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METEOROLOGY

Middle Tropospheric Cyclonic Vortex Formation

Formação de Vórtices Ciclônicos de Médios Níveis

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Abstract

The short-term forecast is based on atmospheric synoptic systems analysis such as the Middle Tropospheric Cyclonic Vortices (MTCV). This research was aimed at analyzing and determining the formation processes of these vortices. Reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) with spatial resolution of 0.25º × 0.25º for nine vertical levels were used to identify the main features of MTCVs over Northeast Brazil and the Equatorial Atlantic Ocean. During 2010, 62 MTCVs were identified over these regions. Most MTCVs were short-lived events compared to similar systems as the South American Upper Tropospheric Cyclonic Vortex (UTCVs) and MTCVs over the Indian continent; 19 MTCVs lasted from 12 to 20 hours, while 15 of them were active from 30 to 42 hours, the other MTCVs (28) lasted for more than 48 hours. More frequently MTCV centers (55% of events, 34 cases) were observed at the level of 700 hPa. Three types of formation processes were identified: 1) Type I, trough in the air current from the west, 2) Type II, trough in the air current from the east, and 3) Type III in the meridional current from both hemispheres. Ten subtypes were distinguished depending on the position of the trough axis before the MTCV formation: meridional, NW - SE and SW – N. The most frequent subtype of Type I (17 events) were formations on troughs with an axis from northwest to southeast. Type II MTCVs developed frequently (13 events) on troughs with an axis from southeast to northwest. Low vorticity (-3 and -4×10^{-5} s^{-1}) dominated in all MTCVs events. Only weak convergence was present in 16 events, while weak divergence and convergence were observed in the rest of the MTCVs. Only 36 out of 62 MTCVs presented both lifting and sinking during the vortex core formation. Prior to the MTCV formation, only sinking motion was observed in half of the events, while in the other half were lifting and sinking. Thus, MTCV study is important for improving short-term weather forecasting.

Keywords: MTCVs; Formation processes; Weather forecasting

Resumo

A previsão do tempo de curto prazo se baseia nas análises dos sistemas sinóticos atmosféricos como os Vórtices Ciclônicos de Médios Níveis (VCMN). Este trabalho teve como principal objetivo analisar e determinar os processos de formação desses vórtices. Utilizou-se dados de reanálise do European Centre for Medium-Range Weather Forecasts (ECMWF) na resolução de 0.25º × 0.25º em 9 níveis atmosféricos padrões para identificar as principais características dos VCMNs sobre o Nordeste do Brasil e a região do Oceano Atlântico Equatorial adjacente. Foram identificados e analisados 62 VCMNs durante o ano de 2010 sobre tais regiões. A maioria dos VCMNs foram eventos de curta duração comparado a sistemas semelhantes como os Vórtices Ciclônicos de Altos Níveis (VCANs) na América do Sul e os VCMNs sobre o continente indiano. Do total de 62 eventos, 19 duraram entre 12 e 20 horas, enquanto 15 deles estavam ativos entre 30 e 42 horas, os demais (28 casos) duraram mais de 48 horas. Os 34 casos mais frequentes de VCMNs (55%) tiveram seus centros formados no nível de 700 hPa. Três tipos de processos de formação foram identificados: 1) Tipo I, formados no cavado na Corrente de Leste, 2) Tipo II, formado no cavado na Corrente de Oeste, e 3) Tipo III, formado na corrente meridional de ambos os hemisférios. Dez subtipos foram distinguidos de acordo com a posição do eixo do cavado antes da formação do VCMN: meridional, NO-SE e SO-N. O subtipo mais frequente do Tipo I (17 casos) foram formações em cavados com o eixo direcionado de NO-SE. Os VCMNs do Tipo II mais frequentes (13 casos) se desenvolveram no cavado com o eixo orientado de SO-N. Fraca vorticidade (-3 e -4×10^{-5} s^{-1}) predominou em todos os VCMNs. Em 16 eventos observou-se apenas fraca convergência, enquanto fraca divergência e convergência foram observadas nos demais eventos. Foram identificados movimentos subsidentes e ascendentes em 36 VCMNs durante o processo de formação do centro do vórtice. Antes da formação do VCMN, apenas subsidência foi observada em metade dos eventos, na outra metade foram observadas subsidências e movimentos ascendentes. O estudo do VCMN é importante para melhorar a previsão do tempo a curto prazo.

Palavras-chave: VCMN; Processos de formação; Previsão do tempo

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1 Introduction

The short-term forecast is based on analysis of atmospheric synoptic systems such as the middle tropospheric vortices (MTCV). As a synoptic system associated with heavy rain, MTCVs need to be forecasted in able time to prevent hazards and further damages. Middle tropospheric vortices are important cyclonic disturbances in the synoptic scale, observed between 700 and 400 hPa levels (Carr 1977). These systems have been observed along the Northeast coast of Brazil (NEB) during all seasons (Fedorova *et al.* 2017) and over the monsoon regions in the Indian continent (Krishnamurti & Hawkins 1970; Carr 1977).

These middle level cyclonic vortices were first described by Krishnamurti and Hawkins (1970) as cyclonic circulations in the synoptic scale, observed mainly in the middle troposphere between 700hPa and 400 hPa. Most of the present research is focused on the description of formation process and climatological aspects of MTCVs over the Indo-Asian continent, where these phenomena are primarily associated with the monsoon system and heavy precipitation (Choudhury *et al.* 2018, Kushwaha *et al.* 2021, 2023).

According to Choudhury *et al.* (2018) the MTCV formation over the Asian continent can occur simultaneously to synoptic systems over the Bay of Bengal (BoB) and the Indian coast, including the Arabian Sea. Other studies (Kushwaha *et al.* 2021, 2023) also relate the development of these vortices as part of a larger low-pressure system and convective activity. Krishnamurti and Hawkins (1970) detailed the MTCVs formation processes in terms of the combination of factors including the presence of a weak vorticity prior to the MTCV formation that moves over the Bay of Bengal and, through a positive feedback from the convective activity specially stratiform type there, intensifies and generate the vortices in the middle troposphere.

These MTCVs are frequent during the boreal summer and early stage of the summer monsoon system; an average of 1 to 4 events were observed by Carr (1977). However, in more recent studies, Kushwaha *et al.* (2021) reported around 3 or 4 MTCVs per month during the summer season, mainly related to the summer monsoon system. Severe weather conditions are associated with MTCVs activities over western Indian regions such as heavy rain that results in flooding over a large area of the continent. Precipitation rates of 60 mm/day were found related to MTCVs events over the western India and northeast Arabian Sea by Kushwaha *et al.* (2023).

Recently, Kushwaha *et al.* (2023) categorized four types of MTCVs over the Arabian Sea and Western India according to their formation processes. Each category was related to different atmospheric processes that can generate those MTCVs. Overall, MTCVs are generated and modulated by large-scale circulation patterns over western India. The four weather regimes associated to each MTCV category can be described as the westward displacement of the Bay of Bengal (BoB) cyclonic systems, cyclonic activity and dynamical interaction between two circulation patterns over the Arabian Sea and BoB, local systems that are formed over the South-Central Arabian Sea and subsequently displaced northward and synoptic systems associated to large-scale cyclonic activity that moves northwestward from the South BoB. These four categories have their own MTCV frequency and region of preferred formation.

Over the South American continent and South Atlantic, these middle level cyclonic vortices have recently been described by Fedorova *et al.* (2017). Over the continental area, these MTCVs were observed mainly over the Northeast Brazil (NEB) region, though very few studies have been conducted about them. Fedorova *et al.* (2006) were the first to observe the MTCV on a frontal system that affected the NEB. This study analyzed three frontal systems that reached the tropical zone (10º S) and resulted in heavy precipitation and the formation of MTCVs. In another study, the synoptic situation over the state of Alagoas was monitored for four years, revealing that several middle tropospheric vortices were linked to extreme precipitation events. A total of 7 cases were identified, accounting for 2% of these events (Pontes da Silva 2008; Pontes da Silva *et al.* 2011). During a three-year period (2008-2010), 696 MTCVs were identified, located mainly over the tropical Atlantic Ocean around 6º-18º S. Case studies on specific MTCV events where the tridimensional structure was analyzed showed that there is a relationship between the vortices and the Mesoscale Convective Complexes (MCC) and adverse events over the state of Alagoas (Silva *et al.* 2014; Silva 2015; Fedorova & Silva 2016).

According to these studies, the South American-Atlantic MTCVs produce heavy precipitation events just as the Indian systems and affect the continental region leading to potential flooding. Santos (2012) identified long-lived MTCVs that occurred close to the Brazilian state of Alagoas and influenced the weather there during the period from 2008 to 2010. In this analysis it was found an association between MTCVs and adverse weather phenomena such as thunderstorms, fog, precipitation and MCCs. Six of these MTCVs produced rain rates of 0.6 to 39 mm/day, two of them were related to thunderstorms and one to a MCC event. Thus, previous studies strengthen the importance this work brings to understanding the formation processes of MTCVs and establishing patterns of this system to assist in short-term weather forecasting.

The rainy season over NEB is modulated on the interannual scale mainly by the Intertropical Convergence Zone (ITCZ) that has its maximum activity around 5° S during the austral summer and autumn. The system remains in the Southern Hemisphere until May, especially in rainy years (Melo *et al.* 2009). Another important aspect of the precipitation pattern over NEB are the Easterly Waves, a wave disturbance that is related to extreme precipitation over NEB. Although these Easterly Waves may be observed all year long, according to Yamazaki & Rao (1977) they can modulate the rainy season in the NEB coast. How these systems are related to MTCVs activities have not been studied yet, thus there is a gap in the knowledge whether they may influence the frequency, duration and weather conditions associated with the vortices. It is important to highlight that MTCVs over NEB may occur simultaneously to these atmospheric systems that modulate the rain over the region, and also may work enhancing or attenuating their impacts there. The role of these systems on modulating, generating or maintaining the MTCVs need to be assessed to accurately determine the environmental, social and economic impacts that these vortices can cause.

However, the influence of MTCVs on precipitation regimes over the NEB region has not yet been completely described and lacking information about their formation process and how they interact with other meteorological systems as well as their seasonal variability and climatology can result in an underestimation of their impacts on society. Understanding the formation processes of the MTCVs may contribute to a broader knowledge on how these systems interact with larger-scale and local atmospheric patterns over NEB, especially over the state of Alagoas.

The objective of the present analysis is to determine the formation processes of MTCVs over the South America and the Atlantic Ocean neighbor regions. It also includes the analysis of the duration, seasonality and preferable levels of activity as well as the vertical motion and structure at the moment of pre-formation and formation of the MTCVs. It should be noted that these studies were carried out in order to obtain an improvement in the quality of short-term weather forecasting and consequently lead to more reliable information given by the Civil Defense to help the general population.

2 Analysis Method

The first step was a revaluation of a preview study (Santos 2012) in order to identify MTCVs that lasted equal or longer than 12 hours. The higher resolution of the ERA-Interim dataset (0.25º × 0.25º) was used against the lower resolution of the National Centers for Environmental Prediction / National Centers for Atmosphere Research (NCEP/NCAR) data set (2.5° × 2.5°) in order to realize this evaluation. Variables used for the reassessment of the MTVC were: meridional (v) and zonal (u) wind components and vertical velocity (w) from surface level to 200 hPa (varying by 100hPa) according to synoptic hours (00, 06, 12 and 18 UTC). From these variables, the following maps were constructed: 1) streamlines, 2) relative vorticity, 3) divergence and 4) vertical velocity.

2.1 Study Area

Study areas include the NEB and the surrounding Atlantic Ocean, from 60° to 0° W and 0° to 30° S. These regions are characterized by synoptic systems that influence weather conditions over NEB such as UTCVs (Kousky & Gan 1981; Pontes da Silva *et al.* 2011) as well as the preferable region for development of MTCVs.

2.2 ECMWF Reanalysis (ERA-Interim)

The ERA-Interim dataset is a global atmospheric reanalysis ranging from 1979 to 2019, updated on a daily basis by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Dee *et al.* 2014). For this study the 0.25º × 0.25º spatial resolution was used, at nine standard vertical levels (1000 to 200 hPa, varying by 100 hPa each level) covering the synoptic times of 00, 06, 12 and 18 UTC. The year 2010 was chosen because it featured an MTCV event linked to an extreme MCC and severe weather conditions, including heavy rainfall and thunderstorms, in December 2010. Previous studies on MTCVs performed for the period between 2008 and 2010 (Silva 2015; Santos 2012) provided information about the duration of long-lived MTCVs that occurred close to the Brazilian state of Alagoas and the weather conditions associated with them. From these studies it was observed through the ECMWF dataset (spatial resolution of 0.125º × 0.125º) that these weather conditions related to MTCVs were found only in vortices observed in 2010 and thus, being this year the main focus of this study.

2.3 Identification Analysis Method, Structure and Vertical movements of MTVC

Identification criteria were defined as: 1) the relative vorticity being equal to or less than -1×10^{-5} s^{-1}; 2) center of the cyclonic circulation between 700 and 400 hPa and 3) diameter of the area with cyclonic circulation equal or greater than 500 km. In order to avoid the same MTCV being identified as two separate system, the following step was taken: when noticing that the same MTCV is detected at two consecutive levels, it was observed that if the core displacement of the vortices during the first day is equal to or less than 5° of latitude or longitude and if the main streamlines are the same then the system is considered to be the same MTCV. This approach was adopted from Fedorova *et al.* (2017), where it can be found in more detail.

Streamlines maps were used to ensure that MTCVs were identified only in middle levels. For example, in Figure 1C the system was identified at 700 hPa and its core was around 19º S - 9º W, but in lower and upper levels (Figures 1A and B, respectively) there were no identifiable cyclonic centers. In addition, streamline maps helped to analyze and characterize the formation processes of these vortices.

Relative vorticity maps were used to verify cyclonic circulations and their values related to each MTCV in order to establish the criteria analysis and their formation processes. Divergence fields were used as the means to analyze convergence and divergence regions over the MTCV. Vertical velocity maps were used to verify vertical movements at the atmospheric level where the MTCVs were found.

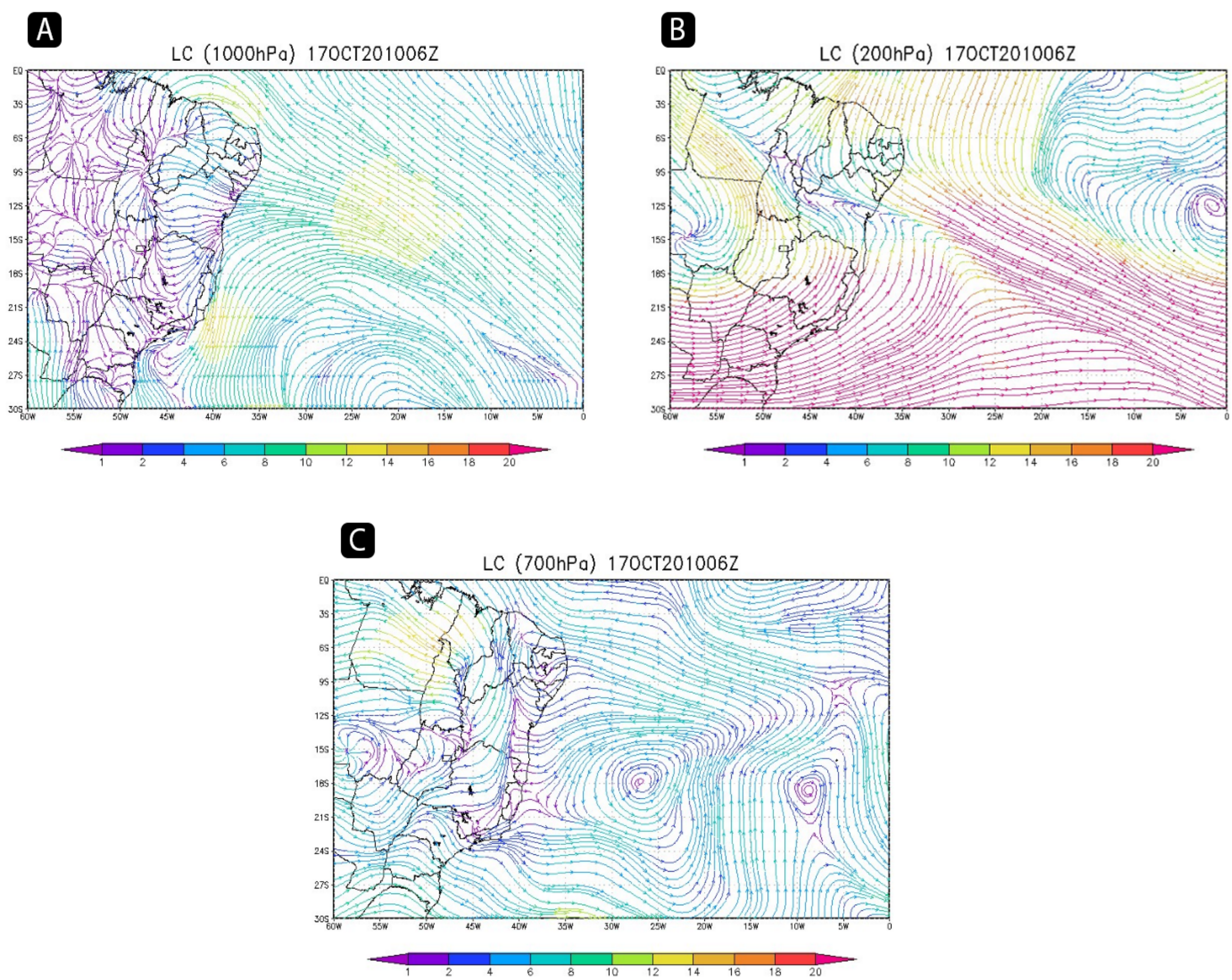

Figure 1 Identification of the MTCV by the composite field of flow and wind magnitude (m s^{-1}). Arrow: MTCV.

3 Results

3.1 MTCV Overview

From the reassessment of the previous study performed by Santos (2012), 62 MTCV cases were identified during 2010 over the study region. Due to differences regarding spatial resolution between the two datasets, these cases included MTCVs that had been previously identified, new ones, and also systems with different durations, positions and at different atmospheric levels. Initial data of the MTCV core formation and its dissipation were analyzed, followed by their atmospheric levels of formation as well as active atmospheric layers during their lifecycle.

Table 1 shows the numbers of MTCVs formed over the continental and oceanic regions. A total of 35 (56.5%) MTCVs originated over the Atlantic Ocean, while 27 (43.5%) MTCVs were formed over the continent or moved into continental areas after they had been formed. From the latter, 16 (25.8%) of them happened near Alagoas state. In both situations these events brought or had the potential to bring severe weather conditions over the NEB coast, particularly over the state of Alagoas. According to Silva (2015), in 2010 two of these 16 MTCVs that occurred over Alagoas brought maximum precipitation volumes around 19 mm and 34 mm in 24 hours, the latter being associated with thunderstorms and a MCC event. The higher resolution data from ECMWF confirmed three important characteristics of MTCVs: duration, preferred formation and development levels, that had been found in previous studies where the NCEP/NCAR dataset was used (Fedorova *et al.* 2017).

Table 1 Cases of MTCV formed over the South Atlantic Ocean and the South American continent in 2010.

Formation region	Number of events	Percentage (%)
Ocean	35	56.5
Continent	27	43.5

The seasonal variability of MTCVs is shown in Table 2. The vortices are well distributed throughout the entire year, meaning that their formation process can be found in all four seasons. However, it was observed that between March and June, the MTCVs frequency was higher than the rest of the year. These months encompass the Autumn and the beginning of the Winter season in the Southern Hemisphere and the rainy season of NEB. During the rainy season it is observed the southward displacement of ITCZ, one of the modulators of rain over NEB, and according to Yamazaki & Rao (1977) it is also the period of the year when the Easterly waves' activities can bring heavy precipitation over the region. Fedorova *et al.* (2017) also described MTCVs activities between 2008 and 2010 as being fairly similar throughout the year with only a slight change in Spring. However, in this study it was observed that the number of MTCV was the lowest during the austral Summer, even though one of the longest lived MTCV (84 hours) was observed in this season.

This feature differs from Indian MTCVs that are mostly related to the summer monsoon system and are most frequent during the boreal summer period (Carr 1977; Choudhury *et al.* 2018; Kushwaha 2021, 2023). It is also important to note that they differ from UTCVs, for these events occur more frequently during the austral spring and summer when the Bolivian High has its maximum activity over the central South American continent (Coutinho *et al.* 2010; De Morais *et al.* 2020). These differences suggest their formation processes are not related.

Table 2 Monthly distribution of MTCV in 2010.

Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Set	Oct	Nov	Dec	Σ
I	1	3	4	1	-	6	-	4	3	1	4	2	29
II	-	-	2	5	2	1	-	-	3	5	-	1	19
III	-	-	-	3	5	1	2	2	1	-	-	-	14

3.2 MTCVs Duration

Figure 2 shows the frequency distribution of MTCVs versus the duration of these systems per hour. MTCVs lasting between 12 hours and up to 192 hours (8 days) were identified, the latter being a single event that occurred in March (started on 27th of March, 18 UTC and ended on 04th of April, 18 UTC, 2010). A linear correlation was observed between the number of cases and how long they were active in the atmosphere, meaning that short lived events were the most frequent while long lived events were rarer.

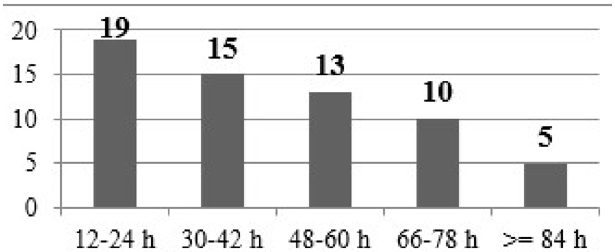

Figure 2 Number of MTCVs by duration interval.

Unlike the MTCVs that happen over the Indian continent (Choudhury *et al.* 2018), most of the MTCVs (34 events) occur within 12 to 42 hours, making them important systems for the short-term weather forecast. The Upper Tropospheric Cyclonic Vortex (UTCV) over the same area also last longer than MTCVs, from some hours up to a week or more (Kousky & Gan 1981; De Morais *et al.* 2020). These results are important because they highlight the differences and similarities between MTCV and UTCV, as well as the MTCVs over the Indian continent. De Morais *et al.* (2020) relate the depths of UTCVs to baroclinic processes and how deeper vortices also last longer than shallow vortices, similar to what was found in this study regarding MTCVs.

3.3 Formation Levels

Figure 3 presents the atmospheric levels of the MTCV during the core formation. The majority of MTCVs are formed at 700 hPa, 34 cases corresponding to 54.8% of MTCVs, followed by 18 cases (29%) being formed at 600 hPa. It was also verified that higher level vortices were formed between 500 and 400 hPa, representing 11.3% (7 events) and 4.8% (3 cases), respectively. These are their preferable level of formation, meaning that their core will be found at these atmospheric levels. These results show another linear pattern similar to what was found related to the frequency and duration of MTCVs, meaning that their preferable levels are in the middle of the troposphere (700 hPa). It was not found a correlation between the atmospheric level of MTCV formation and the duration of these vortices, in other words, short (long) lived MTCVs are not necessarily the same ones formed in lower (higher) levels of the middle troposphere (results not shown).

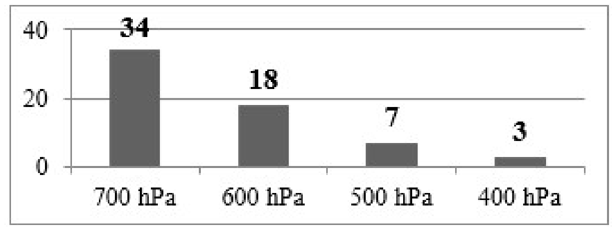

Figure 3 Number of cases by level of the MTCV core formation.

As for the UTCVs over the South America region, their preferable atmospheric layers for formation and development are at 200 hPa even though during the maximum depth phases they can reach lower levels (Kousky & Gan 1981; De Morais *et al.* 2020). MTCVs that develop over the Indian continent are related to the Indian monsoon system, therefore, their main activity happens at middle levels associated with convective activities (Krishnamurti & Hawkins 1970; Carr 1977).

3.4 Types of MTCV Formation Processes

After careful analysis of the 62 MTCVs in 2010, it was possible to observe the formation of vortices and then determine three types of formation processes. Three types of formation processes were identified: 1) Type I, trough in the air current from the west, 2) Type II, trough in the air current from the east, and 3) Type III, in the meridional current from both hemispheres.

The first formation type was identified according to the inclination of the middle level trough in the air current from the east. It was then divided into three subtypes (Figure 4): in the first subtype (Figure 4A) the trough has a northwest-southeast inclination; in the second subtype (Figure 4B) the trough has no inclination and the third subtype (Figure 3C) the trough inclination is formed from northeast to southwest.

Type II regarded to the MTCV formation process has the same identification criteria as Type I but for the trough formed in the air current from west. This type was also divided in three subtypes (Figure 5): subtype I (Figure 5A) the trough inclination is from south to north; subtype II the trough has a southeast to northwest inclination (Figure 5B) and the southwest to northeast trough inclination represents the third subtype (Figure 5C).

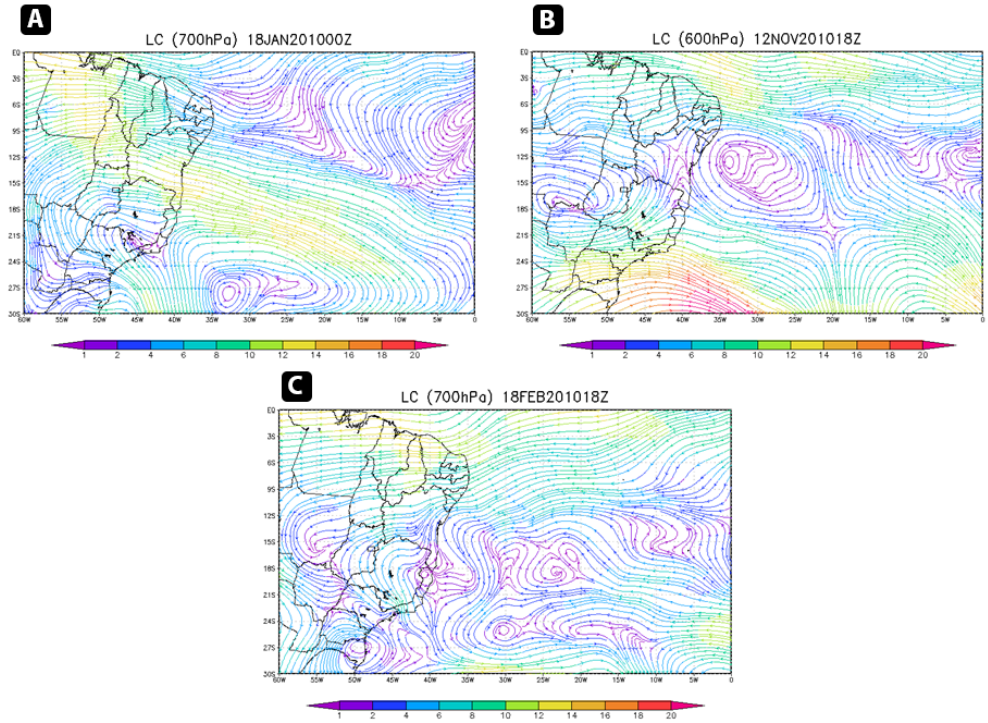

Figure 4 Composite flow and wind magnitude fields (m s-1) at 700 and 600 hPa showing examples of Type I formation processes: A. Type Ia; B. Type Ib; C. Type Ic. Dashed line: axis of the trough.

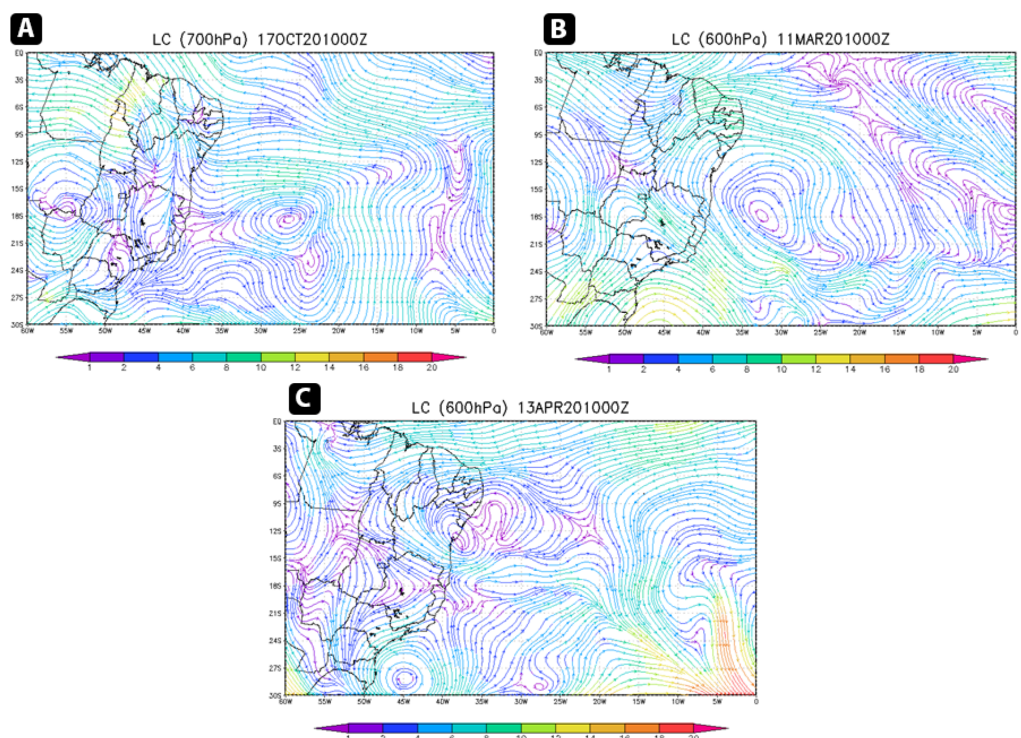

Figure 5 Composite flow and wind magnitude fields (m s-1) at 700 and 600 hPa showing examples of Type II formation processes: A. Type IIa; B. Type IIb; C. Type IIc. Dashed line: axis of the trough.

Type III of MTCV formation process differs from the two previous processes for the vortices are formed through both the Northern and Southern Hemispheres meridional flows (Figure 5). Type III was divided then into four subtypes. In the first subtype (Figure 6A), the MTCV forms in the encounter of the Northern and Southern hemispheres currents. In the second subtype (Figure 6B) it is observed that the vortices are formed in the trough between the southern and northern meridional flow. There are also two more subtypes where the MTCV forms in the south (Figure 6C) or north (Figure 6D) meridional current, respectively.

This classification of MTCV formation types followed the streamflow where the center of the cyclonic circulation was observed apart from higher and lower levels. Indian-Arabic MTCVs also are formed in middle tropospheric levels and recently they were classified in four types according to different weather regimes involved in their formation processes over northeast Arabian Sea and western India (Kushwaha *et al.* 2023). The criteria used by the authors is different and focused on the dynamics fields occurring during rainy days related to cyclonic activity over the region. Their method of classification indicates that MTCVs formation is related to large scale circulation patterns and how they modulate precipitation regimes over the northeast Arabian Sea and western India.

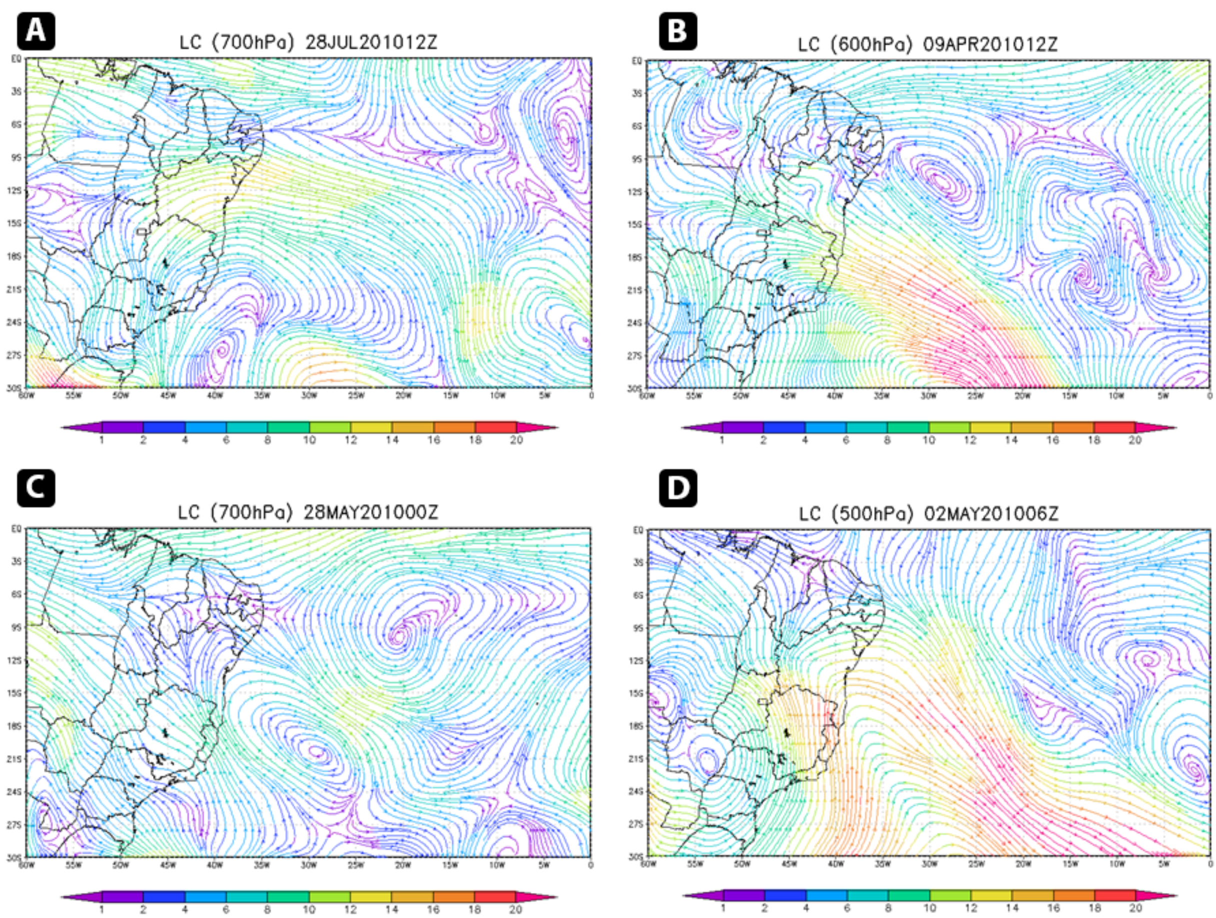

Figure 6 Composite flow and wind magnitude fields (m s-1) at 700, 600 and 500 hPa showing examples of Type III formation processes: A. Type IIIa; B. Type IIIb; C. Type IIIc; D. Type IIId. Dashed line: meridional currents of the two hemispheres and axis of the trough.

3.5 Frequency of MTCV Formation Processes

Table 3 shows the frequency of each type of MTCV formation process according to the identified subtypes.

A total of 29 MTCV were formed on the trough in the east air current (Type I). Subtype Ia was observed in 17 MTCVs during the formation process. While there were 8 MTCVs of the subtype Ib, and 4 events that belonged to the third subtype (Ic). For 19 MTCVs, the predominant type was Type II, where 4 of them were of subtype IIa and in 13 of these events were of subtype IIb. The third subtype happened in two MTCVs formation along the west air current (subtype IIc). For the third type (Type III), 14 events were observed. Five MTCVs were formed in the encounter of the northern and southern flow (subtype IIIa). Only two cases happened between the northern and southern flow (subtype IIIb) while two MTCVs were formed along the northern flow (subtype IIId) and five were observed in the southern flow (subtype IIIc).

Despite their frequency, it is not clear yet whether more frequent events produce higher precipitation volumes or are related to more adverse weather conditions such as thunderstorms and MCC. From the cases analyzed, it could be observed that only three out of the five long-lived MTCVs (> 84 hours) were of the Type Ia, the most frequent type, the other one was of Type Ib and the last one was categorized as Type IIIa. Arabian and Indian MTCVs were also categorized and results showed different amounts of precipitation related to each type. The first type (Type 1) represented 51% of all MTCVs that occur over the region, followed by 31% (Type 2a), 9-10% (Type 2b) and Type 2c representing 7-8% of all vortices (Kushwaha *et al.* 2023). According to this classification, Type 2a is the rainiest MTCV type even though it is not the most frequent. It is important to note that each one of these types is formed through different processes.

3.6 Vertical Structure and Motion During the MTCV Pre-Formation Process

MTCV vertical structure in the initial (pre-formation) and formation phases were analyzed. Table 4 shows the most relevant values in the pre-formation stage. In this phase there are no significant patterns regarding each subtype formation process in any of the investigated variables. However, some results are more remarkable than others in a more generalized analysis.

Vorticity values of cyclonic circulation were observed between -1×10^{-5} s^{-1} and -5×10^{-5} s^{-1}. The most frequent vorticity values at this stage were -3×10^{-5} (31 cases) and -4×10^{-5} s^{-1} (14 cases) as it is shown at Table 4. These strongest vortices are not related to a specific subtype, it was observed MTCVs that reached vorticity values equal or lower than -5×10^{-5} s^{-1} in five of ten subtypes. It is worthy noting that Fedorova *et al.* (2017) reported a MTCV event

Table 3 Types and subtypes of MTCV formation processes and number of events.

Types and subtypes of MTCVs formation process	Number of events	Σ
Type I		
Subtype Ia	17	
Subtype Ib	8	**29**
Subtype Ic	4	
Type II		
Subtype IIa	4	
Subtype IIb	13	**19**
Subtype IIc	2	
Type III		
Subtype IIIa	5	
Subtype IIIb	2	**14**
Subtype IIIc	5	
Subtype IIId	2	

where maximum vorticity values were observed around -3×10^{-5} s^{-1} during its entire life cycle of 42h. It highlights that these are the most frequent vorticity values during the formation process and it may remain as the maximum vorticity through the following formation process.

Weak convergence and divergence were observed in all MTCVs. In the pre-formation phase, the divergence maximum value observed was 2×10^{-5} s^{-1}, while convergence reached -3×10^{-5} s^{-1}. Divergence values were, respectively, 1×10^{-5} and 0.5×10^{-5} s^{-1}, in 14 and 25 MTCVs. Convergence values often happened between -2×10^{-5} and -1×10^{-5} s^{-1}, most of them, representing 19 and 25 events, respectively. Overall, 16 MTCVs cases showed only convergence (divergence equals to zero) and in two cases there was only divergence in the pre-formation phase. Once again, there is no clear pattern relating stronger convergence or divergence values to certain subtypes; they are well distributed through the types.

Similarly, weak lifting and sinking motions were observed in all cases in the pre-formation stage. Vertical velocities ranged from 0.3 Pa s^{-1} (sinking) to -0.2 Pa s^{-1} (lifting) as can be seen in the four most right columns in Table 4. Most of the MTCVs had maximum downward velocity between 0.1 Pa s^{-1} and 0.2 Pa s^{-1}, observed in 42 and 18 events, respectively. The minimum upward velocity was -0.1 Pa s^{-1}, observed in 26 MTCVs. Thus, 32 MTCVs registered only sinking motion against one event presenting only lifting motion during the pre-formation process. No remarkable characteristic was observed about the vertical motion during this stage of MTCVs life cycle.

Table 4 Vorticity, divergence and vertical velocity during the MTCVs preformation stage. N° – number of events. Cyclonic - vorticity. Div – divergence. Conv – convergence. Sink - sinking motion. Lift – lifting motion.

Vorticity ($\times10^{-5}$ s^{-1})		Divergence ($\times10^{-5}$ s^{-1})				Vertical Velocity (Pa s^{-1})			
cyclonic	*Nº*	*Div*	*Nº*	*Conv*	*Nº*	Sink	*Nº*	Lift	*Nº*
-1	*1*	**2**	*7*	**0**	*2*	**0.3**	*1*	**0**	*32*
-2	*5*	**1**	*14*	**-0.5**	*13*	**0.2**	*18*	**-0.1**	*26*
-3	*31*	**0.5**	*25*	**-1**	*25*	**0.1**	*42*	**-0.2**	*4*
-4	*14*	**0**	*16*	**-2**	*19*	**0**	*1*		
≤ -5	*11*			**-3**	*3*				

3.7 Vertical Structure and Motion During the MTCVs Core Formation Process

The vortices structure and vertical motion during the MTCVs core formation were analyzed, this includes all MTCVs development 6 hours after its pre-formation phase. All variables were analyzed within the cyclonic circulation area.

The most frequent values of vorticity spanned from $-3x10^{-5}$ s^{-1}, -4×10^{-5} s^{-1} to $< -5\times10^{-5}$ s^{-1} where an equal number of 16 MTCVs were registered, respectively (Table 5), meaning that there was persistent cyclonic circulation over the area where these values were registered. It's noticed that in the majority of the vortices, there was an intensification of the cyclonic circulation by -1×10^{-5} s^{-1} in comparison to the previous phase. However, even though the MTCVs were more intense, their values could not be compared to UTCVs and MTCVs over the Indian regions (De Morais *et al.* 2020; Choudhury *et al.* 2018). These results suggest that South American MTCVs are weaker than these other systems.

The first analysis of MTCVs over the NEB and South Atlantic tropical region registered three vortices where their maximum vorticity values reached -5×10^{-5} s^{-1} (600 hPa) (Fedorova *et al.* 2006). It is noteworthy that these events intensified in the first 24 hours of their cyclonic vortices being formed. When compared to UTCVs, MTCVs show the same pattern of highest intensity during the formation process (De Morais *et al.* 2020). However, UTCVs have higher vorticity values reaching -22×10^{-5} s^{-1} (400 hPa) depending on the season compared to MTCVs over South America. It is interesting to notice that during their analysis it was observed that UTCVs formed at 600 and 700 hPa were shallower than in the upper levels throughout their entire life cycle. Kushwaha *et al.* (2023) observed that within the categorized MTCVs, the maximum vorticity occurred from 3×10^{-5} s^{-1} to 5×10^{-5} s^{-1} around 600 hPa; these values are similar to MTCVs vorticity over South America and much less intense MTCVs reported by Choudhury *et al.* (2018).

Divergence values were respectively registered as 1×10^{-5} s^{-1} and 0.5×10^{-5} s^{-1} in 18 and 20 cases (Tabela 5).

Negative values of divergence, in other words, convergence values were identified ranging from -2×10^{-5} to -0.5×10^{-5} s^{-1}, represented by 25 (-2×10^{-5} s^{-1}) 19 (-1×10^{-5} s^{-1}) and 14 (-0.5×10^{-5} s^{-1}) cases registered within these thresholds. In 16 cases there was only convergence, while 3 events presented only divergence. These results indicate that stronger convergence was found in the majority of the MTCVs at this stage in comparison to the pre-formation stage, and it corroborates with these systems being related to synoptic and mesoscale systems associated with latent heat release (Fedorova *et al.* 2017). Despite stronger vorticity values, MTCVs over the Indian continent have divergence values similar to the MTCVs over the South America, being observed convergence values at lower levels and divergence above 700 hPa until around 500 hPa (Choudhury *et al.* 2018). The corresponding levels of maximum vorticity and minimum divergent values is related to the vertical heat gradient present in MTCVs over the Indian continent.

Analogously to the previous formation phase, weak downward and upward motions were observed during the formation stage. The maximum and most frequent downward values were 0.1 Pa s^{-1} and 0.2 Pa s^{-1}, observed in 45 and 16 events, respectively (Table 5). The minimum upward value was -0.1 Pa s^{-1}, observed in 35 cases. These values shown in table also present 25 MTCVs that did not have any lifting motion, only sinking in contrast to one MTCVs where only lifting movements were registered during the MTCV core formation phase. However, the highest number of MTCVs with lifting and sinking movements (35 and 45, respectively) lies between the average values of -0.1 Pa s^{-1} and 0.1 Pa s^{-1}, meaning that the majority of these systems did not have strong vertical movements. In contrast, MTCVs over the Indian region have slightly stronger vertical velocity values between 0.4 Pa s^{-1} and 3 Pa s^{-1} with highest intensity around 400-300 hPa to the east of the system (Choudhury *et al.*, 2018).

Table 5 Vorticity, divergence and vertical velocity during the MTCVs core formation stage. N° – number of events. Cyclonic - vorticity. Div – divergence. Conv – convergence. Sink - sinking motion. Lift – lifting motion.

Vorticity ($\times10^{-5}$ s^{-1})		Divergence ($\times10^{-5}$ s^{-1})				Vertical Velocity (Pa s^{-1})			
cyclonic	*Nº*	*Div*	*Nº*	*Conv*	*Nº*	Sink	*Nº*	Lift	*Nº*
-2	*5*	**3**	*1*	**0**	*3*	**0.2**	*16*	**0**	*25*
-3	*16*	**2**	*7*	**-0.5**	*14*	**0.1**	*45*	**-0.1**	*35*
-4	*25*	**1**	*18*	**-1**	*19*	**0**	*1*	**-0.2**	*1*
≤ -5	*16*	**0.5**	*20*	**-2**	*25*			**-0.3**	*1*
		0	*16*	**-3**	*1*				

4 Conclusions

Results found by the present research, including the 62 cases of MTCVs over the Northeast of Brazil and coast of South America during 2010, reinforce the relevance of these events to the study area. It is important to highlight that currently only a few studies have been performed on these MTCVs over the South America-Atlantic and the scarcity of available material presents a challenge to better understand their formation processes and impacts over the study region.

It is important to highlight some relevant considerations regarding MTCVs. As for the spatial distributions of the MTCVs over the study area, it was found that 35 out 62 MTCVs were formed over the Atlantic Ocean adjacent to the NEB coast. There were 27 MTCVs that reached the continental area or were formed there. Most of the MTCVs occur within the range of 12 to 42 hours, placing them as important systems for the short-term weather forecast. These events are short lived phenomena compared to MTCVs over the Indian continent and South American UTCVs (Kousky & Gan 1981; Choudhury *et al.* 2018; De Morais *et al.* 2020). They are well distributed throughout the year as it was found by Fedororva *et al.* (2017), however, the Autumn of 2010 presented a larger number of MTCVs when compared to other seasons especially the Summer that had the lowest number of them.

There are also important differences between MTCVs and UTCVs systems. The MTCVs statistically preferred level of formation is at 700 hPa level comprehending a percentage of 54.8% (34 cases) of all events. MTCVs over the Indian continent are also confined to middle levels for they are associated with convective activity from the summer monsoon systems (Krishnamurti & Hawkins 1970; Carr 1977). While South American UTCVs preferred layers of formation and development are the upper levels of the troposphere (Kousky & Gan 1981; De Morais *et al.* 2020).

Three types of MTCVs formation processes were identified: 1) Type I, trough in the air current from the west, 2) Type II, trough in the air current from the east, and 3) Type III, in the meridional current from both hemispheres. Ten subtypes were distinguished depending on the position of the trough axis before the MTCV formation: meridional, NW - SE and SW - NE. It's worthy to notice that each of these three types of formation process showed a more frequent subtype. Most frequent subtype of Type Ia (17 events) was MTCVs formed on troughs with an axis from northwest to southeast. In Type IIb, MTCVs were frequently formed (13 events) on troughs with an axis from southeast to northwest. The confluence of air flows from both hemispheres (Type IIIa), and a trough in the air flow from the northern (Type IIIc) were observed in 5 events. Similar categorization was performed by Kushwaha *et al.* (2023) where they found four main MTCVs subtypes according to their formation processes. These MTCVs had different frequency and precipitation regimes associated.

In addition to this, different magnitudes related to vertical structure and motion were observed during the MTCVs pre-formation and formation stages. Relative vorticity values of -3×10^{-5} s^{-1} and -4×10^{-5} s^{-1} were found in 31 and 14 events, respectively, during the pre-formation stage. These values are comparable with the weakest values of MTCVs over the Indian continent (Choudhury *et al.* 2018). Weak divergence and convergence values were observed in all cases during the mentioned stage, being 16 of them presenting only convergence while 2 events registered only divergence. Vertical motions were weak in all MTCVs as well as during the pre-formation phase. It is worth mentioning that 32 events presented only sinking motion while just one MTCV presented only lifting motion, out of 62 MTCVs observed.

These results indicate that, during the pre-formation stage, the vortices have weak convergence/divergence values and average vorticity and vertical motion values, even though extreme values were also found. These results are similar to what was found by De Morais *et al.* (2020) on UTCVs that reached lower levels (700 - 600 hPa). They found out that at this stage the vortices show no predominant tilt patterns in the first 06 to 12 hours, especially during the austral winter.

During the MTCVs core formation, vorticity values were found between -3×10^{-5} s^{-1} (16 cases) and -4×10^{-5} s^{-1} (25 cases), 41 vortices in total. It was noticed that, during this stage, most of the MTCVs (25 events) had a more intense vorticity value when compared to the previous stages, indicating that there was an intensification of the vortices over the processes. Even with this intensification, South American MTCVs are still remarkably weaker than MTCVs over the Indian region and South American UTVCs (Choudhury *et al.* 2018; Kushwaha *et al.* 2023; De Morais *et al.* 2020).

Divergence values do not change considerably 6 hours after the pre-formation stage. There were 20 events where the divergence values were 0.5×10^{-5} s^{-1} and in 25 events convergence values were -2×10^{-5} s^{-1}. Most of the MTCVs present both lifting and sinking motions, however, a significant amount of vortices, 25 in total, showed only sinking motion. As it was found in previous studies, these events may be related to latent heat release and synoptic and mesoscale systems (Fedorova *et al.* 2017).

The results discussed in this research reiterated that MTCVs are important systems for weather forecast over the study region. The MTCVs formation processes and its characteristics showed that these systems are similar to MTCVs over other regions such as the Indian monsoon region, even though there are remarkable differences between them regarding duration, vertical motion intensity and vorticity values.

The present study provides basic information that reinforces the importance of studies for the middle layer of the atmosphere. Emphasizing that just as its relationship with adverse characteristics and connection with other systems was identified in previous studies, it can be highlighted that further research on MTCVs spatial location, duration, and vertical structure will be needed to assess how they are related to weather conditions over NEB. There might also be important MTCVs features regarding their thermodynamic and dynamic structures that need further research.

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