Vortices in the ocean

Lecture 4 : Baroclinic vortex processes
Vortex generation by unstable currents (jets, coastal currents)
Vortex generation by baroclinically unstable jets (e.g. Gulf Stream)

Two-layer QG model simulation of surface zonal jet + sine perturbation

\[ q_1(t) \]

\[ q_2(t) \]

\[ \approx(t) \]

14 days 28 days 42 days 56 days
Spectral analysis of previous simulation (zonal modes)
Same jet with short wave perturbation: irregular vortex formation

\[ q_1(t) \]

\[ q_2(t) \]

\[ \Omega(t) \]

63 days 98 days 133 days 168 days
Spectral analysis of previous simulation (zonal modes)
Formation of meanders and filaments from wave-wave interaction

$q_1(t)$

$q_2(t)$

$m(t)$
Two-layer QG model simulations of unstable coastal current (e.g. MW undercurrents along the Iberian continental slope)

Baroclinic dipole formation
Stationary dipole formation

Vortex + meander formation
Filament formation and shedding (strong horizontal velocity shear at the front)
Chart of fully nonlinear regimes in parameter plane: topographic influence, flow baroclinicity, circles = filaments and meanders, diamonds = single vortices, triangles = ejected dipoles, stars = trapped dipoles

Forecast of a weakly nonlinear model (Landau type equation)
\[ \frac{d^2 A}{dt^2} + \bigtriangledown \cdot A + \partial A |A|^2 = 0 \]
circles and squares: stabilizing effects of NL wave interactions, triangles: destabilizing effects of NL wave interaction
Baroclinic instability of vortices, dipoles and tripoles
Mixed barotropic-baroclinic instability of a vortex in a two-layer QG model (study of swoddies)
Baroclinic dipolar breaking

(strong vertical gradient of PV and intense layer coupling - no peripheral PV)
For comparison, barotropic dipolar breaking (strong horiz. Gradient of PV)
Formation of a two-layer tripole from mixed barotropic-baroclinic instability of a circular vortex (stabilizing wave-wave interaction)

The redistribution of peripheral PV into side lobes decreases the shear they exert on the core vortex (like signed core vertically)
Formation of a two-layer tripole from mixed barotropic-baroclinic instability of a circular vortex (opposite signed core vertically)
Baroclinic vortex interactions
Vortex merger in two-layer fluid

Vortex merger is the process by which two like signed vortices with cores at the same depth join and form a single, large vortex, surrounded by peripheral filaments (conservation of angular momentum).

Vortex growth was related in 2D or geostrophic turbulence to the inverse energy cascade, while filament formation was related to the direct enstrophy cascade.

Vortex merger has not often been observed in the ocean: partial mass transfer between eddies in the Gulf Stream region, near the Kuroshio and between meddies (2 obs.)
Original study by Polvani (1988-89): constant PV vortices, no dependence of merger on stratification.
No merger when co-rotating steady states exist
Laboratory experiments by Hopfinger: strong dependence of merger on stratification
Numerical modeling of baroclinic vortex merger by Valcke and Verron (1995) - constant RV profiles
Explanation:

for large $\bullet/R$, nearly 2D situation and $q$ behaves as zeta
constant-$q$ vortices and constant-zeta vortices are similar

decreasing $\bullet/R$, the scale of the $q$-distribution increases and merger is favored

decreasing $\bullet/R$ again, vortex stretching becomes important and a constant-zeta vortex becomes a baroclinic dipole in $q$; baroclinic dipolar effects tend to separate vortices and prevent merger

In the ocean, eddy cores seem to have nearly constant zeta (eddy periphery/vorticity tail much more difficult to measure)
Vertical vortex alignment in two-layer fluid

The vertical alignment of two vortices in different (adjacent) layer, initially separated horizontally, is very important for geostrophic turbulence, where it materializes the energy and enstrophy transfer from the baroclinic to the barotropic mode (Rhines, Salmon; 1980) in the absence of surface forcing and of bottom topography.
Original study by Polvani (1988-89): constant PV vortices
curve for symmetric circular alignment

curve for existence of corotating $N=2$ V-States
Numerical studies by Correard and Carton (1998): vortices with constant RV can create bt or bc dipoles and escape alignment
Alignment of positive PV (blue) and satellite formation with negative PV (red) – streamlines in rotating frame, saddle points and centers

Formation of a baroclinic tripole
Hetonic divergence

Horizontal dipole formation
Baroclinic processes in vortex formation, evolution or interaction can lead to multipoles (dipoles/hetons or tripoles)

Dipoles are more robust than tripoles though these latter resist intense white noise perturbation. Hetons can carry heat and momentum across the ocean (cold-core rings south of the Gulf Stream coupled with Sargasso Sea deep anticyclones, or meddies with MW cyclones). But their association remains relatively loose (e.g. one or two months at most for MW dipoles) ; is it due to the parity bias, to vortex-wave interaction, to specific anticyclonic instabilities ?

A variety of baroclinic tripoles has emerged lately in these process studies though only the swoddy-type has been observed.