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Synoptic scale factors involved in the appearance of tropospheric ducts in the Caribbean Sea†

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Abstract: Tropospheric ducts are an abnormal condition of the atmosphere that affects the propagation of electromagnetic waves, which has a direct impact on the performance of various radio systems, including mobile telephony, which is especially sensitive to these interferences in communications. In Cuba, til the date there is only one investigation focused on the formation of tropospheric ducts, which was carried out by [1], therefore, studying this topic also taking into account its relationship with atmospheric weather is novel. Knowing what meteorological situations lead to the formation of these communications interference events allows us to alert them and take measures in time. In the work, a study is carried out on the use of numerical model outputs for the detection of the occurrence of tropospheric ducts. Based on the ERA5 reanalysis, which was feasible for the development of the research, and the data derived from the methodology used by [1], the behavior of the characteristic parameters of the tropospheric ducts was determined, as well as the conditions of synoptic scale that favor its appearance. As a first result, it was obtained that the thickest ducts (between 75 meters and 80 meters) are seen more frequently in the March-May quarter, while in September and October these values are reduced by half, oscillating between 40 meters and 45 meters. In another order, it was determined that the presence of stable atmospheric conditions in combination with a humid layer at low levels favors the appearance of this phenomenon, therefore, days with a predominance of subtropical high pressures in combination with the passage of tropical waves through the seas south of the island of Cuba or with the arrival of migratory anticyclones guarantee this stability in addition to surface relative humidity values close to 80%.

Keywords: tropospheric ducts, troposphere, weather, atmospheric stability, ERA5

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1. Introduction

According [1,2] in a tropospheric duct, the wave is trapped in a kind of natural guide between the earth's surface and the layer in which the vertical gradient threshold is exceeded, or between two layers with the same condition. Due to this, the wave will propagate in jumps within the guide, with communication ranges that can reach hundreds of kilometers. These waves that travel through the troposphere experience a refraction due to the non-uniformity of the atmospheric layers, which manifests itself as a variation of the refractive index with height. When speaking of ducts reference is made to the most important short-term mechanism. An troposphere duct may have a superficial or elevated base. Taking as a starting point the research of [3] it can be stated that the electromagnetic waves propagating in a surface-based duct bounce between the surface of the earth and the top of the duct layer, while for the duct high bounces between the top and bottom of the duct. For incoming electromagnetic waves to be trapped within a duct layer, their angle in the duct must be close to the paraxial direction or the direction of the duct.

One of the works that stands out the most in the study of tropospheric ducts with meteorological models is by [4] on the climatology of ducts based on the data analyzed from the model of the European Center for Medium-Range Meteorological Forecasts (ECMWF), this investigation served as the basis to extract the main characteristics of tropospheric ducts.

The study of ducts has also been explored by high spatial resolution simulations with mesoscalar models such as the WRF. Some of these studies, such as the one by [5] have managed to represent the behavior of meteorological variables at the local scale and from these a group of products focused on the detection of ducts are obtained, which were used to evaluate the performance of radar observations and improve the quality of the data. In [6] I found that due to the meteorological conditions of the Caribbean and more specifically of Cuba that generated greater refractive gradients as a direct consequence of this is the occurrence of larger fictitious radio. In general, at the national level, research focused on the study of the occurrence of ducts is scarce, hence it is useful to study the occurrence of tropospheric duct events at the national level, specifying what synoptic factors favor the appearance of these, with the objective to have a tool that enables early warning.

There have been many investigations aimed at the study of ducts, but they have not been able to accurately determine which meteorological event generates these alterations in the atmosphere. In fact, at the international level, not many tools of this type have been found, some are of a commercial or for military purposes such as the Advanced Refractive Effects Prediction System (AREPS), and most of some of these are implementations carried out by specialists in the Matlab software, which requires a commercial license and only provides modules with a limited number of applications in their use and for free access is only available with DXINFO (available on [7]), which is a web tool on the Internet that provides real-time numerical forecasts of the Hepburn Tropo Index, which is an empirical index that provides information on the intensity of the pipelines, although it is a product that has low spatial resolution and does not have energy analysis and signal interference services.

Therefore, contributing to the development of a system for analyzing and forecasting interference in radio communications networks caused by anomalous meteorological conditions constitutes a novel topic from a scientific point of view. Implementing this method will allow the generation of short, medium and long-term alerts of possible interruptions in radio communications systems due to refractive anomalies. It is good to clarify that so far there is no known similar system implemented. Therefore, research aimed at the forecast and detection of tropospheric ducts has a positive impact on the radiometeorological diagnosis of the functioning of existing communication links, representing a valuable contribution to the country's economy. Knowledge of the meteorological conditions that can lead to the appearance of ducts can strategically support decision-making that ranges from the way antennas are installed, taking into account orientation and power parameters, as well as the management of the country's telecommunications system. Knowing in advance the possibility of these events occurring allows operators to provide the public with special offers with preferential cost rates that contribute to redirecting the flow of user connections towards other types of networks that are not affected during the interval. time that this type of interference is occurring, thus achieving better use of the equipment, and therefore saving material and human resources. Thanks to the possibility of obtaining products derived from meteorological models, which provide the behavior of meteorological variables for an area, it is possible to avoid carrying out long periods of field tests and other types of similar studies.

2. Materials and Methods

For the accomplishment of this work the ERA-5 reanalysis was used. This reanalysis provides hourly global estimates of atmospheric variables, with a horizontal resolution of

31 km and 137 hybrids (sigma/pressure) vertical levels from the surface to 0.01 hPa. The ERA5 was produced using the 4DVar data assimilation method in the Integrated Forecast System (IFS) of the European Center for Medium-Range Forecasting (ECMWF). This is the successor to the ERA-Interim reanalysis created by [8]. These types of products provide extensive information on the state of the atmosphere and surface variables, and were built using a wide variety of meteorological observations, although it is also important to know the limitations of these fields generated with this numerical model; since two of the main limitations are the non-physical trends and the variability that may be present in the data series due to changes in the observation system, and that the climatologies of some variables, such as surface energy flows, may not be well represented. Thanks to [9] ERA5 has daily updates with approximately 5 days after the real time and average monthly updates are available approximately 5 days after the end of the month. Table 1 reflects a description for ERA5 reanalysis.

Table 1. ERA5 reanalysis description.

Period	**1950–present**
Production period	January 2016 – ended, since that date it continues to work in real time
Temporary Resolution	Monthly / Every 1 hour
Data assimilation system	IFS Cycle 41r2 4D-Var
spatial resolution	0.25° 0.25° x 0.25° km global, 62 km for Ensemble Data Assimilation (EDA), 137 vertical levels down to 0.01 hPa
Output frequency (time resolution)	Hourly analysis fields, every 3 hours for the data assimilation set (EDA) Hourly forecast fields, every 3 hours for the data assimilation set (EDA), up to 18 hours, with frequency reduced to 10 days (no in the initial version)
model input	Appropriate for the climate (for example, CMIP5 greenhouse gases, volcanic eruptions, SST and sea ice cover)
Input remarks	Also, several recently reprocessed datasets and recent instruments that could not be ingested into ERA-Interim
Bias variational scheme	Also ozone data, aircraft and surface pressure.
Satellite data	RTTOV-11, all-sky for various components
New parameters	ERA5 contains over 240 surface and single level parameters, as well as parameters in other types of levels. For specific parameters, please compare the technical documentation linked below.
Product website	https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview

A group of duct parameter products and meteorological variables are available on the website [10] for this reanalysis and are listed below:

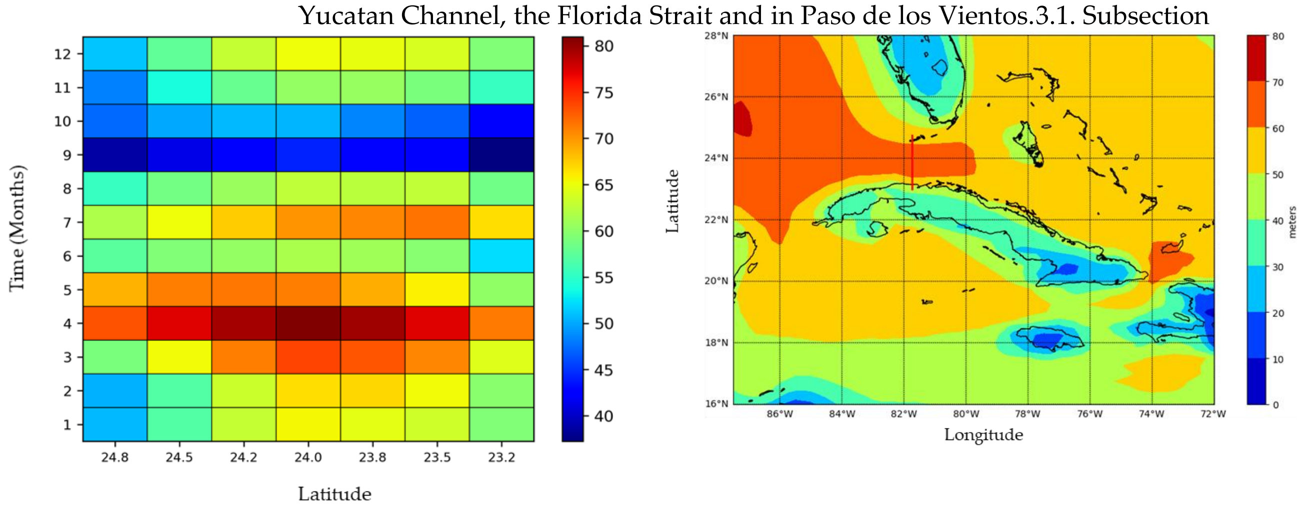
- Duct base height.
- Minimum vertical gradient of refractivity inside trapping layer.
- Trapping layer top height.
- Mean vertical gradient of refractivity inside trapping layer.
- Trapping layer base height.
- Atmospheric pressure adjusted to mean sea level.
- Relative humidity at 2m from the ground.

For this study, was used the data from the record of occurrence of ducts, these records are obtained from products produced by the Ministry of Communications of Cuba, this collects every day with incidence of ducts in a period of five years and one month (2017-January 2022) at the established synoptic times (00Z, 06Z, 12Z, 18Z). It can be affirmed that using a purely statistical method based on the Ducts History to meet the objectives has its limitations, because this data does not constitute cases of confirmed ducts, in fact they are generated from an algorithm that determines if a duct occurs, but it is a procedure that is only valid a few kilometers where the Key West survey is carried out, so it is not possible to establish whether the duct will really affect Cuba. So, given these limitations, was decided to start using numerical modeling in this type of study, in this way, in each cell of the grid it is as if there were many boreholes, this method would be much more realistic from the physical point of view.

Therefore, it was decided that to process the information from the ERA5 reanalysis and from the surveys carried out, it was useful to write a script in the Python programming language. This script will help to combine the data obtained from both sources, achieving that the obtained result is more adjusted to types of synoptic situations with conditions for the occurrence of ducts.

3. Results Discussion

From the processing of the data series of duct parameters available in the ERA5 reanalysis using the Python programming language, the climatic behavior of these variables was obtained for the period 1981-2021. The section selected fot the investigation corresponds to the Florida Straits area , due to the proximity of this area to the country's capital, also due to the socioeconomic interest and the imapct that the occurrence of an interference in this area, which is the most populated in the country, has on communications. The selection of cells described above allows plotting the ducts thickness segments for each month in the period between 1981-2021 (Figure 1a), guaranteeing a better visualization of the monthly average values of the thickness of the ducts layer. Thanks to this type of graphs , it was possible to determine that in the Florida Strait during the months of March to May the greatest thicknesses of ducts are present, also seeing that the maximum values can be in April where for all the analyzed section A the values are greater than 70 meters thick of the duct layer on average. In this analysis, it is important to consider that the highest values of thickness are also associated with more intense ducts, which from these maps it was possible to show that they occur at this time of the year, with average maximum values of 90 meters in the months of April. To generalize the variable in question, figure 1b was prepared, wich reflects the annual behavior of the ducts layer thickness around the archipielgo. It is observed that the highest thickness values are located in the Yucatan Channel, the Florida Strait and in Paso de los Vientos.3.1. Subsection



(**a**) (**b**)

Figure 1. a: Average monthly evolution of the ducts layer thickness in the sections: Havana – Florida of the ERA5 reanalysis grid, b: Annual average evolution of the duct layer thickness in seas adjacents to Cuba (the red line means the selected area for the development of the study).

During the months included in the rainy season (May, June, July, August, September and October) there is a predominance of occurrence of ducts in which the height of the layer oscillates between approximately 150 m and 300 m, while during the dry period (January, February, March and December) these heights are higher, generally between 300 m and 400 m .

This situation occurs because in this period there is a humid layer at low levels, in addition, as throughout this time there is more instability there is less stratification of the atmosphere, this will influence less thermal stratification to predominate, therefore, the incidence of the elevated ducts will be less compared to the surface ones, the absence of forcing phenomena that generate uplift also makes it possible for the ducts to occur at lower heights in this period. At the moment that dry air predominates on the surface due to the advance of the frontal systems over the Gulf of Mexico, the Florida Peninsula and the Atlantic Ocean, an uplift of this humid layer is generated (figure 2), for which reason it is already It will not be located only on the surface. That is why when the monthly averages of the height of the duct base are obtained (figure 3a) there are moments in the same month of the dry season when the height of the base takes high values (greater than 350m) and others where the values decrease (between 250 m and 250 m). When analyzing this same variable but taking into account its behavior during an entire year, as shown in Figure 3b, it is seen that during the period the average values of duct height range between 250 meters and 350 meters to the north and west of Cuba, being inferior to the south of the island.

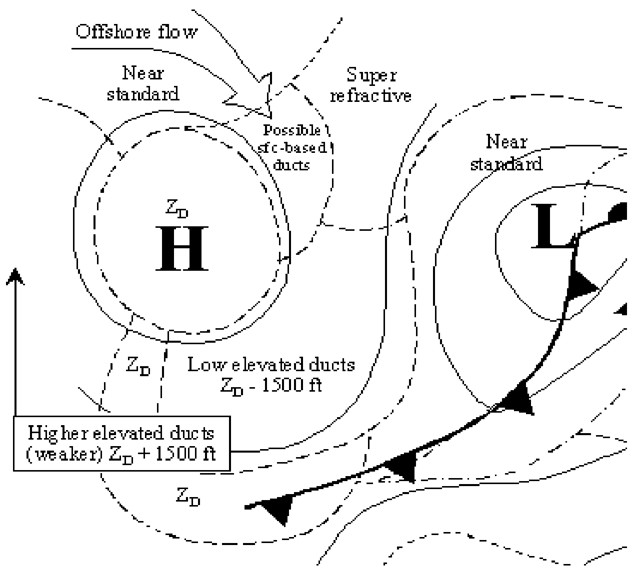
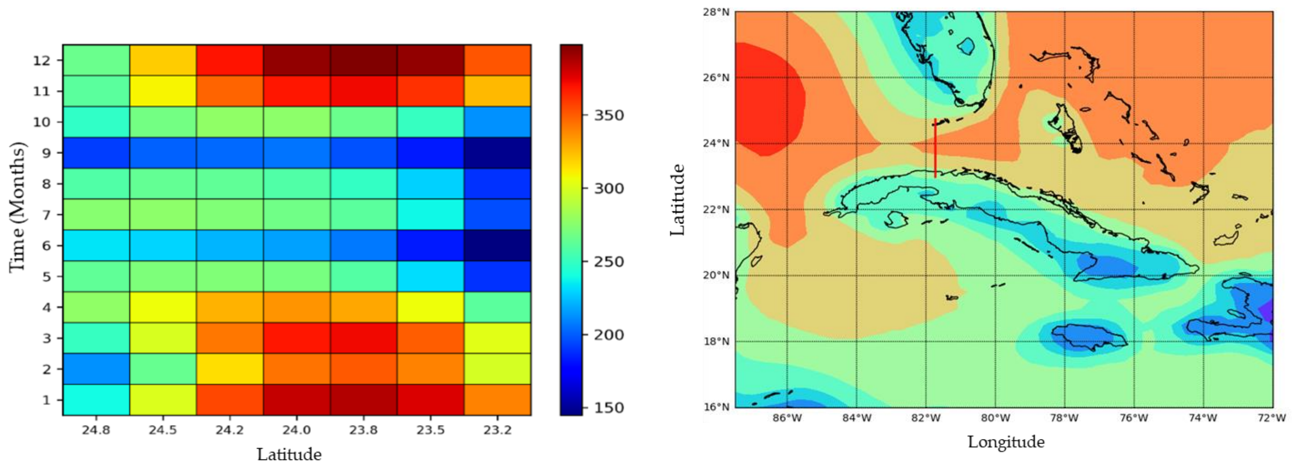


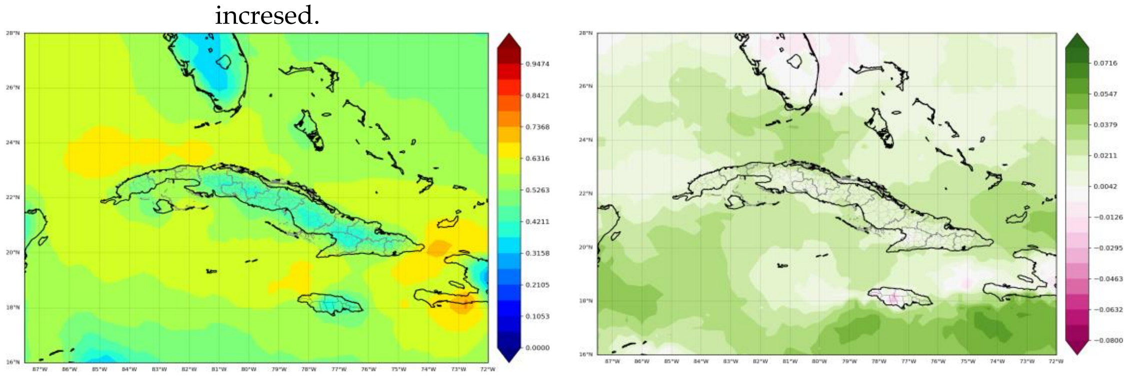
Figure 2. : Influence of migrating anticyclones on the variation of the height of the tropospheric duct layer (Source: [11]).



(**a**) (**b**)

Figure 3. a: Average monthly evolution of the height of the base of the ducts for the Havana – Florida section of the ERA5 reanalysis grid, b: Annual average of the duct base height in seas adjacents to Cuba (the red line means the selected area for the development of the study).

Several studies have shown that the frequency of occurrence of tropospheric ducts has a variable behavior and is dependent on factors such as geographic position, weather conditions, and time of year. Figure 4a shows that in the case of Cuba and adjacent seas this variable has an average annual behavior that presents values close to 0.56 higher in the Straits of Florida, southeast of the Gulf of Mexico and southwest of Granma. When analyzing the sequence of maps corresponding to the average frequency of occurrence of ducts in the period 1981 - 2021, it was observed that there was a tendency to increase this variable in the last 10 years of the period (Figure 4b). This is happeing because in recent years an expanssion in the Atlantic subtropical anticyclon has been observed. Due to this change in circulation the days wiith predominace of stable atmospheric conditions have incresed.



(**a**) (**b**)

Figure 4. a: Annual frequency map between 1981 - 2021, b: Differences in mean annual frequency values of occurrence of pipelines in the last 10 years with respect to the period 1981-2021.

When analyzing the average frequency of duct by month of the year, it is noticeable that during the March-August semester there is an increase in this variable in the seas adjacent to the entire Cuban archipelago (Figure 5). The seas to the east of the eastern provinces are where the highest values of frequency of occurrence of these events are shown, with values higher than 0.85 in the month of July. On the other hand, the areas to the north of the Western region show maximum values above 0.66 in the months of April and July.

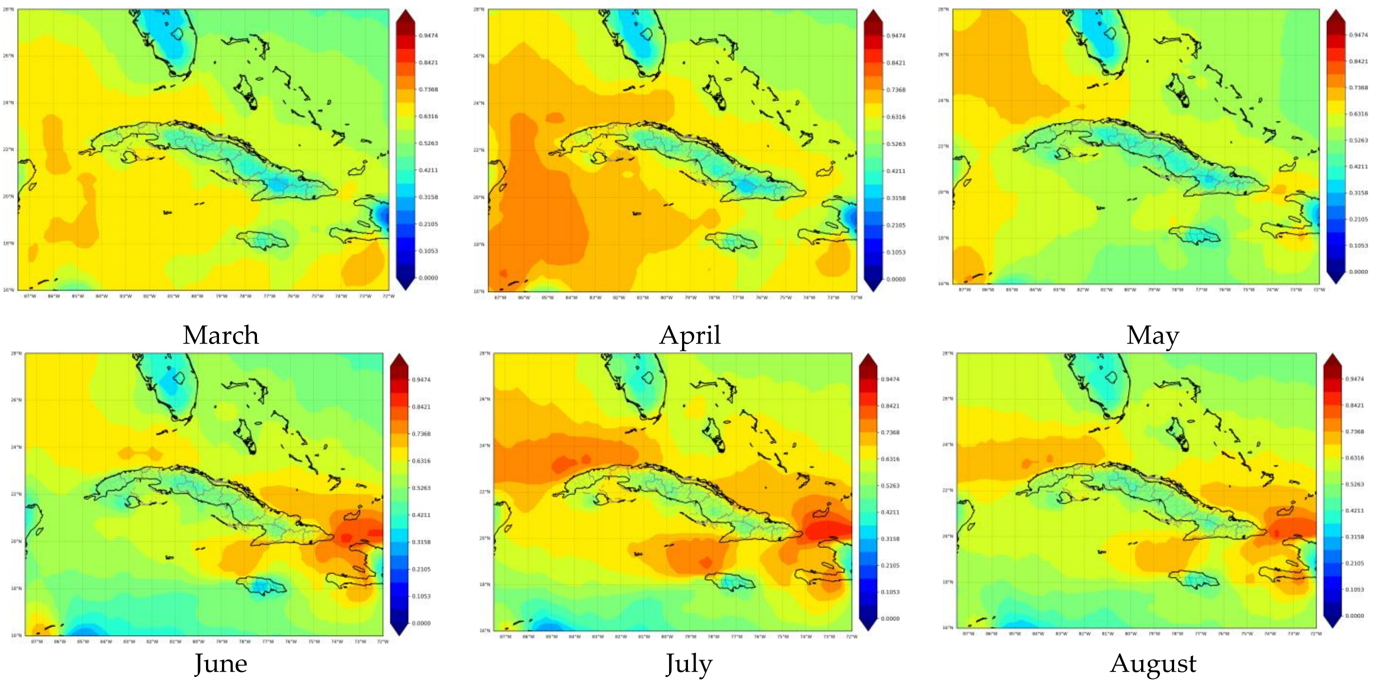


Figure 5. Maps of average monthly frequency between 1981-2022 of occurrence of ducts.

3.1. Identification of the meteorological systems present in the synoptic situations taken from the record of days with ducts conditions between 2017-2021.

The Caribbean geographic basin is subject to the influence of continental anticyclones during the winter period, the centers that move to the southern part of the United States cause intense cold air transport from the center of this country to the western half of Cuba. During this displacement process, the migratory air mass changes slightly, consequently it loses its representation on the surface and ends up being absorbed by the Atlantic Subtropical Anticyclone. The presence of these secondary centers of high pressure favors subsidence, helping moisture to accumulate on the surface. In March, when the subtropical anticyclone is withdrawn, a certain homogeneity is created between its ridge and the ridge of the migratory anticyclone (Figure 6), the latter is also weakened, therefore, successive processes of air mass replacement begin to emerge. and since this cycle is repeated, an accumulation of air takes place that creates a dry layer in the height, confining the humidity on the surface (Figure 7).

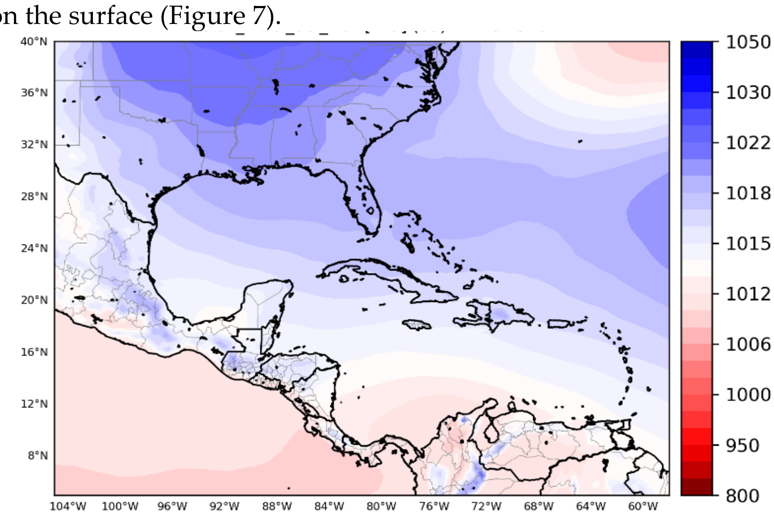


Figure 6. March of mean sea level preassure (MSLP) .

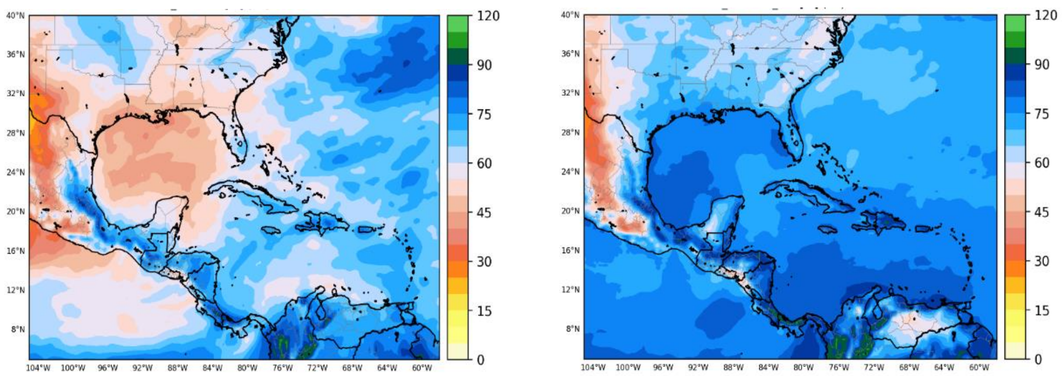


Figure 7. Average in 5 years of relative humidity in the month of March.Left: Relative humidity at altitude (850 mb)Right: Relative humidity on the surface.

In the months of June and July, the subtropical anticyclone reaches its maximum expansion in the ridge, during this period there is no influence of migratory anticyclones either, but these months coincide with the maximum intensity and frequency of the tropical waves from the East, generating a pattern very similar to that observed in the month of March. It is well known that in front of the wave axis there is a presence of divergence and behind it there is convergence with southeasterly winds, so when these waves approach Cuba, said divergence causes subsiding movements and good weather, therefore, conditions of stability and east-northeast winds causing a layer of dry air to originate at height that helps accumulate moisture on the surface. With the arrival of the month of August, the Subtropical Anticyclone begins to withdraw again to begin its interaction with the migratory anticyclones once again with the arrival of the winter season.

4. Conclusions

With this investigation it was demonstrated that the ERA5 reanalysis was feasible to determine the behavior of the parameters associated with the tropospheric ducts in the area of the Caribbean Sea, Gulf of Mexico and Florida Strait, then it can be affirmed that during the quarter March - May in the period between 1981-2021 the greatest thicknesses of the ducts are observed, average values of the layer between 75 m and 80 m approximately are reached, with September and October being the ones with the lowest thickness, with values that oscillate between 40 m and 45 m, while, in the monthly analysis Based on the mean height values of the duct base, it shows that surface ducts are more frequent in the rainy months, and in the dry season, although this type of ducts can also occur, elevated ducts predominate. The presence of atmospheric stability and the combination of a humid layer at low levels with a dry layer at altitude favors the formation of tropospheric ducts, therefore, the possibility of interference in communications increases. The synoptic situations that mainly enable the formation of tropospheric ducts are: Interaction of the Atlantic Subtropical Anticyclone with migratory anticyclones during the winter period, mainly in the March-May quarter, and the interaction of the Atlantic Subtropical Anticyclone with eastern tropical waves during the month of July. These conditions allow a layer with relative humidity between 75% and 80% to exist on the surface, followed by a drier layer where the relative humidity does not exceed 70%.

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