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STUDY OF TROPOPAUSE DYNAMICS OVER NATAL-RN FROM RADIOSONDE DATA OF METEOROLOGICAL BALLOONS

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Abstract

The terrestrial equatorial tropopause is generally analyzed as a region of modest temperature variations and defined only as an interface between the troposphere and the stratosphere. However, recent works has suggested that the tropopause may be a source of disturbances capable of locally affecting the tropospheric climate. In this context, the present work describes a detailed investigation of the characteristics of the equatorial tropopause over Natal-RN, from data of radiosondes of meteorological balloons launched by Barreira do Inferno Launch Centre (CLBI) during the years from 2010 to 2014. In addition, comparisons with semi-empirical computational models such as the MSIS-90 show differences with the studied data. A total of 1849 cases were analyzed, 949 of which were daytime and 900 were nocturnal. The minimum temperatures of the tropopause were compared with the seasons, and it was found that the minimum temperature occurs in autumn and the maximum during winter, whose average values are, respectively, 189.6 K and 194.5 K. The proposed explanation for these results relates the precipitation during these seasons with the release of energy to the upper troposphere.

Keywords: Equatorial Tropopause, MSIS-90, Atmospheric Soundings.

ESTUDO DA DINÂMICA DA TROPOPAUSA SOBRE NATAL-RN UTILIZANDO-SE DE DADOS DE RADIOSSONDAGENS DE BALÕES METEOROLÓGICOS

Resumo

A tropopausa equatorial terrestre é, em geral, analisada como uma região de modestas variações de temperatura e definida apenas como uma interface entre a troposfera e a estratosfera. No entanto, trabalhos recentes têm sugerido que a tropopausa pode ser fonte de perturbações capazes de afetar localmente o clima troposférico. Neste contexto, o presente trabalho descreve uma investigação detalhada das características da tropopausa equatorial sobre a região de Natal-RN, utilizando dados de radiossondagens de balões meteorológicos lançados pelo Centro de Lançamento da Barreira do Inferno (CLBI), entre os anos de 2010 a 2014. Além disso, comparações com modelos computacionais semi-empíricos como o MSIS-90, mostram divergências com os dados estudados. Foram analisados um total de 1849 casos, sendo 949 sondagens diurnas e 900 noturnas. Foram comparadas as temperaturas mínimas da tropopausa com relação às estações do ano, e se constatou que o mínimo de temperatura ocorre no outono e o máximo durante o inverno, cujos valores médios são, respectivamente, 189,6 K e 194,5 K. A explicação proposta para estes resultados, relaciona a precipitação durantes estas estações com a liberação de energia para alta troposfera.

Palavras-chave: Tropopausa Equatorial, MSIS-90, Sondagem Atmosférica.

ESTUDIO DE LA DINÁMICA DE LA TROPOPAUSA SOBRE NATAL-RN UTILIZANDO DATOS DE RADIOSONDAS DE GLOBO METEOROLÓGICO

Resumen

La tropopausa ecuatorial terrestre es, en general, analizada como una región de pequeñas variaciones de temperatura y definida solamente con una interface entre la troposfera y la atmosfera. Sin embargo, estudios recientes han sugerido que la tropopausa puede ser fuente de perturbaciones capaces de afectar localmente el clima troposférico. En este contexto, el presente trabajo describe una investigación detallada de las características de la tropopausa ecuatorial sobre la región de Natal-RN, utilizando datos de radiosondas de globos meteorológicos lanzados por el Centro de Lanzamiento de la Barreira do Inferno (CLBI), entre los años de 2010 hasta 2014. Además, comparaciones con modelos computacionales semi empíricos como el MSIS-90, muestran divergencias con los datos estudiados. Fueran analizados un total de 1849 casos, siendo 949 sondajes diurnas y 900 nocturnas. Se compararon las temperaturas mínimas de la tropopausa con relación a las estaciones del año, y se constató que la temperatura mas baja ocurre en el otoño y la más alta durante el invierno, cuyos valores medios son, respectivamente, 189,6 k y 194,5 k. La explicación propuesta para estos resultados, relaciona la precipitación durante estas estaciones con la liberación de energía para alta troposfera.

Palabras clave: Tropopausa Ecuatorial, MSIS-90, Sondaje Atmosférico.

1. INTRODUCTION

Earth's atmosphere is formed by a set of gases that surrounds the planet and is maintained through gravitational interaction. It is an ideal environment for studying physical, chemical, and climatological phenomena. The principles of thermodynamics are fundamental for the description of most atmospheric phenomena which can be treated as an ideal gas, approximately (GOODY and WALKER, 1972). Its main atmospheric force is the Sun, followed by interactions with the solid land and the oceans. The atmosphere can be structured as follow: the low atmosphere, which is the region from the Earth’s surface to approximately 15 km height, dominated by meteorological phenomena; the medium atmosphere, which is the region between 15 - 60 km, where is found the highest concentration of ozone responsible to absorb the Sun ultraviolet radiation. This is an important mechanism for the radiative balance (MOHANAKUMAR, 2008); and the high atmosphere, which is the region above 60 km, where the ionosphere is present. For this reason, this region is characterized by ions and electrons resulting from the interaction between the atmosphere and ionizing radiation from the Sun (RISHBETH and GARRIOTT, 1969).

Earth's atmosphere can also be described as a series of layers where each layer has its own characteristics in which the temperature varies with respect to altitude. These regions have distinct characteristics and are called: troposphere, stratosphere, mesosphere and thermosphere. The transition borders between them are called: tropopause, stratopause, and mesopause (GOODY and WALKER, 1972).

The troposphere is the lowest part of the atmosphere and extends between 16 – 18 km in the tropics, 10-12 km in the middle latitude, and 6 – 8 km in the polar region (MOHANAKUMAR, 2008). This region is dominated by meteorological processes, in addition to having strong convection. The temperature decreases almost linearly with altitude at a rate of 6 – 7 K/km, since the main heat source is the surface. For low latitude regions, the surface temperature is about 300 K (27 ° C) and the final temperature of the top of the troposphere is 198 K (-75 ° C) approximately (SELKIRK, 1993).

The tropopause has been identified as being of fundamental importance for the climate. The radiative balance of this layer, including clouds, is important for the global energy balance (HAYNES *et al*., 2001). The altitude of the tropopause bottom has a temporal variation, i.e., this region has a vertical movement regarding time. The World Meteorological Organization (WMO) defines that in the tropopause the rate of temperature variation must be less than 2 K/km, while the climatic and atmospheric models consider that this region the temperature is practically constant (OLIVEIRA *et al*., 2016). One of these models is the MSIS-90 and its purpose is to simulate the temperature behavior of the neutral atmosphere. The MSIS-90 is a semi-empirical model where the dataset is based on rocket launch, weather balloon survey and satellite information (HEDIN, 1991), including data from approximately 200 temperature profiles up to a height of 50 km, obtained in Natal-RN by rockets launched by the Barreira do Inferno Launch Centre (CLBI) between 1966-1980 (LABITZKE *et al*., 1985).

The study developed in this work analyzes the minimum and maximum temperature of the tropical tropopause during four years of data, using both experimental data and results from the MSIS-90 model. The seasonal behavior of the tropopause over Natal-RN is also analyzed, beyond the existence of meteorological factors capable of influencing the temperatures recorded in each season.

1.1. Troposphere and tropopause

The troposphere is the first layer of the Earth's atmosphere whose thickness decreases from the equator to the pole and is greater in summer than in winter. In the tropics, the thickness of the troposphere is greater due to the higher incidence of solar radiation on the intertropical surface. The tropospheric gases are transparent to visible solar radiation, which allows the heating of the Earth's surface since it absorbs electromagnetic waves in the visible range and emits in the infrared. The Earth's surface emits long-wave radiation that is absorbed and irradiated again by tropospheric gases, generating the so-called greenhouse effect. The air is heated by sensible heat and latent heat flows. The heated air rises to higher altitudes due to the lower density, increasing the thickness of the troposphere over the tropics. Almost the entire mass of the Earth's atmosphere is contained in the troposphere, approximately 80%, with around 99% being water vapor. The water vapor makes an upward movement, then condenses, and immediately afterward it precipitates, releasing latent heat that will conduct atmospheric phenomena (VAREJÃO-SILVA, 2006).

Since the movements that occur in the troposphere involve large masses of air, the systems are considerably large so that it is possible to ignore the heat exchanges between the moving air parcel and its neighborhood. Therefore, the vertical displacement of air in the troposphere can be treated as adiabatic. Equation (1) shows the tropospheric temperature gradient, calculated from the first law of thermodynamics.

$$\Gamma_T = -\frac{g}{c_P} \quad (1)$$

For dry air *Cp* = 1005 □/□□.□ and $\Gamma\tau = -10$ □/□□ (NAPPO, 2002). The measurement of the adiabatic temperature decay rate ($\Gamma\tau$) must take into account the relative humidity of the atmosphere. Thus, for a humid atmosphere, the theoretical measure used for this coefficient is $\Gamma\tau = -6.5$ K/km (VAREJÃO-SILVA, 2006). The temperature decreases almost linearly with altitude, due to the distance from the surface and the convection process.

The interface between the upper troposphere and the base of the stratosphere is known as the tropopause. In this layer, very sharp changes can occur with altitude. The tropopause acts as a cover, which resists the exchange of air between the troposphere and the stratosphere, and moves downwards as it moves away from the equator, reaching an altitude about 8 km, in the polar latitudes (MOHANAKUMAR, 2008).

In the tropical region, the tropopause is known as the tropical tropopause, although there is no consensus on its definition (HAYNES *et al*., 2001). The tropical tropopause determines the chemical conditions of the borders to the stratosphere, where the radiative balance of this layer, including clouds, is important for the global energy balance.

1.2. Tropical tropopause

The altitude of the tropopause also varies according to the maximum and minimum temperatures, it uses to be low altitude when is colder and high when is warmer (MOHANAKUMAR, 2008). There are several definitions for the tropical tropopause that have some advantages and disadvantages. Examples of these definitions are the Lapse Rate Tropopause (LRT) and the temperature minimum or Cold Point Tropopause (CPT), which are based on the thermal properties of the tropical atmosphere. LRT is defined by the WMO as the lowest level at which the temperature varies by 2 K/km or less since the average rate of a lapse between this level and all the highest levels within 2 km does not exceed 2 K/km. However, this level is arbitrarily defined for operational use and has limited physical significance (REID and GAGE, 1985). The cold point of the tropopause is considered important for the stratosphere-troposphere exchange (SELKIRK, 1993). This point may coincide with the lapse rate, but it is usually above that. This point may coincide with the lapse rate, but it is usually above that. It is also observed that the lapse rate and the minimum temperature are often found within a stable transition layer of variable depth, superimposing the deeper and peripherally stable layer in the upper troposphere. The minimum temperature is just a reliable definition when the lower stratosphere is not close to an isotherm.

The equatorial region of the tropopause is contained within the tropical tropopause, however, the dynamics of the equatorial tropopause have not been dealt with in-depth. The study developed in this work analyzes the tropopause over Natal (5.8° S, 35.2° O) and its metropolitan region in order to understand and highlight equatorial tropopause behaviors.

2. METHODOLOGY

The data used in this work were the temperature measurements obtained by surveys carried out using weather balloons launched by the Barreira do Inferno Launch Centre (CLBI), collected between the years 2010 to 2014.

CLBI is located in a military district located in Parnamirim-RN, metropolitan region of Natal-RN. It is an environmental preservation area on the shores of the South Atlantic Ocean. CLBI performs rocket launch and tracking and has an active weather station since 1967. Routinely it happens launching weather balloons with commercial probes with the purpose of obtaining data of wind orientation, temperature, pressure, and relative humidity, from the surface to a 25 km height, approximately.

The weather balloons are launched carrying Vaisala type probes, as is shown in Figure 1a. The probe transmits data from measurements taken *in situ* to a receiving station on the ground. Figure 1b shows the balloon at the launch base.

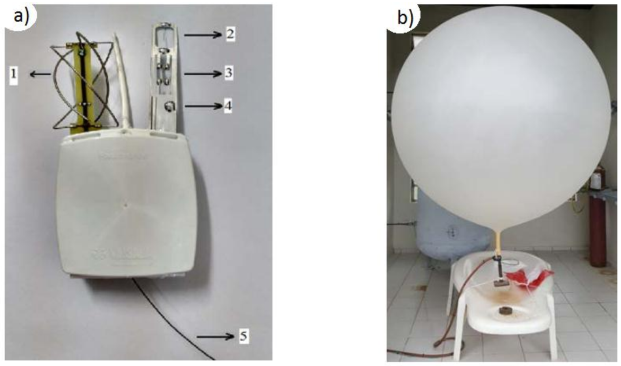

Figure 1 – a) Vaisala probe. The numbers 1 to 5 in parentheses correspond respectively: GPS locator (1), temperature sensor (2), relative humidity sensor (3), atmospheric pressure and wind speed sensor (4), and a UHF transmission antenna (5). b) Weather balloon. Source: Oliveira et al. (2016)

Soundings data has information about the date, time, and coordinates of the launch; beyond flight time, pressure, height, temperature, relative humidity, and wind direction.

Figure 2a shows the construction of several vertical temperature profiles from the sounding data for a few days from the beginning of March of 2014 and the adjusted (fitted) curve. Figure 2b presents the data shown in Figure 2a compared to the profiles generated from the MSIS-90 model.

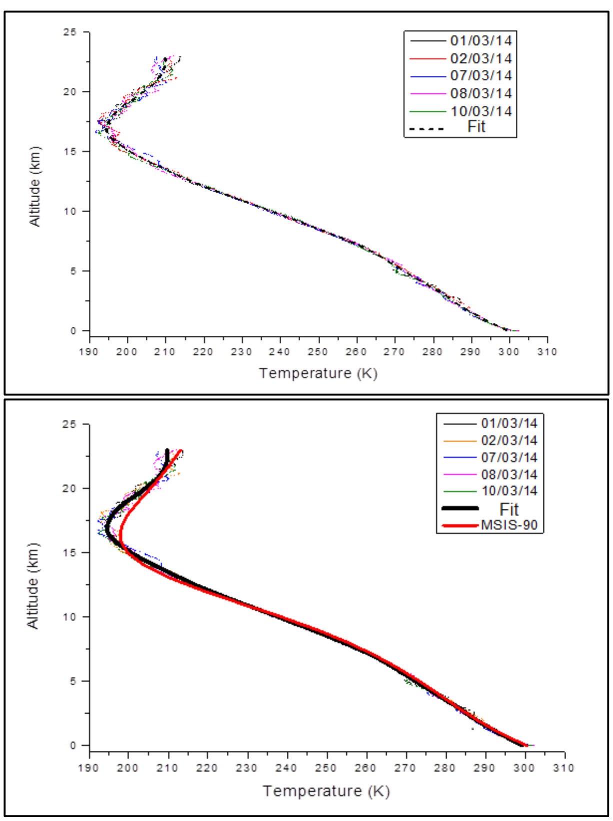

Figure 2 – a) Temperature profiles constructed with the data from the balloons launched by CLBI, for some days of March 2014, compared to the adjusted profile; b) Comparison between the real profiles with the one simulated by MSIS-90.

MSIS (Mass Spectrometer Incoherent Scatter) describes the temperature (in Kelvin units) and the neutral densities in the Earth's atmosphere, from the ground to thermospheric heights. It has several versions, the version used in this work is the MSIS-90, which can be accessed through the electronic address: https://ccmc.gsfc.nasa.gov/modelweb/models/msis_vitmo.php

The geographical coordinates of Natal-RN are 5.8° S; 35.2° W, however, the model requests the coordinates as follows: latitude from -90° to 90° and longitude from 0° to 360°. Therefore, Natal has -5.8° latitude and 324.8° longitude as coordinates.

The MSIS-90 was widely used in comparisons of the low and high atmosphere over Natal, such as the study of gravity waves in the stratosphere (OLIVEIRA *et al*., 2016; CAZUZA, 2018), plasma bubble observations (ABDU *et al.* , 1991), thermosphere study (BIONDI and SIPLER, 1985), electronic density (TAKAHASHI *et al*., 1990), among others.

In order to verify if the variation of the minimum tropopause temperature is related to some meteorological phenomenon, precipitation data were obtained from INMET (National Meteorological Institute) for the same period of the database, for Natal-RN station. Three classifications were made for precipitation:

1) Between 0 mm and 2 mm: dry day;
2) Greater than 2 mm and less than 20 mm: moderate rain;
3) Greater than 20 mm: heavy rain.

3. RESULTS AND DISCUSSION

In this session, we will approach the results obtained with the sounding data. 1.849 cases were analyzed between the period from 10 October 2010 to 30 October 2014, where 949 soundings were daytime, while 900 were nighttime. Table 1 shows the monthly number of soundings used in this study.

Table 01 – Monthly soundings carried out by CLBI in months between 2010 and 2014.

DAYTIME		NIGHT-TIME	
Months	Soundings	Months	Soundings
January	103	January	106
February	74	February	75
March	72	March	74
April	95	April	83
May	117	May	98
June	61	June	55
July	28	July	29

August	34	August	31
September	44	September	41
October	103	October	95
November	105	November	105
December	113	December	108
Total	949	Total	900

Next, the results obtained regards to the minimum tropopause temperatures and the variations suffered by this region due to seasonality will be discussed.

3.1. Minimum tropopause temperature

Initially, the minimum temperatures (cold point tropopause) measured were compared with the MSIS-90 model outputs. Figures 3 and 4 show, respectively, the daytime and nighttime analysis between the experimental data and the model results. The balloon data is represented by the black curve, while the blue curve refers to the model result. Due to the great variability of the experimental data, smoothing with the Savitzky-Golay method was used to better represent the behavior over the days (red curve). This method was created in 1964 and concomitantly performs the filtering and regression of data that at first contains noise, thus generating an adjustment curve that will better describe the graph's behavior (SAVITZKY and GOLAY, 1964).

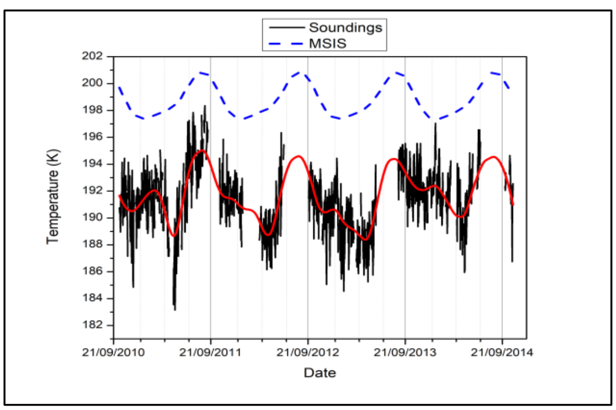

Figure 3 – Comparison between the minimum tropopause temperature experimental data and the model result during daytime.

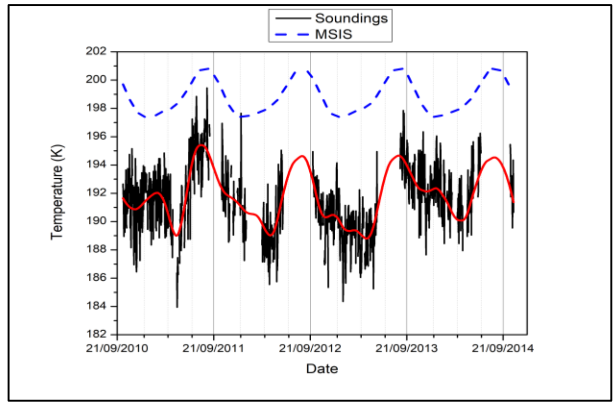

Figure 4 – Comparison between the minimum tropopause temperature experimental data and the model result during nighttime.

Analyzing Figures 3 and 4, it is possible to observe that the minimum temperature measured is lower than the minimum temperature predicted by the MSIS-90 and that there is a temporal variation in the temperature value for both data. Analyzing all 1849 cases, it was found that the average minimum temperature for the model is approximately 198.5 K (-74.7 ° C), while the measurement by the soundings is around 191.4 K (-81.8 ° C). These values vary according to the seasons. It is interesting to note that, despite the difference in amplitude between the profiles provided by the model and the smoothing (blue and red curves), there is an almost sinusoidal pattern of the temperature behavior in both profiles, as daytime as nighttime. However, the increase in temperature values from the minimum to the maximum is much more accentuated in the experimental data than in the model. As the temperature declines, unexpected behavior also occurs. It is possible to notice an oscillation in the curve values regarding the experimental data, probably associated with seasonality.

Figure 5 shows the average minimum temperatures in relation to seasonality. It is observed that the tropopause in the region where the measurements were made, is colder than predicted by the MSIS-90. It is also possible to observe that the minimum temperature during winter is higher than during other seasons, including summer. It is noticed that the average temperatures provided by the model always present higher values, however not exceeding 10 K amplitude. A more detailed analysis shows us that the biggest differences are concentrated during the equinox. However, despite the relative movements between the Sun and the Earth being the main regulator of the temperature of the atmosphere, they are not the only regulator. This can be easily seen in Figure 5, where both the model and the experimental data show a higher average minimum temperature value for the winter.

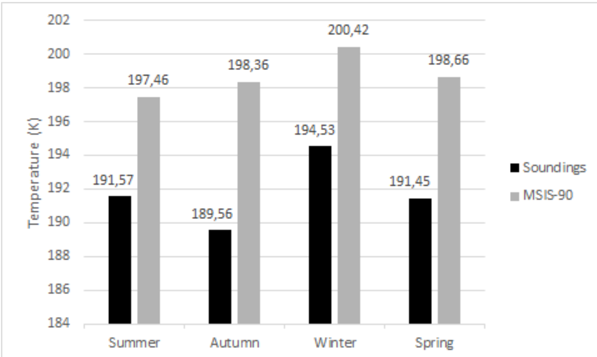

Figure 5 – Minimum tropopause temperature (K) for each season.

In order to verify this behavior, Figure 6 was elaborated. This figure shows the smoothing curves of the tropopause minimum temperature during the daytime (red curve) and nighttime (black curve), beyond to explore in a more detailed its seasonal behavior, represented in colors: white for autumn, gray for winter, blue for spring, and yellow for summer. In this graph, it is possible to verify the maximum average values of temperature occur during the winter of 2011, reaching the maximum value of 195.5 K during the day and 195 K during the night, while the minimum values occur during the autumn, reaching 188.4 K during nighttime and 188.8 K during the daytime. Although autumn has the lowest temperature values, this season is also characterized by the sharp rise in temperature, whose peak is found in winter.

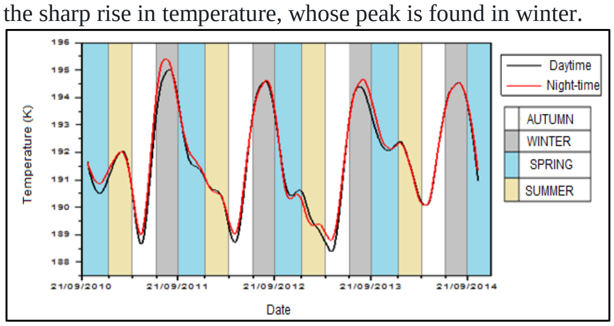

Figure 6 – Minimum tropopause temperature estimated between 13 October 2010 and 30 October 2014.

Regarding the day and night curves, it is also observed that temperatures have the same behavior and little variability between them, however, an analysis that would require a larger database refers to the remarkable fact of the alternating behavior between the coincidence of peaks of maximum values for both periods, day and night. For the days that there were no weather balloons launched, the value equivalent to this day was estimated by experimental data, doing a daily average of the minimum temperature.

Figure 7 presents four graphs relative to the percentage of daily rainfall for each season of the year for the same period of the radiosonde data.

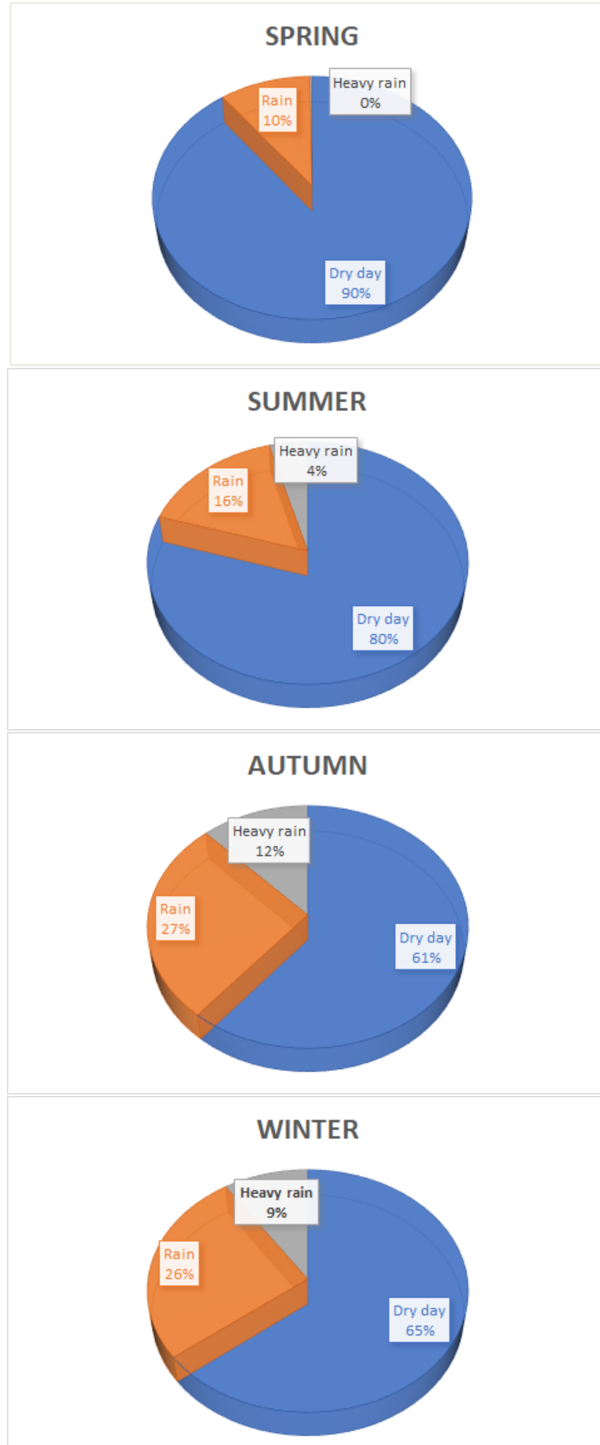

Figure 7 – Percentage graphs of daily rainfall for each season.

The season with the greatest rainfall in Natal is autumn, in which 39% of the days it rains, winter comes next with a percentage of 36% for days when there was precipitation above 2 mm. A hypothesis for the minimum peak temperature in autumn is with the increase in rainfall there is an increase in cloudiness, thus, the amount of radiation reflected into space increases. Therefore, less energy will reach the Earth's surface, altering the albedo and tending cooling in the lower atmosphere. This process initially causes a decrease in the temperature of the tropopause region. However, during the water vapor condensation process, energy is released in the form of latent heat. This energy is received by the average troposphere as sensible heat, and through thermal convection the highest portion of the troposphere is heated, raising its temperature. Nonetheless, this energy deposited in the middle troposphere will not be received by the tropopause immediately, which can be verified during the winter with the increase in the temperature of the tropopause region. Despite winter is the second rainiest season, there is no increase in temperature during this season. A possibility for this occurrence is that in the spring there is a higher concentration of ozone between the tropopause and the stratosphere (LOPO *et al*., 2013), i. e., this fact is what influences the thermodynamics of the tropopause during this period.

4. CONCLUSIONS

In this work, the minimum tropopause temperatures over the region of Natal - RN were analyzed. For this purpose, a 4-year database containing 1849 cases of radiosounding of atmospheric balloons was compared to the MSIS-90 model results. The main results show that the model has a good representation of the average temperature behavior, identifying the average wave behavior of the experimental data, but overestimating the real values in an order of up to 10 K difference. The growth of temperature values from the minimum value registered to the maximum one is much more accentuated in the experimental data than in the model. The temperature decline presents an oscillatory behavior that is not considered in the MSIS-90 simulation. As for seasonality, the tropopause over Natal-RN has a temporal variation such has a maximum temperature during the winter and a minimum during the autumn. Precipitation data were used in this study in order to investigate possible interference from meteorological factors in the temperature profile of the tropical tropopause. The autumn season, which had the minimum peak temperature, also had the highest percentage of rainfall. The hypothesis accepted by the authors of this work is that the energy released during the condensation process of water vapor is transferred to the tropopause leading to the temperature increase seen in the following season. In addition, based on the results found in this work, new analyzes should be developed to understand why, even though winter is the second season with the highest rainfall, the temperature during spring is not influenced by the release of heat. It is necessary to do a detailed study between the middle and upper troposphere region during these seasons, to verify how the energy released during the rains is carried out during the current period of the seasons.

Finally, it is expected that the current study may stimulate future investigations of this region of the atmosphere, which is little explored, mainly in the equatorial region.

5. REFERENCES

ABDU, M. A. *et al*. Rocket observation of equatorial plasma bubbles over Natal, Brazil, using a high- frequency capacitance probe. *Journal of Geophysical Research: Space Physics*, v. 96, n. A5, p. 7689-7695, 1991.

BIONDI, Manfred A.; SIPLER, Dwight P. Horizontal and vertical winds and temperatures in the equatorial thermosphere: Measurements from Natal, Brazil during August–September 1982. *Planetary and space science*, v. 33, n. 7, p. 817-823, 1985.

CAZUZA, E. P. *Um estudo das ondas de gravidade estratosféricas na região equatorial brasileira*. 2018. 90f. Dissertation (Doctoral in Climate Sciences) – Programa de Pós_Graduação em Ciências Climáticas, Federal University of Rio Grande do Norte, 2018. 90 p.

GOODY, R. M.; WALKER, J. C. G. *Atmosferas planetárias*. 1°ed. Editor Blucher, 1972. 139p.

HAYNES, Peter; SCINOCCA, John; GREENSLADE, Michael. Formation and maintenance of the extratropical tropopause by baroclinic eddies. *Geophysical research letters*, v. 28, n. 22, p. 4179-4182, 2001.

HEDIN, Alan E. Extension of the MSIS thermosphere model into the middle and lower atmosphere. *Journal of Geophysical Research: Space Physics*, v. 96, n. A2, p. 1159-1172, 1991.

LABITZKE, K.; BARNETT, J. J.; EDWARDS, B. (NASA) (1985). Middle Atmosphere Program. *Handbook for MAP* (Vol. 16). States United of American: Illinois.

LOPO, A. B. *et al*. Radiação ultravioleta, ozônio total e aerossóis na cidade de Natal-RN. *HOLOS*, v. 6, p. 3-21, 2013.

MOHANAKUMAR, K. *Structure and composition of the lower and middle atmosphere. Stratosphere Troposphere Interactions: An Introduction*. 1°ed. Editor Springer Science & Business Media, 2008. 416 p.

NAPPO, C. J. *An introduction to atmospheric gravity waves*. 1°ed. Editor Academic press, 2002. 400 p.

OLIVEIRA, A. L. P. *et al*. Ondas de gravidade na estratosfera equatorial brasileira: estudo de caso. *HOLOS*, v. 8, p. 24-35, 2016.

REID, George C.; GAGE, Kenneth S. Interannual variations in the height of the tropical tropopause. *Journal of Geophysical Research: Atmospheres*, v. 90, n. D3, p. 5629-5635, 1985.

RISHBETH, H.; GARRIOTT, O. K. *Introduction to Ionospheric Physics*. 1°ed, Editor: Academic Press, 1969. 331p.

SAVITZKY, Abraham; GOLAY, Marcel JE. Smoothing and differentiation of data by simplified least squares procedures. *Analytical chemistry*, v. 36, n. 8, p. 1627-1639, 1964.

SELKIRK, Henry B. The tropopause cold trap in the Australian monsoon during STEP/AMEX 1987. *Journal of Geophysical Research: Atmospheres*, v. 98, n. D5, p. 8591-8610, 1993.

VAREJÃO-SILVA, M. A. *Meteorologia e Climatologia*. 2°ed. Recife: Digital version, 2006. 463 p.

TAKAHASHI, H. *et al*. Equatorial F-region OI 6300 Å and OI 5577 Å emission profiles observed by rocket-borne airglow photometers. *Planetary and space science*, v. 38, n. 4, p. 547-554, 1990.

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