Eddy-Mean Flow Interactions in Western Boundary Current Jets

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INTRODUCTION

The Kuroshio Extension System Study (KESS) is a large-scale observational program of the Kuroshio Extension investigating the processes that govern the jet’s eddy variability and the role of eddy fluxes in driving the jet’s recirculation gyres. Motivated by the KESS observations, we examine the nature and the importance of mesoscale eddy-mean flow interactions in Western Boundary Current (WBC) jet systems from both theoretical and observational perspectives. We use the KESS observations to design the set-up of an idealized quasi-geostrophic numerical model, and use it to study the role of eddies in determining the time-mean flow in the zonal evolution of a baroclinic, unstable, boundary-forced jet. We next test the relevance of these idealized results to actual oceanic WBC jet systems through the comparison of model predictions and observational results.

LESSONS LEARNED FROM AN IDEALIZED MODEL

1. Eddies play a critical role in the downstream evolution of the jet through:
   (i) stabilizing the time-mean jet as it evolves downstream
   (ii) driving the time-mean recirculations

2. Zonal variation is key to the mechanism that permits eddies to drive the time-mean flow.
   i) the eddy effect depends on the zonally-evolving stability of the time-mean jet
   ii) eddies drive the recirculations downstream of jet stabilization
   iii) the zonal advection of eddy enstrophy permits up-gradient eddy pv fluxes

3. The addition of baroclinicity and baroclinic instability does not significantly alter the barotropic mechanism responsible for the eddy-driving of the recirculations.


OBSERVATIONAL TESTS OF MODEL RELEVANCE

1. Consistencies in the downstream evolution of time-mean jet-gyre properties

   Fig. 9. A comparison of the downstream evolution of time-mean jet-gyre structure in the upper layer of an appropriate model run (left) with the observed time-mean jet-gyre structure at 200 m in a series of mooring arrays (middle), and the observed time-mean stream-coordinate description of the surface jet structure from the 14-year altimetry record (right). Downstream locations for the comparison were chosen to be similar to the downstream locations of the mooring arrays relative to the time-mean eddy kinetic energy (EKE) distribution. The observed evolution shows similarities with model behaviour such as a strengthening and sharpening of the jet and the development of westward recirculations upstream of the EKE maximum, and the weakening and broadening of the jet and the weakening of recirculation strength downstream of this location.

2. Consistencies in the downstream evolution of eddy properties

   Fig. 10-11. A comparison of the downstream evolution of eddy properties for an appropriate model run (left) and the observed system (left). Figure 10 shows the time-mean covariance ellipses computed from the depth-averaged mooring observations in the case of the observed system. Both the model and the observations show the same dynamically significant patterns of positive ellipses north of the jet axis and negative ellipses south of the jet axes (consistent with an unstable jet regime) upstream of the EKE maximum, to the reverse pattern (consistent with a wave radiator regime) downstream of the EKE maximum. Figure 11 compares the effective eddy force computed from the altimetry record in the case of the observed system. The observations suggest a similar transition from westward to eastward forcing across the downstream location of maximum recirculation transport as seen in the model system.

Fig. 1. Idealized model set-up: the model is QG, fully nonlinear; 2-layer and forced at the western boundary by an unstable jet inflow in the upper layer at $u=0$.

Fig. 2. Schematic of the Kuroshio Extension System Study (KESS) observational program.

Fig. 3. The effective eddy force in the TEM framework (upper left) and the time-mean eddy vorticity flux divergence (lower left) (see also Togg et al. 2008). Eddies add to stabilize the baroclinically unstable jet and accelerating it at its flanks. They force the recirculations by accelerating flanking westward flow then decelerating them downstream of the location of maximum time-mean recirculation transport.

Fig. 4. The “effective eddy force” (upper left) and the time-mean eddy vorticity flux divergence (lower left) (see also Togg et al. 2008). Eddies add to stabilize the baroclinically unstable jet and accelerating it at its flanks. They force the recirculations by accelerating flanking westward flow then decelerating them downstream of the location of maximum time-mean recirculation transport.

Fig. 5. The eddy vorticity flux divergence (left) showing the dominance of the region downstream of jet stabilization in the eddy forcing. Similarities in the pattern of this dominant contribution with that of a wave radiator model (right) suggest that the mechanism responsible for the eddy-driving of the recirculation gyres in the jet configuration is eddy rectification from wave/eddies generated by a localized source downstream of jet stabilization. Here the localized forcing is being supplied by a localized concentration of eddy energy that results from the stabilization of the jet as it flows downstream.

Fig. 6. Select terms in the time-mean eddy enstrophy budget illustrating that positive eddy enstrophy destruction (up-gradient eddy pv fluxes) in the region downstream of jet stabilization are permitted by an eddy enstrophy advection convergence there. Hence up-gradient eddy fluxes result from the advection of eddies from the upstream region where they are generated by the unstable jet, to the downstream region where they are dissipated.

Fig. 7. Demonstration that eddies generated by an unstable jet drive weakly depth-dependent time-mean recirculations regardless of the stability configuration of the upstream jet that is the source of the eddy variability. Baroclinic instability delays or stabilizes the barotropic mechanism responsible for the eddy-driving of the recirculations, and thickness fluxes force lower layer recirculations at the expense of upper layer recirculation strength.