Daytime breeze cycle characterization in a tropical coastal region using the WRF model: the case of the Gulf of Urabá, Colombia

Caracterización del ciclo de brisas diurnas en una región costera tropical a partir del modelo atmosférico WRF: caso Urabá antioqueño

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Leidys Milena Arroyo Quinto[1], Vladim ir G. Toro[2], Eisinhower Rincón Vargas[3], José Andrés Posada-Marín[4], Rubén Darío Molina Santamaría[5], Juan F. Salazar[6]

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Abstract

Determining the wind fields associated with sea breezes is essential for assessing oceanic-atmospheric processes in coastal areas, such as the transport of pollutants and the generation of wind-sea waves. With this information, it is possible to quantify the effects on the sea produced from the continent, and understand the daily coastal erosion processes. It is important to emphasize that in the coastal part of the Gulf of Urabá, pesticides are frequently sprayed from small planes and that the east coast of the gulf presents accelerated coastal erosion processes. In the present work, the characterization of the diurnal cycle of sea breezes on the coasts of the Gulf of Urabá was carried out using the results of the Weather Research and Forecasting (WRF) model. To this purpose, wind and temperature fields were analyzed for January and February from 2008 to 2013. Wind values at various levels of the vertical and surface wind fields were compared with in situ information. It was found that the breeze system begins its movement from sea to land between 07:00 and 10:00 local time (LT) and reverses between 13:00 and 16:00 LT. Evidence of the change of direction is the surface temperature values which were positively correlated with the wind. As future work, the WRF model is expected to be implemented for recent years to carry out an adequate calibration/validation process using weather stations that have been installed lately.

Keywords: Sea breezes, WRF model, hodograph, Gulf of Urabá.

Resumen

La determinación de los campos de viento asociados a las brisas marinas es indispensable para la valoración de procesos oceánicos-atmosféricos en las zonas costeras, como el transporte de contaminantes y la generación del oleaje tipo wind sea. Con esta información es posible cuantificar efectos producidos

[1] Orcid: 0000-0003-1493-7841. Universidad de Antioquia. E-mail: leidys.arroyo@udea.edu.co

[2] Orcid: 0000-0003-4398-9472. Universidad de Antioquia. E-mail: vladimir.toro@udea.edu.co

[3] Orcid: 0000-0003-4598-523X. Universidad de Antioquia. E-mail: eisinhower.rincon@udea.edu.co

[4] Orcid: 0000-0001-7456-8772. Universidad de Antioquia. E-mail: andres.posada@udea.edu.co

[5] Orcid: 0000-0003-1548-2578. Universidad de Antioquia. E-mail: ruben.molina@udea.edu.co

[6] Orcid: 0000-0001-7963-7466. Universidad de Antioquia. E-mail: juan.salazar@udea.edu.co

desde el continente, en el mar, así como entender los procesos de erosión costera durante el día. Es importante recalcar, que en parte litoral del golfo de Urabá se realiza una frecuente disposición de plaguicidas esparcidos desde avionetas y que la costa este del golfo presenta procesos acelerados de erosión costera. En el presente trabajo se realizó la caracterización del ciclo diurno de las brisas marinas sobre las costas del golfo de Urabá utilizando los resultados del modelo Weather Research and Forecasting (WRF). Con este fin, se analizaron los campos de viento y temperatura de enero y febrero de 2008 a 2013. Los valores del viento en varios niveles de la vertical, así como lo campos de viento superficial fueron comparados con información in situ. Se identificó un sistema de brisas que inicia su desplazamiento de mar a tierra entre las 07:00 y 10:00 hora local (HL) y se invierte entre las 13:00 y 16:00 HL. Una evidencia del cambio de dirección son los valores de temperatura superficial los cuales se correlacionaron positivamente con el viento. Como trabajo futuro se espera que el modelo WRF sea implementado para años recientes, con el fin de realizar un proceso más adecuado de calibración/validación utilizando estaciones climáticas que se han instalado en los últimos años.

Palabras claves: *Brisas marinas, modelo WRF, hodógrafas, golfo de Urabá.*

Introduction

There is a strong relationship between the ocean and the continent, modulated by the atmosphere and the ocean, which allows the occurrence of natural processes that particularly affect coastal areas. An important phenomenon in these places is that of sea breezes, whose daily circulatory regimes significantly influence the dispersion of airborne pollutants (Lalas, Asimakopoulos, Deligiorgi, Helmis, 1983; Salvador and Millán, 2003). In addition, breezes are important in understanding the morphological changes produced on the coast and, specifically, erosion processes, since they could allow the intensification of wave energy reaching the beaches (Pattiaratchi and Masselink, 1997).

To date, there is no consensus in the scientific community regarding a method for identifying breezes in any coastal area (Azorín-Molina and López-Bustins, 2006). However, the common parameters used to characterize breezes are their magnitude, the distance they reach between the coast and the continent, the directions from which they blow (sea/land), as well as the distance and height where the return current begins (Miller, Keim, Talbot and Mao, 2003; Carnesoltas, 2002). The most widely used method considers that the sea breeze is produced when there is a strong change in wind direction and magnitude, as well as a notable thermal difference between the continent and the sea (Azorín-Molina, 2004).

Sea breezes have been determined from in situ measurements (Delgado, Larios and Ocampo, 1994; Huamantinco and Piccolo 2011; Pérez *et al*., 2018) and using numerical modeling (Rani *et al*., 2010; Steele, Dorling, Von Glasow and Bacon, 2013; Comin *et al*., 2015). Recently, the WRF (Weather Research and Forecasting) model has been employed, extensively demonstrating its ability to consistently reproduce this phenomenon. Some of these exercises have focused on the characterization of breezes (Arrillaga, Yagüe, Sastre and Román-Cascón, 2016; Lin *et al*., 2019), others have analyzed their relationship with pollutant dispersion and the diurnal wind cycle near the coast (Parajuli *et al*., 2020; Aravind, *et al*., 2022) and it has also been used to study their modulation in urban meteorology (Ribeiro *et al*., 2018; Bauer, 2020).

In the case of Colombia, the WRF model has been used to characterize atmospheric variables. Research using this model has mainly evaluated parameters such as temperature, wind direction and speed, and accumulated precipitation (Jiménez, 2014). When comparing the results of the model with in situ precipitation data, Jiménez (2014) found that WRF overestimated values in regions with complex topography such as the eastern cordillera of Colombia; while, in the central cordillera, it predicted values similar to those measured (Posada-Marín *et al*., 2018).

Studies have also been conducted in order to characterize atmospheric processes in the Colombian Caribbean (Pérez *et al*., 2018). However, the results have not been conclusive due to the scarce number of meteorological stations near the coastline, as only some coastal sites have historical information on variables such as wind and temperature. It is worth highlighting that in recent years the number of these coastal stations has increased (Moreno and Muñoz, 2006; Castillo-Morales *et al*., 2017; Moreno-Calderón *et al*., 2020).

Most research has used data from global databases and reanalyses with coarse spatial and temporal resolutions of about 30 km and 6 hours, respectively. This type of information is not sufficient to describe mesoscale processes such as sea breezes (Bao and Zhang, 2013), which generates the need for studies with more detailed scales (Posada-Marín *et al*., 2018). A similar situation, in terms of studies and scales, has occurred in the Gulf of Urabá, located in the western part of the Colombian Caribbean Sea.

The Gulf of Urabá is projected to be a pole of economic development for the region and Colombia, given that it is the epicenter of three potential port projects that will serve as terminals for the export of national and regional products (García and Galíndez, 2018). In this sense, it is necessary to expand our knowledge of the physical processes that occur in the gulf and in particular, to characterize the dynamics of sea breezes, as their behavior can be associated with increases in wave energy, something that is relevant to the aforementioned port projects.

In this study, a sea breeze system was described, using data from simulations performed with the WRF model. This research is novel for the region, since it includes, among other things, modeled information of the wind at different vertical levels at high spatial and temporal resolutions, whilst also taking into account the geometric characteristics of the gulf.

Study Area

This study was conducted in the region of the Gulf of Urabá, located in the southern Colombian Caribbean (Figure 1A). The gulf has an elongated shape in a north-south direction, being apprximately 25 km wide and 80 km long.

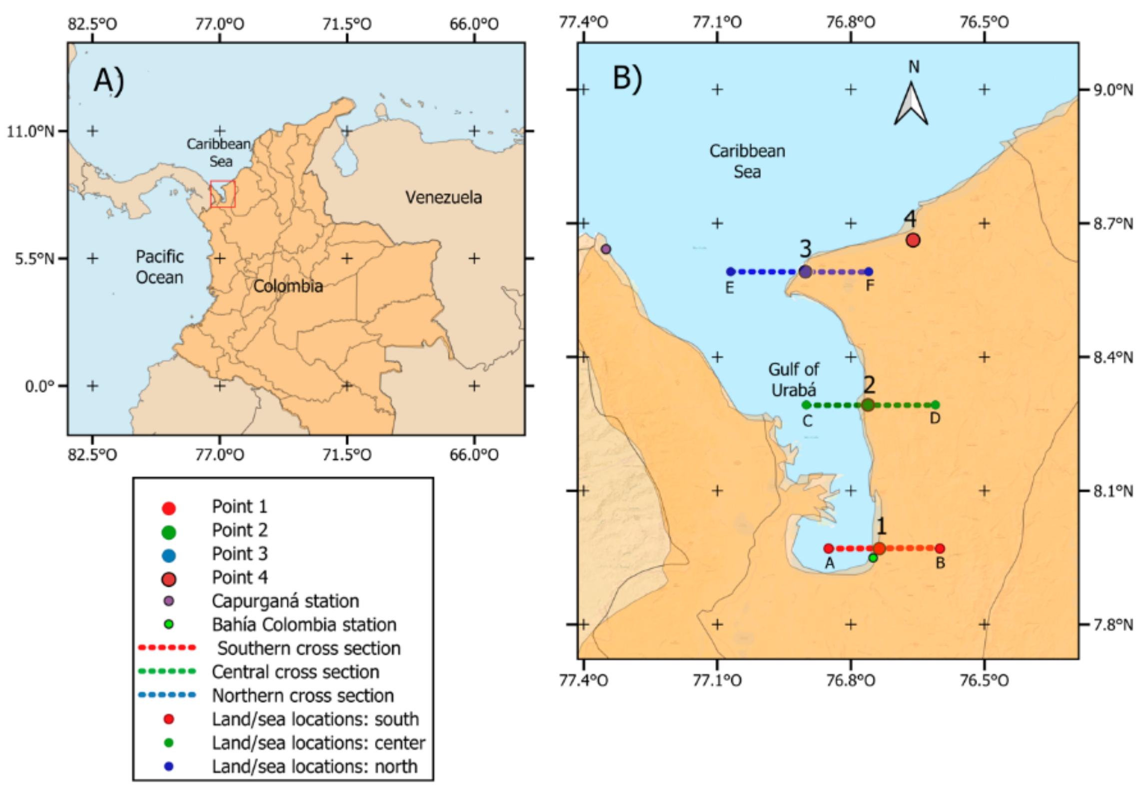


Figure 1. (A) Location of the Gulf in the Colombian Caribbean; **(B)** Study area: the dotted lines show the three cross sections and the large dots show the four analysis sites.

It is characterized by two climatic seasons: a dry season, which runs from December to April, with winds from the northeast at magnitudes of up to 4 m/s; and a wet season, which begins in May and ends in November, with weak winds from the south at magnitudes of up to 2 m/s. Its average annual temperature is 27.2°C (Hernández and Mercado, 2020).

Methodology

The WRF model was used to simulate the wind field over the study area, as it has a set of differential equations capable of representing the dynamic processes and energy relationships of the earth-atmosphere-ocean system (Manta, 2017). In this case, the study analyzed data modeled for the months of January and February between 2008 and 2013. These simulations used the configuration proposed by Posada-Marín *et al*. (2018), which used reanalysis data obtained from the ECMWF ERA-Interim product (Available at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim) for initial and boundary conditions with a 0.75° x 0.75° grid.

Results were obtained in three domains with spatial resolutions of 30 km, 10 km and 3 km, as well as at 37 sigma levels in the vertical up to 50 hPa and with a temporal resolution of 3 hours. The analyses of the present work only use the results of the domain with the highest resolution, since the area of interest is framed there.

With the wind fields, a monthly hourly average was calculated for January and February in the period 2008 to 2013, with which we made the analyses that will be mentioned later. In this article, only the graphs of one of the two months studied (February) are shown, as the two months had very similar results.

Three coastal cross sections (dotted lines) were analyzed: one each in the southern, central and northern parts of the Gulf; as well as 4 sites (points), located near the aforementioned cross sections (Figure 1B). In addition, we included information measured in situ by two meteorological stations: one located in the south, in Bahía Colombia, and the other in the north, in Capurganá. Hourly data for wind speed and direction for January and February 2010 were obtained from these stations and compared with the simulations using bias, mean square error (MSE) and index of agreement (IOA) as statistics.

The changes in wind direction were defined by means of hodographs made with wind data at 10 m above the surface (Salvador and Millán, 2003). This type of graph describes the hourly trajectory of the wind components in the horizontal plane (Delgado, Larios and Campo, 1994). The existence of a sea/land breeze was identified using the method proposed by Gustavsson, Lindvqvist, Borne and Bogren (1995) and Pérez *et al*. (2018), in which the following criteria are considered: the breeze starts with a change in wind direction () ≥ 100° in the sea-land direction, an increase in wind magnitude (v) greater than 0 m/s and less than 10 m/s, and a reduction in the temperature value (T). The cycle ends when there is again a change in wind direction ≥ 100° (land-sea), an increase in velocity and a reduction in temperature.

This study analyzed the vertical profiles of the zonal (U) and vertical (W) components of the wind in the three cross sections mentioned (Figure 1B). The analyses were performed between 07:00 and 19:00 local time (LT) using the first 8 vertical levels (between 1000 hPa and 650 hPa). Subsequently, wind fields of average U, V and T values were analyzed between 07:00 and 22:00 LT. Temperature differences between the marine and continental zones were calculated for the sites in Figure 1B corresponding to specific zones in the south, center and north of the Gulf of Urabá.

Results and Discussion

The times mentioned in the results presented below correspond to the local time in Colombia, calculated as UTC (Coordinated Universal Time) minus 5 hours.

Evaluation of simulation results

Comparisons were made at the points of the model that are closest to the weather stations at Bahía Colombia and Capurganá. The wind roses for these two sites indicate that the wind directions in the months analyzed are mainly between northeast and northwest (Figure 2). However, the model has low agreement with the observations when representing the frequency and value of these directions, especially in Capurganá. Regarding this behavior, Jiménez and Dudhia (2013) found that there are smaller differences between the WRF and the observations in areas with less complexity in the terrain and in this case, Bahía Colombia fits better to these characteristics.

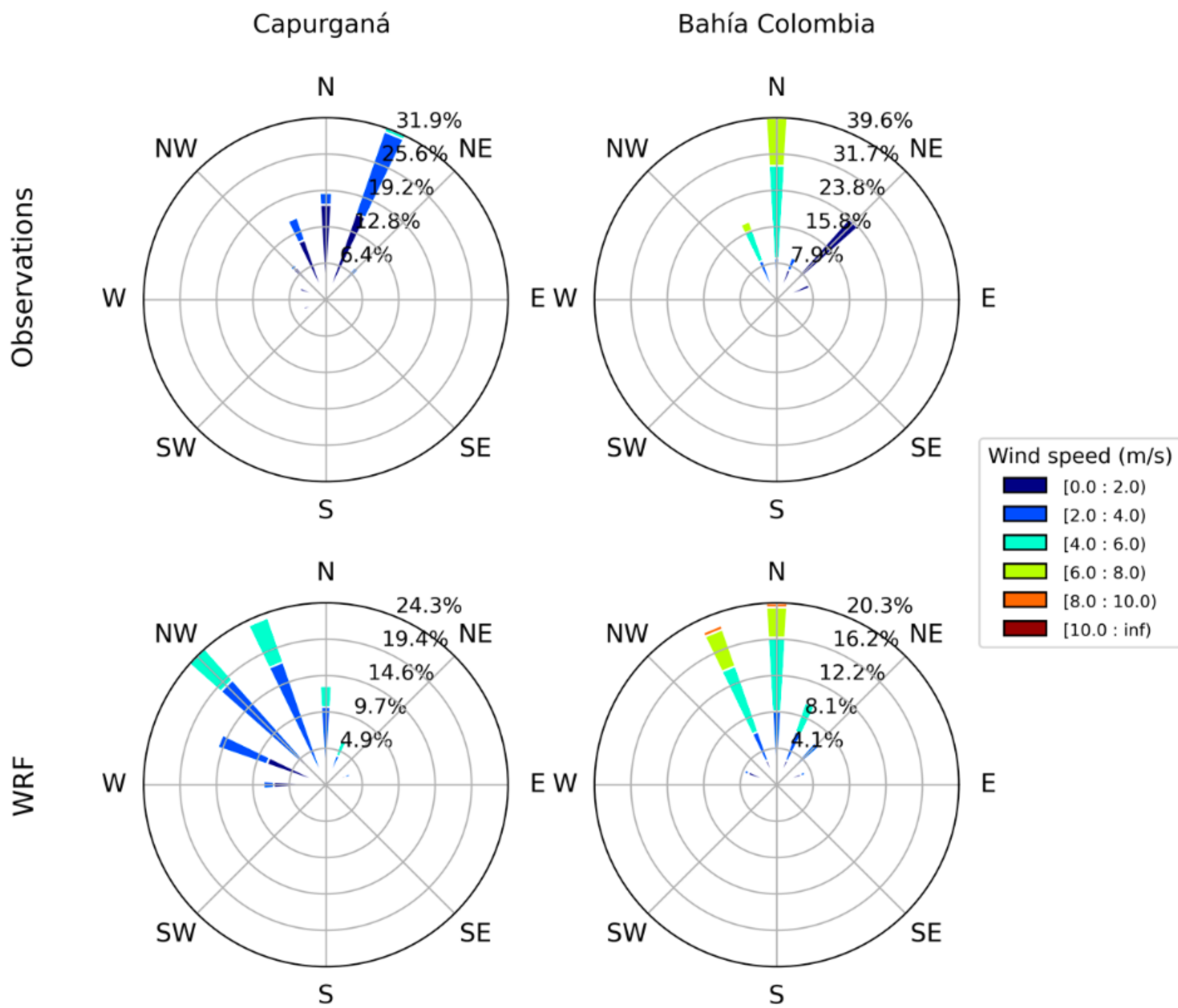


Figure 2. Wind roses of the observations (top) versus WRF (bottom), for Capurganá (left) and Bahía Colombia (right). January and February 2010.

The wind speed values of the model and the stations are of intermediate dispersion. The results suggest a moderate similarity between the model and the observations (IoA with the observations of 0.4 for Capurganá and 0.43 for Bahía Colombia. Figure 3, left panel). It is important to note that comparisons with the Bahia Colombia point show a better fit. This is evident in the density distribution function of the wind speed for the model and the observations (Figure 3b, right panel).

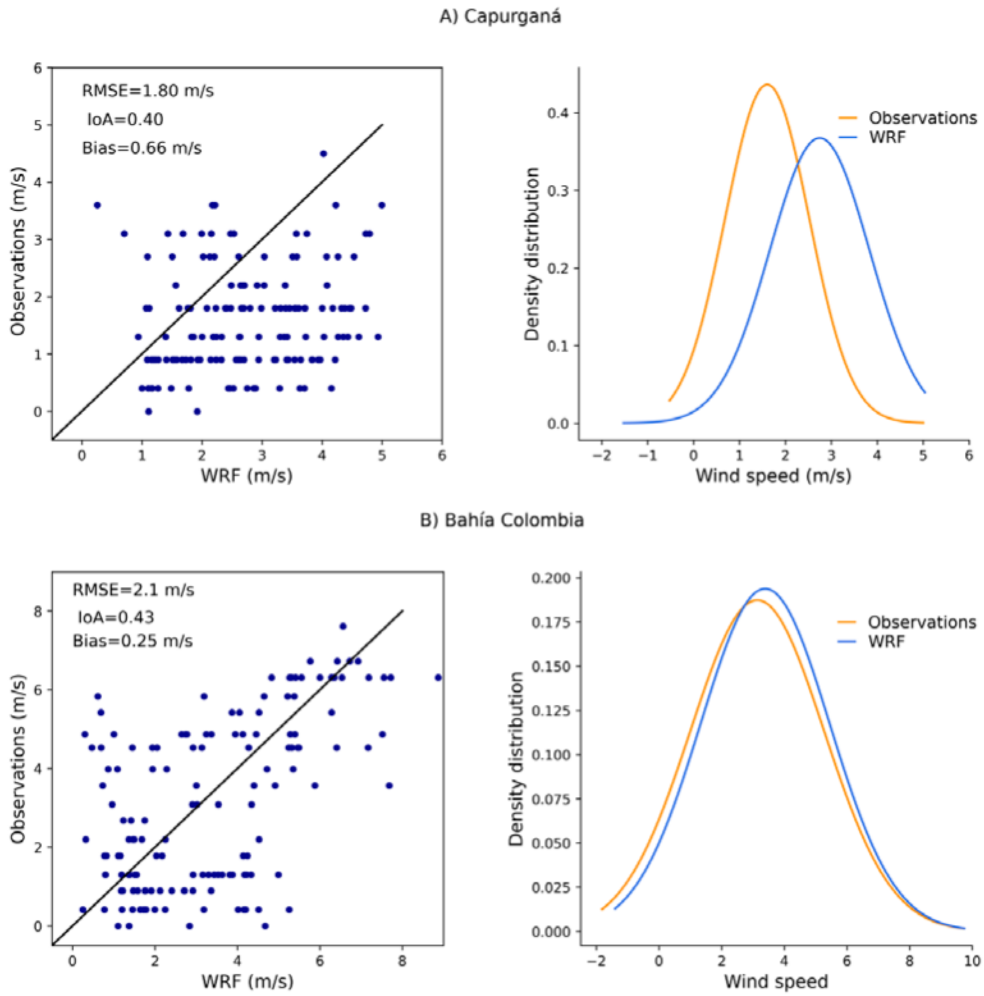


Figure 3. Scatter plot with wind speed data from the model and real-world observations (left). Density distribution functions of the wind speed data for the model and real-world observations (right), at the two stations: **A)** Capurganá and **B)** Bahía Colombia.

Characterization of sea breezes in the Gulf of Urabá

Figure 4 shows the average surface wind fields (vectors) for the month of February every 3 hours between 7:00 and 22:00. The average surface temperature is shown in color. The air temperatures over the gulf, both in the center and at the coast, vary between 26°C and 28°C. The highest temperature values are evident in the afternoon hours (between 13:00 and 19:00), and they decrease after this.

Between 07:00 and 10:00, the wind enters the region from the south and turns in a westerly direction from the Gulf of Urabá. This behavior is modified at 13:00, when the wind begins to move both east and west from the Gulf of Urabá. At 19:00, a weaker wind is observed on the coast along with lower temperatures, and finally at 22:00 the wind takes a northwesterly direction (towards the center of the gulf) and the magnitude of the wind on the coast is further reduced.

The vertical cross sections (Figure 5) show that in the south (A) and center (B) of the coast of the Gulf of Urabá there is a landward flow between 10:00 and 16:00 that starts with a height up to 970 hPa and reaches its peak at 16:00 with a return flow at higher altitudes (below 925 hPa). In in accordance with this, the highest surface temperatures in the coast region occur at this time of day (between 26°C and 27°C).

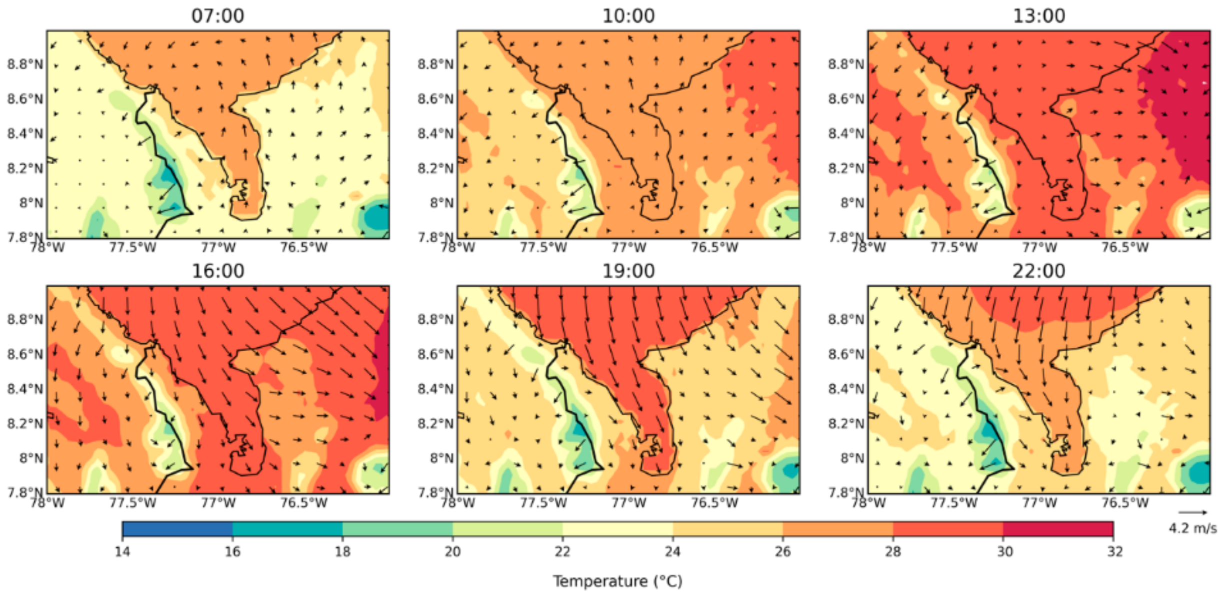
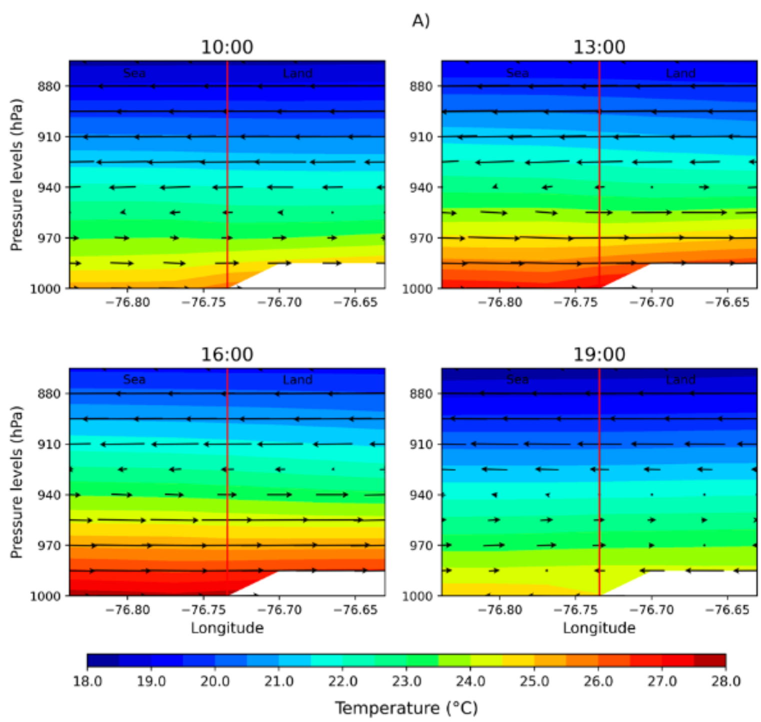


Figure 4. Average wind fields for the month of February between 7:00 and 22:00 (LT) at an average altitude of 10 m above the surface. The temperature values are shown in color.

In the north of the gulf (cross section C), the landward flow occurs between 13:00 and 16:00 and its maximum height reaches 925 hPa with a return flow at 910 hPa. At 19:00 there is a seaward flow all the way up to 865 hPa. The results show changes in the wind direction that suggest the occurrence of sea and land breezes with wind shifts towards the land in hours with greater solar radiation and towards the sea in the night hours. This is in agreement with what has been expressed by several authors (Simpson, 1994; Gustavsson, Lindvqvist, Borne and Bogren, 1995; Salvador *et al*., 2016).



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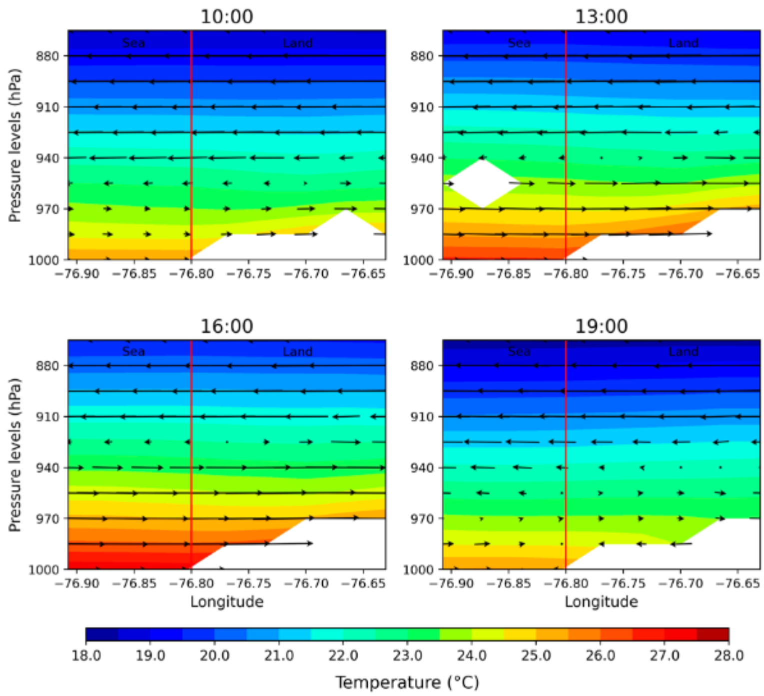

C)

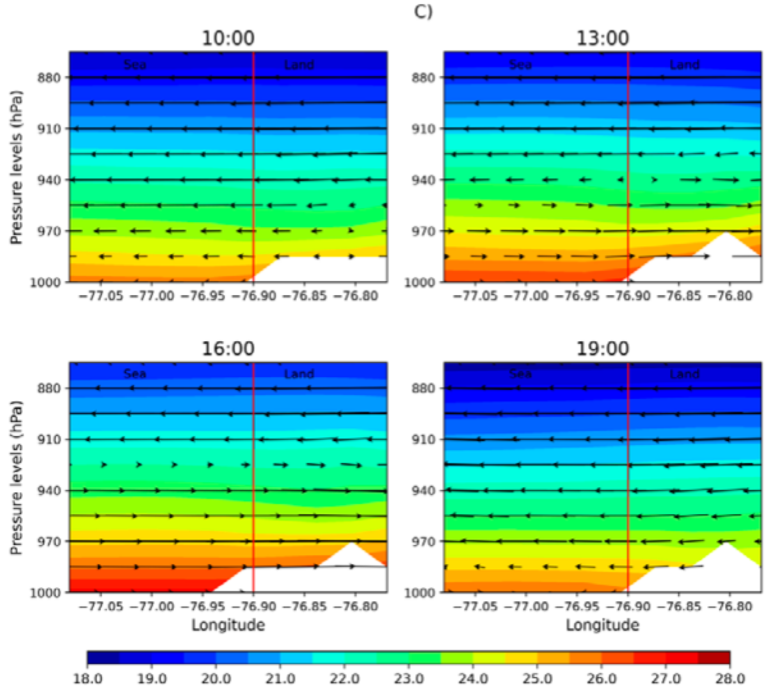

Figure 5. Vertical wind cross sections (arrows) and temperature contours. A) in the south; B) in the center; C) in the north of the Gulf of Urabá.

The differences between the air temperature over the sea and over land are shown in Figure 6. The results show that the highest temperatures differences occur between 01:00 and 13:00 and the lowest differences (0.5°C) between 16:00 and 19:00 in the central and southern points, suggesting an increase in the temperature over the continent. This reduction begins after 10:00 and is consistent with the landward fluxes evident in the surface fields (Figure 4) and vertical cross sections (Figure 5). This is in agreement with the thermal contrast on the coast proposed by Sills (1998).

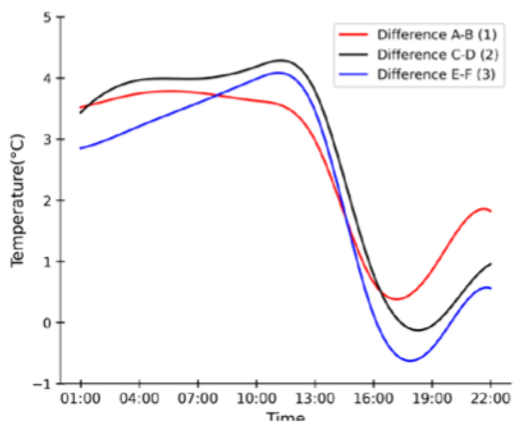

Figure 6. Temperature differences between air over the sea and over land for the points in the south, center and north of the Gulf of Urabá.

The north is the only point where at 16:00 the temperature over land is higher than that over the sea (0.6°C); however, in this area the same general pattern is maintained as at the other sites. The thermal differences that are evident in the results are considered the most determining aspect for the identification of the sea/land breeze according to Pielke and Senegal (1986). In the case of the Colombian Caribbean, authors have found that the difference is not as pronounced as in the case of Urabá, but differences of up to 2°C were sufficient to determine the occurrence of the breeze (Kazakov, Lezhenin and Speransky, 1996; Pérez *et al*., 2018).

Figure 7 shows the hodographs as a function of the U (m/s) and V (m/s) components of the surface wind for the four gulf sites specified in Figure 1B. In general, the hodographs have an elliptical shape and show a clockwise rotation of the wind. According to Carnesoltas (2002), the elliptical geometry is related to breeze formation, and according to Pérez *et al*. (2018), in the Colombian Caribbean coast there is a higher occurrence of sea breezes in the low rainfall season. This coincides with the climatic characteristics of the study ares in the period of analysis.

At point 1 (Figure 7A), the wind direction turns towards the mainland between 04:00 and 07:00 before returning to the sea after 16:00, while at points 2, 3 and 4 (Figures 7B, 7C and 7D) the wind turns towards land between 07:00 and 10:00 and returns to the sea after 19:00, but at all sites the wind is towards the mainland at 13:00.

The average daily progression of temperature, wind direction and wind speed, for all four study points, are shown in Figure 8. Note that the wind direction is referenced to where the wind is coming from and that 0° is oriented to the North. Changes in direction >100° are observed for points 1 and 4 (Figures 8A and 8D) between 07:00 and 13:00, while at points 2 and 3 (Figures 8B and 8C) these changes take place between 10:00 and 16:00. These changes in wind direction represent a shift from northeast (NE) to northwest (NW) and vice versa.

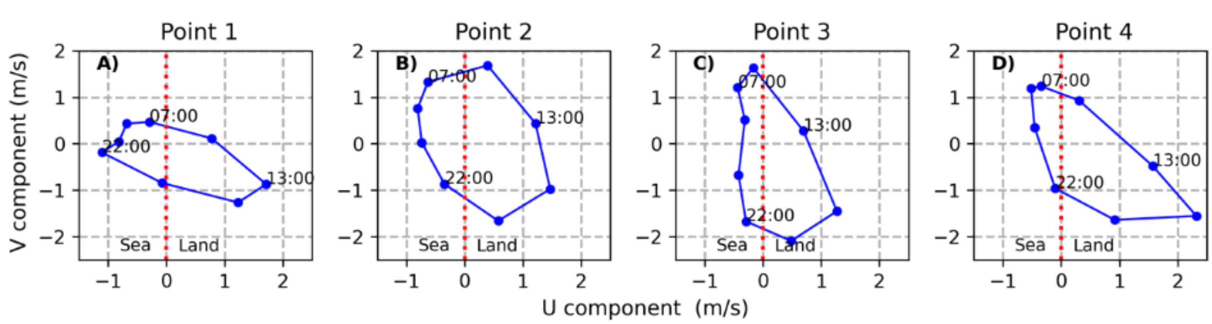

Figure 7. Hodographs as a function of the average U and V components every three hours for the four study sites.

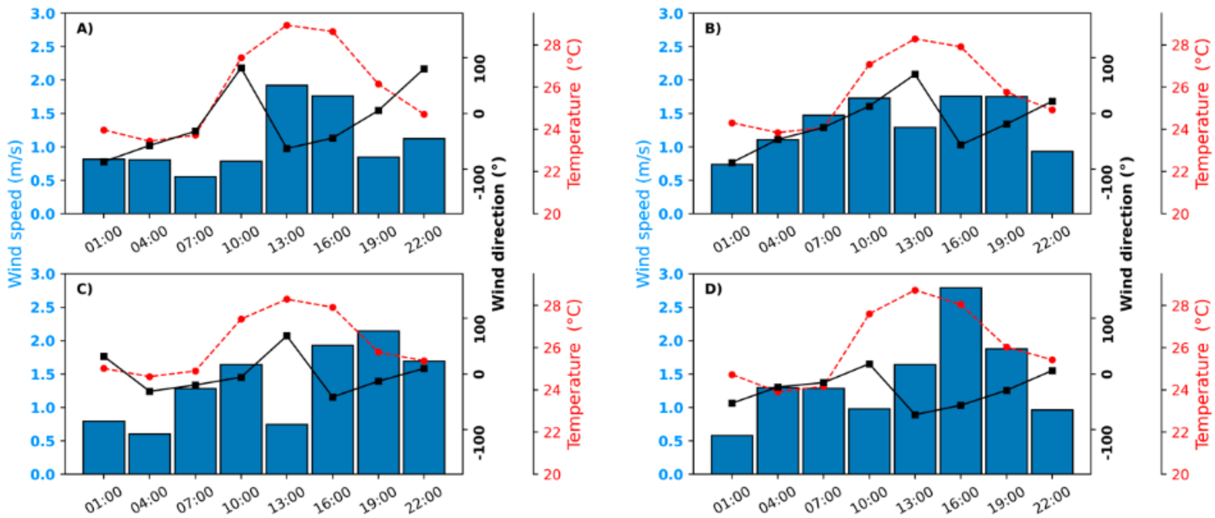

Figure 8. Graphs of wind speed (blue bars), wind direction (solid black line) and temperature (dotted red line) throughout the day. A) point 1; B) point 2; C) point 3 and D) point 4.

During daylight hours, the lowest temperature values at all four points are observed at 07:00 and the maximum values at 13:00 with a slight decrease at 16:00. For its part, the wind speed increases occur during the morning: for point 1 until 13:00, at points 2 and 3 until 10:00 and at point 4 after 10:00. In general, the changes evidenced for temperature and wind direction and speed suggest the onset of the sea breeze after 07:00, with an onshore growth between 10:00 and 13:00, and finally a few hours of transition to land breezes between 19:00 and 22:00.

Conclusions

The results of this study suggest the establishment of a breeze system along the east and south coast of the Gulf of Urabá. According to the changes in wind direction and magnitude, the sea breeze starts at 07:00 LT and turns anticyclonically until 16:00 LT, after which it returns to its starting state. Relative to our cross sections, the breeze starts at sea and moves towards the land during daylight hours. In the evening (19:00 LT) and at night it moves in the direction of the sea. The vertical height of the sea breeze reaches up to the 925 hPa level, while the land breeze in the south and center of the Urabá region only reaches 985 hPa.

These results coincide with the changes in temperature and wind speed and direction over land and sea that mark the beginning and end of the breeze. These results allow us to improve our understanding of the vertical structure of the atmosphere in coastal areas and in particular of sea breezes, which will allow us to improve the estimation of processes such as the intensification of local waves on the coast and the consequent coastal erosion.

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