Length Scales of Eddy Generation and Nonlinear Evolution of the Seasonally–Modulated South Pacific Subtropical Countercurrent

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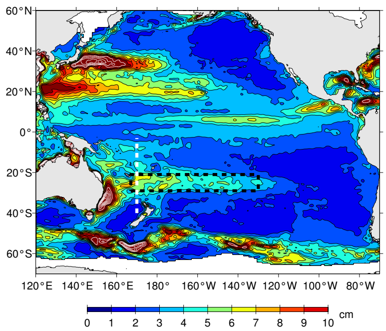
ABSTRACT

The dynamical processes behind the seasonal modulation of the two–dimensional eddy kinetic energy (EKE) wavenumber spectrum in the Subtropical Countercurrent region of the South Pacific are investigated with satellite altimeter data and climatological hydrographic data. We find a seasonally modulated generation of EKE via baroclinic instability in modes with larger meridional length scales. Subsequent nonlinear eddy–eddy interactions redistribute the EKE to larger total horizontal length scales, and larger zonal scales in particular. This is confirmed by diagnosing the spectral transfer of EKE in the surface geostrophic flow, which is found to drive an anisotropic inverse cascade, being redirected in the sense consistent with the beta–effect, as predicted by geostrophic turbulence theory on the beta–plane. Due to the seasonal renewal of meridionally elongated anomalies by baroclinic instability and possibly due to the barotropization process, however, the net outcome for the formation of surface zonal flows is observed to be limited.

1. EKE in STCC: Altimeter Observation

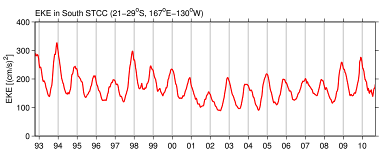
Right: RMS sea surface height variability in the Pacific Ocean based on high-pass filtered satellite altimeter SSH data. The high-pass fileter has a half-power at 180 days. Contour intervals are 0.01 m for black lines, and 0.02 m for white lines starting from 0.12 m.

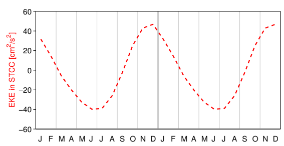


EKE is calculated from the gridded SSH anomaly data h' by assuming geostrophy:

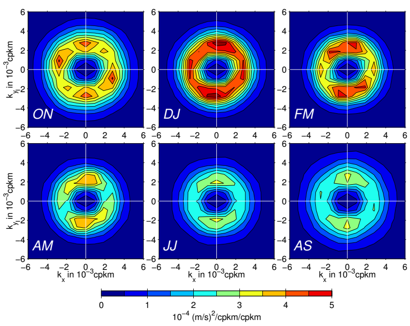
$$\text{EKE} \equiv \frac{g^2}{2f^2}\left[\left(\frac{\partial h'}{\partial x}\right)^2 + \left(\frac{\partial h'}{\partial y}\right)^2\right],$$

where g is the gravity constant and f the Coriolis parameter.





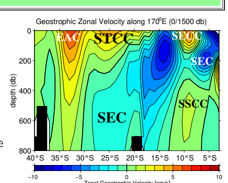
EKE timeseries and its monthly climatology in SPSTCC region. (21°–29°S, 167°E–130°W)



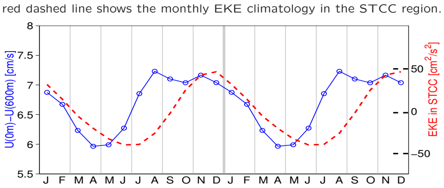
Bimonthly EKE power spectral density distributions as a function of k_x and k_y in the SPSTCC band.

2. Eddy Growth and Baroclinic Instability

Right: Mean zonal velocities along 170°E based on World Ocean Atlas 2005. EAC: East Australia Current, STCC: Subtropical Countercurrent, SECC: South Equatorial Countercurrent, SSCC: South Subsurface Countercurrent, and SEC: South Equatorial Current.



Below: Zonal velocity shear between 0 and 600 m averaged over the STCC-SEC region of 21°–29°S and 180°E–160°W (blue circled line). The red dashed line shows the monthly EKE climatology in the STCC region.



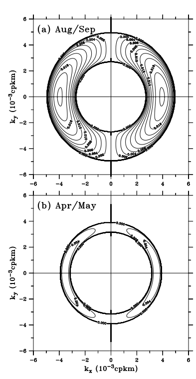
We consider the $2^1/_2$-layer QG model:

$$\left(\frac{\partial}{\partial t} + U_n\frac{\partial}{\partial x}\right) q_n + \frac{\partial \Pi_n}{\partial y}\frac{\partial \phi_n}{\partial x} = 0, \quad n = 1, 2$$

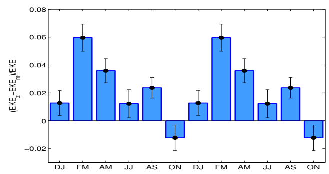
where $\Pi_1 = \beta + \frac{f_0^2}{g' H_1}(U_1 - U_2)$ and $\Pi_2 = \beta - \frac{f_0^2}{g' H_1}(U_1 - U_2 - \frac{\rho_2 - \rho_1}{\rho_3 - \rho_2} U_2)$. For the vertically-sheared STCC-SEC system, $\Pi_{1y} > 0$, and the necessary and sufficient condition for the baroclinic instability

$$\Pi_{2y} < 0, \quad \text{or} \quad U_1 - U_2 > \frac{\beta g' H_1}{f_0^2} + \frac{\rho_2 - \rho_1}{\rho_3 - \rho_2} U_2$$

is satisfied. In austral winter, the STCC/SEC system is baroclinically more unstable than in other seasons due to the large vertical shear and weak stratification. This seasonal variation in the intensity of baroclinic instability is responsible for the seasonal modulation of the STCC's EKE field with a November/December maximum and a June/July minimum. The right figure contrasts the growth rates in August/September and April/May.



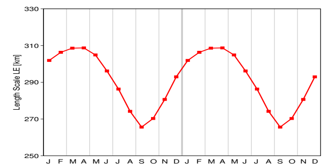
3. Observed Eddy-Eddy Interaction



Zonally Elongated vs. Meridionally Elongated, (EKE$_z$–EKE$_m$)/EKE

$$\begin{aligned} \text{EKE}_z &= \textstyle\sum_{k_y > k_x} \overline{E}(k_x, k_y, t)\Delta k^2 \\ \text{EKE}_m &= \textstyle\sum_{k_x > k_y} \overline{E}(k_x, k_y, t)\Delta k^2, \end{aligned}$$

where $\overline{E}(k_x, k_y, t)$ is the bimonthly averages.



Energy-Containing Length-Scale:

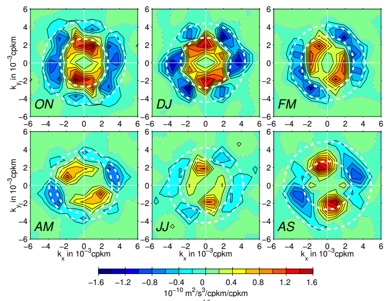
$$L_e(t) = 2\pi \textstyle\sum_{k_x,k_y} \overline{E}(k_x, k_y, t)\Delta k^2 \,/\, \sum_{k_x,k_y} K\, \overline{E}(k_x, k_y, t)\Delta k^2,$$

where $K = \sqrt{k_x^2 + k_y^2}$ is the total wavenumber.

Right: **Spectral Energy Transfer**:

$$T(k_x, k_y, t) \equiv -\Re\{\hat{u}^* \widehat{u_j \frac{\partial u}{\partial x_j}} + \hat{v}^* \widehat{u_j \frac{\partial v}{\partial x_j}}\}/\Delta k^2,$$

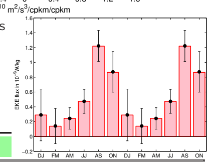
where the star indicates complex conjugate and caret indicates DFT. The $T(k_x, k_y, t)$ represents the redistribution of EKE between different spatial modes due to eddy-eddy interactions. The white circles in each map delineate the boundaries within which the perturbations are subject to baroclinic instability of the vertically-sheared STCC-SEC system.



Right: To represent transfer of EKE from meridionally elongated modes into zonally elongated modes by nonlinear eddy interactions, we define

$$T_z = \sum_{k_y > k_x} \overline{T}(k_x, k_y, t)\Delta k^2,$$

where $\overline{T}(k_x, k_y, t)$ are the bimonthly averages.



4. Summary

Based on the stability analysis of the time-varying mean flow system, as well as the inferred triad eddy interactions, we can separate the observed eddy evolution into three dynamic phases.

(a) Growing phase (August – October) Starting in August when the vertical shear between the eastward-flowing STCC and the westward-flowing SEC reaches the seasonal maximum, the flow system baroclinic instability peaks. Because STCC and SEC are relatively weak, interior-ocean currents, the growth rate of the instability is modest and it takes several months for initial perturbations to attain finite amplitudes. This modest growth leads to a delayed, regional EKE maximum in December. The baroclinic instability preferentially generates meridionally elongated perturbations with greater v than u variance. So in October/November, before the inverse cascade has fully redistributed the EKE, the flow is actually more meridionally elongated.

(b) Maturing phase (November – January) As the instability-induced perturbations attain finite amplitude in this stage, an active inverse cascade takes place. As the EKE level equilibrates during this phase, the energy input supplied by baroclinic instability is balanced by the spectral energy transfer term, $\overline{T}(k_x, k_y, t)$. Due to the cumulative energy transfers from meridional to zonal scales over the growing phase, the peak $\overline{E}(k_x, k_y, t)$ value shifts to small k_x, and $k_y > k_x$ during this maturing phase of eddy evolution.

(c) Decaying phase (March – June) Energy input from baroclinic instability during this phase is weak due to weakened vertical shear between the STCC and SEC. Without the meridionally elongated anomalies supplied by the instability, the inverse cascade into the zonal anomalies wins out during this more "freely-evolving" phase. As in the other two phases, triad eddy interaction works to transfer energy to larger scales where the nonlinear interaction term now acts as an energy sink.

1. Our analysis confirms that the seasonally-modulating baroclinic instability of the STCC-SEC system is the energy source for the eddy generation and their subsequent interactions.
2. Due to the instability nature of the zonal mean flow, baroclinic instability favors the formation of meridionally elongated anomalous flows.
3. The nonlinear eddy-eddy interaction results in an inverse energy cascade with a preference of transferring kinetic energy from the anomalous meridional flows to the zonal ones. This *anisotropic* energy cascade into anomalies with $k_y > k_x$ is likely a result of the β-effect.

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