Transient zonal jets and “storm tracks”: A case study in the eastern North Pacific

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Oleg Melnichenko[1] (oleg@hawaii.edu), Nikolai Maximenko[1], and Hideharu Sasaki[2]

[1] IPRC/SOEST, University of Hawaii, Honolulu, Hawaii, [2] Earth Simulator Center, JAMSTEC, Yokohama, Japan

1. Satellite observations

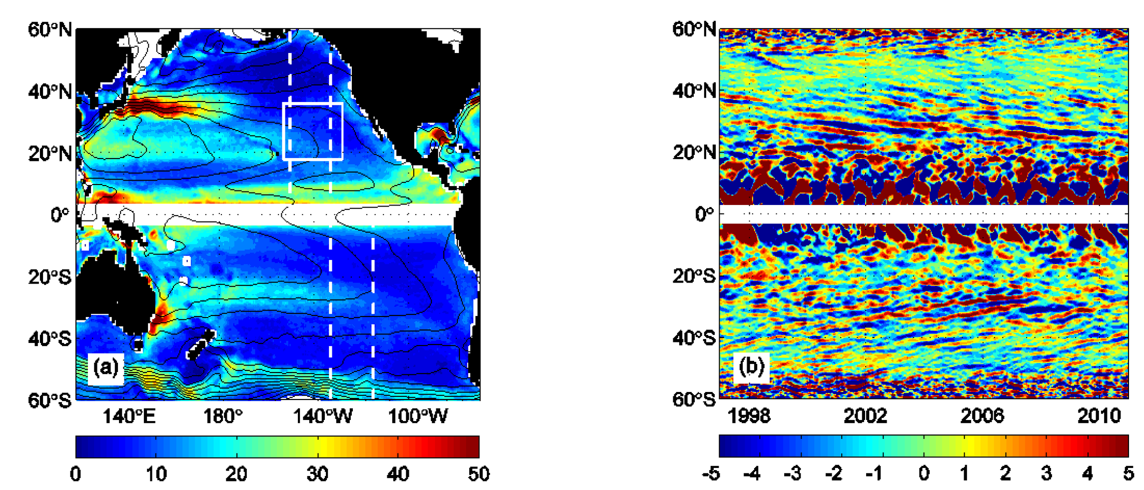

Figure 1. **(a)** RMS surface geostrophic velocity (cm/s; color) based on satellite altimetry data from November 1992 to October 2012. Shown on top are contours of the mean dynamic topography (Maximenko et al., 2009) **(b)** Time-latitude diagram of the zonally averaged zonal velocity anomaly (cm/s). Boundaries of the bands over which the zonal averaging is applied are shown in (a) by the white dashed lines. The white rectangle in (a) delineates the study area.

Zonally averaged zonal flow in the subtropics is dominated by long-lived mesoscale features (striations) that systematically and coherently propagate toward the equator.

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OGCM validated against observations

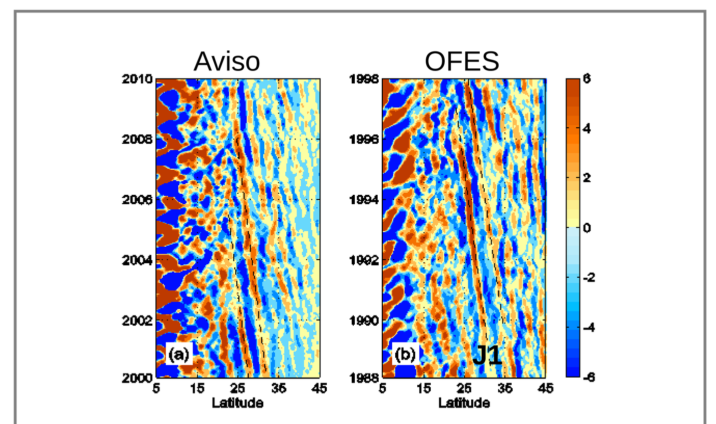

Figure 2. Latitude-time plots of the zonal surface geostrophic velocity anomaly (cm/s) averaged between 150-130°W in the eastern North Pacific: **(a)** AVISO and **(b)** OFES hindcast

2. Ocean model (OFES)

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

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

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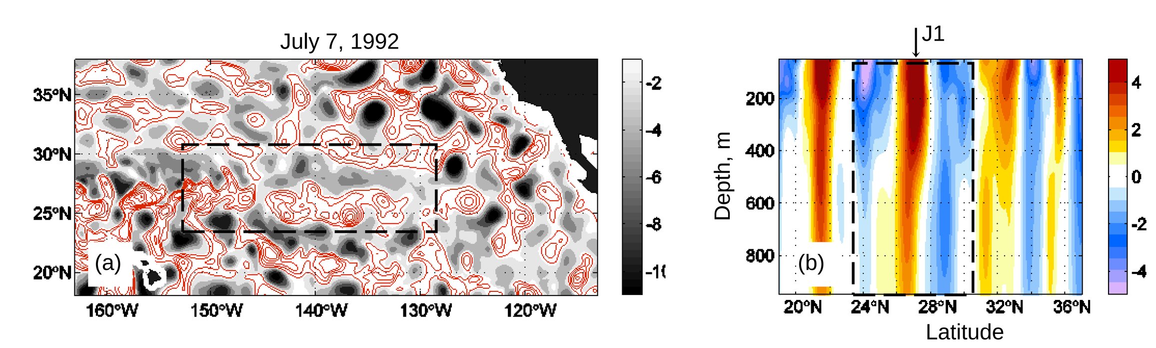


Figure 3. The striations' vertical structure and energetics are analyzed following a volume (~ 500 km-meridional x 2500 km-zonal; H=1000 m) centered at and moving with (C~0.3 km/day) a selected eastward flowing jet (J1). In this illustration of the OFES hindcast on July 12, 1992, the boundaries of the volume are shown by the black dashed lines on top of **(a)** SSH anomaly (cm) and **(b)** meridional section of the zonally averaged zonal velocity anomaly (cm/s).

⇨ **Analysis tool: Time and zonal averaging in a reference frame co-moving with a selected striations (J1; Fig. 2b).**

3. Propagating striations: vertical structure and energetics

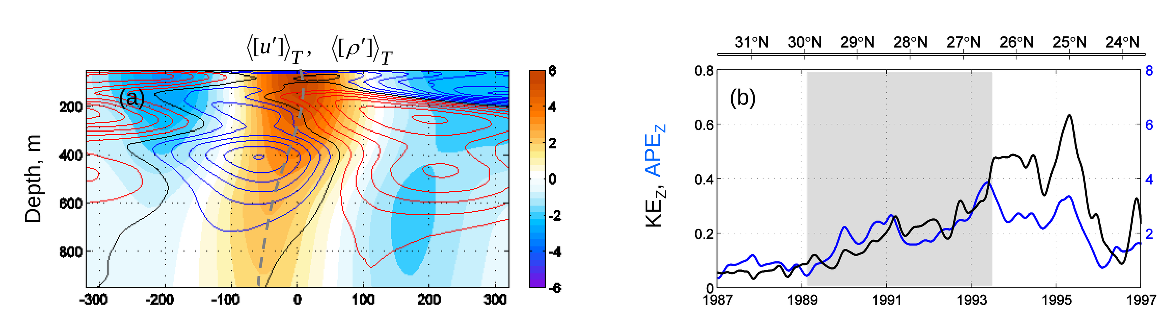


Figure 4. **(a)** Zonal velocity (cm/s; color) and potential density (contours; contour interval 0.01 kg m^{-3}). Blue (red) contours correspond to negative (positive) potential density anomaly. **(b)** Temporal evolution of KE_Z (black) and APE_Z (blue) averaged over the volume moving with the selected jet (J1). Units are kg m^{-1} s^{-2}. The gray box indicates the time period, T, over which vertical sections of different variable were averaged to construct the composites. During the period of the zonal perturbations growth, both KE_Z and APE_Z are increasing – a signature of baroclinically unstable wave.

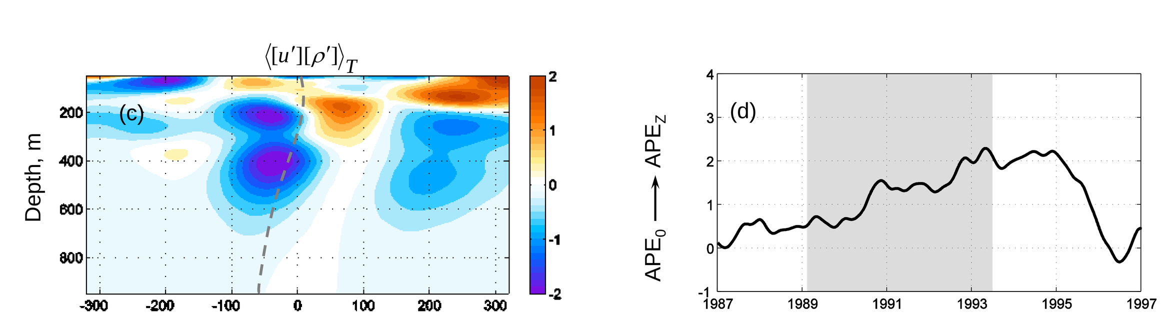


Figure 5. **(a)** Vertical structure of the perturbation density flux due to the zonal striations. **(b)** Temporal evolution of the volume-averaged density flux multiplied by the mean zonal density gradient (10^{-7} kg m^{-1} s^{-3}). The phase shifts with depth, as seen in Fig. 6a, result in the perturbation density flux down the mean density gradient. The striations are continuously fed from the mean potential energy reservoir associated with the sloping isopycnals of the large scale flow field.

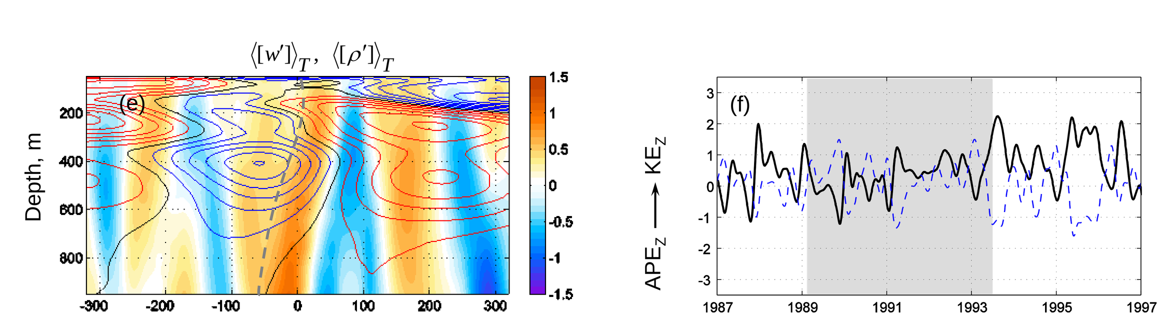


Figure 6. **(a)** Vertical velocity (10^{-4} cm s^{-1}; color) and potential density (contours). **(b)** Time evolution of the volume-averaged baroclinic conversion from APE_Z to KE_Z (10^{-7} kg m^{-1} s^{-3}). The blue dashed line shows the rate of change of APE_Z. Although zonally averaged vertical velocity looks quite different from a simple sinusoidal wave, it still demonstrates the required correlations with density perturbations to provide a net release of APE_Z.

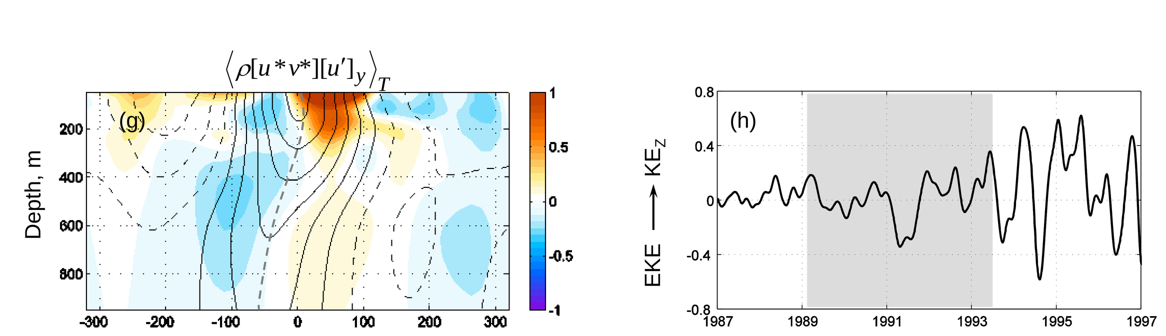
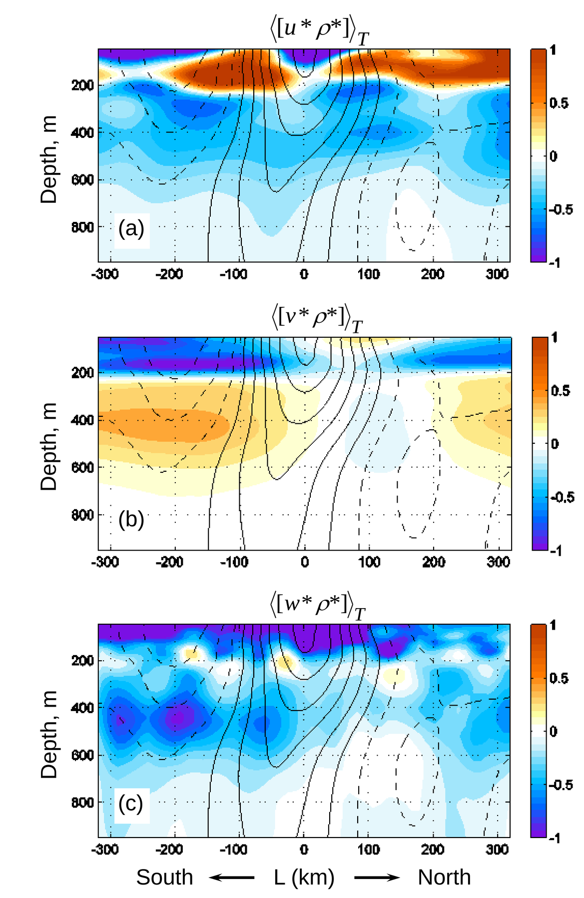


Figure 7. **(a)** The averaged vertical structure of the KE conversion from eddies to the zonal striations due to horizontal Reynolds stresses. **(b)** The volume-averaged eddy term as a function of time. Units are 10^{-7} kg m^{-1} s^{-3}. The eddy term exhibits oscillations between positive and negative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

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

4. Eddy-mean zonal flow interaction and “storm tracks”



⇦ Largely due to perturbations with long zonal scales comparable to the length of the moving channel (L=2500 km), reflecting the fact that striations are not zonally uniform.

⇦ Largely due to perturbations with short zonal scales (L=400-600 km) comparable to the meridional scale of the striations – mesoscale eddies.

⇦ The vertical buoyancy flux is negative (light fluid up) and in phase with the horizontal flux. Together, these features suggest the action of baroclinic instability.

Figure 8. Meridional sections of the mean eddy transports: **(a)** zonal density flux, **(b)** meridional density flux, and **(c)** vertical density flux. The means are based on 3-day zonal averages taken over a 5-year period (1989-1993) in the coordinate system centered at and moving with the selected eastward flowing striation (J1). In each panel, the zonally averaged zonal flow is shown by contours (contour interval 1 cm/s).

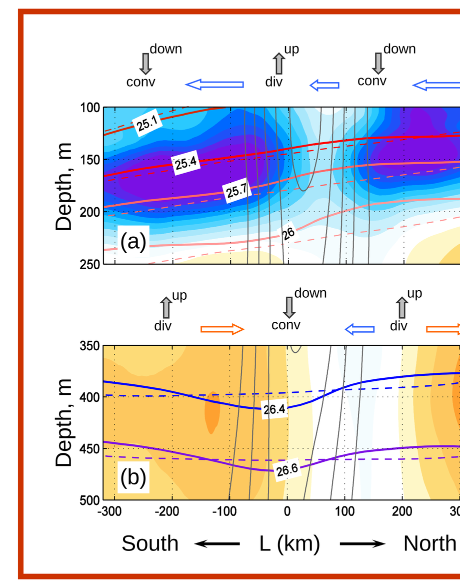


Figure 9. Meridional sections of the zonally averaged meridional eddy density flux (color shading) and potential density (contours) over a 1-year period during the initial phase of the striations' growth: **(a)** 100-250 m, and **(b)** 350-500 m depth layer. The 15-year mean potential density is shown by dashed contours. In each panel, the eastward flowing striation is shown by gray contours (contour interval 1 cm/s).

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The reversal of the meridional eddy buoyancy flux with depth is a consequence of the slowly propagating striations modifying the background density gradient.

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The primary effect of mesoscale eddies is to destroy APE_Z by providing downgradient buoyancy flux where “downgradient” is understood as that associated with the striations rather than the time-mean, large-scale flow.

Eddy generation by baroclinic instability (as indicated by the eddy buoyancy fluxes) occurs primarily between the eastward flowing striations rather than being within them, reminiscent of the “inter-jet disturbances” discussed by Lee (1997).

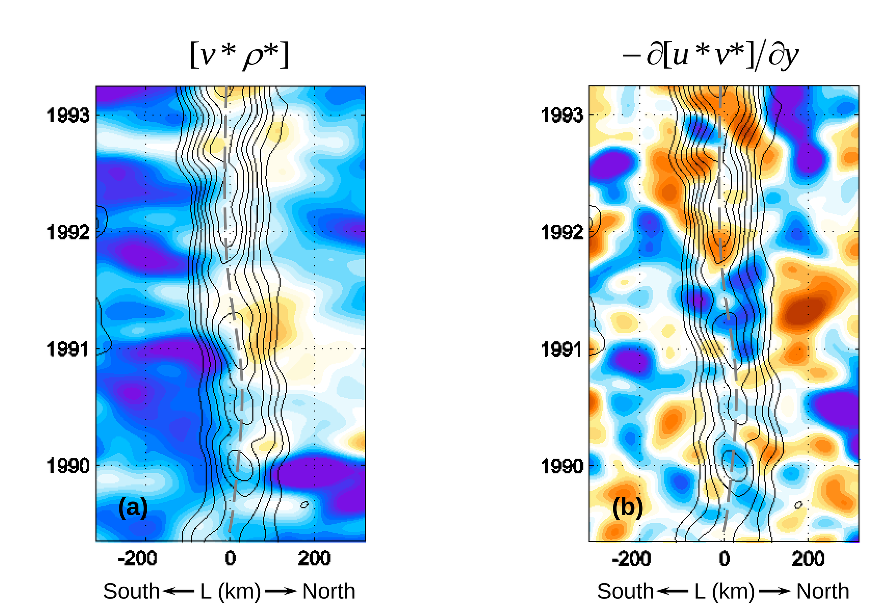


Figure 11. Time evolution of the 50-200 m layer mean **(a)** meridional eddy buoyancy flux and **(b)** eddy momentum flux convergence. The plots are based on 3-day zonal averages taken in the coordinate system centered at and moving with the selected eastward flowing striation (J1). In each panel, the eastward flowing striation is shown by contours (contour interval 1 cm/s).

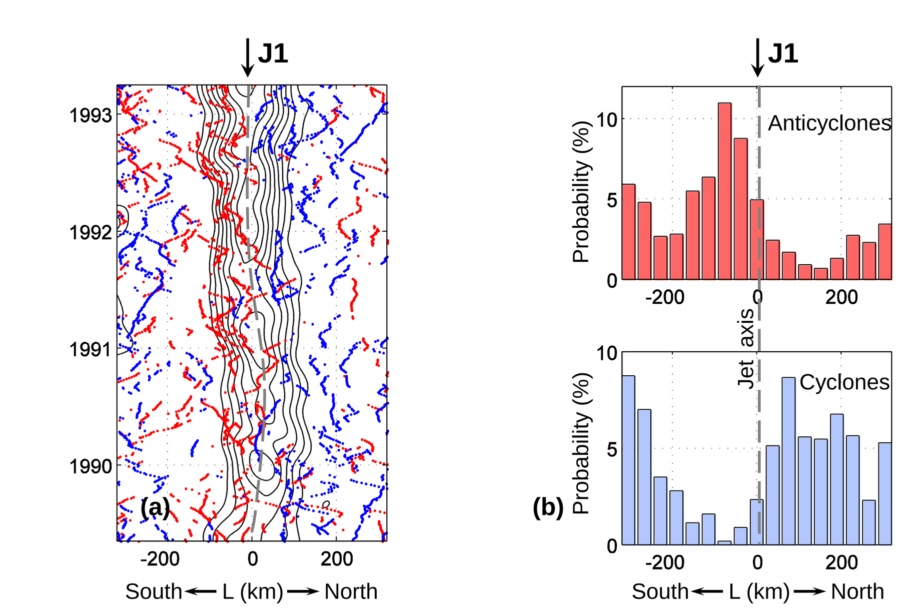
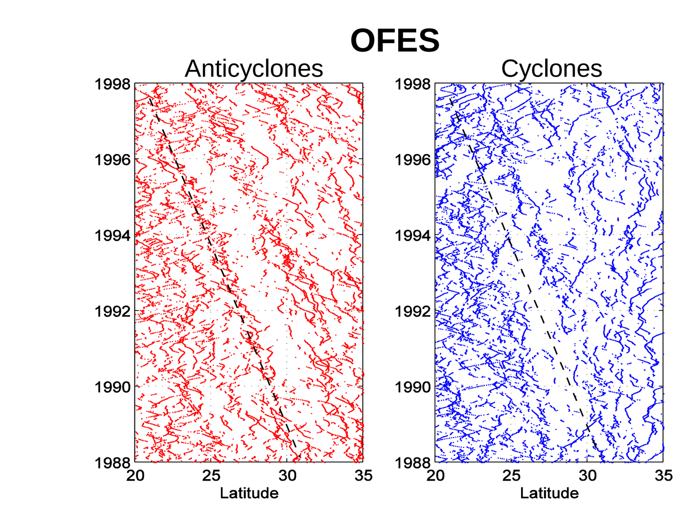


Figure 12. (a) Time-latitude and (b) PDF distribution of eddy centroids in the coordinate system centered at and moving with the selected eastward flowing striation (J1). Red dots indicate anticyclonic eddies, blue dots – cyclonic eddies.

Propagating “storm tracks”



Back to observations

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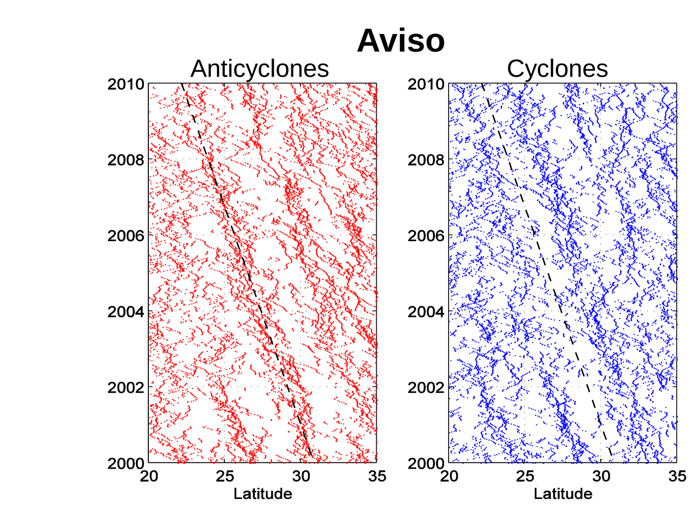

Figure 13. Latitude-time distribution of eddy centroids for eddies that passed through the region 152-128°W, 20-35°N over the 10-year period from 1988 to1998: left-anticyclones, right-cyclones. Eddies were identified and tracked from the model SSHA data using the procedure similar to that of Chelton et al. (2011).

Figure 14. Latitude-time distribution of eddy centroids for eddies with life-times >4 weeks that passed through the region 152-128°W, 20-35°N over the 10-year period from 2000 to 2010: left-anticyclones, right-cyclones. The eddy centroids are from the eddy dataset by Chelton et al. (2011).

6. Conclusions

Transient quasi-zonal jets (striations) in the subtropical gyre can be characterized by two dynamically distinct components. The first one is attributable to baroclinic instability of a large-scale meridional flow in the subtropical gyre, 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.

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