Dipole Rings and Vortex Interactions of the Brazil Current
Stanford B. Hooker and James W. Brown

Abstract—A reexamination of satellite-derived sea surface temperature imagery reveals many examples of Brazil Current rings, both warm and cold, in dipole configurations. The dynamical significance of the dipole model is established by considering the interaction of a cold (cyclonic) eddy with a warm (anticyclonic) ring. The ring is shown to exist as a dipole for about 60 days, or two rotation periods based on its original rotation rate of approximately 12° per day. The observed interaction of the dipole ring with a solitary (or monopole) cold eddy is complicated, but results in the two vortices coalescing. The latter point is particularly important, since coalescence between two eddies with opposing vorticities cannot occur if they are both monopoles—one of them has to be a dipole. After coalescence, the rotation of the dipole ring temporarily reverses due to the addition of cyclonic vorticity, but the original rotation of the dipole is reestablished after an adjustment phase.

I. INTRODUCTION

The most intense mesoscale oceanic eddies are formed from, or in conjunction with, strong western boundary currents. The importance of these eddies is a consequence of the nature of boundary currents which separate two distinctly different water masses. The Gulf Stream, for example, is the boundary between the cold, fresh Shelf and Slope Waters off the U.S. eastern coast and the warmer, saltier Sargasso Sea. In the absence of eddy formation, mixing between these water masses would be greatly curtailed. Eddies allow the redistribution of momentum, chemicals, and biota across frontal zones [19], and permit the transfer of energy from the boundary to mid-ocean areas by transient eddies [6] and dispersive effects [4].

The strongest western boundary currents are the Gulf Stream, the Kuroshio, and the Agulhas, and the weakest are the East Australian and Brazil Currents. Although the latter transport approximately one-tenth the fluid of the former, they all produce mesoscale eddies or rings. The process of ring formation involves the growth, extension, and then relaxation of a current meander. When an extended southward meander of the Gulf Stream pinches off in the Sargasso Sea, for example, a cyclonic or cold core ring (CCR) is formed; the ring is made up of a core of Shelf Water trapped inside a cyclonically rotating current of Gulf Stream water, the so-called high-velocity region. An anticyclonic or warm core ring (WCR) is formed in a similar fashion when a shoreward meander isolates a large volume of Sargasso Sea water north of the Gulf Stream. Ring formation takes several weeks which necessarily limits how many rings can be formed over the course of an annual cycle. Estimates of the frequency of ring formation in the Gulf Stream system, for example, suggest approximately 5–8 of each type are formed each year [16], [7], and [1].

Rings have variable lifetimes, which depend on their formation location and how quickly they move out of the generating area and away from the source current. Irrespective of the details of their environment, the physics of their propagation has been explored by a number of investigators. Mied and Lindemann [15], for example, have shown they move westward at approximately 5 cm s⁻¹ with a small meridional velocity component, decaying as they make their way back to the western boundary where they are ultimately reabsorbed by the jet that produced them. Decay mechanisms include dispersion, instability, interaction with mean flow, small-scale friction, and surface wind mixing [19]. The historical picture of rings treats them as isolated features (no comparable temperature extrema are nearby) with a monopolar circulation (the azimuthal velocity field is unidirectional). The importance of rings is derived from their ability to transport a large volume of anomalous water across great distances while vigorously stirring the fluid surrounding them.

Much of what is known about rings has been obtained from a diverse set of worldwide measurements. One of the most useful tools for studying the oceanic mesoscale is satellite instrumentation, because it delivers synoptic views previously unavailable with in situ measurements. The Advanced Very High Resolution Radiometer (AVHRR) is used to derive images of sea surface temperature (SST) and is an important data set because of its synoptic coverage. Hooker and Brown [9] reanalyzed historical AVHRR data from the western North Atlantic using a new visualization scheme, the so-called zebra palette. They found some fundamentally new results previously undetected by either traditional oceanographic measurements or the original analysis of the AVHRR data. In particular, WCR 82-B, the second Gulf Stream WCR to form in 1982 and a repeated subject of the Warm Core Rings Program [12], was actually a dipole for much of its lifetime. Moreover, the rotation of the secondary cyclone around the primary anticyclone was a constant 14.5° per day for a 2-mo period beginning in late March.

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Holdzkom et al. [8], also used zebra palettes and showed 82-B was in a dipole configuration throughout its 6-mo life cycle. In the later stages, the dipole configuration was found to be due primarily to an edge vortex which initially formed during a Gulf Stream interaction and was subsequently maintained by repeated interactions with the Gulf Stream for the rest of the ring's life. This was confirmed by Hooker et al. [10] who also showed how the AVHRR imagery could only be reproduced if a dipole model were used to force the evolution of a simulated Slope Water regime—a monopole model could not reproduce the SST data.

The wider applicability of the fundamental dipole nature of some Gulf Stream rings was established by Hooker et al. [11] who developed a new analytical method for investigating dipoles and showed other WCR's and CCR's existed in dipole configurations. This new method involves estimating the time evolution of the separatrix, or dividing line, between the two circulation centers. In SST data, the separatrix is usually expressed as a narrow region of increased contrast. For a dipole system, the separatrix is a line of convergence that flattens the local curvature of the eddies (thereby producing a D-shaped primary vortex) and which necessarily rotates at the same rate as the whole system. The changing angular position of the separatrix is, therefore, an estimate of dipole rotation. The reliability of the estimate is a function of how well the separatrix can be discriminated. Although the separatrix is visible in imagery displayed with gradient or banded palettes, it is seen more clearly using the zebra palette.

The significance of these results is clear: Gulf Stream rings need not always assume a monopole configuration—long-lived dipoles are possible. More importantly, the discovery of CCR dipoles eliminates the possibility that the dipole configuration is unique to WCR’s, perhaps due to a topographic interaction between the primary (anticyclonic) eddy and the steep continental slope topography. The presence of open ocean dipoles suggests a fundamental new model for rings should be seriously considered, but an important question posed by Hooker and Brown [9] remains unanswered: Are dipole rings found in other current systems?

II. BRAZIL CURRENT RINGS

Off the coast of Brazil, the warm Brazil Current flows southwestward along the continental shelf. Further south, the cold Falkland Current flows northeastward along the coast of Argentina from its origin as a branch of the Antarctic Circumpolar Current. The two currents meet within the 35–40°S latitude band and then flow seaward. This area of confluence is typified by a complex pattern of meanders and eddies that form from the two currents. Although Southern Hemisphere boundary currents are weaker than their Northern Hemisphere equivalents, and apparently form fewer rings, Brazil Current rings are, nonetheless, dynamically similar to Gulf Stream rings [17].

Fig. 1 is a compendium of Brazil Current rings from 1989 AVHRR global area coverage (GAC) data having a nadir resolution of approximately 4 km. The topography of the observation area is shown in Fig. 1(a). The rings shown in Fig. 1(b)–(g) are WCR’s and the rings in Fig. 1(h)–(i) are CCR’s; all of the rings shown have counterrotating companions. The paucity of dipole CCR observations is the result of seasonal surface warming which obscures the ring’s presence during the summer months. When CCR’s are close to the boundary current they formed from, however, the warmer water entrained around its periphery produces enough thermal contrast to delineate both circulation centers [11].

Many rings were found in the 1989 data set, and all of them were in dipole configurations; virtually none of them were sufficiently isolated during periods of cloud-free viewing that a full rotation of the secondary vortex around the primary vortex could be studied. Although a sequential viewing of the imagery clearly established the rotation of the dipole, any estimates of the rotation rate would be based on so few images as to make them inappropriate for comparison to previous work. Two exceptions to this are the dipole CCR shown in Fig. 1(i) and a dipole WCR which is not presented in Fig. 1 because it is the subject of a detailed investigation in the next section.

Fig. 2 shows the separatrix orientation of the dipole CCR from Fig. 1(i) as a function of time. This ring is close to the jet and interacting with it. The rotation rate of the dipole is simply the slope of the fitted line: approximately 7.2° per day. The rotation of a dipole system is determined by a number of factors including the size of the eddies, their vorticities (or swirl velocities), and the proximity of the dipole with respect to other features. The weaker flow of the Brazil Current suggests Brazil Current dipole rings might rotate more slowly than their Gulf Stream counterparts, but the close proximity of the jet for the CCR in Fig. 1(i) is probably the most likely reason for the lower rotation rate—the jet acts to block the steady motion of the secondary eddy around the primary, thereby slowing the rotation rate.

III. EDDY–EDDY INTERACTIONS

Given the small number of rings formed annually, the opportunities for eddy interactions involving rings are statistically limited and there are very few observations of them. Indeed, one of the least observed mesoscale phenomena is coalescence or fusion. Cresswell [3] observed the merger of two anticyclonic East Australian Current rings into a single eddy off the southeastern coast of Australia. The two warm core eddies coalesced in about 20 days as their centers rotated about a point on the line joining them. Elliott [5] suggested the western part of the Gulf of Mexico is an area of active coalescence for rings generated by the Loop Current, which was confirmed by Lewis and Kirwan [14], and observed one such merger in that area.

These observations are in areas where the topography acts to limit the western translation tendency of rings and, thus, enhance the opportunities for interaction. If the definition of a ring is expanded to include any wrapped-up piece of a major current [17], either surface or subsurface, the intriguing merger of two Mediterranean Water eddies or meddies [18] can be included into the (small but growing) database of coalescence observations.
Fig. 1. The topography of the Brazil Current observation area (a) along with a selection of WCR's (b)-(g) and CCR's (h)-(i) from 1989 AVHRR GAC data. The geographic location of each ring is keyed to (a), that is, (b) is located by the rectangle labeled "b" in (a).

The paucity of eddy-eddy interaction observations is curious given the extensive use of remote sensing imagery used to map the ocean surface. Although there are probably many reasons for this, two reasons seem particularly relevant. First, the role of this sensor in oceanography has usually been ancillary, with the instrument being used in support of traditional oceanographic methods. Second, the interpretation of mesoscale data has very often focused on the most apparent (i.e., monopole) features in the spatial variability. This has resulted in a misinterpretation of the flow field and how it is interacting. The synergy of these two approaches has resulted in a preference for imagery that fits the accepted (monopole) model and an underrepresentation of imagery that does not.

The Falkland confluence would appear to be an excellent area to look for eddy-eddy interactions, since cold (cyclonic) eddies form from the Falkland Current and warm (anticyclonic) rings form from the Brazil Current in a small area topographically confined by the continental shelf to the west and south (Fig. 1(a)). Adding to the confining geometry and the interaction opportunity is the jet itself which limits the translation range of the eddies under any circumstance, but its meandering can also push the circulation features closer together. All of this should increase the probability of eddy interactions.

A convenient measure of the strength of a ring is the area-integrated vorticity \( \nabla \times \mathbf{v} \), which is related by Stokes' theorem to the circulation \( \Gamma \)

\[
\iint_A \nabla \times \mathbf{v} \, dA = \oint_{\partial A} \mathbf{v} \cdot \mathbf{n} \, dl = \Gamma
\]
where \( A \) is the area of the eddy. In a monopole model of eddy interactions, four types of interactions are possible between two finite area circulations \( \Gamma_A \) and \( \Gamma_B \):

1) \( \Gamma_A = \Gamma_B > 0 \), which leads to circular motion with coincident orbits. The vorticity field of one eddy can induce shape deformations in the other; and if they are sufficiently close, they will exchange mass or coalesce.

2) \( \Gamma_A = -\Gamma_B \), which leads to parallel linear motion with shape deformation.

3) \( \Gamma_A > \Gamma_B > 0 \), which leads to circular motion with concentric orbits and shape deformation. Again, if the eddies are close enough they will exchange mass or coalesce.

4) \( \Gamma_A > |\Gamma_B| > 0 \), where \( \Gamma_B < 0 \), which leads to parallel circular motion and shape deformation, but not merger.

Although the eddies influence one another by altering each other’s shape and translation, the only destructive interaction—mass exchange or coalescence—occurs if the two eddies have the same circulation and are sufficiently close to one another. For barotropic eddies with similar vortical intensities, merger takes place if they have a center-to-center separation on the order of three eddy radii [20].

A monopole WCR from the Brazil Current cannot coalesce with a monopole cold eddy from the Falkland Current because the two eddies have opposite circulations—they can only pair up and thereby influence each other’s trajectory and shape. As has already been shown, however, some WCR’s appear to be dipoles. Since a dipole has two oppositely signed circulations, several new interactions are possible. In particular, vortex coalescence with a monopole is a possibility.

Fig. 3 contains a sequence of AVHRR images from the Falkland Confluence (Fig. 3(a)) during the latter part of 1989. The first image (Fig. 3(b)) shows a WCR dipole to the south and a monopole cold eddy to the north. Although the eddies are almost 200 km apart, a warm streamer of fluid can be seen stretching from the western side of the dipole (which defines the farthest extent of its second circulation center) all the way up to the cold eddy. A week later (Fig. 3(c)), the cold eddy has moved further south and the WCR has rotated counterclockwise (CCW) almost 90°. The two features are still interacting as evidenced by the continuing presence of the warm streamer.

Over the next 12 days, the cold eddy moves steadily southward while the dipole continues its CCW rotation. The two eddies increasingly interact with one another and, to a much lesser extent, with the Brazil Current to the east. The phasing of the dipole’s rotation is such that as the cold circulation core rotates around the warm core, it is positioned to immediately interact with the cold eddy and the two coalesce. The interaction process involves a slowing and then reversing of the dipole’s rotation so that it is rotating clockwise (CW) once coalescence is complete—evidently the combined vorticity from the two cyclones exceeds the vorticity associated with the anticyclone and forces a new rotation direction. Not surprisingly, the original dipole appears larger and more energetic at this point in time (Fig. 3(d)). Apparently, the interaction event involves the creation of a third cyclonic center which forms immediately to the southwest of the anticycloic pole.

The circulation of the third pole intensifies over the next 10 days; although it is smaller than the other cyclonic pole, its vortical wrapping appears quite clearly in Fig. 3(e). This image also shows warm Brazil Current water being advected into the multipole system, which is driven by the other two poles. The third pole acts to retard the CW rotation, which was established immediately after coalescence, and over the ensuing week (September 29 to October 5) the original CCW rotation of the WCR is reestablished (Fig. 3(f)). At this point in time, the full complexity of the system is revealed: the third pole has weakened and rotated CCW, the interaction with the Brazil Current has diminished, another small cyclonic pole can be seen to the north of the multipole system, and the two larger poles are rotating CCW more rapidly. Note the two smaller poles are axially symmetric with respect to the other larger poles—the line joining their centers crosses through the center of the separatrix dividing the larger poles.

Four days later (Fig. 3(g)), the system is in the middle of an adjustment period lasting approximately two weeks. The anticycloic pole is peanut-shaped with spiral arms of warm fluid being ejected to the north and south. This type of mass adjustment process is reminiscent of coalescence signatures seen in numerical models [20]. Although the southernmost spiral arm appears to interfere with the entrainment of warm water from the Brazil Current, it does not prevent its occurrence. There is also a steady strength diminishment of the two extra cyclonic poles and their axial symmetry with respect to the dipole; part of the degradation is a consequence of the southernmost cyclone interacting with the Brazil Current. Once the adjustment period is over, the rotation of the dipole increases, the two additional cyclonic poles are no longer visible, and the dipole translates off to the northwest (Fig. 3(h)).
Fig. 3. (a) The topography of the Falkland Confluence and (b)-(d) a sequence of images showing the interaction of a Brazil Current WCR and a Falkland Current cold eddy.

An idealized schematic of the interactions depicted in Fig. 3 is presented in Fig. 4. In this abbreviated summary, the entire sequence is divided into four phases. The initial interaction phase (Fig. 4(a)) includes the starting geometry of the eddies (Fig. 3(b)) and their approach to one another (Fig. 3(c)). The eddy coalescence phase (Fig. 4(b)) is dominated by the fusion of the cold eddy with the dipole’s cyclonic pole, the formation of a third cyclonic pole, and the reversal of the dipole’s rotation (Fig. 3(d)). The vortical adjustment phase (Fig. 4(c)) involves the continuing evolution of the third cyclonic pole (Fig. 3(e)), the formation of a fourth cyclonic pole (Fig. 3(f)), and the mass adjustment of the anticyclone (Fig. 3(g)). The extra cyclonic poles are no longer present in the final phase (Fig. 4(d)), and the dipole is smaller in size, rotating more rapidly, and moving northwestward (Fig. 3(h)).

The interaction sequence is also well summarized by considering the time evolution of the dipole’s separatrix which is presented in Fig. 5. The basic expressions of the system idealized in Fig. 4 are seen distinctly as separate periods of constant rotation. During the initial interaction of the WCR dipole and the cold eddy, the rotation of the dipole is approximately $-12.1^\circ$ per day (circles). Once the cold eddy coalesces with the dipole, the rotation completely reverses to approximately $7.9^\circ$ per day (squares). Part of the coalescence response is the generation of a third cyclonic pole which ultimately acts to help slow, and then reverse, the rotation of the system.
(crossed squares). The adjustment of the multipole system after coalescence results in an increase of the reestablished CCW rotation rate (diamonds) to approximately $-1.2^\circ$ per day. The reduction in mass of the anticyclonic pole yields a smaller more rapidly rotating dipole (triangles) with a rotation rate of approximately $-5.8^\circ$ per day, which is almost half the original rotation rate of the dipole ($-12.2^\circ$ per day).

**IV. CONCLUSIONS**

The motivation for this investigation was to discover if rings in another western boundary current, besides the Gulf Stream, express themselves as dipoles. Although the formation mechanism for the many examples of Brazil Current dipoles shown in Fig. 1 is unknown, the existence of both warm and cold dipole eddies demonstrates the ubiquity of this new model for rings. The longevity and resistance to disruption of these dipoles are best demonstrated by considering two points.

1) The WCR studied in Fig. 3 existed as a dipole for approximately 60 days (or two rotation periods based on its original rotation period of approximately 30 days).
2) The observed interaction of the WCR with a cold eddy appeared to be coalescence, which requires a dipole given that the two features contained opposing vorticity, and not simple pairing, which could occur with two monopoles.

The second point is the most compelling, since the longevity of ring dipoles has been reported elsewhere ([8] and [10]). Dipole rings would be vortically more active than monopole
The opportunity for fusion in a multipole system also suggests fission should be possible, since it frequently involves a multipole forcing geometry [2].

The formation of dipole rings from both strong (Gulf Stream) and weak (Brazil Current) western boundary currents suggests dipole ring formation does not depend on the strength of the current. Consequently, dipole rings should be found in the western boundary currents not considered so far, like the Kuroshio. Of course, each western boundary current has unique factors associated with the topography of the region and the presence of other currents or fronts, so differences in the range of dipole expressions are probably inevitable. In the case of the Kuroshio, for example, the Oyashio front north of the jet should provide an obstacle to the steady rotation of many WCR dipoles thereby producing a population of dipole rings with a larger number that rotate more slowly.

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