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The mesoscale variability in the Caribbean Sea. Part II: Energy sources

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ABSTRACT

The processes which drive the production and the growth of the strong mesoscale eddy field in the Caribbean Sea are examined using a general circulation model. Diagnostics of the simulations suggest that:

(1) The mean currents in the Caribbean Sea are intrinsically unstable. The nature of the instability and its strength vary spatially due to strong differences of current structure among basins.

(2) The greatest and most energetic eddies of the Caribbean Sea originate in the Venezuela Basin by mixed barotropic-baroclinic instability of an intense jet, formed with waters mostly from the surface return flow of the Meridional Overturning Circulation and the North Equatorial Current which converge and accelerate through the Grenada Passage. The vertical shear of this inflow is enhanced by an eastward undercurrent, which flows along the south American Coast between 100 and 250 m depth. The shallow eddies (less than 200 m depth) formed in the vicinity of the Grenada Passage get rapidly deeper (down to 1000 m depth) and stronger by their interaction with the deep interior flow of the Subtropical Gyre, which enters through passages north of St. Lucia. These main eastern Caribbean inflows merge and form the southern Caribbean Current, whose baroclinic instability is responsible for the westward growth and strengthening of these eddies from the Venezuela to the Colombia Basin.

(3) Eddies of lesser strength are produced in other regions of the Caribbean Sea. Their generation and growth is also linked with instability of the local currents. First, cyclones are formed in the cyclonic shear of the northern Caribbean Current, but appear to be rapidly dissipated or absorbed by the large anticyclones coming from the southern Caribbean. Second, eddies in the Cayman Sea, which impact the Yucatan region, are locally produced and enhanced by barotropic instability of the deep Cayman Current.

(4) The role of the North Brazil Current (NBC) rings is mostly to act as a finite perturbation for the instability of the mean flow. Their presence near the Lesser Antilles is ubiquitous and they appear to be linked with most of the Caribbean eddies. There are some evidences that the frequency at which they form near the Grenada Passage is influenced by the frequency at which the NBC rings impinge the Lesser Antilles. But large Caribbean eddies also form without a close influence of any ring, and comparison between simulations shows that mean eddy kinetic energy and eddy population in the Caribbean Sea are not substantially different in absence or presence of NBC rings: their presence is not a necessary condition for the generation and growth of the Caribbean eddies.

1. Introduction

Previous observations based and model based studies did not permit to draw a clear view of which processes set the characteristics of the eddy field in the Caribbean Sea, but rather showed several points of controversy. The reason is perhaps that many processes can potentially drive the variability and explain the enhanced eddy production in the region. There is neither a general agreement on whether the energetic eddies originate from local processes such as windstress, current instability or topographic effects or from remote processes such as propagation of Atlantic Rossby waves or advection of North Brazil Current (NBC) rings.

Among the local processes, the presence of a strong mean windstress curl (WSC, see Fig. 2) in the Central Caribbean has been proposed to be a source of energy for the Caribbean mesoscale activity. A model study which excludes incoming perturbations from the Atlantic shows eddies produced southwest of Hispaniola (Oey et al., 2003). The authors suggest that the local mean WSC is responsible for this generation, although they admit that the instability of the Caribbean Current could be inadequately simulated in their experiments. Andrade and Barton (2000) associate the enhancement of eddy activity in the central Caribbean during July-October with the maximum curl of the North Trade Wind during this period. However they do not consider the influence of NBC

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rings and that the mean Caribbean Current may also have annual variability correlated with eddy production. Recent observations suggest local wind generation is not enough to explain the eddies vertical structure. The real eddies observed by Silander (2005) in the Venezuela Basin are deep and energetic (maximum swirl speed ranged from 0.3 to 0.6 m s^{-1}): it is unlikely that pure wind stress curl, which is not particularly strong in the Venezuela Basin, can spun up in just few weeks at these latitudes such energetic eddies reaching more than 1000 m depth. In addition, altimetry data (e.g., Guerrero et al., 2004) show that most of the anticyclones occur in the southern part of the Caribbean Sea where the WSC is mostly cyclonic.

Another local process which can be responsible for eddy generation and growth is the instability of the main Caribbean Current. Conversion from Mean Kinetic Energy (MKE) to Mean Eddy Kinetic Energy (MEKE) has been proposed to contribute to eddy growth (Carton and Chao, 1999) but not demonstrated. Other hypothesis, provided by Andrade and Barton (2000) is that unstable meandering of the Caribbean Current could form some eddies. Richardson (2005) also suggests that instabilities of the anticyclonic shear of Caribbean jets could help the incoming NBC rings vorticity to organize and amplify into energetic eddies. Diagnostics of our simulations discussed below in Section 2 demonstrate that the main Caribbean currents are prone to be unstable and calculations of energy conversion terms between mean flow (mean kinetic energy and mean stratification) and eddies confirm that the two fields exchange energy. Although the eddy field can transfer energy to the mean flow in some particular regions (Yucatan and Nicaraguan coasts), conversions of energy mainly benefit the eddy field. In addition, we noticed a close correspondence between regions of maximum conversion and regions where MEKE increases. Some regions are dominated by barotropic instability (e.g., the Cayman Sea), whereas other regions are dominated by baroclinic instability (Colombia and Venezuela Basins).

Topography and geography of the Caribbean Sea are quite complex (see Fig. 1 in Jouanno et al., 2008) and they might also have some local influence on both growth and decay of the eddy field. The main Caribbean Current (which we refer to here as the southern Caribbean Current, sCC) flows along the continental coast; our simulations show that the shape of the coast line and the narrowness of the Lesser Antilles passages accelerate the current and modify its instability properties. Topography and geography can also dissipate energy and destroy coherent structures. Altimetry data (Andrade and Barton, 2000) and simulations (Carton and Chao, 1999) show that most of the eastern Caribbean eddies seem dissipated by topographic features in the coastal waters of Nicaragua and do not reach the Yucatan Channel. Our simulations suggest that the strong decrease of MEKE along the Nicaraguan coast in association with an acceleration of the mean flow through the narrow Chibcha Channel allows the Cayman Basin to develop variability with its own particular characteristics.

Concerning a possible remote origin of the variability, the process most often proposed in the literature is the advection of NBC rings through the Lesser Antilles. They originate in the equator, where the reflection of long Rossby waves on the Brazilian coast generates a cyclonic-anticyclonic system which travels northwestward along this coast. Nonlinear interactions with the coast and the β-effect contribute to the growth of anticyclonic eddies (Jochum and Rizzoli, 2003) which can reach the narrow and shallow passages of the Lesser Antilles (Fratantoni et al., 1995). Carton and Chao (1999) suggest that the interaction of the incoming NBC rings with the topography around the Island of Trinidad and Tobago, results in pairs of cyclones anticyclones which become part and interact with the Caribbean Current. Murphy et al. (1999) also invoke the NBC retroflection and suggest that potential vorticity (PV) of the NBC rings is advected through the Lesser Antilles, and acts as finite amplitude perturbations for mixed barotropic and internal mode baroclinic instabilities which result in mesoscale features. Analyzing drifter data, Richardson (2005) proposes that anticyclones in the Venezuela Basin could originate with the vorticity advected by the NBC rings, hypothesis consistent with process studies on eddy flux through islands chains (Simmons and Nof, 2002; Tanabe and Cenedese, 2008). Nevertheless, drifters show few direct evidences of rings entering completely. Another process study demonstrates that Atlantic Rossby Waves can pass through ocean barriers such as the Lesser Antilles (Pedlosky, 2000).

Recently, Chérubin and Richardson (2007) proposed a link between the number of eddies in the eastern Caribbean, inferred from drifters, and the presence of the fresh water plume, which would enhance the potential vorticity gradients during August-December. It is interesting to contrast their results with surface geostrophic velocity anomalies derived from 15 years of altimetry data (AVISO). They indicate that the maximum of eddy energy in the eastern Caribbean occurs during June-July (see Fig. 1). Clearly, it is difficult to relate the arrival of the freshwater plume in the eastern Caribbean during August–December with the local maximum of eddy energy two months before and also use it as the source of energetic eddies all along the year. The arrival of the freshwater plume can certainly impact eddy generation and maintenance (e.g during the period September-November) but given the characteristics of the instability processes in the model and altimetry observations, it is difficult to make it the main source of variability in the eastern Caribbean.

So there is no consensus on what are the energy sources of the Caribbean eddies and questions remain open:

- What is the dominant process in the genesis of the most energetic Caribbean eddies?
- Which processes are responsible for the westward intensification of the eddy energy in the Caribbean Sea?
- What is the real impact of the NBC rings on the Caribbean eddy variability?

The aim of this paper is to try to answer these questions. The different numerical experiments used to solve this problem, as well as the characteristics of the Caribbean mean flow and eddy field, are described in part I of this study (Jouanno et al., 2008). As shown in part I, the most energetic mesoscale variability is embedded or occurs in the sCC, so we mainly focus on this current. We start by analyzing its conditions of instability in Section 2 and by examining in Section 3 the exchange between mean and eddy field along its core. In Section 4 we discuss how the various Carib-

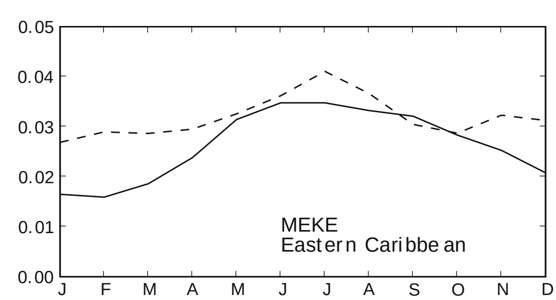

Fig. 1. Monthly Mean Eddy Kinetic Energy (MEKE) ($m^2 s^{-2}$) at the surface calculated with 15 years (1992-10-14 to 2007-04-18) of geostrophic velocity anomalies derived from altimetry data (solid line) and 6 years of surface velocity from NOSLIP experiment (see Jouanno et al., 2008). Surface velocities were sorted by month to compute monthly mean velocities. The monthly MEKE is then computed from velocity anomalies with respect to the corresponding monthly mean velocity. Results are averaged over the area 62–70°W, 11–18°N.