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An objective reference system for studying rings in the ocean

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ABSTRACT

Rings are marine vortices with a scale of hundreds of kilometers that can last for months, whose associated transport and mixing play an important role in the ocean dynamics. Such features are traditionally treated as a geostrophic flow, but since the centrifugal acceleration is not negligible in the inner core, the cyclo-geostrophic balance is a better approximation for the rings. In the present work, we describe a novel objective technique to identify the ring center, which is used as the origin of a convenient framework to handle rings under the cyclo-geostrophic balance. Furthermore, we correct the velocity field by the translation to isolate the swirl movement, a procedure ignored by other methodologies. We show that the lack of such correction would lead to an error of 30 km on the center definition of a ship surveyed North Brazil Current Ring with 160 km of radius. Another distinct characteristic of our approach is the flexibility in the spatio-temporal structure of the data, because it allows for ungridded data, an important ability for *in situ* observations. That also enables the use of a hybrid dataset composed from different instruments. The error on the Monte Carlo experiments to identify the center of the propagating ring is less than 10 km, and depends on the level of noise, sampling strategy, and strength of the ring, among other factors. This technique was fully implemented in PyRings, an open Python library with a collection of procedures to handle oceanic rings and mesoscale eddies in general.

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1. Introduction

The term *ring* was initially used to describe eddies detached from meanders of the Gulf Stream, carrying anomalies through the jet front. Later, its use was extended to include all intense eddies, or vortices, that carry enclosed water masses from major currents around the globe, as the Kuroshio, Agulhas, East Australian and Brazil Currents, among others (Olson, 1991; Fuglister, 1972). Rings can last from weeks to months and propagate along hundreds to thousands of kilometers, and therefore are an important process in transporting anomalies of physical, chemical and biological properties (Olson, 1991).

The relevance of the rings goes beyond the mixing on its own scale. The Agulhas Current Rings, for example, are closely related to the leakage from the Indian to the Atlantic Ocean and subsequent transport along the Meridional Overturning Circulation (MOC) (Beal et al., 2011; Souza et al., 2011). Further northwest, the North Brazil Current Rings (NBCR) have its turn, and transports over half of the warm return flow of the Atlantic MOC (Johns et al., 2003; Fratantoni et al., 2000). Mixing enhancement parameterization cannot alone explain such complex dynamics, and for that reason, high-quality climate simulations require eddy resolving numerical models to achieve adequate global budgets (Kirtman et al., 2012). The rings are an important piece of the puzzle, thus the precision on which it is handled is relevant to the quality of the explained ocean dynamics.

The widely used geostrophic approximation is not the most adequate for studying rings, since the centripetal acceleration is non-negligible. Instead of that, a cyclo-geostrophic balance is required, which is more conveniently handled in a cylindrical coordinate system (Holton, 2004; Olson, 1991). Transforming the velocity data from the commonly used Cartesian coordinate system into a cylindrical coordinate system requires a high-quality identification of the ring center. The recent improvements on the observation systems, the advance of numerical simulations and the establishment of consistent remote sensing methodologies allows study of the rings with an unprecedented quality. However, to fully take advantage of that, it must be followed by a more careful technique of handling the rings. To attend this specific demand, a novel objective technique to identify the center of propagating rings is presented in detail here.

The technique proposed here has its origins in 2004, during an oceanographic cruise, when Dr. Johns designated the task of better identifying the center of NBCR from Acoustic Doppler Current Profiler (ADCP) data. At that point, the first prototype was based in

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brute force technique to maximize the kinetic energy associated to a ring. That approach evolved while it was being used to study the NBCR (Castelão and Johns, 2006, 2011), and now it is generalized to extend to other rings and mesoscale eddies. The main characteristics of this technique are reproducibility, robustness, freedom on the data position to be used, and building with as minimal initial constraints as possible, without requiring interpolation. Therefore, this is an objective framework for automated analysis of operational procedures and the processing of large volumes of data. PyRings[1] is an open Python[2] library with a collection of procedures to handle rings and mesoscale eddies in general. It was planned to take over three major problems, the first one being presented here: identifying the ring center in an objective and robust way and extracting its characteristics.

This paper is organized as follows – first we review other methodologies to identity the ring center (Section 2), then we explain our method in detail (Section 3), discuss the improvements and limitations (Section 4), and evaluate our performance (Section 5). A summary is presented in Section 6, followed by a list of symbols in the appendix.

2. Overview on other methodologies

During the last decades, several methods to identify rings, and determine their centers with accuracy, have been developed among oceanographers. Most of them were recently reviewed by Chelton et al. (2011) and are based either on physical or geometrical properties of the rings. The Winding-Angle (WA) method (Portela, 1997; Sadarjoen and Post, 2000; Chaigneau et al., 2008) detects eddies by selecting looping streamlines and clustering them. For a given streamline S_i, the center $\overline{S_i}$ is obtained by taking the average of all the points of that streamline. Then, the streamline centers are grouped in clusters, C_k, one for each vortex. For a given cluster, the eddy center $\overline{C_k}$ is defined as the average of the streamline centers belonging to that cluster: $\overline{C_k} = 1/\,|C_k| \sum_{n=1}^{n=|C_K|} \overline{S}_{k,n}$, where $|C_k|$ is the number of streamlines in the cluster number k.

Another approach to determine the position of the ring centers, also based on averages, was applied by Isern-Fontanet et al. (2003) and Chelton et al. (2007), using the Okubo–Weiss (OW) method (Okubo, 1970; Weiss, 1991). The geostrophic velocities are estimated from sea surface height (SSH) data, in order to calculate the main dynamic properties of the flow field, such as relative vorticity (ζ) and normal (S_n) and shear (S_s) components of the strain tensor. These properties are then used to compute the Okubo–Weiss parameter ($W = S_s^2 + S_n^2 - \zeta^2$). Eddies are generally characterized as regions where vorticity dominates strain, which corresponds to negative values of W. Therefore, each eddy is identified by finding closed contours of $W < W_0$, where W_0 is the background threshold value. The center of each eddy is finally defined as the geometrical mean of SSH within the contour of W.

Nencioli et al. (2010), applied a vector geometry-based algorithm (VG) to detect eddies on the velocity vector fields from numerical model and high frequency radar surface velocities in the Southern California Bight. The eddy centers were marked at points where all the following constraints were simultaneously satisfied: Along a meridional (zonal) section, the zonal (meridional) component of the velocity has to change its sign across the eddy center and its magnitude has to increase as you move from the center to the eddy edge; the eddy center corresponds to a local minimum of velocity magnitude; around the center, the velocity vectors must change keeping the same sense of rotation; and at least one component of two neighboring velocity vectors must have the same sign.

Furthermore, another method using model output was proposed by Doglioli et al. (2007), based on the wavelet analysis of modeled relative vorticity ζ. The relative vorticity is expanded on the basis that minimizes a cost function. Then, only the wavelets with the largest coefficients are used to reconstruct a smoothed field for which eddies are identified as connected regions where $\zeta \neq 0$ and the center of each eddy is defined as the grid point of local maximum of $|\zeta|$.

All the methods presented so far require regular gridded data. A solution adopted in the case of a single section, like along track altimetry (Goni and Johns, 2003) or virtual section composed from a mooring (Johns et al., 2003), was to consider the section coincident to the ring center and treat it as a lower bound size estimate. In the case of multiple sections, the ring center was manually defined. The manual identification was also used in altimetric maps (Fang and Morrow, 2003) and drifters (Fratantoni and Richardson, 2006).

3. Ring center identification

One way to identify and track rings is through fundamental rotating fingerprint on the velocity field ($\vec{V}$). The Cartesian system (x, y) is widely used among oceanographers, defining u and v as the zonal and the meridional velocity components, respectively. However, a more convenient way to handle rings is using instead a cylindrical coordinate system, defining the azimuthal (v_θ) and the radial (v_r) components as

$$v_r = u\ \cos(\theta) + v\ \sin(\theta), \tag{1}$$

$$v_\theta = -u\ \sin(\theta) + v\ \cos(\theta), \tag{2}$$

where $\theta = \arctan(y_r/x_r)$, and x_r and y_r are the Cartesian position of each velocity measurement in respect to the center of the cylindrical coordinate system (x_0, y_0). Thus, the magnitudes of the azimuthal and the radial components depend on the choice of the reference (x_0, y_0), but the absolute velocity, $|\vec{V}| = \sqrt{u^2+v^2} = \sqrt{v_\theta^2 + v_r^2}$, is preserved independently of the reference. Fig. 1 illustrates the notation used here.

For a stationary ring, the horizontal momentum can be well approximated by the cyclo-geostrophic balance (Holton, 2004),

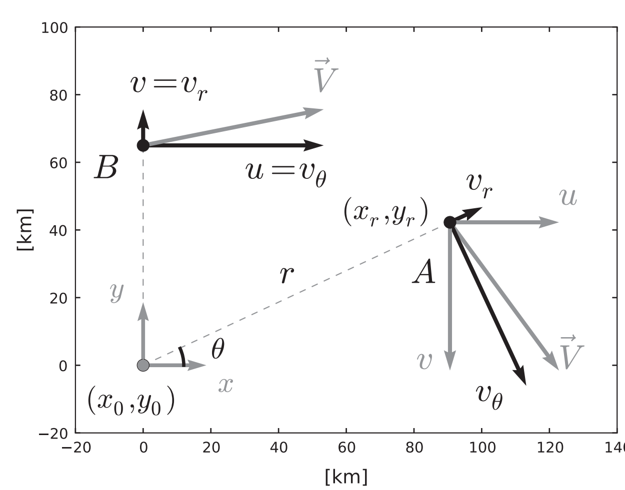

Fig. 1. Examples of the cylindrical coordinate transformation with the used nomenclature, considering the center at (0, 0). The v_r and v_θ are the same in both cases, A and B, but $\vec{V}$, u and v are, hence, different. Not all variables are shown for the B case.

[1] http://pyrings.castelao.net
[2] http://www.python.org/

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