Oceanographic conditions of the Seaflower biosphere reserve 2014-2016

Condiciones oceanográficas de la reserva de biosfera Seaflower 2014–2016

DOI: 10.26640/22159045.449 **Reception date:** 2018-07-13 **/ Acceptance date:** 2018-09-20

Claudia J. Dagua P.*, Ricardo R. Torres P. & Julio C. Monroy S.*****

Dagua, C., Torres, R. & Monroy, J. (2018). *Oceanographic conditions of the Seaflower biosphere reserve 2014–2016.* Bol. Cient. CIOH (37):53-74. ISSN 0120-0542 and ISSN online 2215-9045. DOI: 10.26640/22159045.449

Abstract

As part of the Seaflower Scientific Expedition, on board of the research vessel "ARC Providencia" of Colomiba's Maritime Directorate – DIMAR, two oceanographic research cruises were done in 2014 and 2016 in the San Andres, Providencia and Santa Catalina Archipelago in the Caribbean Sea. During these campaigns, the physical conditions of the water column were measured at 46 stations between the island-cays Roncador, Serrana and Quitasueño, in two different climatic seasons, March-April of 2014, and August of 2016. In this work, a general description of the observed oceanographic conditions during the two cruisers is presented, as well as a comparative assessment of the representative conditions for each season, including the behavior of the Isotermal Depth Layer (IDL), which showed spatial and temporal variability between the two cruisers. Furthermore, the ocean and atmospheric conditions of the 7th of April 2014 are described, as produced by a cold front which entered this day to the Caribbean Sea, and marginally affected the area of study. Differences were found in the water column behavior between the 2014 and 2016 campaigns, due to the season in which the cruise was done, with higher temperature and salinity values in the later, corresponding to the rainy season affected by the Midsummer Draught. The effect of wind and mesoscale eddies in the IDL variability was assessed, but a dominant forcing could not be determined.

KEY WORDS: Seaflower, physical oceanography, cold front.

Resumen

En el marco de la Expedición Científica Seaflower, en los años 2014 y 2016, empleando la plataforma de investigación ARC Providencia de la Dirección General Marítima, se realizaron dos cruceros de investigación oceanográfica en el archipiélago de San Andrés, Providencia y Santa Catalina, en aguas del mar Caribe. Durante estas dos campañas, se midieron las condiciones físicas de la columna de agua entre las islas cayos de Roncador, Serrana y Quitasueño, con la recolección de 46 perfiles de temperatura, salinidad y presión, en dos épocas climáticas diferentes, marzo-abril de 2014 y agosto de 2016. En este trabajo se presenta la descripción general de las condiciones oceanográficas observadas durante estas campañas y se hace un análisis comparativo de las condiciones representativas de cada época, incluyendo un análisis del comportamiento de la profundidad de la capa isotermal, la cual mostró variación espacial y temporal en los dos cruceros. De igual forma, se describen las condiciones océano atmosféricas el 7 de abril de 2014, producidas por un frente frío, fenómeno meteorológico que ingresó en esa fecha al mar Caribe y afectó marginalmente el área de estudio. Se encontraron diferencias en el comportamiento de la columna de agua entre la campaña de 2014 y la campaña de 2016, lo que está asociado con la época en la que se desarrolló cada crucero, con valores mayores tanto de temperatura como de salinidad, para la campaña de 2016, correspondiente a la época de lluvia afectada por el veranillo de San Juan. Se analizó el efecto del viento y giros de mesoescala en la variabilidad de la capa isotermal, sin lograr determinarse un forzante dominante.

PALABRAS CLAVE: *Seaflower, oceanografía física, frente frío.*

* Caribbean Oceanographic and Hydrographic Research Center (CIOH). E-mail: cdagua@dimar.mil.co
** Universidad del Norte (Uninorte). E-mail: rrtorres@uninorte.edu.co
*** Almirante Padilla" Naval Academy, Colombian Navy. E-mail: julio.monroy@armada.mil.co

Introduction

The Biosphere Reserve (BR) Seaflower has become one of the most representative icons of the maritime protection in Colombia. Since its declaration as a biosphere reserve in the year 2000, it is shown as an important conservation strategy in situ and it is a sustainable development scenario, where the ecosystem services, as well as the natural and cultural heritage are preserved (Murillo & Ortiz, 2013).

The General Maritime Directorate, Dimar, as the Colombian maritime authority, has led and developed scientific maritime research in the Archipelago of San Andres and Providencia since 1972, generating projects and publications of great interest, contributing in this way to the exercise of the Colombian sovereignty in the biosphere reserve Seaflower. The DIMAR's Oceanographic and Hydrographic Research Center of the Caribbean (CIOH), deployed its scientific and operational knowledge in the years 2014 and 2016, to support this new initiative of interinstitutional cooperation in the search for deepening the knowledge about the Colombian maritime territories.

The oceanographic conditions observed in the expeditions recorded during March-April 2014 and August 2016, are described in the present investigation. In the same way, it is sought to explore how these oceanographic conditions were affected by the presence of a cold front that entered to the Caribbean Sea on April 07th 2014, during the first cruiser.

Study area

The study area is located in the Caribbean Sea, specifically in the Archipelago of San Andrées, Providencia and Santa Catalina, composed of the islands of San Andres, Providencia, Santa Catalina; island cays of Albuquerque, East, Southeast, Roncador, Serrana, Quitasueño, Serranilla, and Bajo Nuevo, as well as the other islands, islets, cays, hillocks, banks, low tide elevations, and reefs adjacent to each one of these islands, in accordance with decree 1946 of September 9th 2013.

Unesco declared on November 9th, 2000, as a world reserve of "Seaflower" biosphere, three hundred thousand square kilometers (300 000 km^2) of the archipelago; this reserve derives its name in memory of the first English Puritan ship arrived at San Andrés in 1631 (Espinosa, 2001). The oceanographic campaigns of 2014 and 2016 were carried out between meridians 81.6º W and 79.9º W and between latitudes 13.4º N and 14.8º N, in the vicinity of the northern cays (Figure 1).

The seasonal variability of the atmosphere in the Caribbean Sea is governed by the position of the North Atlantic Subtropical High (NASH) that influences in the position of the Intertropical Convergence Zone (ICZ) and at the same time, that determines the precipitation rate (Montoya, 2014). Thus, the climate patterns in the region are determined by the annual migration of the ICZ, generating wet and dry seasons (Montoya, 2014). From December to April (dry season), when the ICZ is located further south (around 2°N), the trade winds from the northeast are very intensive, causing a weakening of the rains and an increase in upwelling processes in the coast of Venezuela and Colombia (Andrade & Barton, The Guajira upwelling system, 2005).

The rest of the annual cycle (May to November) the cloud coverage, associated with the presence of the ICZ in the center of the Caribbean Sea causes the increase in the precipitations. In this wet season, the winds decrease and the heavy rains modify the salinity (and density), and consequently, the surface current (Montoya, 2014; Andrade C., 1991). Figure 2 shows the climatology of the wind speed and direction in the Caribbean Sea, for the months in which the expeditions were carried out in 2014 and 2016 and figures 3, 4 and 5 show the climatological information on temperature, salinity and surface currents for the same time period.

During the months of July and August, the rainy season is interrupted by a minimum of rainfall in the Caribbean. This relatively dry period is known as mid-summer drought (MSD), or Indian summer (Wang, 2007; Small & Szoeke, 2007).

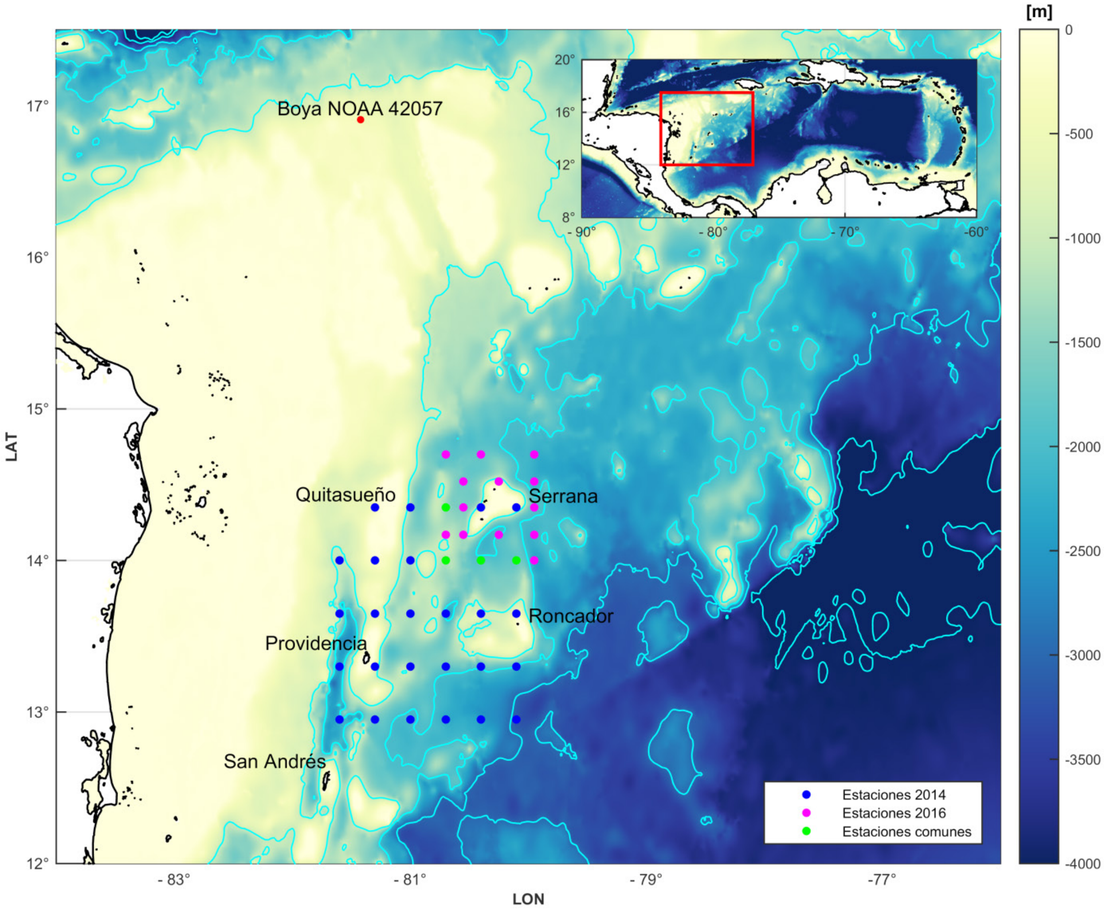

Figure 1. Study area indicating the bathymetry (Source: GEBCO) in colors. The stations sampled are represented with color dots. In blue, the stations sampled in 2014, in magenta, the stations sampled in 2016 and in green, the stations sampled in both campaigns. The NOAA 42057 buoy closest to the study area is also shown (16.90° N and 81.42° W). The cyan lines show the cliffs of 1000 m, 2000 m and 3000 m.

The passage of cold fronts in the boreal winter produces intense meteorological events in the Caribbean Sea (Mooers & Maul, 1998; Ortiz, Otero, Restrepo, Ruiz, & Cadena, 2013). Cold fronts may reach low latitudes, altering the weather conditions on these zones. These events in the Caribbean are characterized by an intrusion of cold air towards latitudes between 30° N and 10° N, a high-pressure gradient in the low troposphere (generated by a high pressure, characterized by a cold air mass and a low pressure due to the ICZ) and a subsequent abrupt intrusion of cold air in the tropic (Hastenrath, 1991).

The effect of the fronts is the increase in the speed and the change of direction in the surface winds, due to the high-pressure gradients. When these fronts become seasonal, they may produce surges lo sufficiently strong to generate floods and affect the coastal morphology in the Caribbean (Andrade, Thomas, Lerma, Durand & Anselme, 2013; Lerma, Thomas, Durand, Torres & Andrade, 2008; Torres & Tsimplis, 2014).

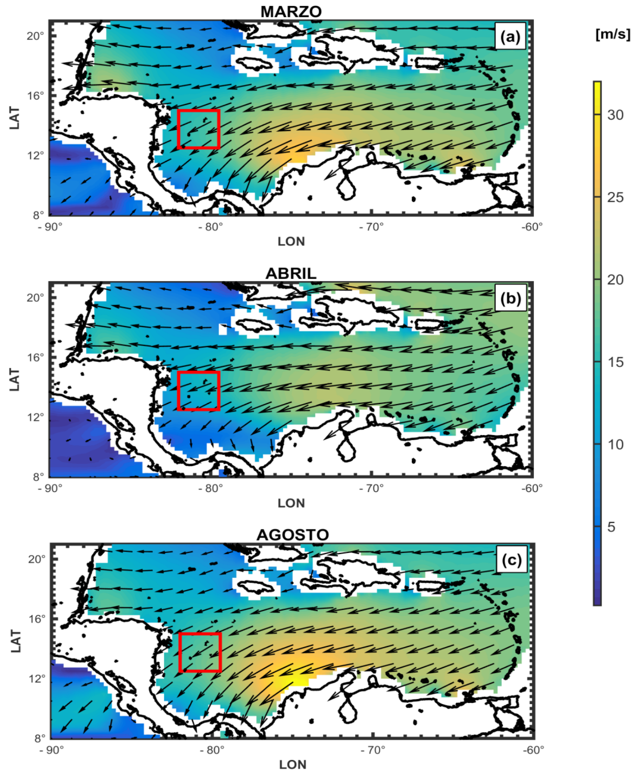

Figure 2. Climatological data on wind strength and direction in the Caribbean Sea for the months of (a) March; (b) April and (c) August, months in which the data collection from the expeditions 2014–2016 was carried out. The red square indicates the zone sampled. (Taken from: NARR re-analysis).

The temperature in the upper part of the ocean shows important seasonal and interannual variations, specifically in tropical latitudes. This upper layer of between 25 and 200 m deep usually have the same temperature of the sea surface due to the intense mixture that happens mainly by the atmospheric forcing (Montoya, 2014). The seasonal variability of the water properties in the Surface layer of the Caribbean Sea has been associated mainly with the influence of the rotation of the effort of the surface wind and the fresh water discharges from the continent (Chelton, 2004; Ruiz-Ochoa, Beier, Bernal & Barton, 2012; Montoya, 2014); At interannual scales, the region is influenced by the remote forcing given by the occurrence of ENSO events in the eastern equatorial Pacific (Enfield, Mestas-Núñez, Mayer & Cid-Serrano, 1999; Montoya, 2014). Figure 3 shows the climatological data on the surface temperature of the sea for the sampled months of the stations from World Ocean Atlas version 2013 data. In the same way, the information contained in the Atlas on the Oceanographic Data of Colombia 1922-2013 was consulted (Andrade, Rangel & Herrera, 2015), and concordant values in water temperature and salinity were found.

Table 1. Climatological values on surface temperature of the water and salinity, approximate for the Biosphere Reserve Seaflower, during the sampling months according to the Atlas on the Oceanographic Data of Colombia.

Month / Parameter	Surface temperature of the sea (°C)	Salinidty
March	27.5	36.2
April	28	36
August	29	35.8

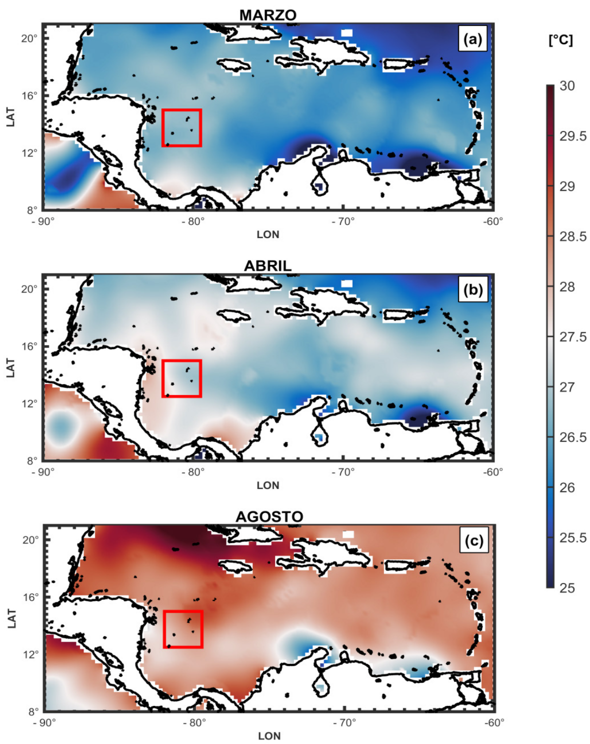

Figure 3. Climatological data on surface temperature in the Caribbean Sea for the months of (a) March; (b) April and (c) August, months in which the data collection from the expeditions 2014 – 2016 was carried out. The red square indicates the zone sampled. (Taken from WOA 2013).

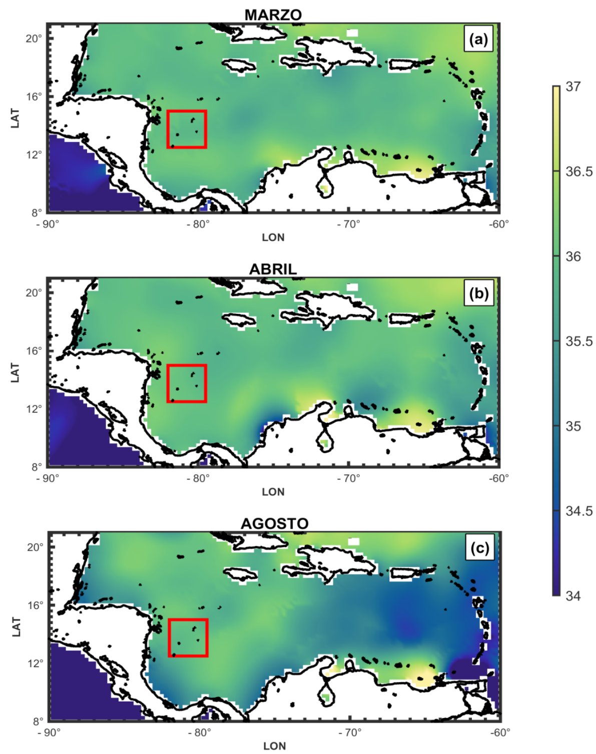

Figure 4. Climatological data on water salinity n in the Caribbean Sea for the months of (a) March; (b) April and (c) August, months in which the data collection from the expeditions 2014 – 2016 was carried out. The red square indicates the zone sampled. (Taken from WOA 2013).

The Caribbean current that dominates the circulation in the study area (Figure 5), is oriented zonally and transports the waters that enter through the existing passages between the islands located in the east and is displaced through the Yucatán Channel to the Gulf of Mexico (Montoya, 2014). The eddy Panama-Colombia dominates the circulation in the south of the Colombia Basin (Andrade & Barton, 2000); (Mooers & Maul, 1998); (Richardson, 2005), with a marked seasonal variability (Torres & Tsimplis, 2012). Jouanno, *et al.,* (2008), found dynamic differences between the different inner basins of the Caribbean Sea, organizing primarily in two jets and also determining that the meso-scale activity is stronger when it passes from the Venezuela Basin to the Colombia Basin.

An archipelago is an insular territory located in the intertropical zone, affected by different meso-scale factors, such as the cyclonic and anticyclonic whirlwinds transported by the Caribbean Current, which contribute with the generation of extremes of the sea level in the Caribbean (Torres & Tsimplis, 2014). Moreover, it is located on a submarine topography that shows diverse geoforms, which generates a complex oceanographic dynamic.

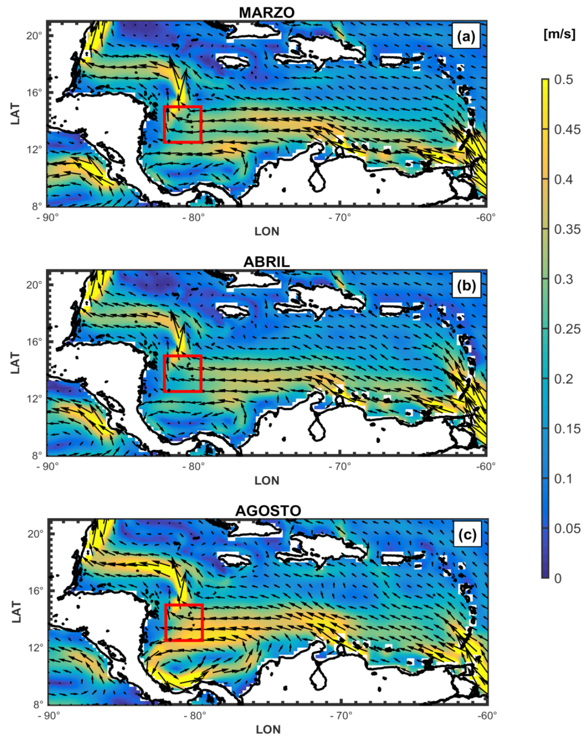

Figure 5. Climatological data on surface currents in the Caribbean Sea for the months of March (left), April (center) and August (right), months in which the data collection from the expeditions 2014–2016 was carried out. The red square indicates the zone sampled. (Taken from COPERNICUS project).

Materials and methods

The cruisers of 2014 and 2016 were carried out on board the oceanographic vessel ARC Providencia, in which temperature, conductivity and pressure profiles were taken in the water column up to a depth of 1600 meters, in the oceanographic stations indicated in Figure 1. Considering that these cruisers were made in the framework on the scientific expedition Seaflower, in which multiple research projects were carried out, the performance of the stations was not made continuously due to the vessel had to make activities for other projects.

The 29 stations made between March 21st and April 08th 2014 are equidistant within a regular grid that covers all the sampling area, including the islands of Providencia, island cay of Roncador, Quitasueño, and Serrana. Between August 10th and 25th 2016, the sampling of 17 stations was focused on the vicinities of the island cay Serrana (Figure 1).

The instrument used for the sampling was an SBE-19 plus V2 model CTD. The data were pre - processed with the Seasoft CTD software and the Data convertion, Filter, align ctd, Cell Thermal Mass, Loop Edit, Derive, Bin Average, Split and ASCII Out filter were applied.

Using the daily temperature and salinity profiles, the isothermal layer deepness (ILD) was estimated, it is such deepness whose temperature of the water column remains very similar to the temperature of the surface. Having as a reference the temperature at 10 m deep (T_0) and a ΔT = 0.5°C, the methodology described in (Kara, Rockford & Hurlburt, 2000) was used for the calculation of the IDL, in such a way that the lower limit of the isothermal layer was estimated for the largest depth h_i(m) which verifies that:

$$T_0 - T(h_i) \leq 0.5 \qquad \textbf{(1)}$$

Where $T(h_i)$ (°C) is the temperature value in the dept h_i and T_o is the temperature of the sea in surface (Navia, Garavito, Rodríguez, & Villegas, 2015). The potential temperature used for this calculation and the density of the sea water were calculated with the UNESCO'S algorithms TEOS-10.

The meteorological data used correspond to the data from the meteorological stations of the General Maritime Directorate's Marine Meteorology and Oceanographic Parameters Measurement System Network (SMPOMM), specifically the station located in the island of Providencia (latitude 13.38° N and latitude 81.36° W), due to its proximity to the sampling zone. This station is automatic and has a satellite transmission system, from the OTT house. Additionally, for the campaign of 2016, a DAVIS portable meteorological station, model Vantage PRO 2 was used to record the variables for air temperature, relative humidity, wind speed (magnitude) and direction and atmospheric pressure in each oceanographic station.

On the other hand, maps of absolute dynamic topography produced by SSALTO/DUACS and distributed by AVISO were used, employing the products at post-process global scale, with all the satellites available, using files with a spatial resolution in a cartesian grid of 0.25º. These maps have oceanic and terrestrial tide corrections, effect of inverted barometer, wet and dry troposphere among others. The most detailed description of the product can be found in the user guide SSALTO/DUACS (CLS-DOS-NT-06-034 of 2014/11/18).

Results

Vertical temperature profiles for the water column

In the 29 vertical water temperature profiles for the year 2014 (Figure 6 in blue), a surface temperature of 27.5 °C and a depth of the mixture layer varying its thickness between 23 m and 82 m were observed (Figure 6). From this depth, the temperature decreases rapidly from 27.5 °C to 10 °C, at a depth of approximately 500 m. From this depth, the water temperature continues to decrease up to approximately 5 °C close to 1000 m, where the variation as a function of the depth decreases.

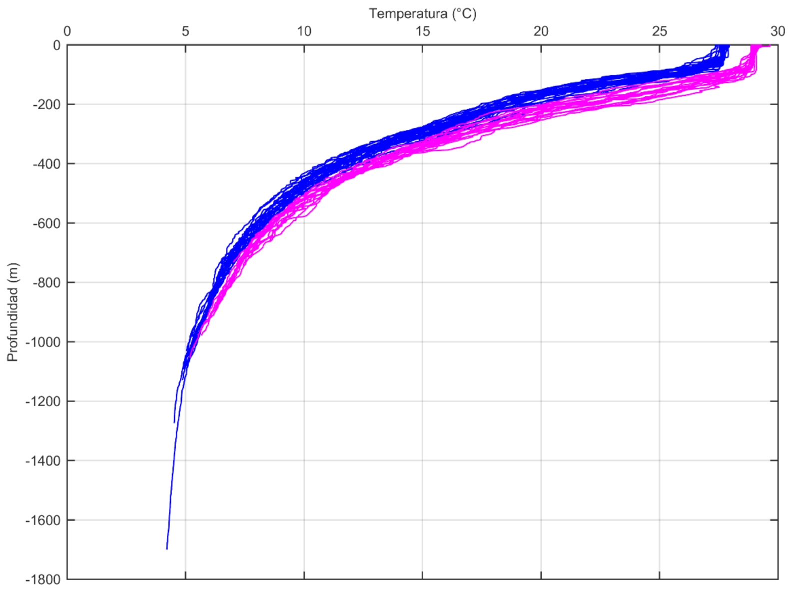

Figure 6. Vertical temperature profiles for the water column in the stations sampled. The profiles of 2014 are shown in blue and the profiles in 2016 are shown in magenta.

In the profiles of 2016 (Figure 6 in magenta), a surface temperature of 29 °C and how the thickness of the mixture layer is of approximately 100 m are observed. The thermocline starts from this depth, where the temperature decreases rapidly from 29° C to 10° C, at a depth of 500 m. The temperature in depth continues to decrease until temperatures around 5° C at 1000 m. The highest surface temperature observed in August, corresponds to the climatology shown in Figure 3. The profiles of August show a higher temperature to all the depths, as compared with the profiles of March and April.

Water temperature at 10 m depth

This result is presented in order to show the spatial variation of the sea temperature during the cruisers. The variation at 10 m deep is shown to eliminate any bias in the data profile due to the "skin effect" in the ocean surface (Fairall, *el al.,* 1996) in (Kara, Rockford & Hurlburt, 2000). In most of the cases, the temperature at 10 m deep is very close to the surface temperature of the ocean (Kara, Rockford, & Hurlburt, 2000); in (Montoya, 2014). This result is the initial reference value (T_0) used in the equation (1) for the calculation of IDL.

The difference in the water temperature at 10 m deep is observed in Figure 7 for different climatic periods (transition 2014 and Indian summer 2016), with higher temperature values in Indian summer with respect to the transition period, in average of 1.5 °C. These measured values correspond with the climatologic data indicated in Table 1 and coincide with the description which indicates that these values at 10 m are very close to the surface data due to the heavy mixture.

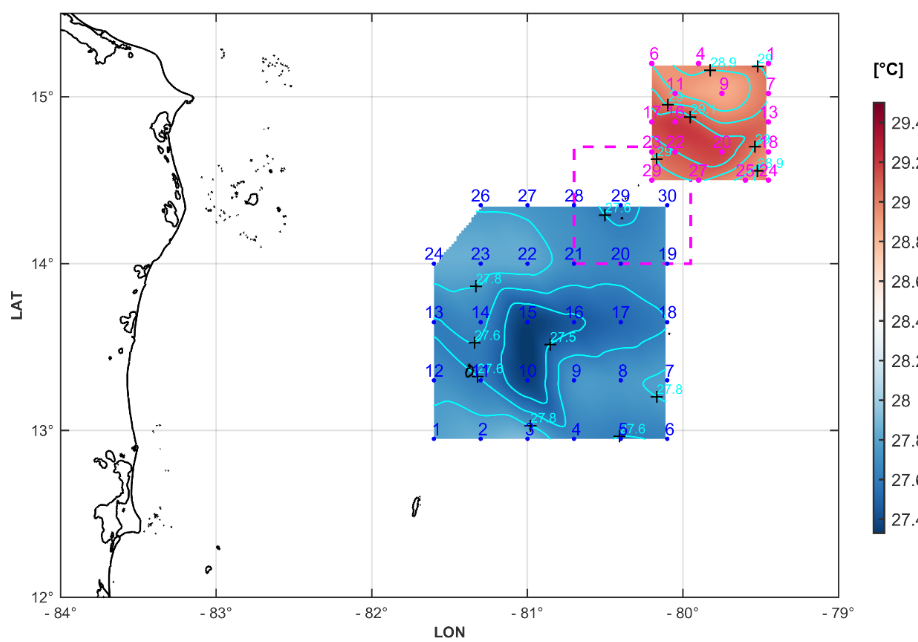

Figure 7. Spatial variation of the water temperature at 10 m deep for the campaign of 2014 (stations in blue) and 2016 (dotted line in magenta). For the visualization in the map, the data from 2016 have a displacement of 0.5° in latitude and longitude. The numbers correspond to the station sampled. The isotherms are shown in white every 0.1 °C

For the campaign of 2014, the variation of the temperature at 10 m deep was observed between 27.4 ° C and 27.9 °C, with differences around 0.5 °C across the area sampled, reason why it is shown as a zone with homogeneous temperature, with slightly colder waters to the east of the Island of Providencia and hotter in the rest of the study area. If it is taken into account that the 29 stations were carried out in a period of 18 days, the small variations observed in the temperature may be due to both spatial variations in the study area and temporal variations.

For the campaign of 2016, as well as the observed in 2014, very small variations of the water temperature at 10 m were found, with variations between 28.9 ° C and 29.4 °C (Figure 7), which is expected for a relatively small zone sampled, compared with the zone sampled in 2014.

These results coincide with the climatological data shown in Figure 3, where there is a difference of more than 1 °C of temperature between March and April, with respect to the temperature of August in the study area.

Mixture layer

The temperature profiles for both campaigns up to 150 m deep were plotted to know the behavior of the water temperature during the first meters in depth in detail (Figure 8). In this figure, a significant change in the depth of the mixture layer between the different stations can be observed for both campaigns, with differences of up to 40 m between profiles from the same campaign, reason why the factors that may be affecting the deepening or wave shoaling of this layer will be examined later on.

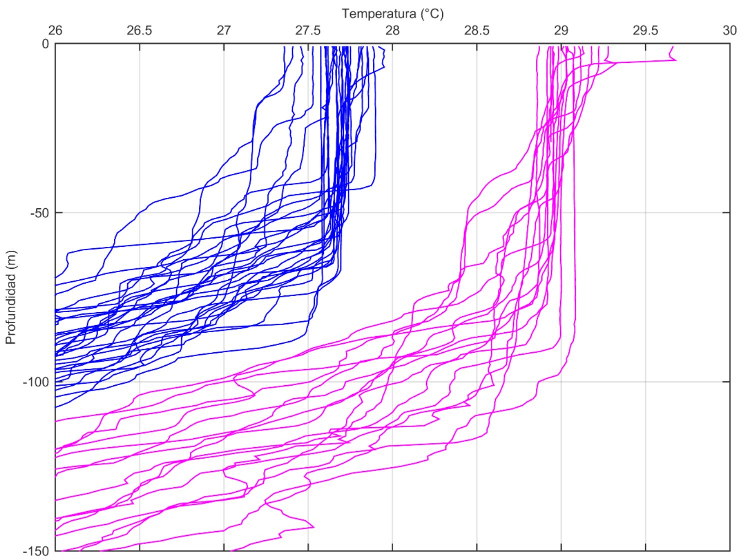

Figure 8. Temperature profiles for the water temperature higher than 26°C in the first 150 m deep, to highlight the mixture layer. The profiles taken in 2014 are represented in blue. The profiles taken in 2016 are represented in magenta.

Isothermal layer 2014

According to the meteorological information recorder by the DIMAR in the Island of Providencia (latitude 13.579° N and 81.215° W, (Figure 1), environment temperatures in average of 28.2 °C, relative humidity of 74.5%; with winds of 3.5 m/s with predominant direction ENE and an atmospheric pressure of 1012 mbar were presented during the campaign. As mentioned in the above sections, a cold front that affected the climatic conditions in the study area occurred in April.

On the other hand, due to the great variation in depth of the behavior of the profiles during the first 100 m (Figure 8), the depth of the isothermal layer (IDL) was calculated for each profile (Table 2). The results show the difference in the thickness of the IDL between the stations made for 18 days. Given the variability of the mixture layer, a possible relationship between the IDL and any specific atmospheric event, such as wind, the presence of a cold front or a meso-scale eddy in the study area was sought.

Table 2. Isothermal Depth Layer (IDL), calculated for each cruiser station made in 2014, organized chronologically.

Station	Date (dd-mm)	Colombian local time	Latitude (° N)	Longitude (° W)	IDL (m)
1	21-Mar	12:00	12.95	-81.60	60.4
2	21-Mar	17:25	12.95	-81.30	47.8
3	21-Mar	22:00	12.95	-81.00	44.9
4	22-Mar	02:31	12.95	-80.70	52.7
5	22-Mar	07:00	12.95	-80.40	56.5
6	22-Mar	10:45	12.95	-80.10	75.3
7	22-Mar	15:25	13.30	-80.10	61
8	22-Mar	18:42	13.30	-80.40	64
17	22-Mar	22:47	13.65	-80.40	39
18	23-Mar	04:15	13.65	-80.10	45.4
9	25-Mar	21:30	13.30	-80.70	67.6
12	30-Mar	03:16	13.30	-81.60	59.7
13	30-Mar	06:45	13.65	-81.60	72
14	30-Mar	11:24	13.65	-81.30	55.8
23	30-Mar	15:30	14.00	-81.30	72
24	30-Mar	18:30	14.00	-81.60	66.9
26	31-Mar	04:37	14.35	-81.30	62.8
22	03-Apr	19:10	14.00	-81.00	88.7
28	04-Apr	03:20	14.35	-80.70	68.1
27	04-Apr	05:00	14.35	-81.00	57.5
29	04-Apr	07:22	14.35	-80.40	83.7
30	06-Apr	22:20	14.35	-80.10	72.9
19	07-Apr	02:30	14.00	-80.10	70.1
20	07-Apr	05:00	14.00	-80.40	72.7
21	07-Apr	09:30	14.00	-80.70	75.5
15	07-Apr	14:39	13.65	-81.00	79.6
16	07-Apr	18:45	13.65	-80.70	62.8
10	07-Apr	23:29	13.30	-81.00	44.9
11	08-Apr	02:05	13.30	-81.30	55.4

With the information from Table 2, two types of plots were generated: the first one with the time line for the variation of the depth of the IDL (Figure 9) and the second one, where the depth contours of IDL are observed in detail (Figure 11). Figure 9 visualizes the great variation of the IDL especially the first days (March 21st to 23rd) and the last sampling days (April 6th to 8th). Although the samplings of the other stations were not taken with the same temporal frequency, as in the cases mentioned above, an average value in the IDL is observed for the 29 approximately 63-meter stations, with maximum isothermal depth values on April third (03rd) at 7:10 pm (88.7 m) and minimum on March twenty-second (22nd) at 10:47 pm (39 m), indicating a range of the data of almost 50 m.

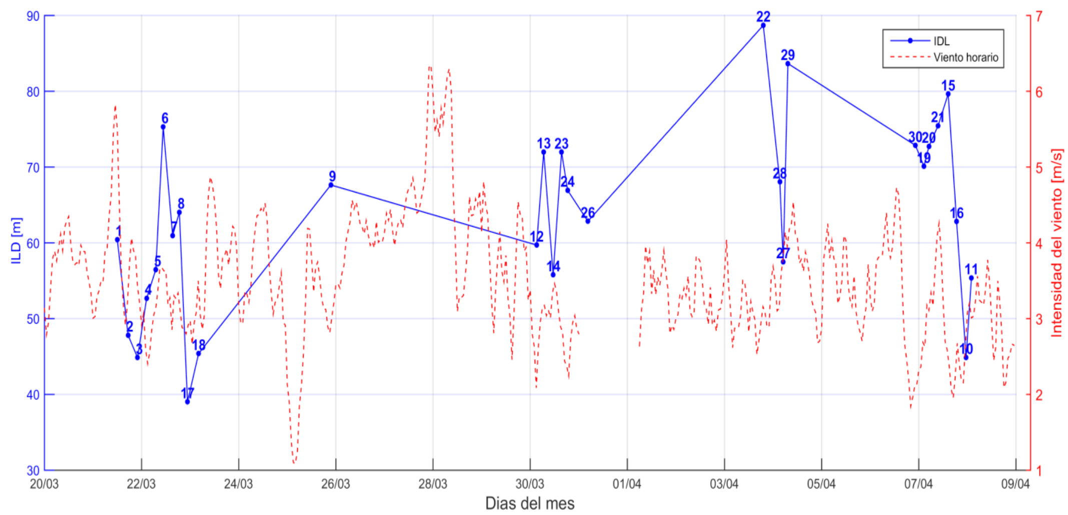

Figure 9. Temporal variation of the IDL in meters of the stations sampled in the cruiser of 2014 (blue) and variation of the wind strength (red) during the sampling days in m/s. The numbers in the blue line, indicate the station as shown in Figure 1 and Table 2.

Additionally, Figure 9 shows the relationship between the temporal variation of the IDL and the variation of the wind strength recorded in the station of the island of Providencia (Figure 1). The wind data were filtered with moving averages every 3 hours. It is expected that a deepening of IDL may be presented at a higher wind strength, however, a correlation between the hourly wind data and the depth of the mixture layer is not observed from Figure 9.

To establish quantitatively the linear correlation between these two variables, the data were selected in coincidental times between the time of the station and the wind strength recorded at that same time. As the wind time series has missing data, the data from both the wind and the IDL corresponding to March 31st 2018 were omitted for the calculation of the correlation.

Furthermore, the calculation was made for the wind recorded 3, 6, and 12 hours before the station, finding in all the cases that the correlations are not statistically significant at 95 %. In the same way, the filtered time series was correlated with moving average of 3 hours, for the wind strength values at the coinciding time of the station and 3, 6 and 12 hours before the station time. As well as in the previous case, no association statistically significant between the filtered wind and the IDL was found.

As the IDL of the stations sampled does not correlate significantly with the wind strength recorded in the Island of Providencia, nor in coincidental times, nor with gaps of 3, 6 nor 12 hours, the meso-scale eddies were analyzed as another possible cause of the deepening of the IDL.

Isothermal layer 2016

During this campaign, adverse meteorological phenomena were not presented and according to the data from the station of the island of Providencia (Figure 1), average environment temperatures of 29.6 °C were recorded, with winds of 3.76 m/s with predominant direction E and an atmospheric pressure of 1010 mbar. The relative humidity in the region was 83.4 % in average.

As well as for the campaign of 2014, for the profiles collected in 2016, the value of the isothermal layer was calculated for each station and the results are shown in Table 3. With these data, both the temporal variation of the isothermal layer (Figure 10), and the spatial distribution of the information calculated for the stations (Figure 11) were plotted. For station 6 (August 20th 2016 at 8:20), the collected profile only reached until a depth of 33 m and due to the methodology for the calculation, it was impossible to obtain the value of the IDL of this station.

Table 3. Isothermal depth layer (IDL), calculated for each profile of 2016, organized chronologically.

Station	Date (dd-mm)	Colombian local time	Latitude (° N)	Longitude (° W)	IDL (m)
22	10-Aug	16:03	14.17	-80.55	39.42
18	11-Aug	07:59	14.17	-79.95	79.93
24	11-Aug	11:04	14.00	-79.95	82.18
17	15-Aug	10:31	14.35	-80.70	77.4
16	15-Aug	15:22	14.35	-80.55	52.49
25	16-Aug	07:00	14.00	-80.10	91.69
27	16-Aug	10:50	14.00	-80.40	86.41
6	20-Aug	08:20	14.70	-80.70	N/A
4	20-Aug	15:15	14.70	-80.40	102.93
1	21-Aug	06:30	14.70	-79.95	109.57
7	21-Aug	12:12	14.52	-79.95	113.7
13	21-Aug	16:30	14.35	-79.95	97.37
9	22-Aug	06:30	14.52	-80.25	70.81
11	22-Aug	12:50	14.52	-80.55	52.54
20	24-Aug	14:55	14.17	-80.25	93.14
29	25-Aug	08:15	14.00	-80.70	81.68
23	25-ag Aug o	12:58	14.17	-80.70	88.75

The variation of the IDL is observed in Figure 10, which was higher than the variation of 2014 (Figure 9), despite being a smaller area and in a shorter period of time. The lowest depth was observed on August 10th (39 m), whereas the highest depth occurred on August 21st (114 m), showing a difference of 75 meters. This high variation of the IDL is observed in short periods of time, as between station 7 and 11, where in a period higher than 24 hours, the difference in the IDL is 61 meters. The homogeneous atmospheric behavior in this period of time shows that the possible cause of the differences of the IDL between these stations, which are located at approximately 10 nautical miles of distance is dominated by spatial variations of the ocean.

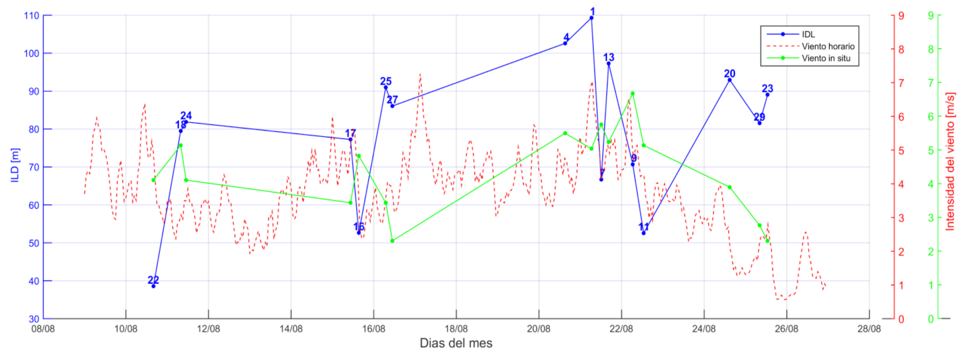

Figure 10. Temporal variation of the IDL (m) for the stations sampled in the cruiser of 2016. The numbers indicate the station as shown in Figure 1 and Table 3. The red line indicates the wind speed measured in Providencia. The green line indicates the true wind strength registered with the portable meteorological station on board.

The sample for the variation of the IDL (blue line) is shown for the campaign of 2016 in Figure 10, as well as it was made for the data of 2014, with respect to the wind strength for the station of Providencia (red line), as well as the variation of the wind strength recorded with the portable station that was carried on board the vessel (green line), during the samplings. The linear correlation coefficient between the IDL and the winds in coincidental times and in 3, 6 and 12 hours before the station were calculated, with both the instant data and the wind data averaged every 3 hours. In this occasion, no association statistically significant between the wind strength data and the IDL, at 95 % was found in any of the cases studied.

Spatial variation of the isothermal depth layer

Figure 11 examines the spatial distribution de la isothermal depth layer for the campaigns of 2014 and 2016. A great variation in IDL values is observed despite being in a small sampling zone and with a temporal variation of some days.

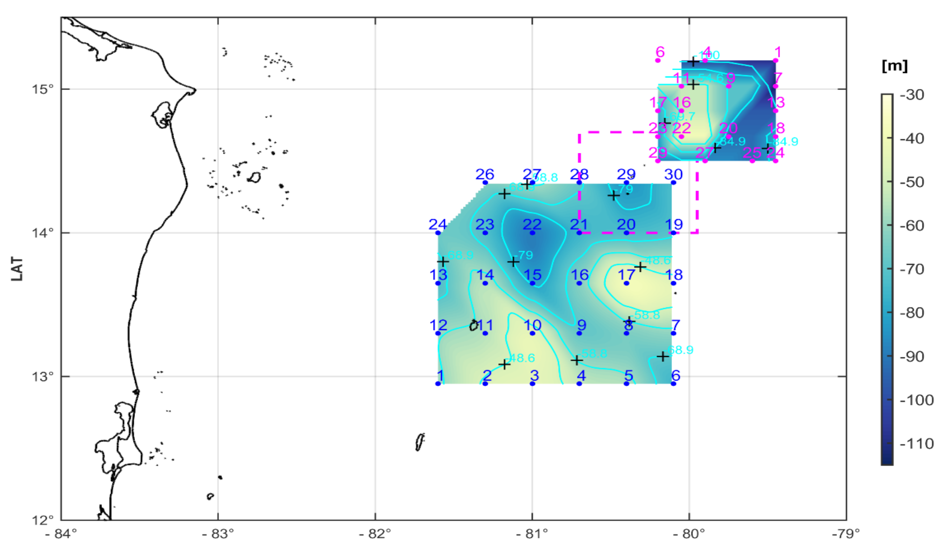

Figure 11. Spatial IDL variation (in m) for the campaign of 2014 (stations in blue) and 2016 (dotted line in magenta). For the visualization in the map, the data of 2016 have a displacement of 0.5° in latitude and longitude. The numbers correspond to the station sampled. The depth isolines are shown in gray.

Two sectors with shallow IDL values of approximately 40 m deep were observed in 2014: one centered in latitude 13.65 ° N and longitude 80.40 ° W (station 17) and another in latitude 13.30 ° N and longitud 81 ° W (station 10). The deepest IDL is observed centered in station 22.

The highest depths of the IDL (110 m) were observed in campaign of 2016 centered in latitude 14.7° N and longitude 79.95° W (station 1), and the shallowest IDL (39 m) towards station 22 in latitude 14.17° N and longitude 80.55° W.

Four stations were repeated in the two cruisers. Thus, for example, station 19 of 2014, spatially corresponds to station 25 of 2016. In this station, the IDL in the first cruiser was 70 m depth, while it was deeper at 92 m in the second cruiser, which reaffirms the temporal variation of the IDL in this region.

Vertical salinity profiles for the water colum

The salinity profiles registered in 2014 (Figure 12, in blue), show surface salinities around 36.25. Between 50 and 150 m approximately, a layer with an increase in the salinity from 36.2 to 36.8 is observed. Between 150 m and 750 m depth, the salinity decreases from 36.8 to a close minimum at 34.8. From 750 m deep, the salinity tends to stabilize around 35.

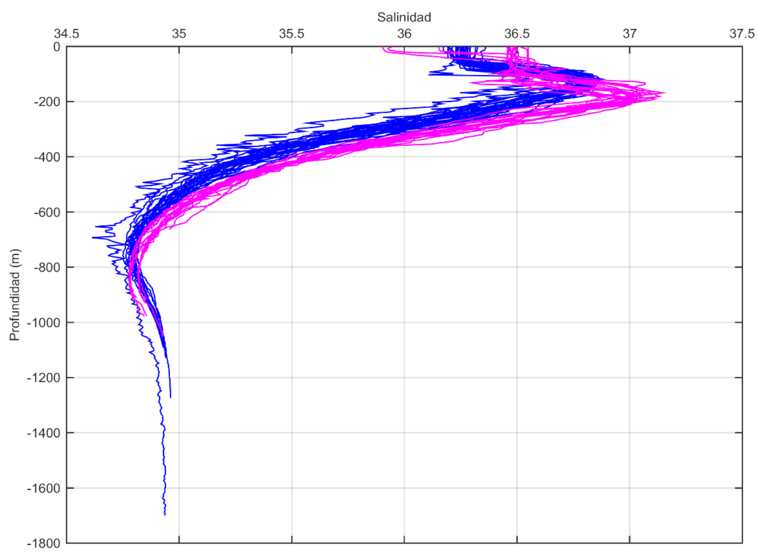

Figure 12. Vertical salinity profiles for the water column in the stations sampled in the cruisers of 2014 (blue) and 2016 (magenta).

The salinity profiles of the expedition Seaflower 2016 (Figure 12 in magenta), show a higher surface salinity with respect to the observed in 2014, which was around 36.5. In 2016, the profiles record salinity values higher than 37 at a depth between 160 and 200 m. The minimum salinity value was found at a depth around 750 m with a value of 34.8.

When comparing the salinity profiles between the two cruisers, a deeper mixed layer is observed in 2016, as well as higher salinity values in all the depths in the second cruiser, except for three stations with surface salinity values close to 36.

Surface water salinity

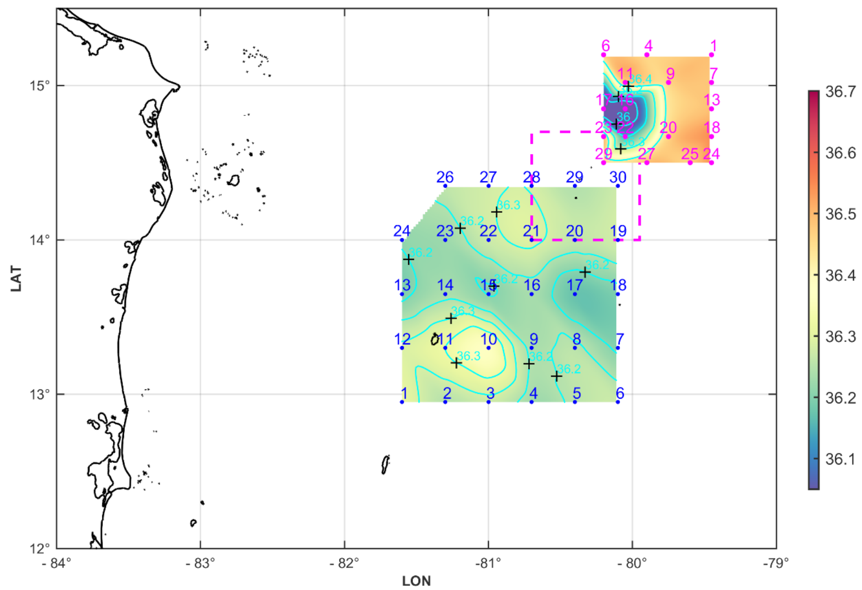

Figure 13. Spatial variation of the salinity at 10 m deep for the data from the cruisers 2014 (stations in blue) and 2016 (dotted line in magenta). For the visualization in the map, the data from 2016 have a displacement of 0.5° in latitude and longitude. The numbers correspond to the station sampled. The isohalines are shown in gray every 0.1.

Figure 13 shows the behavior of the water salinity at 10 m deep for campaigns 2014 and 2016. In 2014, the average of the 29 stations at this deep is 36.2 and the variation in all the area was around 0.2, with slightly higher salinity values to the northern and southwestern area of the study region. The stations of 2016 show an average around 36.4, and values between 35.9 and 36.5, with a range of 0.4. Slightly higher salinity values towards the eastern side of the study region can be observed. A difference between the salinity date from 2014 and 2016, around 0.2 is observed.

Presence of a cold front in the Caribbean from April 8th-11th 2014

On the other hand, the aim was to verify whether as well as the documented in 2004 by Morales *et al.,* (2004), a similar effect in the isothermal layer occurred for the event of the cold front of 2014, where the deepening of the mixture layer was evidenced during the passage of a wave from the east through the study area, As it is known, the cold fronts that displace from high to medium latitudes and present a high-pressure gradient with the consequent increase in the wind speed and change of its direction, which cause a deepening of the mixture layer.

A cold front that affected the atmospheric conditions of the study area and the navigability of the vessel where the data collection from the expedition Seaflower was developed, entered to the Caribbean from April 8th 2014. The wind and Surface pressure with the progression of the front towards the central Caribbean from days April 7th-12th 2014 are observed in Figure 14. During the days April 7th and 8th, the expedition was in its final phase data collection from the water column, por since the effects of the front in the environmental and navigability conditions, especially in the waves were felt (Figure 16)

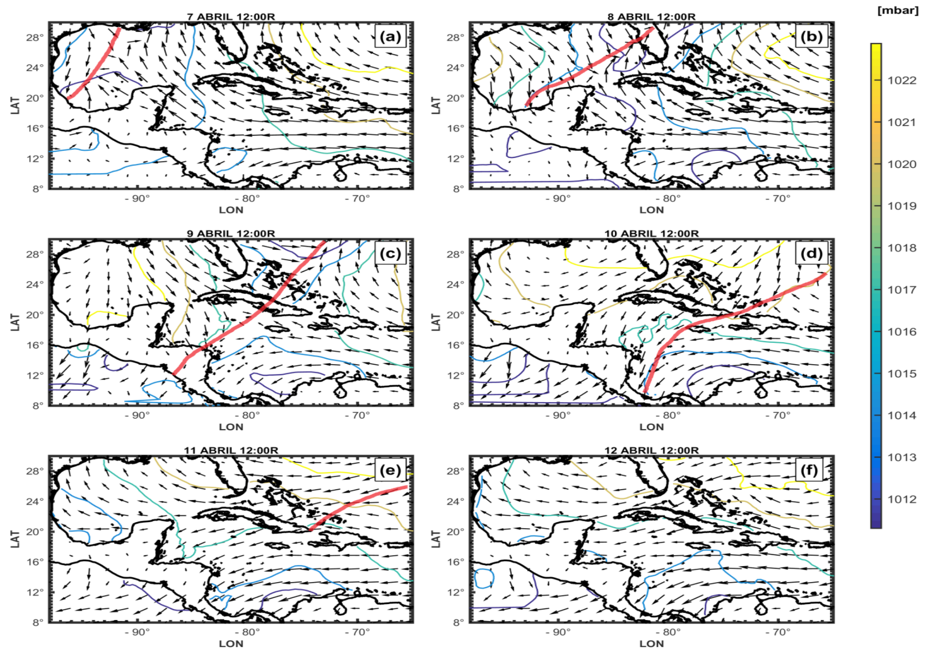

Figure 14. Wind (CCMP) and surface (NARR) pressure data by 12:00 m GMT. (a) and (b) April 7th and 8th respectively with the cold front in the Gulf of Mexico; (c) and (d) April 9th and 10th with the season a cold front in the Colombia Basin; (e) and (f) April 11th and 12th with the cold front departing from the Caribbean Sea. The approximate position of the cold front is indicated with the red line.

To verify the alterations in the wind conditions in the study region for the passage of the cold front, the information of the NOAA 42057 buoy (latitude 16.75 ° N and longitude 81.55 ° W) was used, in the location shown in Figure 1. Figure 15 shows the zonal and meridional wind components and other variables measured, for the period of the cruiser in 2014.

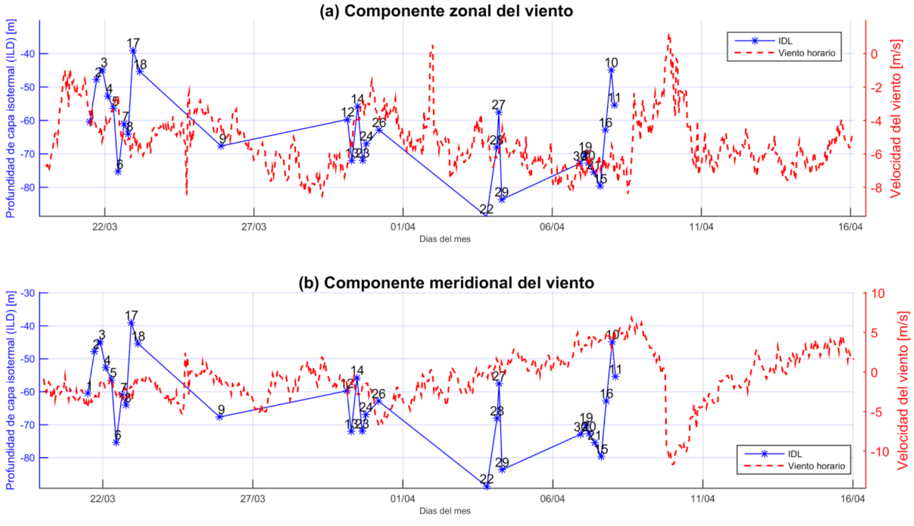

Figure 15. Zonal and meridional components registered by the NOAA 42057 buoy between April 1st and 30th 2014. Data in Colombian local time.

In normal conditions, the winds in the Caribbean Sea have negative zonal component; Figure 15 shows the disruption caused by the cold front. In the values of the zonal wind component during the days of the front, with the decrease in the wind strength April 9th 2014. Furthermore, Figure 15 shows clearly how the cold front affected the behavior of the meridional wind component, where a direction change is observed, passing from a positive component (to the north) to a negative one (to the south). Although there are differences especially between the location of the buoy and the cruiser area, a relation between the IDL and the windmeasured by the la buoy is not observed.

Unfortunately, by the date of the passage of the front through the study region, the sample collection in the water column had already finished to verify the effect of the cold front in the surface layer of the ocean. However, it can be observed in Figure 16, how most of the atmospheric and oceanographic variables recorded by the NOAA buoy showed important disruptions in the values recorded during the passage of the front, with respect to the data from the rest of the month.

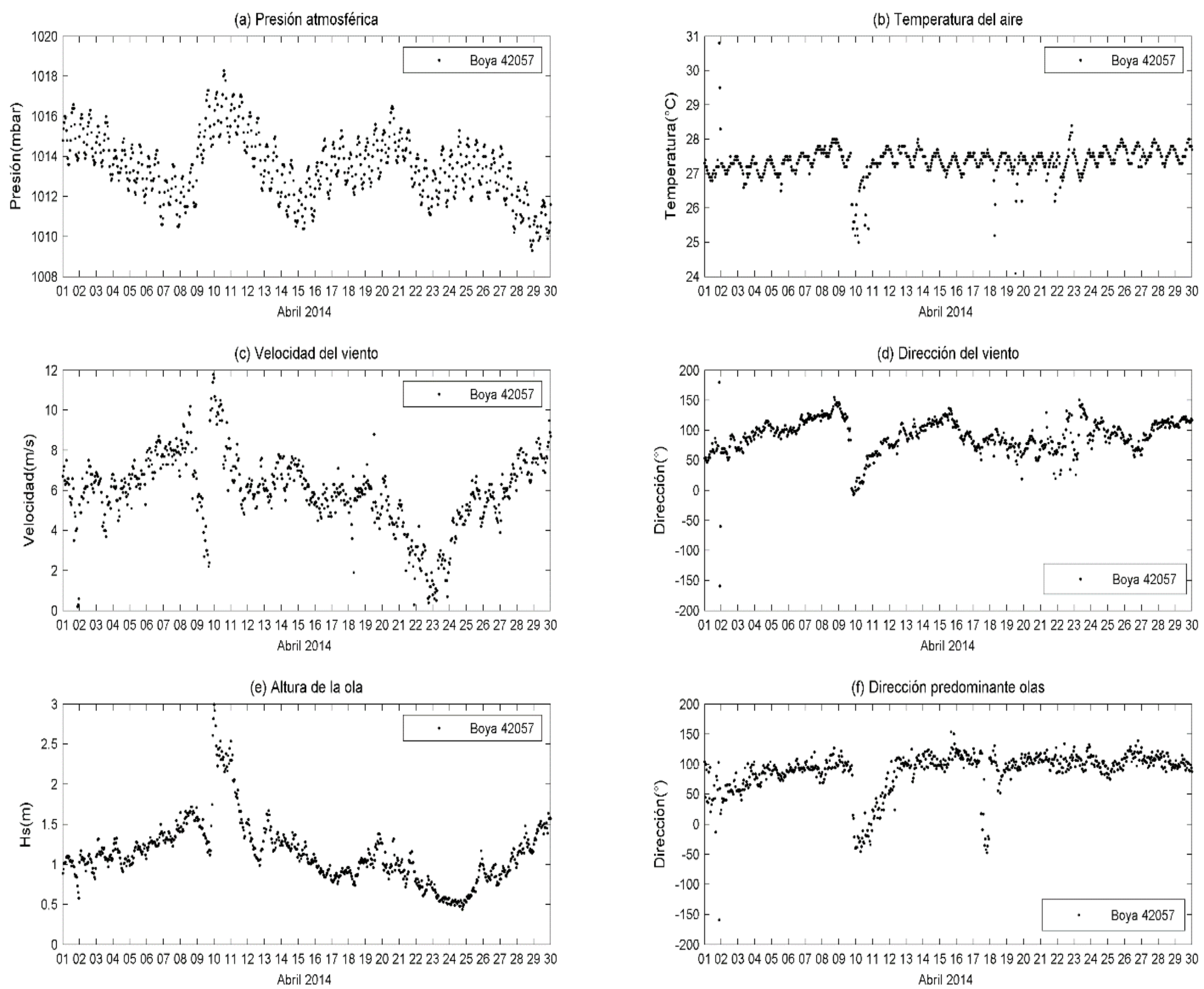

Figure 16. Data registered by the NOAA 42057 buoy between April 1st and 30th 2014. Data in Colombian local time.

The data from Table 4 indicate that for the days of cold front, the atmospheric pressure increased in close to 2 mbar, the wind speed increased in 0.73 m/s, the wave height increased in close to 0.8 m, with maximum values of up to 2 m above the average, with respect to the data from the rest of the month.

Table 4. Basic data on the main environmental variables from April 2014, recorded by the NOAA 42057 buoy. The data from the days with cold front and those from the rest of the month are shown.

Value	Atmospheric pressure (mbar)	Air temperature (°C)	Wind speed (m/s)	Wave height (m)	Dominant period (s)
Data from days of cold front (April 8th-11th) (95 data)					
Average	1015.09	27.17	3.72	1.82	7.74
Minimum	1011.20	25.00	1.13	1.12	4.55
Maximum	1018.30	28.00	6.07	3.00	10.00
Month data without cold front (624 data)					
Average	1013.18	27.40	2.99	1.06	7.51
Minimum	1009.30	24.10	0.1	0.44	4.00
Maximum	1016.60	30.80	5.19	1.92	11.43

The data from Table 4 indicate that for the days of cold front, the atmospheric pressure increased in close to 2 mbar, the wind speed increased in 0.73 m/s, the wave height increased in close to 0.8 m, with maximum values of up to 2 m above the average, with respect to the data from the rest of the month.

Considering the increase in the wind speed, a deepening of the mixture layer would be expected, however, the effect observed (Figure 15) in the stations made on April 7th, was a shallowing of this layer and a cooling of the surface waters (station 10 in Figure 7). It is pertinent to mention that a decrease in the wind strength in the buoy passing from 8 m/s to 2 m/s is observed in Figure 16-c, which occurred between April 8th and 9th 2014, reason why there would be no relation with the swallowing of the IDL observed in the evening of April 7th 14. Despite the above, it is interesting to observe that the passage of the cold front generates a variation in the wind direction, but also may generate an increase or a decrease in the wind strength, according to its position.

Passage of eddies in the study area

In order to study whether the passage of eddies in the study area had an influence in these changes of the IDL in 2014, the Absolute Dynamic Topography (ADT) in the area was plotted in Figure 17, for the days March 23rd, March 30th, April 4th, and April 7th period where there was sampling (Figure 9), from de AVISO program's data.

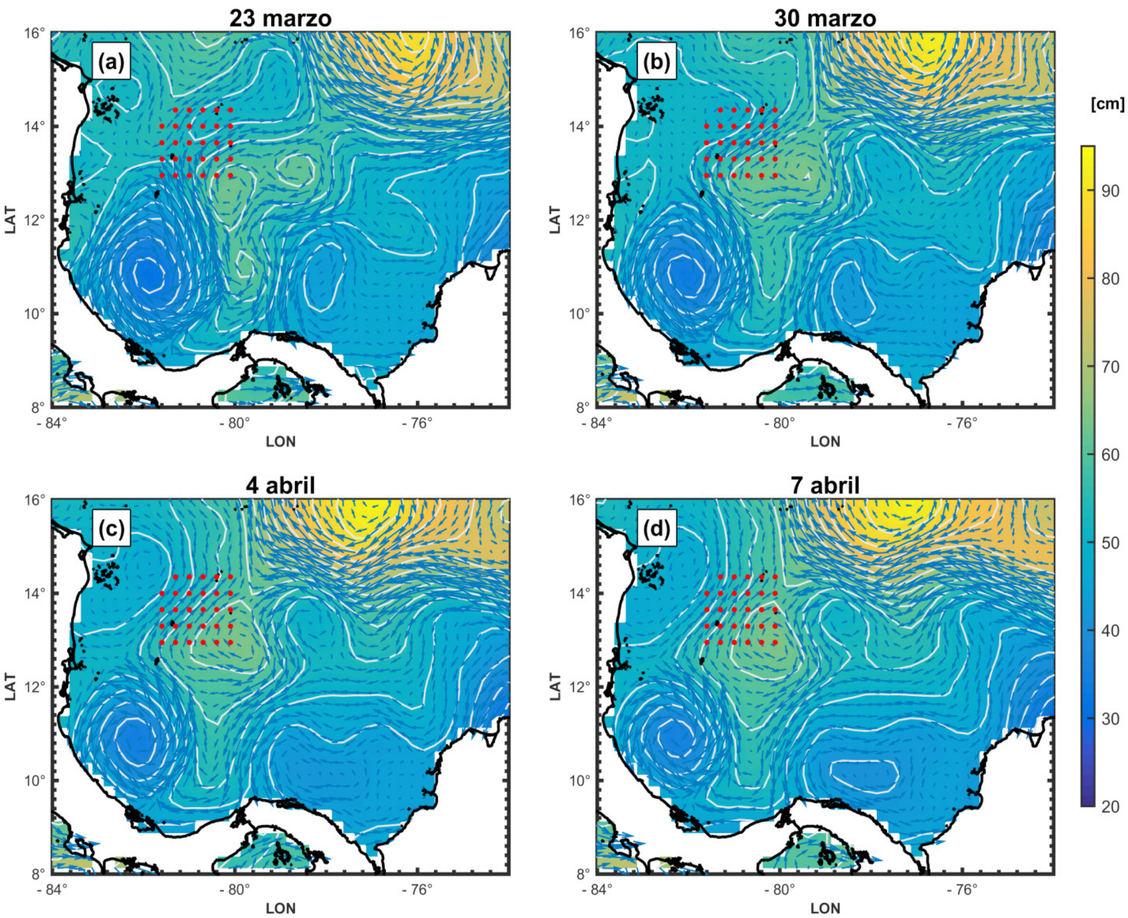

Figure 17. Absolute Dynamic topography (ADT) of the study region in accordance with the color scale, for the days: (a) March 23rd; (b) March 30th; (c) April 4th and (d) April 7th 2014 and their corresponding surface geostrophic currents (u, v in cm s-1) indicated by the vectors. The red points represent the sampled stations. The white lines represent the contours of the sea level.

The ADT measures the variations of the sea level with reference to the geoid, reason why it includes the variations in the sea level caused by the average field of the permanent currents, as well as the anomalies of the sea level by the variations in these currents generated by meso-scale phenomena, such as for example the passage of eddies.

In the northern hemisphere, the anticyclonic eddies (clockwise circulation), are centered in the elevated dynamic topography and its circulation makes that the mixture layer deepens, on the contrary, the cyclonic eddies (counterclockwise circulation) have a depression centered in the dynamic topography and its circulation makes that the mixture layer swallows.

Figure 17 shows the field of absolute dynamic topography and the vectors of the current, along with the stations sampled in 2014. The transit of an anticyclonic eddy westwards is observed in the northeast of the region shown in the figure; on the contrary, the eddy Panama-Colombia with cyclonic rotation is observed in the southwest, but decreasing its diameter between March 23rd and April 7th 2014. A less heavy anti-cyclonic eddy than the indicated in the northeast of the figure is observed southeastwards the sampled area (red dots) between these two cyclones, generating an increase in the absolute dynamic topography, which affects the stations made in different measure during the cruiser. It would be expected that this anti-cyclonic eddy deepened the mixture layer, especially towards the stations in the southwest of the sampled zone, however, this especially coherent behavior is not observed in Figure 11.

This lack of spatial coherence may be due to the period of time between the data collection at the stations, especially due to the dynamics of the eddies in the study area, evident in Figure 17. However, the effects on the eddies in the depth of IDL are perceived in the following cases. Station 6 was taken when the anti-cyclonic eddy affected only the southwest of the study area (Figure 17a), and has the deepest IDL among the stations sampled between March 21st and 23rd 2014 (Figures 9 and 11). Stations 22 and 29 show the deepest IDL of the stations made on April 3rd and 4th 2014 (Figure 9), which is consequent with the location of the anti-cyclonic eddy in the study area (Figure 17c), which affects all the stations except for those in the northwest of the study area, where station 27 and 28 are located (Figure 11).

Discussion

In two different climatic periods, it was possible to describe the physical conditions of a part of the sea, in the archipelago of San Andrés, Providencia and Santa Catalina, thanks to the cruises made in 2014 and 2016. Thus, by 2014 (March-April), a sea surface temperature of around 27.5 °C with a maximum of 27.9 °C in surface and a minimum of 4.5° C at 1700 m deep was observed, whereas by 2016 (August), the surface temperature was in average of 1.5 °C above the average of 2014, with a maximum of 29.6° C in surface and a minimum of 5 °C at 1100 m. These results coincide with the climatological data shown in Figure 3, where there is a difference of more than 1 °C of temperature between the months of March and April, with respect to the temperature of August in the study area.

The water surface salinity values by 2014 were around 36.2, and the values in 2016 were 36.4. The maximum salinity value was recorded in 2016, with a value of 37.2 at 190 m deep and the minimum value was recorded in 2014 with a value of 34.6 at 700 m deep. These salinity values registered for these two periods coincide with the data reported in (Rangel, Herrera, Palomino, Herrera, & Andrade, 2015; Molares, Vanegas, Bustamante, & Andrade, 2004; Cabrera & Donoso, 1993) among others. Furthermore, the salinity values correspond with the climatological salinity data in the sea surface, shown in Figure 4, where the salinity values do not show higher variations for the study region.

Higher temperature and salinity values were observed in 2016 (August) compared with those from 2014 (March-April). Given the proximity between the stations of the two cruisers, the differences found are assumed as a consequence of the stational variations.

On the other hand, a great variation in the IDL was found in both campaigns, with ranges between 49 and 76 m deep on a same day for 2014 and between 52 and 91 m on the same day for 2016. In both cases, the influence of the wind strength in the deepening/shallowing of the IDL was verified through the calculation of correlation coefficients for coincidental hours and 3, 6 and 12 hours before the station, without finding a direct influence in the daily variations of IDL. By 2014, it was sought to explain analyzing the effect on the mixture layer due to the presence of a cold front on April 7th 2014, as well as due to the passage of eddies.

A clear influence of events such as a cold front or the presence of eddies in the variation of the depths of the isothermal layer could not be established, with respect to the profiles of 2014. This suggests that the depth of layer in this area may be due to a sum of factors that are not easily recognizable and that may be studied in detail, reason why a permanent monitoring of the atmospheric and water column variables during at least one year would be necessary.

Part of the difficulty in understanding the behavior of the IDL in the study area is due to the complex oceanographic dynamics in this archipelago, where the island further north (Serranilla and Bajo Nuevo) are influenced by the Caribbean Current and the permanent presence of eddies affected by the limitations imposed by the bathymetry in its transit towards the Cayman sea; while the other islands are affected by the Eddie Panama-Colombia, with Quitasueño and Serrana in the border of the eddy, whereas the other islands with a more direct influence on the seasonality of this eddy (Torres, Sánchez & Moreno, 2017).

Acknowledgements

The authors acknowledge the crew of the General Maritime Directorate's oceanographic vessels for their timely support during the sampling campaigns, as well as professor Raúl Montoya for his valuable contributions to this work that helped to enrich this manuscript.

References

Andrade, C. (1991). *Mesoscale variability of the Caribbean Sea from GEOSAT.* Monterrey, CA: Naval Postgaduate School.

Andrade, C. (2009). Variaciones temporales termohalinas en la cuenca Colombia. *Boletín Científico CIOH*(27), 8-21.

Andrade, C. A. (2015). *Oceanografía dinámica de la cuenca de Colombia.* Cartagena de Indias, Bolívar, Colombia: Alpha Editores.

Andrade, C. A. & Barton, E. D. (2005). The Guajira upwelling system. *Continental Shelf Research, 25*, 1003-1022.

Andrade, C. A., Thomas, Y. F., Lerma, A., Durand, P. & Anselme, B. (2013). Coastal flooding hazard related to swell events in Cartagena de Indias, Colombia. *Coastal Res., 29(5)*, 1126-1136.

Andrade, C. & Barton, E. (2000). Eddy development and motion in the Caribbean Sea. *J. Geophys. Res. 105*, 26191-26201.

Andrade, C., Giraldo, S. & Lonin, S. (1996). Nota sobre la circulación de las aguas en el Bajo Alicia y el sector de San Andrés. *Boletín Científico CIOH*(17), 27-36.

Andrade, C., Rangel, O. & Herrera, E. (2015). *Atlas de los datos oceanográficos de Colombia 1922-2013 Temperatura, Salinidad, Densidad, Velocidad Geostrófica.* Bogotá, Colombia: Dirección General Marítima - Ecopetrol S.A. Ed. Dimar.

Cabrera, E. & Donoso, M. (1993). Estudio de las características oceanográficas del Caribe colombiano, región III, zona 1, PDCTM. *Bol. Cient. CIOH*(13), 19-32.

Chelton, D. B. (2004). Satellite Measurements Reveal Persistent Small-Scale Features in Ocean Winds. *Science, 303*, 978-983.

Enfield, D. B., Mestas-Núñez, A. M., Mayer, D. A. & Cid-Serrano, L. (1999). How ubiquitous is the dipole relationship in tropical Atlantic sea surface temperatures? *J. Geophys. Res., 104*, 7841-7848.

Espinosa, R. (17 de enero de 2001). *Oficializada reserva de la biosfera en San Andrés.* Recuperado el 27 de 03 de 2017, de www.eltiempo.com: http://www.eltiempo.com/archivo/documento/MAM-644886

Fairall, C. W., Bradley, E. F., Godfrey, J. S., Wick, G. A., Edson, J. B. & Young, G. S. (1996). Cool-Skin and warm-layer effects on sea surface temperature. *J. Geophys. Res., 101*, 1295-1308.

Garay, J. F., Castillo, F., Andrade, C., Aguilera, J., Niño, L., De la pava, M. & Márquez, G. (1988). Estudio oceanográfico del Caribe colombiano en el área del archipiélago de San Andrés y Providencia y cayos adyacentes. *Boletín Científico CIOH*(9), 3 - 73.

Gonzáles, E. (1987). Oceanografía Física descriptiva del archipiélago de San Andrés y Providencia con base en el análisis de los cruceros OCEANO VI a IX. *Boletín Científico CIOH*(7), 73-100.

Hastenrath, S. (1991). *Climate dynamics of the Tropics.* The Netherlands: Kluwer Academic Publishers.

Jouanno, J., Sheinbaum, J., Barnier, B., Molines, J. & Debreu, L. (2008). The mesoscale variability in the Caribbean Sea. Part I: Simulations and characteristics with an embedded model. *Ocean Modell., 23 (3-4)*, 82-101.

Kara, A., Rockford, P. A. & Hurlburt, H. E. (2000). An optimal definition for ocean mixed leyer depth. *J. Geophys. Res.,105*, 16803-16821.

Lerma, A., Thomas, Y., Durand, P., Torres, R. R. & Andrade, C. (2008). Sea-evel variability from 1950 to 2000 and hazards linked to storm surge episodes in Bocagrande and Castillogrande peninsulas. *Boletín Científico CIOH, 26*, 72-85.

Molares, R., Vanegas, T., Bustamante, J. & Andrade, C. (2004). Aspectos oceanográficos sobre la Depresión Providencia en mayo de 2004. *Boletín Científico CIOH*(22), 11-25.

Montoya, R. (2014). *Variabilidad estacional e interanual del balance de calor en la capa de mezcla superficial en el mar Caribe.* Medellín: Universidad Nacional de Colombia Sede Medellín.

Mooers, C. N. & Maul, G. A. (1998). IntraAmericas sea circulation. *The Sea vol II edited by K. H. Brink, A. R. Robinson*, 183-208.

Murillo, I. & Ortiz, R. (2013). *Análisis de los metadatos sobre proyectos de investigación científica marina desarrollados en el área de la Reserva de Biósfera Seaflower.* Bogotá D.C.: APC - CCO.

Narvaez, G. & León, G. (2003). Intrusión de aire frío en áreas tropicales. Estudio del caso del 5 al 8 de enero del 2002. *Revista de Meteorología Colombiana*, 99-108.

Navia, J. D., Garavito, J. D., Rodríguez, A. T. & Villegas, N. L. (2015). Determinación de las capas isotérmica y activa, contenido y flujo de calor en aguas oceánicas de la cuenca del Pacífico colombiano. *Bol. Cient. CIOH, 33*, 39-51.

Ortiz, J. C., Otero, L. J., Restrepo, J. C., Ruiz, J. & Cadena, M. (2013). Cold fronts in the Colombian Caribbean Sea and their relationship to extreme wave events. *Nat. Hazards Earth Syst. Sci., 13*, 2797-2804.

Rangel, O., Herrera, E., Palomino, A., Herrera, G. & Andrade, C. (2015). Análisis de rasgos del clima regional en el Atlas de los Datos Oceanográficos de Colombia 1922 - 2013. *Boletín Científico CIOH*(33), 3-17.

Richardson, P. L. (2005). Caribbean Current and eddies as observed by surface drifters. *Deep Sea Res., Part II, 52(3–4)*, 429-463.

Ruiz-Ochoa, M., Beier, E., Bernal, G. & Barton, E. D. (2012). Sea surface variability in the Colombian Basin, Caribbean Sea. *Deep-Sea Res., Part I, 64*, 43-53.

Small, R. & Szoeke, S. (2007). The Central American Midsummer Drought: Regional Aspects and Large-Scale Forcing. *J. Climate, 20*, 4853-4873.

Torres, R. R. & Tsimplis, M. N. (2012). Seasonal sea level cycle in the Caribbean Sea. *J. Geophys. Res., 117*, CO7011.

Torres, R. & Tsimplis, M. N. (2014). Sea level extremes in the Caribbean Sea. *J. Geophys. Res. Oceans 119*, 4714-4731.

Torres, R., Sánchez, D. & Moreno, M. (2017). Variación estacional del nivel del mar en el archipiélago de San Andrés, Providencia y Santa Catalina, mar Caribe. *Revista de Biología Marina y Oceanografía, 52*(2), 343-352.

Wang, C. (2007). Variability of the Caribbean Low-Level Jet and its relations to climate. *Clim. Dyn., 29*, 411-422.

Whyte, F., Taylor, M., Stephenson, T. & Campbell, J. (2008). Features of the Caribbean low level Jet. *Int. J. Climatol., 28*, 99-128.