Detection, monitoring and kinematic analysis of a mesoscale turn based on in situ observations and satellite altimetry data in the Colombian Caribbean Sea basin

Detección, seguimiento y análisis cinemático de un giro de mesoescala a partir de observaciones in situ y datos de altimetría satelital en la cuenca Colombia–mar Caribe

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Abstract

Some physical variables were analyzed in the southwest Caribbean Sea during the lifetime of a cyclonic eddy detected initially by in situ observations with seven CTD profiles. After verifying satellite altimetry data, it was noted that this eddy showed a sea level anomaly of -0.1 m within the transect of CTD stations and -0.2 m in its center. It was possible to observe a vertical influence from the cyclonic eddy down to a depth that ranged between 350 and 400 m, with surface currents between 20 and 70 $cm \cdot s^{-1}$. Using an algorithm to detect and track eddies' centers, it was possible to establish an approximate lifetime of 40 days and its birth in an instability between the flow of the Panamá – Colombia Gyre (GPC) and a previous eddy that transited through the center of the basin days before. Likewise, it was determined that the eddy in its firsts days moved north with a velocity of 7.45 km/day, which afterwards accelerated up to 21.1 km/day while moving on the NW between days 10 and 20 (when it entered the main flow of the Caribe current). This eddy was last tracked moving in SW direction with a velocity of 16.94 km/day, finally delivering its kinetic energy to the GPC, to the southeast of Providencia Island.

KEYWORDS: mesoscale, eddy, hydrodynamic, vorticity, San Andrés Island, Colombia basin.

Resumen

Se analizaron algunos factores físicos durante el tiempo de vida de un giro ciclónico de mesoescala detectado inicialmente mediante observaciones in situ con siete perfiles de CTD, en el mar Caribe suroccidental. Con datos de altimetría satelital se constató que este giro presentó una anomalía del nivel del mar de -0.1 m en el transecto de estaciones y de -0.2 m en su centro. Se pudo observar una influencia vertical del giro ciclónico hasta una profundidad entre 350 y 400 m, con corrientes superficiales entre 20 y 70 $cm \cdot s^{-1}$*. Así, implementando un algoritmo para detección y rastreo de centros de giros de mesoescala, se estableció la fecha aproximada de nacimiento y desaparición del giro, estimando un tiempo de duración de 40 días y origen en una inestabilidad entre el flujo del giro Panamá – Colombia (GPC) y un eddy que transitó por el centro de la cuenca en días anteriores. Se estableció que el giro en sus primeros días se desplazó hacia el norte con una velocidad de avance de 7.45 km/día y luego aceleró hasta 21.1 km/día con dirección NW entre los días 10 al 20 del mes, al ingresar al flujo principal de la corriente del Caribe. Su último trayecto registrado tuvo un rumbo SW con una velocidad de 16.94 km/día, para finalmente entregar su energía cinética al GPC al sureste de la isla de Providencia.*

PALABRAS CLAVE: *mesoescala, eddy, hidrodinámica, vorticidad, San Andrés Isla, cuenca Colombia*.

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Introduction

The Colombian Basin is the sector of the Caribbean Sea limited by Central America and Colombia on its western, southern, and eastern borders, and by the islands of Jamaica and Hispaniola to the north. The Beata mountain chain range to the east separates it from the basin of Venezuela, and the Central American elevation separates it from the Cayman Sea to the west. Among its main circulatory features are the recirculation of the Caribbean Current called Giro Panama Colombia (GPC) and its coastal arm over South America, the countercurrent Panama Colombia (Andrade, 2009). This basin houses the Seaflower Biosphere Reserve, which covers an approximate area of 180 000 km^2, corresponding mainly to the extension of the Archipelago of San Andrés, Providencia and Santa Catalina, a Colombian territory 480 nautical miles northwest of the continental territory formed of 10 islands, banks and depressions. This archipelago is distinguished by having one of the highest rates of marine biodiversity in the Caribbean Sea (Colombian Ocean Commission, 2015).

It is well known that there is a strong mesoscale activity in the Caribbean Sea, whose nature and local and regional effects on hydrodynamics, transport of properties, and their interaction with the atmosphere are currently under study (Torres & Tsimplis, 2014; Montoya, 2014, Andrade, 2015, Guerrero, 2016). The mesoscale gyres or 'eddies' are ubiquitous features of the circulation of the Caribbean Sea, playing an important role in the dynamics and environmental conditions (Jouanno *et al*, 2012). It has been shown, for example, that eddies in the Caribbean Sea transport nutrient-rich waters to the west that are trapped in their vortex when the filaments from the upwelling of La Guajira extend northward, entering the path of the eddies from the basin of Venezuela (Andrade & Barton, 2005).

Most of the characteristics of the mesoscale turns in the Caribbean Sea are inferred from analysis of satellite altimetry data, which constitute the only source of continuous multiannual data, given the scarcity of in situ data (Jouanno *et al*, 2008). The 6 primary missions of satellite altimetry (ERS-1, Topex/Poseidon, ERS-2, Envisat, Jason-1, Spot) and the 6 missions carried out to date by cruiser (Sentinel-3, Jason-2, Jason- 3, Saral, HY-2 and Criosat), account for a global time series of continuous altimetry since 1992.

It has been determined in previous investigations that the most energetic gyres are anticyclonic, and that they get bigger as they move towards the Colombian Basin. The mechanisms of both generation and subsequent growth have been attributed to the instabilities within the Caribbean Current and the force of the wind in the center of the Caribbean Sea. To this are added some results of numerical models that propose the influence of eddies produced in the North Brazilian Current (Jouanno *et al*, 2012).

The topography and geography of the Caribbean Sea in general is very complex, a situation that also greatly influences both the growth and the weakening of the mesoscale gyres. Satellite altimetry data and simulations show that a large number of eddies are dissipated by topographic features in the waters off the coast of Nicaragua (Jouanno *et al*, 2009), the Central American elevation, and the archipelago of San Andrés, Providencia and Santa Catalina.

In depth knowledge of these structures, which dominate the mesoscale hydrodynamics in the basin, is important due to their fundamental role in the advection of energy, variation of sea level, and oceanic properties. This affects dynamics, ocean-atmosphere interaction, and human activities such as fishing and aquaculture (Matsuoka *et al*, 2016). The present investigation intends to contribute to the knowledge available on this subject in the Colombian Basin, by making a description of the observed characteristics of a cyclonic gyre detected simultaneously with in situ samplings and data from satellite sensors.

Study area

From 19-21 September 2016, seven oceanographic stations with conductivity, temperature, and depth profiles (CTD) of up to 1 000 meters were carried out on board the oceanographic research vessel ARC Malpelo, between the islands of Providencia and Cayo Bajo Nuevo (Figure 1).

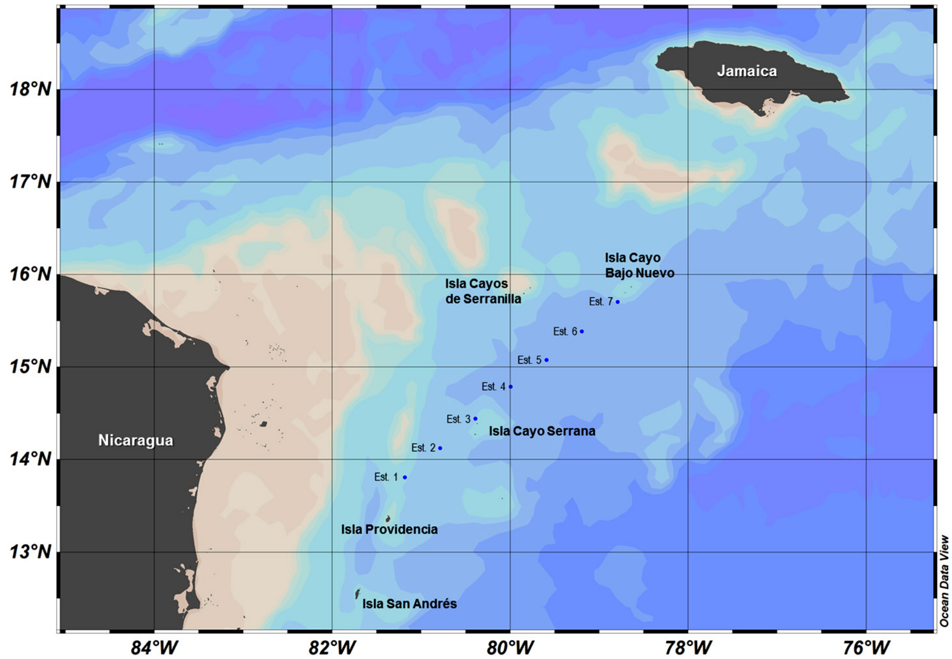

Figure 1. CTD sampling stations from September 19-21, 2016.

This zone corresponds to the north of the Archipelago of San Andrés and Providencia, a group of islands belonging to Colombia in the Caribbean Sea and which also constitute the Seaflower biosphere reserve, which covers a significant area of 180 000 km^2. Andrade *et al.,* (1996) describes this set of islands as having a volcanic origin, the insular shelf being independent of the Central American continental shelf, and separated by the Providencia depression with depths of up to 2400 m.

Methodology

Geostrophic velocity

From the seven CTD profiles carried out, a geostrophic velocity transect was calculated using the geostrophic flows calculation tool of the Ocean Data View software. This tool derives geostrophic velocities from dynamic height differences between hydrographic stations in two steps: 1) Data from two contiguous stations are converted to standard depths by the least squares method in a linear regression; 2) the dynamic heights in the standardized depths are calculated and the geostrophic velocity is obtained from the differences in these heights. In addition, the transect is interpolated with the Variational Analysis Tool for Data Interpolation - DIVA (Schlitzer, 2016).

Satellite altimetry

For the initial detection of mesoscale events in the area of in situ measurements, the information was consulted for September 20, 2016 from the multimission product processed by the *Segment Sol multimissions d'Altimétrie, d'Orbitographie et de localization précise (SSALTO) and the Data Unification and Altimeter Combination System* (DUACS) distributed by the French program Archiving, Validation and Interpretation of Satellite Ocean Data (AVISO). This data set corresponds to the reference series of AVISO, which joins data from at least two simultaneous satellite missions, resulting in a homogeneous spatial distribution, projected on a grid of 1/4 ° relative to an average of 7 years (AVISO, 2016).

Sea surface velocity fields

The surface velocity information used in the present work was that generated by the Ocean Surface Current Analyses Real-time (OSCAR) project of the Earth and Space Research Institute

(ESR, 2009). This information is calculated from anomaly gradients of satellite altimetry (all available sensors), surface wind vectors and sea surface temperature fields, using analysis of geostrophic dynamics, Ekman, and winds. The spatial and temporal resolution of the data used is 1/3 ° and 5 days, respectively, and a total of 20 years were used between 1996 and 2016, in the area of the Caribbean Sea known as the Colombian Basin.

From the velocity fields (with the components u and v), the average flow components $\langle u \rangle$ and $\langle v \rangle$ were calculated for the entire series. From this field, the anomaly fields u' and v' were obtained, subtracting the average component of each field in the whole time series, in order to filter the average flow and be able to analyze in more detail the mesoscale processes:

$$u' = u - \langle u \rangle$$

$$v' = v - \langle v \rangle$$

Gyre detection and tracking method

The algorithms for the detection and automated tracking of eddies can be classified into two main groups: physical algorithms and geometric algorithms. The former perform an analysis of specific physical characteristics, classified according to a threshold, which can group certain sectors of the altimetry field and recognize them as eddies. The second group analyzes the vector field of currents calculated from satellite altimetry and its function for currents, in order to locate the centers and extension of each eddy. Several studies on the subject (McWilliams, 1990, Sadarjoen & Post, 2000, Doglioli *et al.,* 2007, Chaigneau *et al.*, 2008, Nencioli *et al.*, 2010), have promoted new ways of improving or even combining the algorithms in order to locate eddies much more effectively, mainly by minimizing the exceedance or the omission of detections of eddies and their characteristics in two dimensions.

In the present investigation, the methodology proposed by Nencioli *et al.,* (2010) was used to detect the centers of the eddies (Figure 2). It consists of evaluating 4 characteristics of the vector field of the zonal and meridional components of the velocity, which are:

1. In the east-west direction, the velocity v has to change polarity along the center of the eddy, and its magnitude has to increase as it moves away from it (Figure 2a).

2. In the north-south direction, the velocity u has to change polarity along the center of the eddy, and its magnitude has to increase as it moves away from it; the direction of rotation must be the same detected fo*r v* (Figure 2b).

3. The magnitude of the velocity has a local minimum at the center of the *eddy (*Figure 2c).

4. Around the center of the eddy, the directions of the vectors must change with a constant rotation direction, and the directions of two neighboring velocity vectors must be in the same or adjacent quadrant, when analyzed on a Cartesian plane (Figure 2d).

With this method, the fields of anomalies u 'and v' were analyzed, between September 01 and October 11, 2016, the dates on which the beginning and end was detected of the cyclonic eddy found during the dates of the samplings of CTD.

RESULTS

Seven profiles of CTD were obtained in the stations indicated in Figure 3. The analysis shows a surface density around 1022.9 kg·m^{-3} for all the stations. The lower limit of the pycnocline was established between 180 m (station 1) and 230 m (station 7), observing a gradual deepening, in a SW-NE direction. The profiles converge close to 630 m depth, corresponding to a density value of 1 030 kg·m^{-3} (Figure 3c).

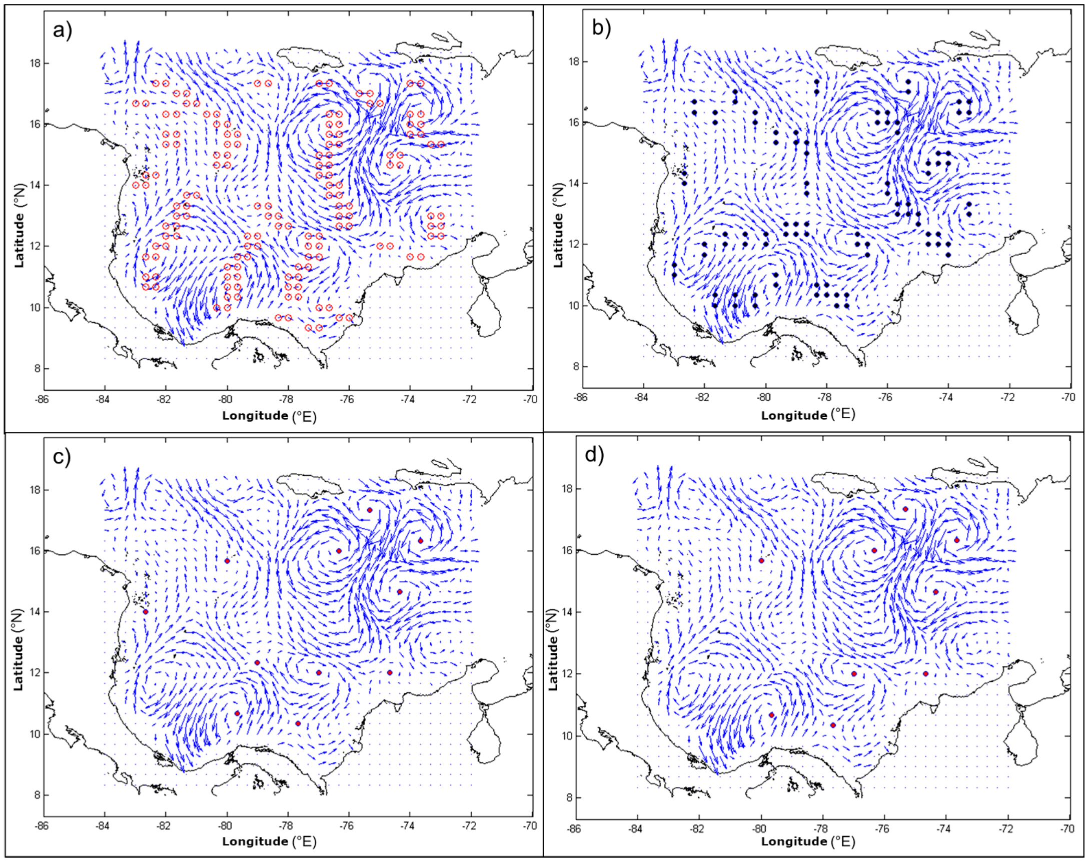

Figure 2. Step by step in the detection of eddy centers using the method proposed by Nencioli *et al.,* (2010). With a field of tested anomalies of surface velocity calculated from altimetry data, corresponding to February 10, 1997: a) Location of data pairs v' with a polarity change in the x direction. b) Location of data pairs u' with a polarity change in the y direction. c) Matching points between the first two criteria, which are also local minimums in their neighborhood. d) Eddy centers determined by having a sense of consistent rotation within a certain area around it.

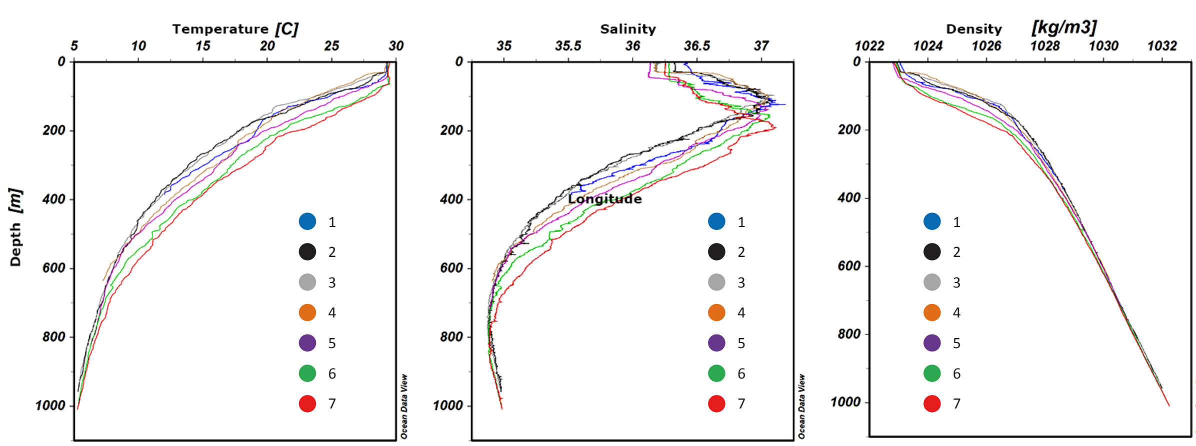

Figure 3. Temperature profiles (a), salinity (b) and density (c) for the 7 CTD stations carried out between September 19 and 21, between Providencia Island (station 1) and Cayo Bajo Nuevo Island (station 7).

When building the density transect with the CTD stations (Figure 4), it can be seen that the isopycnal do not have constant depth in the layers over 300 m deep. This indicates a mesoscale flow taking place in the area during the dates of the stations. The above was corroborated with the image of Sea Level Anomaly (SLA), taken from the AVISO database for September 20, 2016 (Figure 5).

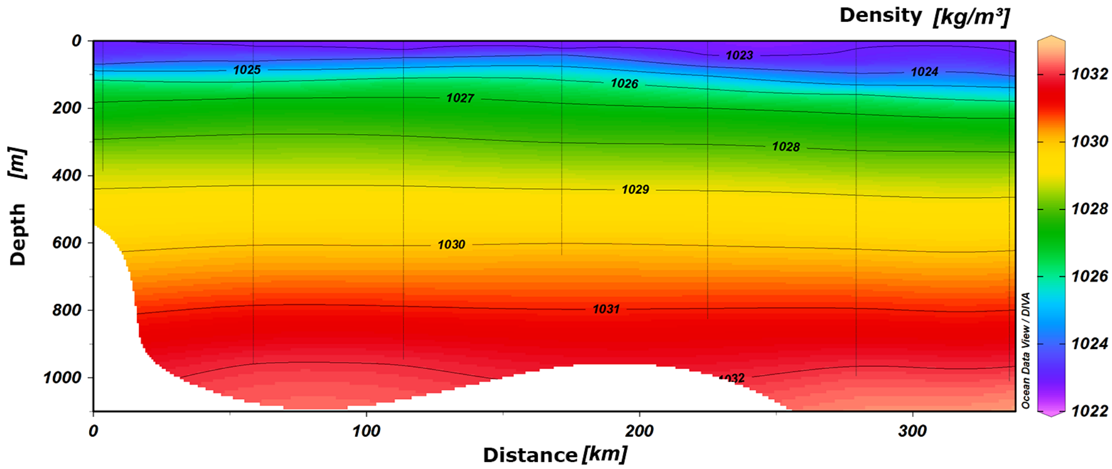

Figure 4. Density transect calculated from the 7 CTD stations carried out between September 19 and 21, 2016 from Providence Island (distance 0) to Cayo Bajo Nuevo Island. The vertical lines represent each CTD station.

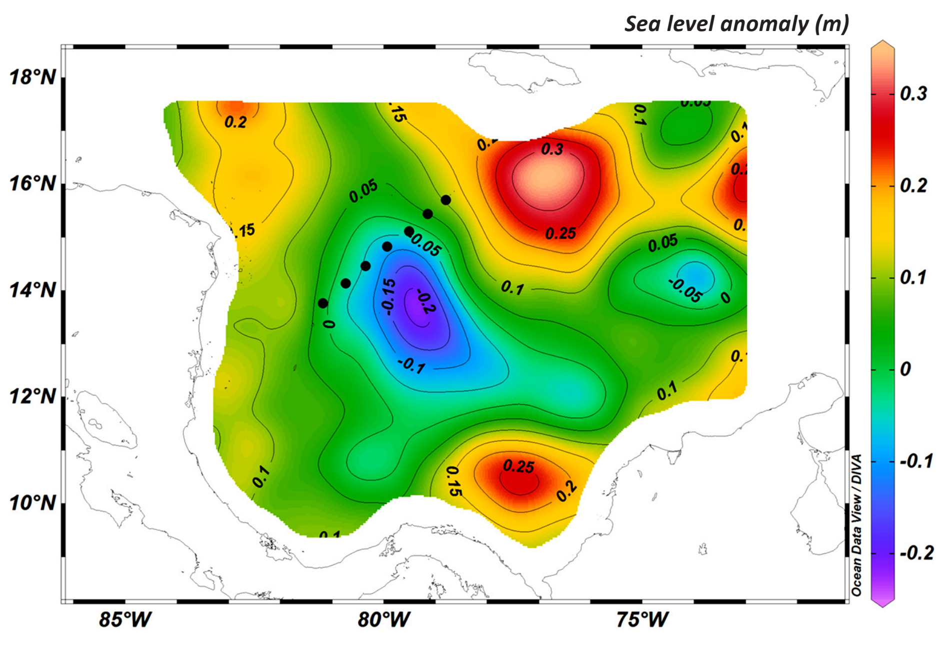

Figure 5. Sea level anomaly field (in meters) for September 20, 2016 in the Colombian Basin calculated from satellite measurements. The black dots indicate the transect of CTD stations illustrated in Figure 4. Source: database AVISO+.

The SLA field (Figure 5) for the Colombian Basin (20-Sept-16), shows that for the station dates anomalies of sea level appeared between 0.1 and -0.1 m approximately, which is reflected in the behavior of the isopycnal of the transect, and the variation of depth of the pycnocline observed in the CTD profiles (Figure 4). Within the time series of the velocity field for the Colombian Basin obtained from the OSCAR project, the date closest to those of the stations is September 21, which was the last day of sampling. As can be seen in Figure 6 ,there is a cyclonic eddy present in the area of the stations, strongly influenced by another anticyclonic eddy to the northeast, which is also seen in Figure 5 with a positive anomaly of more than 30 cm. This generates a strong current resulting between the two, in the NW direction with a maximum velocity of approximately 0.8 m·s^{-1}, and a velocity near the sampling stations of 0.4 - 0.5 m·s^{-1}.

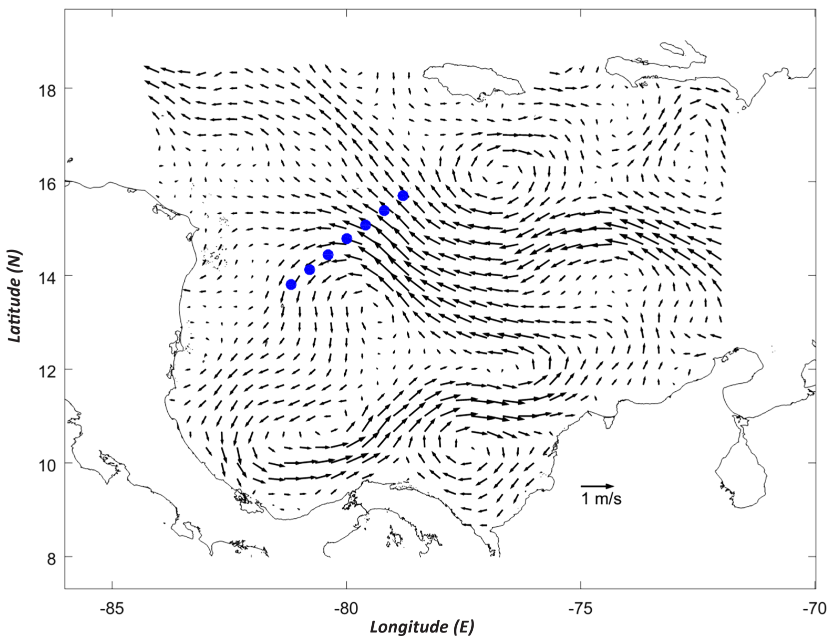

Figure 6. Total surface velocity field calculated for day 21-Sept/16 from OSCAR project data. The blue dots indicate the location of the CTD stations carried out between September 19 and 21, 2016. Source: ESR-OSCAR.

The velocity field of Figure 6, although it shows the great flow created by the cyclonic and anticyclonic circulation between Jamaica and the island of Providencia, does not show the mesoscale eddies in their full extension, since the average flow plays a very important role. For the same day, when the average flow of 20 years for the period (1996-2016) was removed, the mesoscale circulation and the eddies present on that date in the Colombian Basin can be more clearly appreciated (Figure 7).

The velocity calculations obtained from satellite altimetry, mainly by the ESR-OSCAR, agree withthe geostrophic velocity calculations made with the data from the CTD stations, taking the depth of 1 000 m as the reference layer (V = 0), shown in (Figure 8). A maximum geostrophic velocity of 0.4 m·s^{-1} is observed perpendicular to the transect, and a flow in the southeast-northwest direction through stations 4 to 7, with an opposite flow in northwest-southeast direction between stations 1 and 2. In the middle of the transect, an area of movement close to zero is observed, which is located around station number 3 (Figure 8).

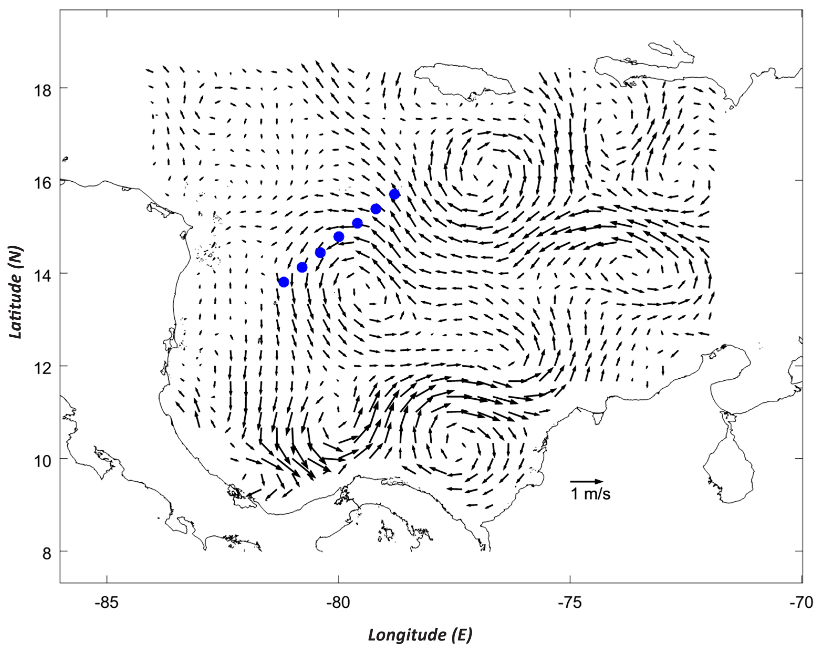

Figure 7. Surface velocity anomaly field for day 21-Sep /16. The blue dots represent the location of the CTD stations carried out between September 19 and 21, 2016. Source: ESR-OSCAR.

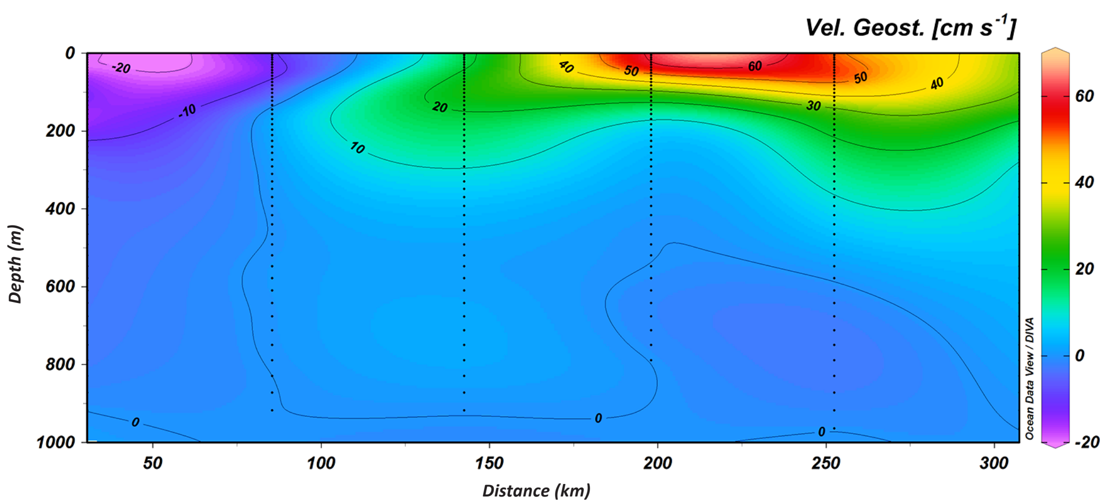

Figure 8. Geostrophic velocity transect calculated from the 7 CTD stations carried out between 19 and 21 Sept/16.

In the calculated geostrophic velocity transect, it can be observed that the influence in the water column of the cyclonic gyre reaches approximately to a depth of between 300 and 400 m, with speeds between 0.8 (bottom of the eddy) and 70 cm·s^{-1} (surface). The high velocities registered between the 200 and 250 kilometers of the transect, result from the combination of velocity and an anticyclonic gyre towards the north of the stations, clearly visible in (Figure 7).

In order to study its movement, the cyclonic gyre was localized using the methodology proposed by Nencioli *et al.,* (2010), applying it to the velocity anomaly field of day 21-Sept/16 (Figure 7). As a result, the center of the gyre (which was identified as EC1) could be traced in the field on 21 Sept/16, and the center could be located in the other velocity fields of previous currents, available every 5 days. This exercise made it possible to locate its approximate origin, 270 km NW of Cartagena around 1 Sept/17, apparently as a result of the instability in the meanders formed between the Panamá–Colombia gyre, and the central flow of the Caribbean Current. This instability seems to have been caused by the passage of a large cyclonic gyre several days before (Figure 9a). It is possible that what happened was a division of this primordial gyre, when losing stability given its great extension.

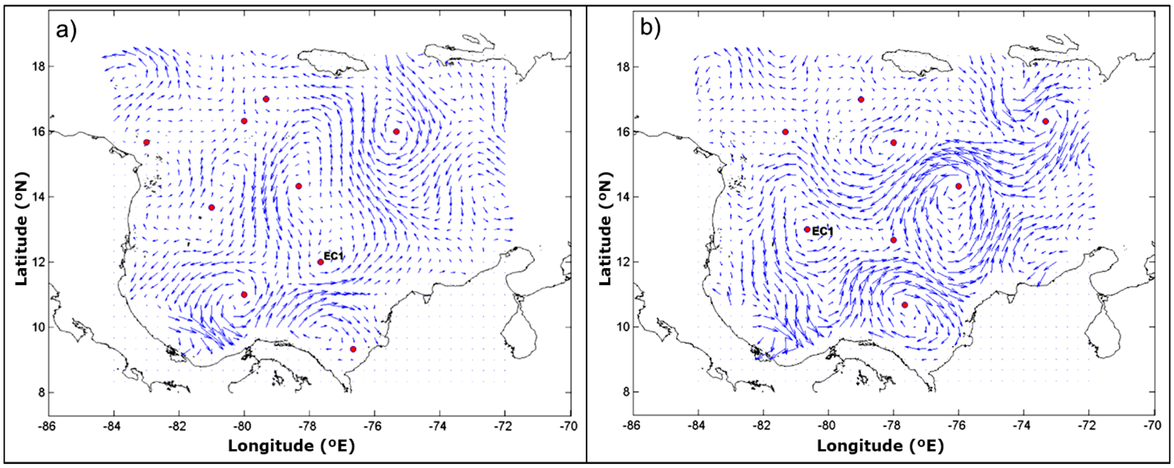

Figure 9. Surface velocity anomaly fields for 1-sept/16 and 11-oct/16, with the result of the rotation center localization algorithm. The EC1 center was formed near the coast of Colombia and ended its life near the island of Providencia.

From the date of detection (Figure 9a), it was monitored with the gyre tracking algorithm set on the detected center EC1. As a result, the center disappeared around October 11 (Figure 9b), with a life expectancy of approximately 40 days (Figure 10). In its first 10 days of life, the eddy moved northward advancing at a speed of approximately 7.45 km/day, covering half of the basin, covering a distance close to 74 km. Then it went towards the NW, probably due to meeting the main flow of the Caribbean current, increasing its advancing speed to 21.1 km/day.

Around its 20th day, while the seven stations described initially were being carried out, the system began to take a SW course at an approximate speed of 16.94 km/day, pushed south by the strong anticyclonic eddy close to Jamaica (Figure 10), to exist for another 20 days until disappearing 100 km SE of Providencia island, returning its kinetic energy to the flow of the Panama - Colombia.

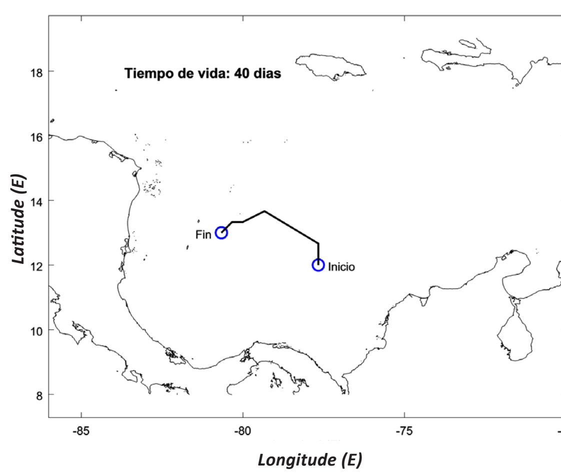

Figure 10. Monitoring of eddy EC1 during its life time in the Colombian Basin.

Discussion

The results obtained in the calculation of the geostrophic velocity (Figure 8) agree with that described by Andrade (2015) for the same climatic period of 1997 in a transect of six CTD stations between the island of Providencia and Cayo Bajo Nuevo, finding at that moment, a surface current of 0.4 m·s-1 and an incidence in depth up to around 350 m. In this opportunity, it can be considered that there is a representative horizontal movement, up to a depth of 400 meters.

This behavior makes it possible to deduce that the instabilities caused by flows found between the GPC, the Caribbean Current and other mesoscale events moving east - west, can produce new eddies. These develop within the basin, with a high probability of remaining there and returning their energy to the GPC or the Caribbean current. Richardson (2005), suggests three possible mechanisms for the formation of eddies within the Colombian Basin: the first, would consist of the shearing effect of the Caribbean current upon entering the basin and moving away from the coast of Colombia; the second, as a "piece" formed to the east of the GPC that is separated from the more intense flow that occurs towards the west; and the third, as an inverse result of the anticyclones formed to the south of Hispaniola, by a local maximum of the rotor of the wind stress that coincides with the cyclonic movement. Jouanno *et al.,* (2009), suggests a fourth mechanism: instability in the GPC that would have the capacity to generate eddies. The cyclonic eddy analyzed seems to have a component of the second mechanism suggested by Richardson (2005). However, the previous presence of a large eddy in the center of the basin (also cyclonic), apparently contributed greatly to its formation, suggesting that it is a "piece" of this large eddy that separated off with the help of the GPC, and not the other way around. Therefore, the proposal of Jouanno *et al.,* (2009) could not apply in this case either, because it was not exclusively generated by the GPC.

The disappearance of the eddy EC1 in the Archipelago of San Andrés and Providencia can be explained in accordance with what was established by Andrade and Barton (2005), where it was observed that the larger eddies are weakened by topographic effects rather than by other mechanisms. After day 20, the cyclone entered the archipelago with an extension of ~ 330 km in diameter, enough to interact with the topography of both the islands and the continental shelf of Central America.

The dynamics of the eddies can be monitored by means of a data assimilation algorithm of the sea level anomaly. In (Lonin & Anduckia, 2004), an attempt was made to relate the level of the sea with the profiles of temperature and salinity. In (Lonin, Torres, Díaz & De la Rosa, 2008), the method was extended to the fields of water density, obtained in situ simultaneously with the satellite measurement of the level throughout an orbit. According to the results obtained in the present investigation, the sea level variation of 0.1 m (Figure 5), corresponds to an isopycnal inclination between 180 and 230 m (Figures 3 and 4). In this case, the difference in hydrostatic pressure dP = 1 000 Pa, approximately. The latter corresponds to a bias between the density profiles dh = dP/g $(\dot{\rho}_0 - \rho_h)$, where g is gravity and ρ is the density that varies between 1025 and 1027 kg m^{-3} in the respective layer. The application of the last formula gives the value dh = 50 m, exactly equal to the difference between the depths of 180 and 230 m.

Conclusions

It was previously possible to determine the existence of a cyclonic eddy from in situ observations, performing the geostrophic velocity calculation from vertical profiles of CTD. This was also useful to establish an approximation of the depth of incidence of this cyclonic eddy, which was located between 300 and 350 meters. This is an important indicator that is consistent with that explained by Carlton and Yi (1999), where an eddy is observed at a longitude of 70 ° W that is confined to the thermocline (~ 200 m); but close to Nicaragua at a longitude of 80 ° W, a greater penetration is observed, up to 600 m within the water column. Through systematic observations of this phenomenon within the Colombian Basin and in other locations in the Caribbean Sea, the mechanisms that deepen this vertical incidence could be established with greater certainty. It can be thought in this case that the large original cyclonic eddy from which the detected eddy was detached, also had this vertical structure which was ceded at the moment of detachment.

It is very interesting to observe another eddy formation mechanism within the Colombian Basin, the alteration and transformation of larger eddies due to the shearing effect with the GPC. This can be directly related to the extension of the coherent structure of the eddy, which probably exceeds Rossby's deformation radius and becomes more sensitive to any force upon it.

The behavior of the cyclone studied since its formation, reveals three stages of life. An early stage in which it gains size as it moves northward with a moderate rate of advance; an intermediate stage in which it is affected by the main flow of the Caribbean Current and changes its course towards the northwest at a much faster rate, and with a continuous increase in its horizontal extension; and a final stage in which it is displaced by an anticyclone from the north and is also affected by the topography and geography of the San Andrés archipelago. It then continues on a southwest course, finally reaching the continental shelf of Central America and the GPC, and ceasing its existence as an organized structure. Each stage is the kinematic response of the vortex to a series of forces: birth and growth: shearing action between the GPC and a cyclonic formation in the middle of the basin; intermediate age: the combination of relative movement and the momentum of both the Caribbean Current and a large anticyclone to the north; decline and disappearance: tangential force from an anticyclone moving northeast – southwest, and the effect of friction with insular and continental land masses, and changes in bathymetry.

For a better understanding of the real effects of mesoscale eddies in the transport of surface and subsurface characteristics of the Colombian Basin, it is essential to continue with their study trying to combine field observations and satellite data. Due to the presence of the upwelling of La Guajira on the border with the Venezuelan Basin, it would be important to establish a mechanism for calculating nutrient availability in the western area of the Colombian Basin, with the early detection of the passage of the eddies and their capacity to retain the properties of the upwelling waters. This could be a significant productivity indicator for areas such as the archipelago of San Andrés and Providencia.

Acknowledgements

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