STABILITY OF CYCLONES AND ANTICYCLONES IN A 5-LAYER QUASI-GEOSTROPHIC MODEL, WITH APPLICATION TO MEDITERRANEAN WATER EDDIES

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Summary In a five layer quasi-geostrophic model, the linear stability and nonlinear evolution of thermocline intensified cyclones and anti- cyclones (meddies) is investigated numerically. The physical parameters of these vortices (size, intensity, internal structure) are fitted on observations. Variations of these parameters are allowed to test the sensitivity of barotropic and baroclinic instabilities to the vortex structures, and to account for uncertainties in measurements. Cyclones appear more unstable than anticyclones only due to a stronger horizontal velocity shear and tend to be more surface intensified in observations.

INTRODUCTION

The Mediterranean Sea is a basin of intense evaporation which forms salty and dense water (a mixture of Levantine Intermediate Water and of Deep Western Mediterranean Water). This water accumulates in the Alboran Sea before exiting via the Straits of Gibraltar. These straits are the locus of a two-layer exchange, where fresher North Atlantic Central Water enters the Mediterranean Sea at the surface, and the saltier and deeper Mediterranean Water (hereafter MW) flows out of the Mediterranean Sea into the Gulf of Cadiz. In the Gulf of Cadiz, the MW mixes with surrounding fresher water and finally adjusts as three slope currents, the deeper two encountering submarine canyons and destabilizing. These two currents lie at about 800 and 1200 m depths. When they destabilize, they form anticyclonic vortex lenses known as Meddies (Mediterranean Water eddies), of radius close to 50 km, thickness on the order of 1000 m and temperature and salinity anomalies which can reach 4^oC and 1 psu compared to the surrounding waters ([1, 2, 3]). In [4]-[5], some aspects of the dynamics of MW lenses were studied, where meddies were considered as vortex patches in the middle layer of 3-layer QG model. In the past fifteen years, several experiments at sea have shown that the formation of these meddies is often accompanied by that of more surface intensified cyclones. These cyclones have been observed in the Gulf of Cadiz and they are of considerable importance for the mesoscale and regional circulation there ([6, 7]). But they have not been identified further south or west, thereby suggesting that they may disappear rapidly.

Here, we investigate possible reasons for a different stability of meddy-like and MW cyclone-like eddies.

MODEL

In a five-layer quasi-geostrophic model, we set the stratification and layer depths to best reproduce the internal deformation radii and the three-dimensional structure of eddy velocity (layer 1 lies at the surface and layer 5 at the bottom). Our meddies have non zero velocity initially only in layer 2, 3, and 4, layer 3 being the meddy core. Our cyclones are more surface intensified: their initial velocity concentrates in the upper 3 layers (layers numer 1, 2, 3). The horizontal velocity profiles are chosen as power-exponentials of the radius and the layerwise magnitude of velocity is first determined from in-situ data. With this setting, we compute the linear growth rates of normal mode perturbations on these eddies and we simulate their nonlinear evolutions with a pseudo-spectral code. To take into account the variety of meddies and MW cyclones measured in the ocean, we vary the vortex size, the horizontal and vertical shears of velocity, and the wavenumber of the perturbation.
The results are the following.

LINEAR STABILITY OF MEDDIES AND OF CYCLONES

For meddies with Gaussian radial velocity profile, and size comparable with the first internal radius of deformation, growth rates are very weak for both antisymmetric and elliptical perturbations; they correspond to e-growing times of 100 to 400 days. For meddies with cubic exponential profile and similar size, the growth rates are still very weak for the antisymmetric mode but 4 times larger for the elliptical mode. The barotropic and baroclinic instabilities do not overlap, except in the latter case. For cyclones, the growth rates are generally larger than for anticyclones, even if they remain

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weak for Gaussian vortices. The antisymmetric and elliptical modes have comparable growth rates; the antisymmetric mode even dominates for Gaussian vortices. Furthermore, there is substantial overlapping of the barotropic and baroclinic instabilities. Finally, growth rates for anticyclones are sensitive to both ratios U_2/U_3 (where U_j is the velocity maximum in layer j) and U_4/U_3 whereas those for cyclones are sensitive mostly to to U_3/U_2 and little to U_1/U_2. This can be explained by the respective intensities of the layer couplings.

NONLINEAR EVOLUTION OF LINEARLY UNSTABLE MEDDIES AND CYCLONES

The nonlinear evolution of both cyclones and anticyclones shows the formation of several types of tripolar structures, when the vortices equilibrate at finite amplitude with an elliptical perturbation. These tripoles can be barotropic, or baroclinic; then they are A-, X- or Y-shaped; this classification indicates that the cores and satellite vortices gather vertically under the form of such letters. An X-shaped tripole has a core in the middle layer and satellites on each part of the core, in the layers above and below. An A-shaped tripole has a core in the middle layer and above, and satellites in the middle layer and below. A Y-shaped tripole has a core in the middle layer and below, and satellites above. The antisymmetric perturbation either leads to vertical splitting of the initial vortex or to a transition towards the elliptical mode. The triangular perturbation shows little finite amplitude stabilization, except for very steep horizontal profiles of velocity. Mostly, it degenerates into lower modes. Unbounded nonlinear growth of linearly unstable perturbations leads to dipolar breaking. Much similarity is observed between the evolutions of cyclones and of anticyclones, in particular that unstable perturbations equilibrate mostly for vertically co-rotating vortices. For eddies of similar strength, size, and vertical shear, but of different polarities, the differences are the following: for Gaussian eddies, anticyclones break less often into baroclinic dipoles; moreover, cyclones are more prone to asymmetric breaking than anticyclones. But the main difference between MW cyclones and anticyclones (meddies) is that cyclones appear to have a stronger horizontal velocity shear (due to faster velocity and smaller size than that of companion meddies) in observations, and thus may be more prone to barotropic instability.

CONCLUSIONS

As an application to the MW eddies, it can be concluded that meddies, which are co-rotating, with size comparable with the first internal radius of deformation, may be linearly unstable to elliptical perturbations (see also [8]), but they equilibrate nonlinearly; comparable cyclones are also fairly stable. Only a combination of steeper horizontal velocity profile and higher sensitivity to asymmetric breaking can be invoked to explain the observed meddy-cyclone bias with our 5-layer QG model. More asymmetry will certainly appear (in particular due to the local variations of deformation radii) if a primitive equation model is used. This latter case is presently under investigation.

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