taken over a 5-yr period (1989-1993) in the reference frame co-moving with the jets. Note the vertical phase shifts with depth, consistent with baroclinic instability mechanism.

Meridional section of the mean meridional eddy density flux. The zonally averaged zonal flow is shown by contours (contour interval 1 cm/s; solid (dashed) contours correspond to eastward (westward) velocity). The mean distribution of the meridional eddy density flux compares very favorably with the distribution of the zonally averaged potential density anomaly, suggesting that mesoscale disturbances grow baroclinically from APE of the zonal jets.

The rate of transfer of EKE to KEZ (10^{-7} kg m^{-1} s^{-3}). There is an up-gradient (down-gradient) flux of zonal momentum north (south) of the eastward-flowing jet. The average effect of the eddy forcing is thus to sharpen the eastward-flowing jet and, simultaneously, displace it equatorward.

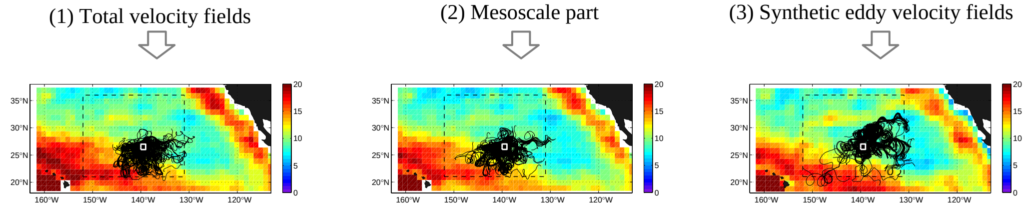
The effect of the jets is to locally alter the mean potential vorticity distribution associated with the large-scale background flow in which they reside. This alteration seems to be responsible for the formation of eddies preferentially along the jets, consistently with the meridionally localized regions of enhanced or reduced baroclinicity and stabilizing or destabilizing effect of the planetary vorticity gradient and horizontal shear. When the jets move, the dynamics that generate eddies move with them, producing migrating “eddy trains”. Eddies feed back onto the zonal flow, reinforcing the pattern of the jets.

Effects on the transport of tracers

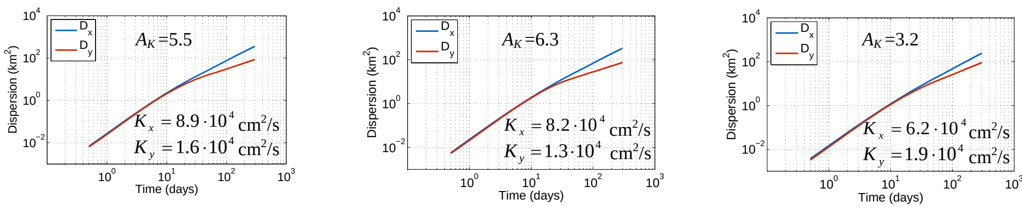
The eastern North Pacific is divided into 1°x1° bins. In each bin, a group of 100 particles are released monthly within a six-year period (from 2000 to 2005) and tracked for 300 days. Particle trajectories are used to compute Lagrangian single-particle statistics

$$D_x = \frac{1}{N}\sum_{n=1}^{N}[x_n(t) - \bar{x}(t)], \quad D_y = \frac{1}{N}\sum_{n=1}^{N}[y_n(t) - \bar{y}(t)], \quad K_x = \frac{1}{2}\frac{\partial D_x}{\partial t}, \quad K_y = \frac{1}{2}\frac{\partial D_y}{\partial t}, \quad A_K = \frac{K_x}{K_y},$$

(1) Total velocity fields | (2) Mesoscale part | (3) Synthetic eddy velocity fields



Examples of particle spreading over a period of 300 days from initial locations in the white rectangle. Color shows the spatial distribution of RMS velocity (cm/s).



Particle dispersion in the zonal (blue) and meridional (red) directions for deployments in the area 152-130°W, 21-37°N. Estimates of the zonal and meridional components of Lagrangian diffusivity are obtained by fitting straight lines to dispersion curves over *t* from 182 to 300 days.

The effect of the jets and eddy organization on the horizontal transport and mixing of tracers is investigated using Lagrangian particle trajectories. Numerical experiments with "virtual" particles are conducted in the eastern North Pacific and utilize altimetry-derived velocity fields. To separate the effects of the large-scale flow, quasi-zonal jets and eddies, three different experiments are conducted, using

(1) Total velocity fields (include large-scale and mesoscale),
(2) High-pass filtered velocity fields to retain only mesoscale phenomena (include zonal jets and eddies) and
(3) Synthetic eddy velocity fields composed of contributions of perfectly isotropic Gaussian eddies, but distributed in space and time as the observed mesoscale eddies in the eddy dataset.

The results demonstrate that, in all three cases, spreading rates in the zonal direction systematically exceed spreading rates in the meridional direction. The zonal anisotropy is mainly due to quasi-zonal jets. The secondary and generally weaker effect is due to eddy organization. This effect is not negligible, however. Despite the fact that the jets are weak relative to mesoscale eddies, their role in localizing eddy pathways can be very important for mixing distribution.

Summary

- Dynamics of multiple, migrating quasi-zonal jets in the circulation of the ocean are investigated using satellite altimetry and ocean model data.

- Transient quasi-zonal jets (striations) in the subtropical gyres can be characterized by two dynamically distinct components. The first one is attributable to baroclinic instability of a large-scale meridional flow, which serves as the main energy source for the zonal striations. The second component arises from the nonlinear interaction between the zonal striations and eddies and can be put into the context of quasi-geostrophic turbulence theory.

- Transient striations organize the eddy field into propagating “storm tracks”. Slowly moving striations locally alter the mean PV distribution associated with the large-scale flow in which they reside. This alteration is in turn responsible for the formation of eddies preferentially along the striations. When the striations move, the dynamics that generates eddies move with them, producing migrating “storm tracks”. Aligned eddies feed back onto the zonal flow, reinforcing the pattern of the striations.

- Transient striations and eddy organization have a profound effect on the horizontal transport and mixing of tracers. Perfectly isotropic eddies can cause strongly anisotropic material transport if their distribution is not random but localized on the zonal striations. The striations themselves can be very weak, i.e., “latent”, but their role in localizing eddy pathways can be very important for mixing distribution.