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Ciclo Energético de Ciclones no Atlântico Sul: Padrões, Modelagem e Interação Oceano-Atmosfera

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sua dedicatoria aqui!

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“一、努力の精神を養うこと”

“*Primeiro, Criar o intuito do esforço*”

Kanga Sakukawa

Resumo

Resumo

Abstract

Abstract

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Capítulo 1

Introdução

1.1 *Objetivo e pergunta de pesquisa*

- Como a interação oceano-atmosfera afeta a energética de sistemas ciclônicos no Atlântico Sul?

1.2 *Objetivos específicos*

- Determinar padrões, através do Ciclo Energético de Lorenz, para os ciclones atuantes no Atlântico Sul dentre o período 1979-2020;
- Avaliar qual o conjunto de parametrizações microfísicas e de convecção propiciam que o modelo MPAS-A apresente simulações mais realistas do Furacão Catarina, em diferentes estágios de desenvolvimento do sistema;
- Determinar o impacto das diferentes configurações do modelo na energética do sistema;
- Avaliar o impacto da pertubação da temperatura da superfície do mar na energética de sistemas ciclônicos atuantes no Atlântico Sul, através do estudo de casos representativos

Capítulo 2

Fundamentos Teóricos

2.1 *Cyclones: Categories and Definitions*

For effective analysis and study, a phenomenon must first be accurately defined. The Glossary of Meteorology by American Meteorological Society (2012) characterizes a "cyclone"as "An atmospheric cyclonic circulation, a closed circulation. A cyclone's direction of rotation (counterclockwise in the Northern Hemisphere) is opposite to that of an anticyclone. (...) Because cyclonic circulation and relative low atmospheric pressure usually coexist, in common practice the terms cyclone and low are used interchangeably. Also, because cyclones are nearly always accompanied by inclement (often destructive) weather, they are frequently referred to simply as storms". This definition categorizes cyclones into sub-types based on their occurrence location: tropical, extratropical, and subtropical cyclones (Reboita et al., 2017, e.g.). This classification is supported by the assumption that cyclones within the same latitude bands share genesis environments and dynamic maintenance processes. There are also cyclones whose genesis is found in high latitudes, called polar lows (Emanuel e Rotunno, 1989; Harrold e Browning, 1969, e.g.). These will not be discussed in depth as the focus of the present study is on the systems whose genesis is found in the regions adjacent to the South American coast.

The aforementioned definition, while broad, lacks precise criteria. Thus, subsequent sections will employ the Aristotelian approach to elucidate physical phenomena (Aristotle e Aristotle, 1933). Aristotelian causes, foundational to Aristotle's philosophy, offer a comprehensive explanation for an object or phenomenon's existence through four types: material, formal, efficient, and final causes. The ensuing subsections will detail each cause, enhancing the understanding of related phenomena. For each cyclone type — extratropical and tropical — a discussion of the causes will facilitate a direct comparison between the systems.

It is important to note that the structure and mechanisms underlying the genesis and development of cyclones have been well-documented since the mid-twentieth century, leading to the inclusion of many historical references. The aim is to highlight distinctions between cyclone types, a comparison not commonly made in literature. Meteorologists often specialize as "tropical meteorologists" or "mid-latitude meteorologists", a division reflected in educational materials. Some texts focus exclusively on mid-latitude or tropical dynamics (Chan e Kepert, 2010; Bluestein, 1992, e.g.), while others that address both, treat them separately (Holton, 1973; Donald Ahrens e Henson, 2015, e.g.). Although this separation is customary and beneficial, juxtaposing the two offers novel insights, as explored in the following sections.

2.1.1 Material Causes

Material cause, within the Aristotelian framework, denotes the substance or constituents that form an object. It encompasses the matter or physical elements constituting an entity, serving as the foundation for its existence. For instance, wood acts as the material cause for a table, just as water serves as the material cause for a river. Applied to cyclonic systems, the material cause encompasses the air masses forming these systems, particularly emphasizing their thermal structure. This section elaborates on this concept, showcasing its relevance in defining and categorizing cyclonic systems.

The concept of an air mass, as introduced by Swedish meteorologist Tor Bergeron in 1928, describes a large body of air characterized by uniform temperature, moisture, and other properties, extending over 500 to 5000 km and encompassing the troposphere's full height (Stull, 2015). Air masses are classified based on their temperature, moisture content, stratification, and turbidity levels. Additionally, air masses originate from specific source regions, areas conducive to their formation. The characteristics of an air mass are significantly influenced by its source region's surface conditions, necessitating a flat terrain and mild winds for its development (Donald Ahrens e Henson, 2015). Heat transfer between the surface and the air is gradual, requiring the air mass to remain over its source region for an extended period to assimilate its properties (Spiridonov e Ćurić, 2021). Therefore, mid-latitudes, characterized by variable meteorological conditions and strong winds, are generally unsuitable for air mass formation.

Bergeron's classification system is the most widely accepted methodology for categorizing air masses. It utilizes letters to denote the moisture content and the origin of air masses (Spiridonov e Ćurić, 2021). The initial letter signifies the air mass's moisture source—continental (dry) or maritime (moist)—while the subsequent letter indicates the geographical origin of the air mass, whether it be tropical (T), polar (P), arctic/antarctic (A), equatorial (E), or monsoonal (M). Figure 2.1 illustrates the spatial distribution of air masses according to Bergeron's scheme. Upon the encounter of two distinct air masses, immediate mixing does not occur, resulting in a temporary discontinuity at their intersection, known as fronts (Spiridonov e Ćurić, 2021; Donald Ahrens e Henson, 2015).

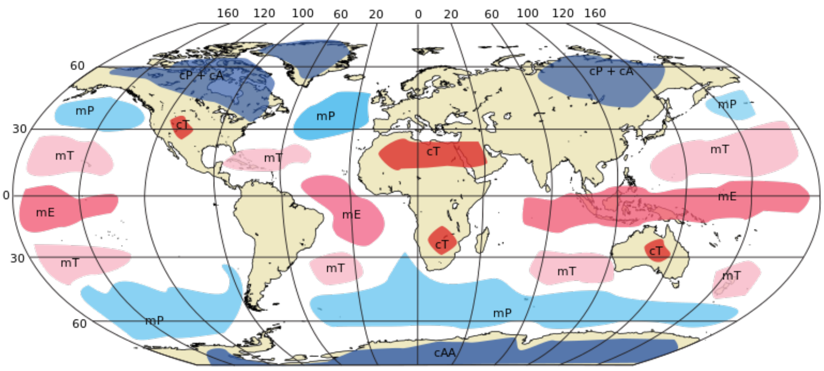

Figura 2.1: Spatial distribution of air masses according to Bergeron's classification. Credit: public domain (https://commons.wikimedia.org/w/index.php?curid=12526643).

Therefore, the validity of the traditional cyclone classification—tropical, extratropical, and subtropical—relies on the premise that different types of cyclones are initiated by distinct air masses. Specifically, tropical cyclones originate from warm, moist air masses that span the entire troposphere and form over warm tropical waters (Gray, 1968; Frank, 1977a; Ramage, 1959; Riehl, 1948). In contrast, extratropical cyclones are associated with frontal zones at mid-latitudes, where two different air masses meet, and are typically linked to cold cores (Bjerknes e Holmboe, 1944; Shapiro e Keyser, 1990; Hart, 2003). However, intense marine extratropical cyclones can experience warm seclusion, resulting in a warm core at the system's center (Hart, 2003; Shapiro e Keyser, 1990). Subtropical cyclones feature a hybrid structure between tropical and extratropical systems, with warm, moist cores that are less pronounced and shallower than those in tropical cyclones (Hart, 2003).

Hart (2003) offers an objective methodology for identifying the thermal structure of cyclonic systems. This analysis focuses solely on tropospheric levels (up to 300 hPa) because cyclones display an opposing thermal signal in the stratosphere. The study examines layers between 900 and 600 hPa and between 600 and 300 hPa, which have comparable masses. Levels below 900 hPa are excluded to prevent extrapolation below the ground or into the boundary layer, which may not accurately represent the cyclone's structure in the free atmosphere. Consequently, the variable corresponding to the cyclonic perturbation in height is defined as follows:

$$\Delta Z = Z_{MAX} - Z_{MIN} \tag{2.1}$$

Where Z_{MAX} and Z_{MIN} represent the maximum and minimum geopotential heights at a specific isobaric level, measured within a 500 km radius from the cyclone's center. Following this definition:

$$\Delta Z = \frac{dg|V_g|}{f} \tag{2.2}$$

Here, d denotes the distance between the geopotential height extremes, g is the acceleration due to gravity, f represents the Coriolis parameter, and V_g is the geostrophic wind speed. Consequently, the cyclone's vertical structure (indicative of a cold or warm core) is determined by the vertical gradient of ΔZ, which is proportional to the magnitude of the scaled thermal wind (V_T) for a constant d, applied across two tropospheric layers of equal mass:

$$\left.\frac{\partial(\Delta Z)}{\partial \ln p}\right|_{600hPa}^{300hPa} = -|V_T^U| \tag{2.3}$$

$$\left.\frac{\partial(\Delta Z)}{\partial \ln p}\right|_{900hPa}^{600hPa} = -|V_T^L| \tag{2.4}$$

where V_T^U and V_T^L symbolize the thermal winds at upper and lower levels, respectively. As such, positive values of $-V_T$ signify a warm core within the respective layer, whereas negative values indicate a cold core.

The relationship between the temperature and depth of the core within cyclonic systems is detailed through a phase diagram by Hart (2003), depicted in Figure 2.2. This diagram utilizes the abscissas to represent the parameter $-V_T^L$, illustrating the low-level core's thermal structure. The ordinates display $-V_T^U$, portraying the high-level core's thermal structure. Integrating these metrics allows for discerning whether a system possesses a warm or cold core, and if it is shallow or deep. Figure 2.2 includes typical positions representative of different cyclonic types within the phase space. As noted by Hart (2003), a system may shift within this diagram throughout its lifecycle, making the depiction general for each cyclone category. Additionally, Hart proposes a diagram for the horizontal structure of these systems, related to their formal causes, which is addressed in Section 2.1.2.

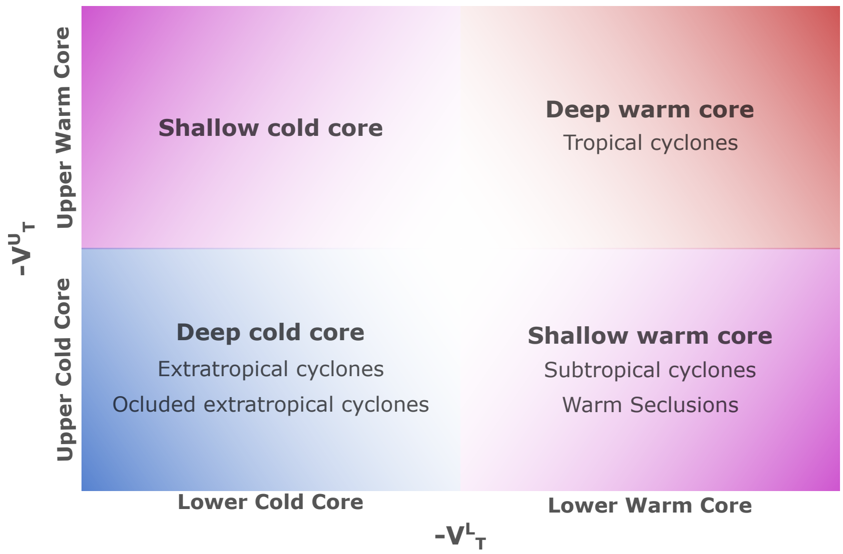

Figura 2.2: Phase diagram showing the relationship between the core temperature of cyclonic systems and their classification. Adapted from Hart (2003).

Thus, material causes, tied to the thermal structure of cyclonic systems, offer a foundational method for classifying and differentiating cyclone types. This classification leverages the phase diagram by Hart (2003) for an objective categorization. Accordingly, extratropical cyclones are characterized by cold, deep cores, whereas tropical cyclones feature warm, deep cores. This spectrum isn't binary; there exists a gradient of thermal structures with systems exhibiting intermediate features classified as subtropical cyclones. Nevertheless, relying solely on thermal attributes for classification is insufficient. For instance, extratropical cyclones, through the warm seclusion process (Shapiro e Keyser, 1990, e.g.), can develop warm, shallow cores (Hart, 2003), indicating the necessity for a broader analysis incorporating additional Aristotelian causes for a comprehensive classification.

2.1.2 *Formal Causes*

The formal cause concerns the essence or identity that defines a thing, essentially its design, structure, or conceptual blueprint that marks it as a particular type. To revisit the earlier example of a table from Section 2.1.1, its formal cause is the design that qualifies it as a table rather than a chair. In the context of cyclones, the formal cause refers to the system's organizational structure, such as the configuration of convection bands and/or fronts, along with the low-pressure pattern.

Extratropical cyclones, typically associated with mid-latitudes and frontal structures, exhibit an average diameter between 1200 and 1800 km. This size fluctuates over their lifecycle, with the cyclone's diameter expanding by up to 150% during its intensification phase (Simmonds, 2000; Rudeva e Gulev, 2007). However, the spatial complexity and variability of these systems throughout their lifecycle pose methodological challenges for accurately estimating their dimensions and comparing findings across different studies.

The seminal model describing the formation and horizontal structure of extratropical cyclones was introduced by Bjerknes (1919), illustrated in Figure 2.3. This model showcases the cyclone's movement along a central horizontal line, with the "steer line"demarcating the boundary that influences the cyclone's trajectory, characterized by warm air masses to its left. The "squall line"indicates a zone of intense meteorological activity, marked by strong winds and often heavy precipitation, with cold air masses located to its left. The "fore runner"represents a region of diverging airflow.

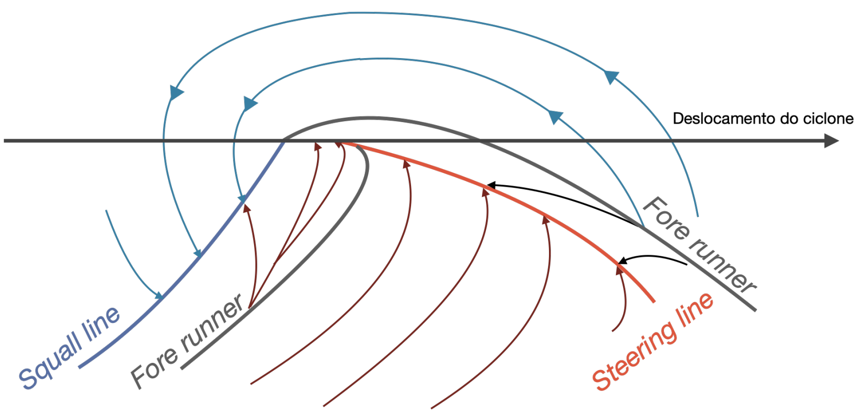

Figura 2.3: Representation of the Bjerknes model for the extratropical cyclone formation process and its horizontal structure. Cold air regions are illustrated with blue lines, while warm air regions with red lines. Adapted from Bjerknes (1919).

Bjerknes e Solberg (1922) realized that the model proposed in Bjerknes (1919) represented just one phase in the life cycle of cyclones, indicating that there are several stages of development. Bjerknes e Solberg (1922) established the Polar Front Theory, which is the foundation of the so-called Norwegian cyclone model. Schultz et al. (1998) synthesizes and describes the development of extratropical cyclones according to this theory, so that a visual representation of the horizontal structure at the surface during different stages of cyclone evolution is found in Figure 2.4a. In the first stage, the incipient cyclone presents a narrow and long cold front, and a wide and short warm front (Figure 2.4aI). After this, the cyclone deepens, with a narrowing of the warm section of the cyclone through the rotation of the cold front towards the warm front (Figure 2.4aII). As cold air is denser and, therefore, facilitates more intense horizontal pressure gradients, it moves faster than the warm air. As the cold air at the front of the cyclone approaches the cold air at the rear of the system (Figure 2.4aIII), the warm air is trapped in the center of the system, a phenomenon called warm seclusion. As the cold front continues to move, the warm air at the surface is overtaken by the cold air and is forced to ascend to upper levels. This process is called occlusion, being responsible for trapping the cold air in the core of the system (Figure 2.4aIV). With the continuation of occlusion, the baroclinicity along the warm front can become so diffuse that the cyclone appears not to have a well-defined warm front.

Bjerknes e Solberg (1922) acknowledged that the model presented in Bjerknes (1919) captured only a singular phase in the life cycle of cyclones, leading to the development of the Polar Front Theory. This theory defines what is known as the Norwegian cyclone model. Schultz et al. (1998) provides a synthesis of extratropical cyclone development according to this theory, including a depiction of the surface horizontal structure at various stages of cyclone evolution in Figure 2.4a. Initially, the nascent cyclone features a narrow, elongated cold front and a broader, shorter warm front (Figure 2.4aI). Subsequently, the cyclone deepens as the cold front rotates toward the warm front, narrowing the cyclone's warm sector (Figure 2.4aII). Given the greater density of cold air, which generates stronger horizontal pressure gradients and moves more swiftly than warm air, the cold front eventually encroaches on the system's rear cold air (Figure 2.4aIII), trapping warm air at the system's center—a process known as warm seclusion. As the cold front progresses, the surface-level warm air is displaced by cold air and forced upward, a phenomenon termed occlusion, which entraps cold air at the system's core (Figure 2.4aIV). The occlusion process may eventually diffuse the baroclinicity along the warm front to such an extent that the cyclone seems to lack a distinct warm front.

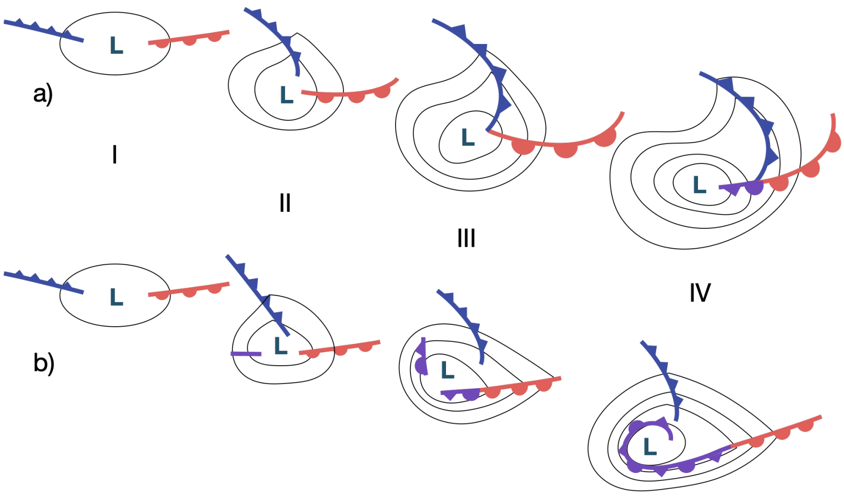

Figura 2.4: Cyclonic models by Bjerknes (1919) (a) and Shapiro e Keyser (1990) (b), illustrating the systems' horizontal structure across different developmental stages (I to IV). Adapted from Schultz et al. (1998).

From the advancements enabled by the satellite era, Shapiro e Keyser (1990) introduced a revised cyclonic model, acknowledging that not all observed cyclones conformed to the Norwegian model. Termed the Shapiro-Keyser model, it is also summarized by Schultz et al. (1998), with its visualization in (Figure 2.4b). Initially mirroring the development outlined by Bjerknes e Solberg (1922) (Figure 2.4bI), this model diverges as the cold front extends perpendicularly to the warm front instead of encircling the system (Figure 2.4bII). As the system strengthens, the polar side of the cold front weakens, allowing the warm front to encircle the system's western sector (Figure 2.4bIII). At peak intensity, cold air encases the warm air near the cyclone's center, creating a warm seclusion (Figure 2.4bIV).

Schultz et al. (1998) emphasizes that these models are complementary rather than mutually exclusive, suggesting that the Norwegian model is more applicable to systems forming under diffluent flow with significant amplitude, often at the terminal end of storm tracks and on western continental edges, characterized by a meridional elongation of the cyclone and its fronts. Conversely, the Shapiro-Keyser model is more suited to systems emerging under confluent, low amplitude base flow, typically exhibiting east-west elongation. However, these models alone do not fully account for the formal causes of extratropical cyclones, indicating a continuum where different systems may align more closely with one model or the other (Schultz et al., 1998).

Tropical cyclones, unlike their extratropical counterparts, lack frontal structures and exhibit organized, symmetric circulation near the surface, forming over warm tropical or subtropical waters with intense winds below the surface (Frank, 1977a; Gray, 1968). Their diameters vary, ranging from 100 to 1000 km at maturity, expanding up to 2000 km during intensification. However, the area of intense convection and stronger winds typically spans a radius of about 100 km (Holton, 1973).

Characterized by a central cyclonic circulation at lower tropospheric levels and anticyclonic circulation in the upper troposphere, tropical cyclones are associated with intense precipitation and horizontal pressure gradients, leading to spiraled winds near the surface that become increasingly circular towards the system's center, or eye (Frank, 1977a,b; Terry, 2007; Weatherford e Gray, 1988). These systems exhibit more intense pressure gradients—and consequently stronger winds—than extratropical cyclones (Spiridonov e Ćurić, 2021). Based on wind speed, they are classified into tropical depressions (maximum winds less than 60 km/h), tropical storms (winds between 60 and 110 km/h), and tropical cyclones (winds exceeding 110 km/h) (Spiridonov e Ćurić, 2021). Their nomenclature varies by region: "hurricanes"in the North Atlantic and North Pacific, "typhoons"in the Northwest Pacific, and "cyclones"in the Indian Ocean (Donald Ahrens e Henson, 2015).

The structure of tropical cyclones comprises three main components: the eye, the eye wall, and surrounding convection bands (Figure 2.5). The eye is the calm, warm central region, with a radius of 5 to 50 km, encircled by the eye wall—a cloud ring about 10 to 20 km wide where intense upward vertical movements occur, facilitating mass transport to higher levels (Shea e Gray, 1973; Jorgensen et al., 1985). Although these vertical movements are typically less vigorous than those in extratropical cyclones (Jorgensen et al., 1985), the inner core, consisting of the eye and eye wall, hosts the most intense winds and lowest atmospheric pressures (Weatherford e Gray, 1988). The primary convection band, a nearly stationary feature, spirals inward from the system's outer edges towards the eye wall, where it becomes roughly tangent (Willoughby et al., 1984).

Given the delineated formal causes (organizational structure) for both extratropical and tropical cyclones, it's evident that their structures diverge significantly. Simplified, extratropical cyclones, forming at the interface between distinct air masses, are associated with frontal systems, providing them an asymmetric feature. Conversely, tropical cyclones exhibit symmetry, characterized by a circular eye and spiraled convection bands extending

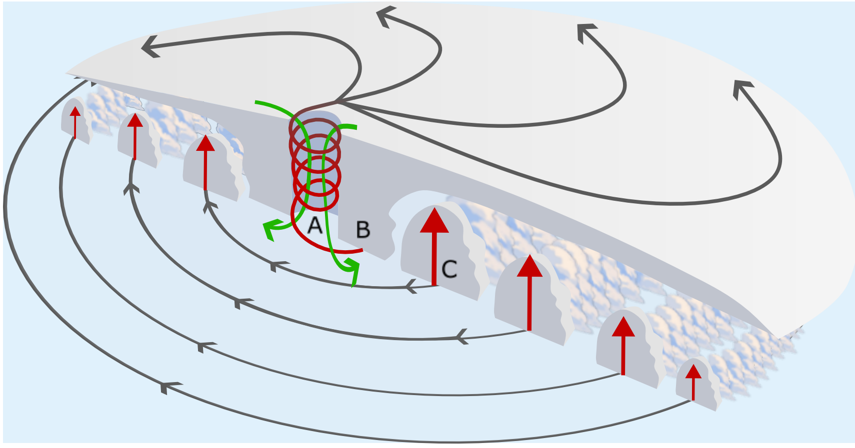

Figura 2.5: Cross-sectional view of a mature tropical cyclone in the Southern Hemisphere, illustrating the eye (A), eye walls (B), and convection bands (C), along with upward (red arrows) and downward (green arrows) vertical movements, horizontal wind movement (grey arrows), and sea-level pressure contours. Inspired from: Bluestein (1992).

from the eye wall. Addressing this distinction, Hart (2003) introduces a metric assessing the relative thickness asymmetry between the 900 and 600 hPa levels, termed the B parameter:

$$B = h\left(\overline{Z_{600hPa} - Z_{900hPa}}|_R - \overline{Z_{600hPa} - Z_{900hPa}}|_L\right) \tag{2.5}$$

where Z represents the isobaric height, R and L denote the right and left sides relative to the system's motion, the overbar signifies an average over a 500 km semicircle, as defined in Equation 2.1, and h is a constant set to +1 or -1 for the northern and southern hemispheres, respectively. Mature tropical cyclones exhibit a B value near zero, indicating thermal symmetry (non-frontal), while extratropical cyclones show significant B values, signaling thermal asymmetry (frontal). Positive B values suggest the presence of warm air to the right of the cyclone in the southern hemisphere (and vice versa in the northern hemisphere), aligning with the thermal wind relationship from quasi-geostrophic theory (Sutcliffe, 1947; Trenberth, 1978).

Hart (2003) proposed a diagram correlating symmetry with V_T^L (Equation 2.4), depicted in Figure 2.6, offering a supplementary classification to that shown in Figure 2.2. Here, extratropical cyclones are categorized as cold and asymmetric (frontal), whereas tropical cyclones are warm and symmetric (non-frontal). Like the earlier diagram, this classification suggests a continuum, with systems displaying intermediate features labeled as subtropical. Unlike solely thermal-based classifications, this model allows for differentiation of extratropical cyclones undergoing occlusion, as these systems begin to exhibit symmetry during this phase. Hence, the diagram involving the B parameter and V_T^L presents an objective methodology to classify cyclones' formal causes.

While the phase diagrams by Hart (2003) facilitate objective classification criteria for cyclonic systems, gaps remain. For instance, warm seclusions share formal and material causes with hybrid systems, leading to potential misclassification by forecasters and climate data analysis algorithms using these diagrams exclusively. Additionally, polar lows, characterized by both a warm core and symmetric structure, were initially likened to hurricanes (Rasmussen, 1989; Emanuel e Rotunno, 1989; Nordeng e Rasmussen, 1992; Rasmussen, 1985, 1979). However, recent studies, such as Stoll et al. (2021), suggest their spiral bands and thermal core may result from the warm seclusion process, as per the Shapiro-Keyser cyclone development model. These discussions underscore that material and formal causes alone do not suffice for a comprehensive cyclone classification, necessitating further analysis.

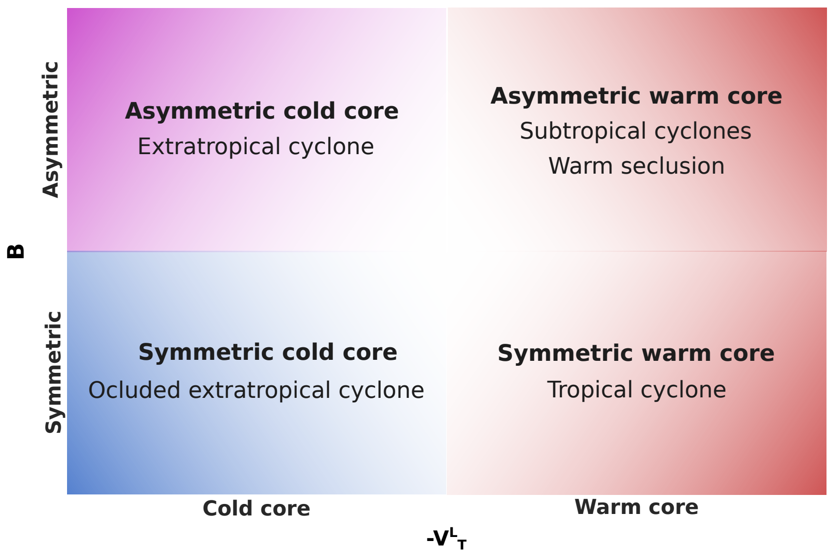

Figura 2.6: Phase diagram illustrating the relationship between cyclonic systems' core temperature and symmetry, offering a distinct classification procedure. Adapted from Hart (2003).

2.1.3 Efficient Causes

The efficient cause represents the agent or process that leads to the creation or transformation of something, answering the "how" or "why" behind an occurrence. It encompasses the actions or processes that result in the existence of an entity. For example, in the creation of a table, the carpenter serves as the efficient cause. In the context of cyclones, the efficient cause includes the physical and dynamic processes responsible for their formation and intensification. These processes essentially act as destabilization mechanisms, triggering atmospheric disturbances that evolve into a cyclonic configuration.

While the polar front theory offers a descriptive perspective, it falls short of providing a comprehensive theoretical model for the physical processes involved in system formation. Still, it related these processes with thermal contrasts in the atmosphere, or baroclinic zones (Bjerknes, 1919; Bjerknes e Solberg, 1922), describing cyclones as emergent phenomena arising at the boundary of two distinct air currents—polar and tropical—flowing in opposite directions (east-west and west-east, respectively), differentiated by thermal contrasts (cold and warm, respectively). A destabilization of the flow occurs when the velocity difference between these currents surpasses a critical threshold, generating a frontal wave that intertwines the currents and reduces their velocity contrast. Some of these frontal waves are unstable and can spontaneously amplify, representing the genesis mechanism of cyclones according to this theory.

The Polar Front Theory provides a detailed account of the structure and formation processes of extratropical cyclones, as shown in Figure 2.7, depicting a transverse model of a developing cyclone (Bjerknes e Solberg, 1922). This model features horizontal isotherms indicative of temperature variations parallel to the ground, with warm air central to the model, characteristic of the warm front, and cold air on the edges. Initially (Figure 2.7a), the isotherms of cold air extend horizontally until convergence forces the ascent of warm air to higher atmospheric levels. This conversion of potential to kinetic energy continues as the cold air from both sides of the cyclone advances to mid-atmospheric levels, further driving the ascent of warm air. The adiabatic cooling of ascending warm air leads to temperature equalization and depletion of the system's potential energy reserve, while the air mass movement is then sustained by inertia. After occlusion (Figure 2.7b and c), inertia maintains the ascent of cold air, which cools adiabatically, utilizing the system's kinetic energy to counteract gravity. Initially, there is still kinetic energy production at high levels and its consumption at low levels. However, as the elevated warm sector cools and temperatures equalize (Figure 2.7d), kinetic energy production halts. Eventually, friction outweighs kinetic energy production, leading to its dissipation.

Since the advent of the polar front theory, our comprehension of atmospheric dynamics

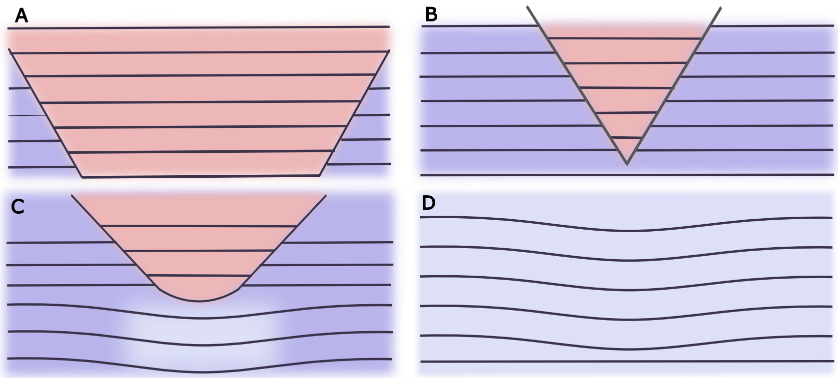

Figura 2.7: Cross-sectional depiction of an extratropical cyclone's development stages, highlighting the warm (red) and cold (blue) sectors and isotherm lines. Adapted from Bjerknes e Solberg (1922).

has evolved significantly, incorporating new concepts into the understanding of extratropical cyclones. This evolution has led to a diverse array of approaches aimed at describing the dynamic and thermodynamic processes underlying the genesis and development of these systems. Consequently, there is no singular, unified theory regarding extratropical cyclogenesis. For instance, Bjerknes e Holmboe (1944) identified the formation regions of extratropical cyclones as zones of dynamic instability associated with the westward-flowing jet stream, employing the tendency equation to analyze atmospheric instability. Other studies have approached cyclogenesis through various lenses, including slantwise convection, the omega equation, potential vorticity, primitive equations, and diabatic processes (Hoskins, 1990, e.g.). Additionally, Schultz et al. (1998)'s work categorizes cyclones into those aligning with the Norwegian model versus the Shapiro-Keyser model, differentiating them based on environmental conditions related to the base state flow (diffluent for the former and confluent for the latter). This section will primarily focus on the development of these systems from the perspective of dynamic destabilization mechanisms in the atmosphere, linking these mechanisms to the energetics of transient atmospheric systems, further explored in Section 2.4.

Baroclinic instability (I_{BC}) is identified as the principal mechanism behind the development of typical extratropical cyclones (Charney, 1947; Bjerknes e Solberg, 1922). As Holton (1973) explains, I_{BC} involves the amplification of small disturbances in areas with strong velocity shears, such as jet streams, where the disturbances extract energy from the jet and grow in size and intensity. In the Earth's atmosphere, I_{BC} is primarily driven by the meridional temperature gradient, especially at lower levels, and is linked to vertical shear via the thermal wind (V_T) relationship, frequently occurring in the polar frontal zone. Baroclinic disturbances can also intensify existing temperature gradients, leading to the formation of frontal zones.

Charney (1947)'s seminal study on I_{BC} sheds light on the intricate mechanisms behind the formation and evolution of weather patterns, including cyclones and long waves in middle and high latitudes. Employing a simplified model that allows for analytical solutions, Charney not only corroborated previously theorized concepts about atmospheric behavior but also deepened the understanding of how wind shear and temperature variations vertically contribute to atmospheric instability. His analysis indicates that mid-latitude westward-flowing currents are inherently dynamically unstable. This insight elucidates how specific disturbances can exponentially grow within a large-scale atmospheric flow field, explicating the process through which such disturbances can amplify and culminate in the characteristic weather systems observed in middle and high latitudes.

Eady (1949) made significant advancements in the understanding of I_{BC} in the atmosphere, building on the work of Charney (1947). Eady's research, which employed a solvable simplified model, delved into the atmospheric instability arising from disturbances that exponentially grow within a large-scale atmospheric motion context. His analysis elucidated how specific conditions of stability, wind shear, and vertical temperature variations contribute to I_{BC}, proposing a mechanism for the formation and evolution of weather patterns such as cyclones and long waves in middle and high latitudes. Eady highlighted that certain disturbances grow exponentially faster than others, akin to a process of natural selection in the atmosphere, leading to the emergence of predominant weather patterns observed in middle latitudes, including cyclonic systems.

Following the seminal works of Charney (1947) and Eady (1949), Palmén e Newton (1969) synthesized the main findings from the subsequent extensive literature on I_{BC}. Firstly, it is noted that the amplification of atmospheric disturbances is wavelength-dependent, with disturbances below a critical length never amplifying. The optimal growth occurs in intermediate wavelengths (between 2500 and 5000 km), with an inverse relationship between this optimum and latitude—the closer to the Equator, the larger the critical size below which all waves are unstable. Additionally, there exists a proportional relationship between the intensification rate and vertical wind shear for wavelengths of maximum instability, and for longer waves, an increase in wavelength necessitates stronger shear to maintain equivalent growth rates.

In his analysis, Petterssen e Smebye (1971) categorizes extratropical cyclones into types based on the dynamic processes driving their development. Type A cyclones follow the Polar Front Theory model, with the initial disturbance arising at low levels within a maximal baroclinic zone (frontal), beneath a nearly zonal upper-level jet (Figure 2.8iA). As these cyclones develop, a cold trough forms at high levels (Figure 2.8iB), remaining inclined to the cyclone's axis until occlusion occurs and surface baroclinicity diminishes (Figure 2.8iC). Conversely, type B cyclones initiate from high-level forcing, as an upper-level trough moves over an area not necessarily featuring a frontal zone (Figure 2.8iiA). As these systems mature, the gap between the high-level trough and the surface system narrows, with an increase in surface baroclinicity relative to the initial stage (Figure 2.8iiB), culminating in the alignment of the high-level cyclonic vortex with the surface low, leading to system occlusion (Figure 2.8iiC).

Just as Hart (2003)'s classification presents a continuum, so too does Petterssen e Smebye (1971)'s delineation of cyclone types, with A and B not being distinct categories due to the existence of systems displaying hybrid characteristics. Petterssen e Smebye (1971) observed that purely type A cyclones are more common, whereas purely type B cyclones are rare, attributing this to the fact that some type of baroclinicity is often present in the mid-latitudes. However, Petterssen noted a tendency for type A cyclones to develop over oceans and type B cyclones over continents, though subsequent research, such as by McLennan (1988) and Deveson et al. (2002), has identified type B systems forming over oceanic regions as well. Furthermore, Deveson et al. (2002) introduced a new classification, type C cyclones, found in high latitudes with similarities to polar lows, characterized by an even stronger high-level forcing related to the movement of a broad trough over oceanic regions. This study also highlighted the potential for cyclones to transition between types throughout their lifecycle.

The central role of baroclinic instability (I_{BC}) in the development of extratropical cyclones is well-established, yet the significance of heat flows and diabatic heating cannot be overstated. Diabatic heating involves heat exchanges between a system and its surroundings through processes such as condensation, evaporation, or radiation. Convective activities leading to upward atmospheric movements cause diabatic expansion and thus

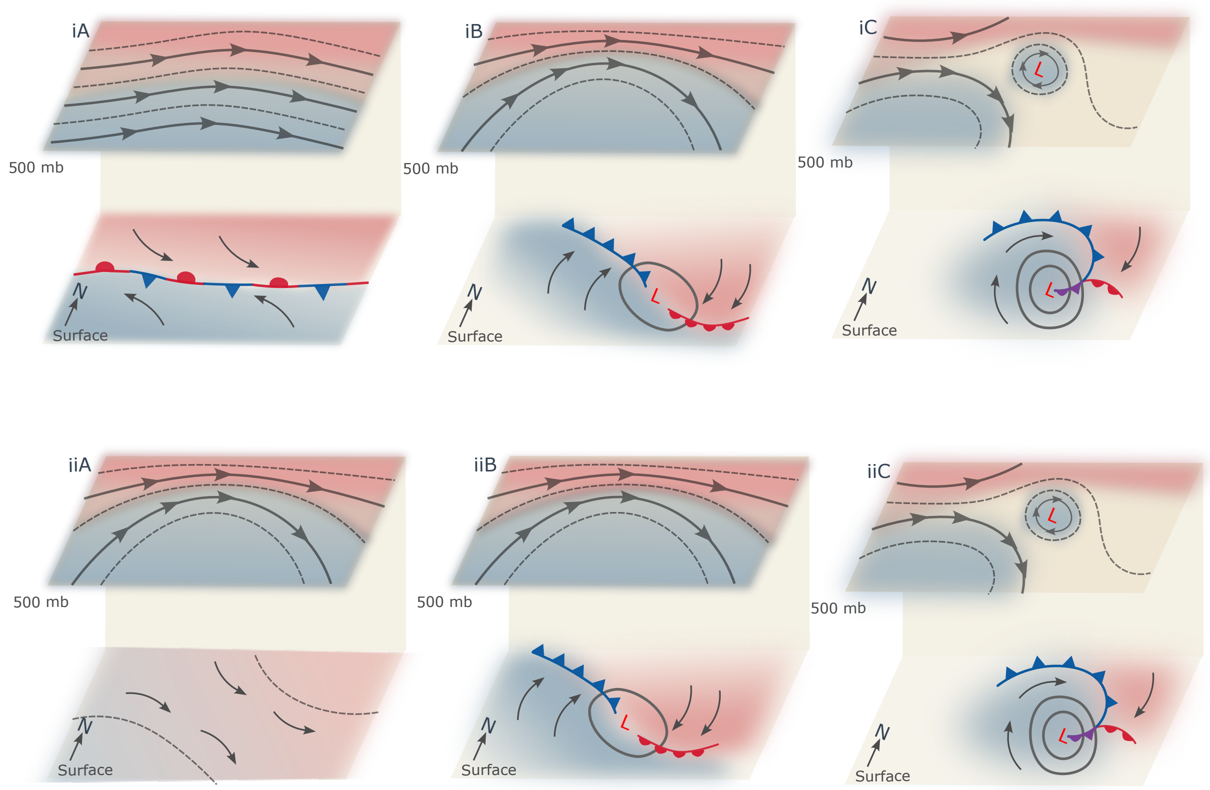

Figura 2.8: Illustration of the development model for cyclones types A (i) and B (ii), depicting the stages of formation (A), intensification (B), and maturity (C), as proposed by Petterssen e Smebye (1971). Inspired by Donald Ahrens e Henson (2015).

cooling in air parcels, leading to saturation and the release of latent heat. Such mechanisms provide an additional energy source for the development of extratropical cyclones, as documented in the literature (Chang et al., 2002, e.g.). Numerical models incorporating I_{BC} alongside heat flows have shown that instabilities generated under these conditions yield more intense cyclones with faster development rates (Gall, 1976; Whitaker e Davis, 1994; Gutowski et al., 1992), a phenomenon referred to as moist baroclinic instability.

A pivotal study by Hoskins e Valdes (1990) underscores the importance of diabatic fluxes in the development of extratropical cyclones, demonstrating that cyclonic development is preferentially located in regions of maximal baroclinicity over the oceans. However, the heat transport facilitated by these systems tends to mitigate the baroclinicity. The study suggests that diabatic heating, through the latent heat release from individual systems, contributes to sustaining regional baroclinicity. It also highlights the role of sensible heat exchanges between the cold air associated with these systems and the warm ocean currents along the eastern coastlines of continents.

Tropical cyclone formation, a topic of ongoing discussion among meteorologists, typically occurs over tropical or subtropical oceans, a region where the scarcity of in situ observations challenges the validation of theoretical models for formation and intensification. During World War II, data collected from the military base in Guam facilitated Riehl (1948) in proposing that the instability necessary for typhoon formation originates within the trade winds, contradicting the then-prevailing belief of inter-hemispheric air mass interactions being the primary cause. Subsequently, Yanai (1961)'s study on Typhoon Doris furthered the understanding of typhoon genesis, highlighting the significant role of latent heat released by convection. Yanai suggested a model for typhoon development, beginning with a disturbance in the trade winds and culminating in the formation of a typhoon characterized by a stabilized warm core.

Charney e Eliassen (1964) detailed the process of tropical cyclone intensification known as conditional instability of the second kind (CISK), which was the most accepted theory at the time (Figure 2.9i). According to CISK, the condensation of water vapor within convective areas releases latent heat, which can amplify pre-existing atmospheric vortices given an adequate moisture supply. This release of heat not only promotes further convection but also lowers sea-level pressure, thereby strengthening surface winds, enhancing moisture influx, and establishing a positive feedback loop. Charney underscored the ocean's surface role in providing the moisture necessary for sustaining convection, as well as the importance of surface friction in dissipating kinetic energy and fostering wind convergence within the moist surface boundary layer, thereby fueling the system with thermal energy from latent heat. This mechanism emphasizes the pivotal role of latent heat release at the cyclone's center as a disturbance amplification factor, leading to the intensification of the tropical depression.

However, it is important to note that the work of Charney e Eliassen (1964) consists of formulating a mathematical model and, therefore, does not offer a direct and didactic explanation of the processes involved. Thus, the interpretation of the proposed mechanisms is largely left as an exercise for the reader, which has resulted, over the years, in multiple interpretations, not all of them correct (Ooyama, 1982). Therefore, the explanation provided above seeks only to simplify the main processes proposed by Charney e Eliassen (1964).

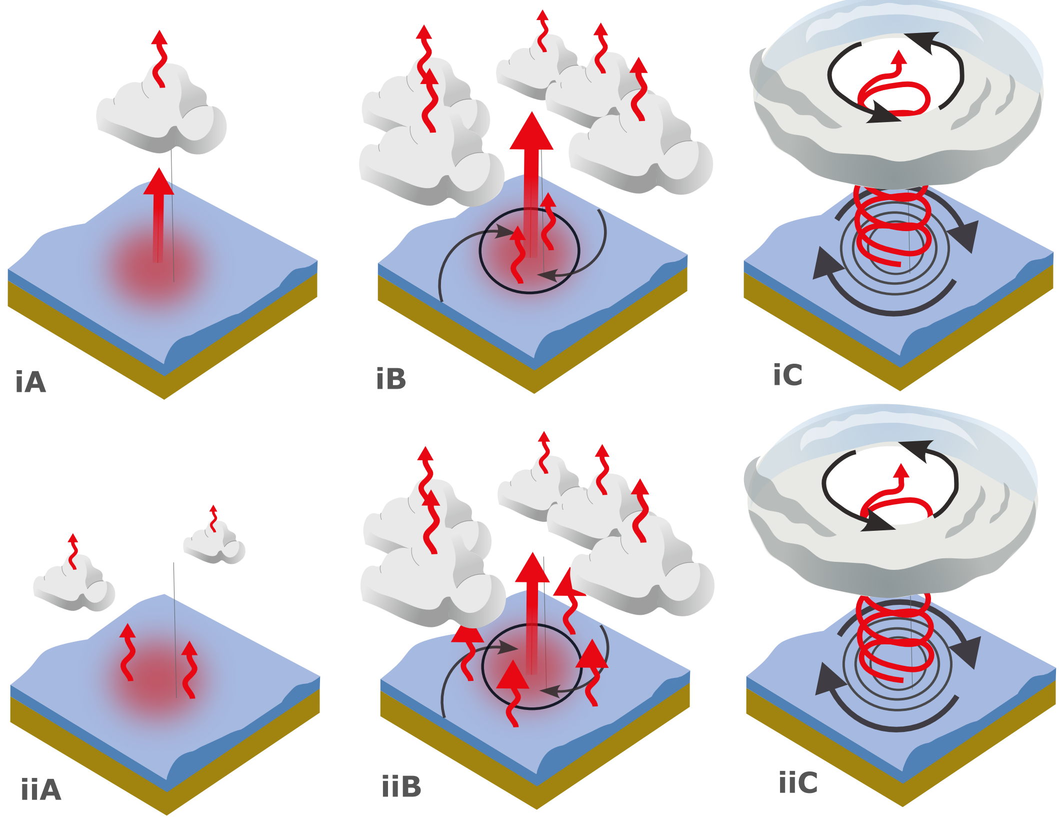

Figura 2.9: Comparative illustration of the CISK (i) and WISHE (ii) theories. A depicts the initial disturbance over warm ocean temperatures. Under CISK, the disturbance is initially fueled by latent heat from convection, whereas WISHE attributes the initial energy source to latent heat transfer from the ocean to the atmosphere. In the early development stage (B), both theories observe an increase in convection. CISK suggests this leads to reduced central pressure, drawing in more moisture and enhancing convection, which releases additional heat. WISHE proposes that surface wind interaction with the sea surface at low central pressure enhances heat release from surface water evaporation, further driving convection and subsequent latent heat release. By the tropical storm phase (C), the theories align on the feedback mechanisms fueling system intensification.

While Charney e Eliassen (1964)'s work introduces a mathematical model for understanding tropical cyclone intensification through the CISK process, it doesn't offer a straightforward, didactic explanation of the involved mechanisms. This has left room for various interpretations over the years, not all of which have been accurate, as noted by Ooyama (1982). The explanation provided here aims to to simplify the main processes proposed by Charney's for clarity.

Challenging the CISK theory, Emanuel (1986), later refined by Yano e Emanuel (1991), introduced the Wind-Induced Surface Heat Exchange (WISHE) theory, emphasizing ocean-atmosphere interaction as the primary intensification mechanism for tropical cyclones (Figure 2.9ii). WISHE posits that the development of these systems depends on the thermal contrast between the atmosphere and the sea surface, mediated by latent heat transfer from the ocean to the atmosphere. This transfer is significantly amplified by surface wind speeds, with intense winds elevating evaporation rates and thus, moisture transfer. An initial atmospheric disturbance that promotes wind convergence toward its center can enhance this moisture transfer and convection intensity, fostering a positive feedback cycle. WISHE theory emphasizes the necessity of ocean temperatures exceeding 26°C for sufficient boundary layer convergence, vital for maintaining the system. Similar to CISK, interpretations of WISHE vary, with not all encapsulating the theory's full scope or accuracy (Montgomery e Smith, 2014); thus, the provided explanation concentrates on fundamental aspects for comparative purposes with CISK.

Despite advancements in identifying the prerequisites for tropical cyclone development—such as requisite sea surface temperatures, minimal vertical wind shear, and specific atmospheric conditions—consensus on the precise dynamic processes driving both formation and intensification remains elusive. This ongoing debate in meteorology is exemplified by the contrasting theories of CISK and WISHE, each proposing different intensification mechanisms for tropical cyclones (Craig e Gray, 1996; Gray, 1998; Montgomery et al., 2015; Ooyama, 1982; Montgomery e Smith, 2014, e.g.,). Nonetheless, a common point between them is the acknowledgment that diabatic processes, fueled by ocean-atmosphere interactions and given an initial disturbance, are critical for providing energy and further intensifying the system. This section's goal is to delineate the development mechanisms of tropical versus extratropical cyclones, for which the simplified descriptions provided herein offer an adequate overview.

The role of diabatic heating in the intensification of tropical cyclones is underscored by the need for an initial atmospheric disturbance. Frank (1970) conducted an analysis of systems in the North Atlantic that give rise to disturbances capable of developing into tropical cyclones. He identified several sources of these disturbances, including those originating from the Intertropical Convergence Zone (ITCZ) and convection zones within the Caribbean Sea. However, the majority are associated with tropical waves primarily emanating from the African continent. Frank also highlighted the process whereby baroclinic systems transition into warm-core structures through the convection-driven release of latent heat, effectively diminishing the system's original baroclinicity. This phenomenon is now recognized as the tropical transition of extratropical cyclones, a process further explored and detailed in works such as those by Hart (2003).

The genesis of tropical cyclones in the North Atlantic is intricately linked to the formation and development of African easterly waves, with the thermal contrast between the Sahara Desert and cooler southern regions playing a pivotal role in creating the African Easterly Jet (AEJ)—a key factor in generating these waves (Holton, 1973). The foundation for understanding such phenomena was laid by Kuo (1949), who pinpointed barotropic instability in zonal atmospheric flows as a vital mechanism. This instability, marked by a change in the sign of absolute vorticity, involves horizontal wind shear and allows vortexes to extract kinetic energy from the zonal wind flow (Holton, 1973).

Burpee (1972) initially connected African easterly wave development with the instability of the AEJ, due to both horizontal and vertical shears, pointing to the complex interaction between barotropic and baroclinic instabilities in the region. Following this, Rennick (1976) applied a linear pseudo-spectral model based on primitive equations, deducing that barotropic instability acts as a primary catalyst for wave development, while downplaying the roles of vertical shear and latent heat release in the early stages. This assertion was supported by Reed et al. (1977) through observational data, demonstrating that medium and low-level easterly waves meet the criteria for barotropic instability.

An energetic analysis by Norquist et al. (1977) differentiated the destabilization processes over land and ocean, with baroclinic conversion dominating over the continent and barotropic instability gaining importance over oceanic regions—where tropical cyclones predominantly form. More recently, Wu et al. (2012) employed reanalysis data to establish a geographical link between the AEJ's barotropic instability and the origination points of North Atlantic tropical cyclones, affirming the significance of the AEJ's barotropic instability in relation to tropical cyclogenesis.

The exploration of barotropic instability's role in tropical cyclone genesis extends beyond the North Atlantic, encompassing various global regions where similar dynamics foster local tropical cyclogenesis. While initial studies illuminated the significance of barotropic instability in the genesis of African easterly waves and their impact on North Atlantic tropical cyclone formation, subsequent research has broadened our understanding to include other tropical areas. For instance, Zehr (1992) discovered that most tropical cyclogenesis events in the North Pacific are associated with a monsoon trough that encourages local convection.

In addition to easterly waves, different types of tropical disturbances can also disrupt the base state and instigate tropical cyclogenesis. Ferreira e Schubert (1997) used a shallow water model to show how barotropic instability related to the ITCZ's collapse can initiate a series of tropical disturbances, with some progressing to become tropical cyclones. Further, Bembenek et al. (2021) employed a global aquaplanet circulation model to illustrate the significant roles played by the ITCZ's latitudinal position and moisture effects in modulating barotropic instability and, consequently, tropical cyclone genesis, indicating the global influence of barotropic instability on tropical cyclogenesis through theoretical studies.

Observational evidence supports these theoretical insights. Maloney e Hartmann (2001) observed that the Madden-Julian Oscillation (MJO) phases conducive to westerly winds along the Pacific enhance barotropic conversions at low levels, thereby aiding tropical cyclone formation in both the Western and Eastern Pacific. Molinari et al. (1997) noted that temporal variations in the MJO can create conditions favorable for easterly wave growth, thereby affecting tropical cyclogenesis in the Eastern Pacific. Molinari et al. (2000) identified a link between the barotropic instability of the base state, associated with easterly wave occurrence, topographical effects, and the monsoon trough in fostering tropical cyclogenesis in the Eastern Pacific. Lastly, Cao et al. (2012) found that enhanced ITCZ convection during active phases of the Intraseasonal Oscillation generates a mean flow state conducive to barotropic instability, promoting tropical cyclogenesis in the Northwest Pacific.

While subtropical cyclones were identified in earlier works (Simpson, 1952), it wasn't until the study by Hart (2003) that they began receiving significant attention. The body of literature on these systems is still developing, with the processes behind subtropical cyclogenesis and development remaining an active area of research. Yanase et al. (2014) advanced the understanding of cyclone genesis by developing an Environmental Parameter Space, analyzing how cyclone genesis latitude correlates with factors like baroclinicity, relative humidity, vertical velocity, and potential intensity. This last metric predicts a tropical cyclone's maximum possible strength based on environmental conditions such as sea surface temperature and atmospheric temperature profiles. The study found a clear correlation: extratropical cyclones are closely linked to baroclinicity, while tropical cyclones are associated with potential intensity. Conversely, an inverse relationship was noted—extratropical cyclones inversely relate to potential intensity and tropical cyclones to baroclinicity. Subtropical cyclones emerged in a transitional space, influenced by both baroclinicity and potential intensity, which supports the notion of these systems as hybrids between tropical and extratropical cyclones (Hart, 2003, e.g). Additionally, da Rocha et al. (2019) suggested that subtropical cyclogenesis could be linked to various synoptic patterns, such as a shallow trough at mid-upper levels, a mid-upper level cutoff low, or a Rex blocking pattern. However, a comprehensive discussion delineating the principal environmental dynamics associated with subtropical cyclone development remains elusive, indicating a need for further investigation in this area.

The discussion provided thus far can be synthesized by comparing the efficient causes related to the development of both extratropical and tropical cyclones. Extratropical systems primarily develop through baroclinic instability, which may be initiated by disruptions in the surface meridional temperature gradient or by the influence of an upper-level trough, linking to baroclinic regions via the thermal wind relationship (Holton, 1973; Spiridonov e Ćurić, 2021). In contrast, tropical cyclone genesis is largely influenced by barotropic instability within the base state atmosphere, with subsequent disturbances intensifying through processes related to latent heat release, as explained by either CISK or WISHE theories.

This comparison illustrates that extratropical cyclone formation is closely tied to thermal variance driving baroclinic instability, whereas tropical cyclone genesis hinges on barotropic instability, succeeded by a reinforcing latent heat release feedback mechanism. Despite the absence of a unified diagram akin to Hart (2003)'s material and formal causes of cyclones, Silva Dias et al. (2004) proposed a conceptual model potentially bridging this gap (Figure 2.10). This model situates extratropical cyclones within the domain of baroclinic instability; tropical cyclones under barotropic instability; and subtropical cyclones where both instabilities might coexist or compete. The model also distinguishes systems by their reliance on diabatic processes, particularly latent heat release.

The viewpoint of Silva Dias et al. (2004) gains partial validation through Yanase et al. (2014)'s analysis, which linked different cyclone types to specific environmental parameters. Furthermore, Yanase et al. (2014) emphasized the critical role of relative humidity across all cyclone categories, supporting Silva Dias et al. (2004)'s emphasis on the essential role of latent heat release in cyclone dynamics. The current study will introduce a conceptual model, detailed in Chapter 5, aiming to synthesize the primary mechanisms driving cyclonic development and explore their broader implications.

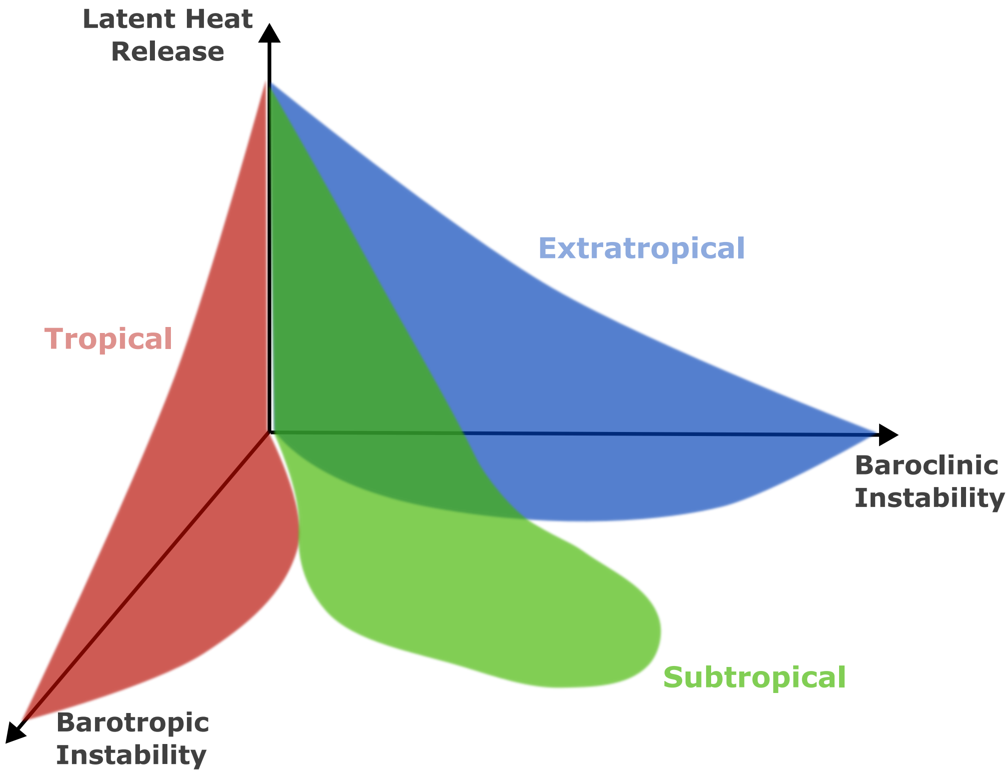

Figura 2.10: Proposed conceptual model correlating atmospheric destabilization mechanisms with cyclone types. Each axis within the three-dimensional schema represents a different process of atmospheric destabilization, allowing the categorization of cyclone types across the spectrum. Adapted from Silva Dias et al. (2004).

2.1.4 Final Causes

Final causes delve into the purpose or ultimate reason for the existence of something, offering insights into the "why" behind its occurrence. For instance, the final cause of a table is to serve as a platform for activities such as writing, eating, or working. When considering cyclones, their final cause could be viewed as the facilitation of heat and moisture redistribution within the atmosphere, thus playing a crucial role in maintaining global climatic equilibrium and acting as a mechanism for dissipating excess heat.

The Earth's climate system is fundamentally driven by solar radiation, while simultaneously losing heat through infrared radiation emitted into space. The unequal distribution of solar radiation, exacerbated by the tilt of the Earth's axis, results in energy surpluses in equatorial regions and deficits in polar areas. This differential heating prompts the formation of warm air masses near the equator and cold air masses in polar regions, instigating atmospheric circulation as an effort to achieve thermal equilibrium, a state that remains elusive due to ongoing differential heating between tropical and polar zones.

Historical and recent advancements in atmospheric science have underscored the significance of general atmospheric circulation in climate dynamics (Lorenz, 1967; Hadley, 1735; Stull, 2015; Schneider, 2006). The Hadley Cell emerges as a critical response to the disparity in solar radiation received at the equator compared to the poles. Warmed air rises near the equator, creating low-pressure zones at the surface and high pressure aloft. This ascending air, replaced by cooler air from higher latitudes, moves poleward at elevated altitudes due to mass conservation. The conservation of angular momentum is crucial as this air, moving away from the equator (where surface rotational speed is maximum), must increase its eastward velocity as it approaches the poles. This dynamic leads to the formation of subtropical jet streams around 30° latitude. The Polar Cell, integral to high-latitude atmospheric circulation, is driven by the thermal contrast between the poles and regions at 60° latitude. This temperature difference induces opposing north-south pressure gradients, generating equatorward winds that, due to the Coriolis force, become polar easterlies. At higher levels, winds flow poleward but are deflected eastward, forming an upper-level westerly flow around the polar low, thus completing the Polar Cell circulation.

Together, the Hadley and Polar Cells underscore a comprehensive circulation pattern that transports warm air and angular momentum from the equator towards the poles and vice versa, facilitating Earth's energy balance. Although initially conceptualized as symmetrical circulations extending from the equator to the poles, subsequent research has emphasized the pivotal role of large-scale eddies in heat and angular momentum transfer (Schneider, 2006). These eddies, critical to atmospheric dynamics, emerge due to baroclinic zones in mid-latitudes and are intrinsic to the structure and function of the Ferrel Cell in mid-latitudes(Held, 1999; Schneider, 2006). Arising from mid-latitude baroclinic zones, they are indispensable to the Ferrel Cell's operation, influencing wind patterns across latitudes and enhancing heat transfer between the tropics and poles (Stull, 2015; Held, 1999).

Due to their relatively small scale compared to extratropical cyclones, tropical cyclones are not directly associated with the three-cell model of global circulation. They arise in regions of low baroclinicity, where thermal contrasts are minimal, relying instead on the atmosphere's ability to generate energy from internal heat sources. These sources are largely the warm temperatures of tropical oceans and the air above them (Palmén e Newton, 1969). Often conceptualized as a Carnot heat engine, tropical cyclones draw heat from the ocean surface—primarily through the latent heat of vaporization—and release it into space via longwave radiation (Emanuel, 1987; Ozawa e Shimokawa, 2015; Wang et al., 2022, e.g.,). The cyclone's intensity depends on the efficiency of this heat engine, which is determined by the temperature difference between the heat source (ocean) and sink (upper atmosphere). Friction, especially near the ocean surface within the boundary layer, plays a crucial role by causing energy loss that can lessen wind speeds and alter angular momentum, impacting the cyclone's energy conversion efficiency.

We can see then that tropical cyclones serve to dissipate excess heat in the tropics, utilizing oceanic heat to fuel the system while dissipating energy through radiation at the upper levels or friction at the surface. Given this model's applicability, Emanuel (1987) predicted that rising atmospheric CO_2 levels would lead to more intense tropical cyclones in the future. Recent climate models suggest an increase in tropical cyclone intensity, though there's no global consensus on frequency changes (Knutson et al., 2010; Walsh, 2004; Walsh et al., 2016, 2019). As discussed in Section **??**, understanding tropical cyclone development remains a significant scientific endeavor, complicating precise predictions of their response to climate change and their regulatory effect on climate.

In exploring subtropical cyclones, much remains to be discovered. The global distribution of cyclonic activity exhibits a bimodal pattern, with tropical cyclones forming in tropical regions and extratropical cyclones in mid-latitudes, leaving subtropical areas relatively calm in terms of cyclonic development (Yanase et al., 2014). It's speculative—emphasis on "speculate"—to suggest that subtropical systems share the final causes of their tropical and extratropical counterparts, acting to erase thermal gradients by redistributing heat globally or dissipating excess heat. However, subtropical cyclones might perform these functions under hybrid environmental conditions, possibly moderating gradients in regions with an abundance of heat. Ongoing research into subtropical cyclones promises to provide further clarity on their impact on global circulation patterns and their role within the broader climatic system.

2.1.5 Summary

This section has explored the Aristotelian causes as they pertain to cyclones, comparing the various types—extratropical, tropical, and subtropical—while also acknowledging the existence of other cyclonic phenomena like warm seclusions and polar lows. For succinctness, the discussion primarily centered on the main types, suggesting that cyclonic systems form a continuum: extratropical systems at one end, tropical cyclones at the other, and subtropical systems exhibiting hybrid characteristics.

Initially, we discussed that cyclones' material causes are linked to the air masses constituting them. Extratropical cyclones are associated with cold cores throughout the troposphere, whereas tropical cyclones are characterized by warm cores. Subtropical cyclones, however, display warm cores at the surface and cold cores at higher tropospheric levels.

Regarding formal causes, the cyclones differ in structure. Extratropical cyclones, identified by their frontal features, show asymmetry. Tropical cyclones, described as symmetric, feature convection bands spiraling the central eye. Subtropical cyclones, meanwhile, may present a range of spatial configurations, neither fully asymmetric nor symmetric.

Efficient causes, the dynamic mechanisms behind cyclone development, vary. Extratropical cyclones are primarily driven by baroclinic instability, a comprehensive mechanism underlying their formation. Tropical cyclone genesis and intensification lack a unified theoretical model, with current theories suggesting that barotropic instability in tropical waves—coupled with diabatic processes like latent heat release—might describe their development. Subtropical systems, given the incipient state of research, are speculatively linked by the author to both baroclinic and barotropic instabilities, with diabatic heat playing a role.

The final causes reflect cyclones' contributions to global circulation. Extratropical cyclones are recognized for redistributing heat, mitigating temperature gradients in mid-latitudes. Tropical cyclones, functioning as thermal engines, dissipate excess heat in tropical regions. The role of subtropical cyclones in the climate system remains speculative; they are hypothesized to simultaneously embody the functions of the other two types.

One important feature noted is that most classifications adopted for cyclone classification are based on Hart (2003) diagrams that objectively distinguishes these systems based on their material and formal causes. Although much knowledge exists regarding the efficient and final causes of tropical and especially extratropical systems, such objective criterion for these causes is still lacking. The current research proposes such objective classification procedure in the hopes of aiding the investigation of such causes related to cyclonic systems.

A notable point is the reliance on Hart (2003)'s diagrams for cyclone classification, objectively differentiating systems by their material and formal causes. While extensive knowledge exists on the efficient and final causes of tropical and particularly extratropical systems, a clear criterion for these causes is absent. This work proposes an objective classification procedure to aid in investigating cyclonic systems' related causes.

2.2 *Life cycle of extratropical cyclones*

- Here, I will use the references I have from the paper about life cycle and present a briev overview of the life cycle of the cyclones and examples of studies that attempted to objectively classify distinct life stages.

2.3 *Cyclones climatologies in South America*

- Papers from Gan, Hoskins, Reboita and Gramcianinov. Show that the three regions are well described in the literature, contrast the differences in position due to distinct tracking algorithms and brifely mention the genesis mechanisms.

2.4 *Atmosphere Energetics*

A radiação solar é a fonte primária de energia no sistema terrestre. Ao mesmo tempo, ao redor de todo o globo, a atmosfera perde calor por emissão de radiação infravermelha para o espaço. Devido à inclinação do eixo de Terra, há uma diferença na incidência radiativa entra as regiões tropicais e polares: nas regiões equatoriais, a superfície terrestre recebe mais energia solar do que perde para o espaço, resultando em um excedente de energia, enquanto que, nas regiões polares, ocorre o contrário; a superfície perde mais energia para o espaço do que recebe, levando a um deficit de energia. Isso faz com que haja um aquecimento diferencial e, levando em conta a transmissão de calor da superfície para a atmosfera, há a formação de massas de ar quentes nas regiões tropicais e massas de ar frias na região equatorial. Esse desbalanço de calor é responsável pela manutenção da circulação atmosférica, que surge como um mecanismo para obtenção do equilíbrio, que nunca é atingido devido ao contínuo aquecimento diferencial entre as regiões tropicais e polares Stull (2015).

2.4.1 Ciclo Energético de Lorenz: Perspectiva Histórica

O Ciclo Energético de Lorenz (Lorenz, 1955) é um conceito fundamental para entender a distribuição e transformação de energia na atmosfera, fornecendo uma perspectiva da circulação geral onde esta é responsável por modular a estrutura dinâmica e termodinâmica da atmosfera e os fluxos e transportes atmosféricos de calor, umidade e momento angular. Em seu trabalho, Lorenz propôs um método para estudar a energética da atmosfera baseado nas duas principais formas que a energia pode assumir no sistema terrestre: energia cinética (*Kinectic Enrgy* - K) e energia potencial disponível (*Available Potential Energy* - APE), sendo estas particionadas em suas formas zonais e turbulentas. Nos próximos parágrafos serão abordados os coenitos por trás dessas formas de energia e como estas relacionam-se entre si.

Lorenz (1955) discute que a energia potencial total (*Total Potential Energy* - P) não é uma medida adequada da quantidade de energia que estaria disponível para a conversão em K na atmosfera e, então, alimentar a circulação global. Ele propõe o seguinte experimento mental para exemplificar essa questão: Digamos que a atmosfera esteja horizontalmente estratificada globalmente; neste caso, apesar de haver P, por conta da ausência de gradientes horizontais não há movimento das massas de ar e, consequentemente, não há K (Figura 2.11a). Caso haja aquecimento de alguma área na atmosfera, ocorrem movimentos verticais ascendentes, criando gradientes de pressão e, consequentemente, a estratificação horizontal se desfaz (Figura 2.11b). Entretanto, caso haja algum resfriamento em alguma região, ocorre o mesmo processo descrito anteriormente, porém, neste caso, os movimentos verticais são descendentes (Figura 2.11c). Em ambos os casos, há alteração em P do sistema, que é convertido em K. Porém, no primeiro caso P aumenta, enquanto que no segundo, diminui, ou seja, tanto adição quanto remoção de P são responsáveis por fazer com que energia fique disponível para a circulação atmosférica.

O conceito de APE foi inicialmente proposto por Margules (1903), que estava interessado nos processos que geram K em tempestades (Marquet, 2017). Para entendermos

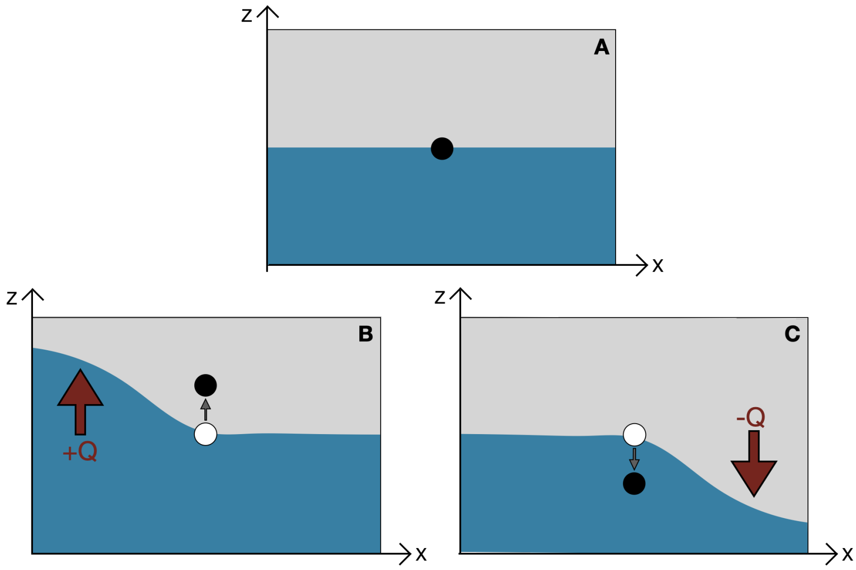

Figura 2.11: Experimento mental proposto por Lorenz (1955) para demonstrar a relação entre P total e K, onde temos a representação de uma atmosfera com duas camadas. A) atmosfera horizontalmente estratificada. B) Pertubação na estratificação horizontal causada por aquecimento (+Q) em uma determinada região, causando movimentos verticais ascendentes. C) Mesmo que B), mas causada por esfriamento (-Q) e causando movimentos verticais descendentes. Os círculos pretos representam o centro de massa da atmosfera, enquanto que os círculos brancos representam o centro de massa anterior à pertubação.

esse conceito, podemos partir da mesma situação proposta por Lorenz (1955), onde há um aquecimento diferencial, resultando em movimentos ascendentes e uma distribuição heterogênea de massa na atmosfera (Figura 2.12a). Nesse caso, os gradientes de pressão resultantes dessa distribuição fazem com que haja aceleração do campo de vento (Figura 2.12b), redistribuindo a massa na atmosfera. Assumindo que esse fluxo seja adiabático, o resultado final é uma atmosfera horizontalmente estratificada (Figura 2.12c). No primeiro passo, ambas formas de energia potencial (total e disponível) são máximas. Com a redistribuição de massa, ocorre aumento da K, enquanto que as energias potencial total e disponível sofrem diminuições. No estágio final, P é mínimo, porém não nula, enquanto que a APE é nula. Desse modo, APE pode ser definida como a quantidade de energia potencial disponível para a conversão em K sob uma distribuição adiabática de massa.

Deste modo, Lorenz (1955) postula que a APE é a fonte fundamental de K na atmosfera, e, consequentemente, a circulação geral da atmosfera pode ser em grande parte explicada pelos processos que envolvem a geração, dissipação e conversão destas formas de energia. O termo 'em grande parte' é utilizado pois processos não-adiabáticos e a fricção também

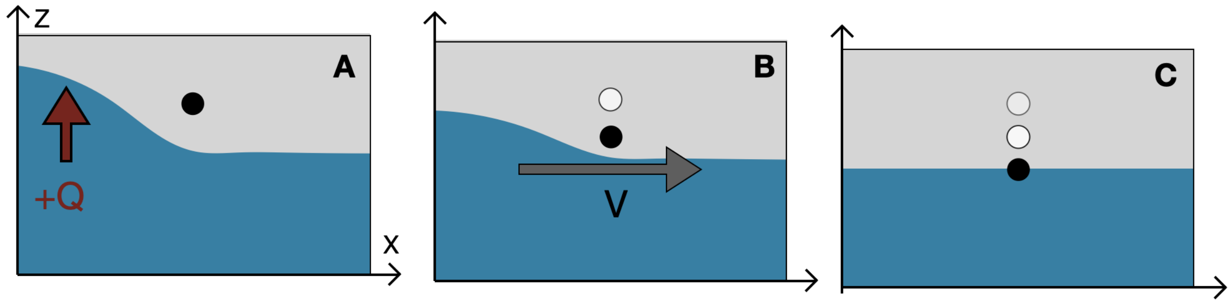

Figura 2.12: Esquema representando o conceito de energia potencial disponível (APE). A) Estado da atmosfera, onde aquecimento diferencial causa uma distribuição heterogênea de massa na atmosfera. B) Redistribuição e homogenização da massa pelo campo de vento. C) Estado final, onde há estratificação horizontal da atmosfera. Os círculos pretos representam o centro de massa da atmosfera no momento indicado, enquanto que os círculos brancos brancos representam o centro de massa em instante de tempo anteriores.

influenciam a circulação atmosférica. Entretanto, tais processos não são detalhadamente abordados em seu trabalho, devido à complexidade envolvida e à dificuldade de estimar e mensurar esses fenômenos. Assim, em seu estudo, Lorenz (1955) utiliza um modelo idealizado da atmosfera para desenvolver a formulação matemática que descreve os processos pelos quais a APE é transformada em K e, consequentemente, impulsiona a circulação atmosférica. É importante notar que nesta formulação a atmosfera é tratada como um sistema fechado, e que, tanto a APE quanto a K são particionadas em suas componentes zonais e *eddies* (turbulentas). Isso é feito por diversas razões. Na década anterior, Starr (1953) já havia demonstrado a importância dos turbilhões para a manutenção da circulação atmosférica, em especial, na transferência de K destes para o fluxo zonal, ao contrário do que se acreditava anteriormente. Starr (1953) ainda comenta que qualquer teoria geral da circulação atmosférica que desconsidere a ação dos turbilhões seria deficiente e desconexa da realidade. Além disso, a Lorenz (1955) faz essa separação para possibilitar o entendimento dos processos relacionados à formação e manutenção de sistemas meteorológicos (por exemplo, sistemas ciclônicos) e como estes influenciam a circulação atmosférica. Posteriormente, Wiin-Nielsen et al. (1963), demonstrou a importância dos turbilhões para o transporte de calor e momento globais, mostrando as contribuições diferentes de cada número de onda para os balanços globais.

Dessa forma, o ciclo energético pode ser representado pelas seguintes equações, representando o balanço energético para cada componente do ciclo:

$$\frac{\partial A_Z}{\partial t} = -C_Z - C_A + G_Z \tag{2.6}$$
$$\frac{\partial A_E}{\partial t} = -C_E + C_A + G_E \tag{2.7}$$
$$\frac{\partial K_Z}{\partial t} = C_Z - C_K - D_Z \tag{2.8}$$
$$\frac{\partial K_E}{\partial t} = C_E + C_K - D_E \tag{2.9}$$

Neste conjunto de equações, APE está particionada em sua forma zonal (A_Z) e turbulenta (A_E), tal como K (K_Z e K_E, respectivamente) e ambos estão representados pelas tendências temporais ao invés dos termos explcítos de energia, de modo a fechar um balanço completo. Os processos de conversão entre as quatro formas de energia são indicados pela letra C, com os sobrescritos Z e E indicando a conversão entre as formas zonais e turbulentas de energia, enquanto que A e K indicam conversões entre as componentes zonais e turbulentas de APE e K. Ou seja, a conversão entre A_Z e A_E é dada por C_A, a conversão entre A_E e K_E é dada por C_E, a conversão entre K_E e K_Z é dada por C_K e, por fim, a conversão entre A_Z e K_Z é dada por C_Z. Similarmente, os termos de geração de APE e dissipração de K, que são indicados pela letra G e D. Desse modo, G_Z e G_E indicam geração de A_Z e A_E, respectivamente, enquanto que D_Z e D_E indicam a dissipação de D_Z e D_E, respectivamente. As formulações matemáticas completas para cada expressão são apresentadas e discutidas na seção 2.4.2.

Após o trabalho de Lorenz (1955), diversos trabalhos surgiram com a finalidade de realizar estimativas do ciclo energético global - ou pelo menos, do hemisfério norte, dada as limitações observacionais da época (Starr, 1959; Saltzman e Fleisher, 1961; Holopainen, 1964; Jensen, 1961; Brown Jr, 1964; Wiin-Nielsen, 1959, e.g.). Oort (1964) compilou resultados das estimativas disponíveis, com o objetivo de estabelecer uma representação do ciclo energético anual do Hemisfério Norte. Ele também dividiu a análise energética em 'domínios' distintos. O primeiro é o domínio espacial, onde as variáveis são analisadas a partir de médias espaciais, relacionadas com a manutenção e comportamento de estados zonais médios e perturbações zonais. Esse domínio permite o entendimento de padrões zonais de larga escala, como jatos e ventos de oeste. O segundo é o domínio temporal, onde são realizadas médias e desvios temporais, relacionados com a manutenção de estados temporais médios e perturbações passageiras, permitindo o entendimento de tendências de longo prazo e fenômenos de baixa frequência. Por último, o domínio misto espaço-tempo permite uma análise integrada dos fenômenos atmosféricos, fornecendo uma perspectiva sobre como os estados médios espaço-temporais e a soma das perturbações, tanto passageiras quanto estacionárias, são mantidos. Entretanto, o autor ressalta que, em sua época, a maioria dos estudos se concentrava em estimativas energéticas para o domínio espacial, com poucos estudos abordando o domínio misto, enquanto havia uma carência de estudos considerando o domínio temporal.

A partir dessas estimativas, Oort (1964) estabelece um diagrama que fornece uma representação visual do ciclo energético encontrado (Figura 2.13). O diagrama demonstra visualmente como as diferentes formas de energia são geradas, convertidas e dissipadas, sintetizando os processos dinâmicos em formato gráfico e didático. Além disso, tal representação permite uma fácil comparação comparação de diferentes resultados. É importante ressaltar que, como mencionado pelo autor, os termos de fricção não podem ser diretamente computados e portanto são obtidos como resíduos, através do balanço para os termos zonais e turbulentos de K.

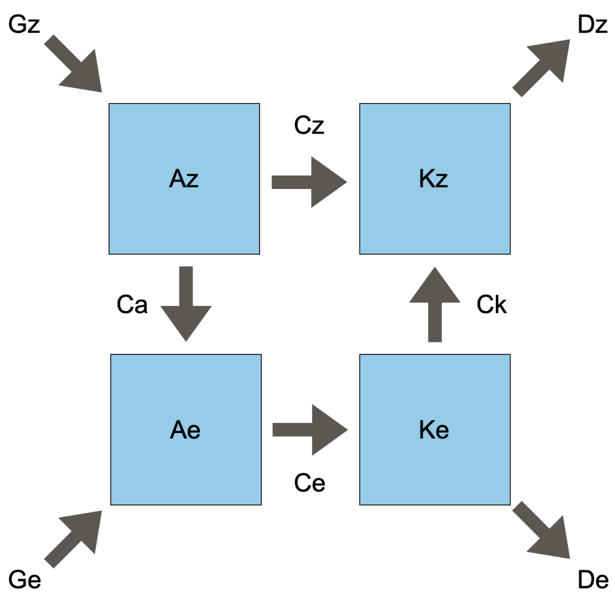

Figura 2.13: Ciclo Energético tal como formulado por Lorenz (1955) e esquematizado por Oort (1964). Nele, temos as quatro formas distintas de energia, representadas pelos termos zonais e turbulentos de K e APE, tal como as conversões dentre as respectivas fromas de energia, e seus termos de geração e dissipação.

Como mencionado anteriormente, a formulação proposta por Lorenz (1955) estima a energética da atmosfera assumindo um sistema fechado, isto é, sem trocas de energia nas fronteiras. O primeiro estudo a considerar a energética para um sistema aberto foi feito por Reed et al. (1963), onde um evento de aquecimento estratosférico repentino no Hemisfério Norte foi analisado. Neste estudo, a estratosfera foi considerada como um sistema aberto, permitindo trocas de energia com outras camadas atmosféricas, como a troposfera. A partir deste estudo, Muench (1965), interessado na dinâmica estratosférica, progrediu na teoria formulada por Lorenz (1955) e propôs uma nova representação do ciclo energético.

A Figura 2.14 contém a representação do ciclo energético, tal como apresentado por Muench (1965). A principal diferença desta figura para a Figura 2.13 está no fato do autor apresentar os termos que representam o fluxo de energia através das fronteiras, representados pela letra B. Desse modo, as equações para o balanço energético podem ser atualizadas para:

$$\frac{\partial A_Z}{\partial t} = BA_Z - C_Z - C_A + G_Z \tag{2.10}$$
$$\frac{\partial A_E}{\partial t} = BA_E - C_E + C_A + G_E \tag{2.11}$$
$$\frac{\partial K_Z}{\partial t} = BK_Z + C_Z - C_K + B\Phi_Z - D_Z \tag{2.12}$$
$$\frac{\partial K_E}{\partial t} = BK_E + C_E + C_K + B\Phi_E - D_E \tag{2.13}$$

Onde BA_Z, BA_E, BK_Z e BK_E representam, respectivamente, os fluxos de APE e K zonal e turbulento, através das fronteiras. Os termos $B\Phi_Z$ e $B\Phi_E$ aparecem representados em conjunto com os termos C_Z e C_E, respectivamente, pois ambos surgem do mesmo processo de derivação dos balanços de K_Z e K_E. Muench (1965) reconhece a dificuldade na interpretação dos termos $B\Phi_Z$ e $B\Phi_E$, indicando que estes estão relacionados ao fluxo de energia cinética em direção a altitudes menores, representando o aparecimento de energia cinética nas fronteiras do domínio computacional.

Apesar de considerar os fluxos de energia através das fronteiras, o domínio adotado por Muench (1965) era apenas parcialmente aberto, visto que se estendia até a região polar e longitudinalmente englobava todo o hemisfério norte. Deste modo, a única fronteira estava na porção sul do domínio, em 30°N. Uma derivação do ciclo energético para regiões limitadas foi apenas apresentada em Smith (1969). Porém, neste trabalho, o autor deixa claro que seu objetivo é apresentar uma formulação que permitisse avaliar contribuição de uma região limitada para a energética global, sendo que uma forma exata de computar a

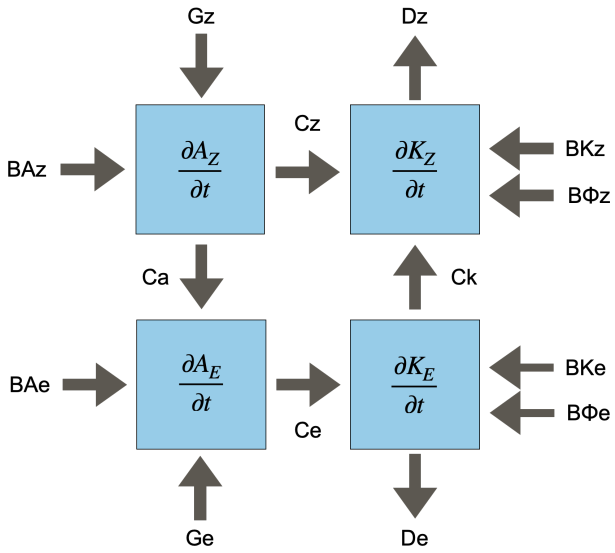

Figura 2.14: Ciclo Energético tal como formulado por Lorenz (1955), após os avanços de Muench (1965). Além das formas de energia contidas na 2.13, temos as derivadas locais das partições zonais e turbulentas de APE e K, além dos termos relacionados a fluxos de energia nas fronteiras.

energética local estaria além do escopo de seu trabalho. Além disso, o autor não particiona as formas de APE e K em suas componentes zonais e turbulentas.

Paralelamente ao trabalho apresentado por Smith (1969), Johnson (1970), a partir da formulação proposta por Dutton e Johnson (1967), apresenta uma derivação para o ciclo energético de áreas limitadas a partir de um referencial semi-Lagrangiano. Ou seja, a área delimitada para que sejam realizados os cálculos da energética não é fixa, seguindo o sistema meteorológico de interesse através de N áreas fixas que se deslocam no espaço. Essa análise demonstra que a APE global é o resultado do somatório de todas as regiões abertas possíveis na atmosfera, mais uma componente representando o contraste termodinâmico de tais regiões. Além disso, é importante ressaltar que Smith (1969); Dutton e Johnson (1967) discutem que ao analisar a APE de uma região limitada, esta deve ser interpretada como a contribuição da região para a energética global e não como a APE contida dentro da região em si. Isso se deve ao fato da dificuldade que há em definir a APE para um região em específico ou tempestade individual em isolamento da APE global: dado que a atmosfera está interconectada, a energética global afeta as regiões/sistemas individuais (i.e., estes não estão isolados) e vice-versa.

O trabalho de Dutton e Johnson (1967) oferece uma crítica à uma formulação de Lorenz (1955), demonstrando que, em uma escala global, sua formulação subestima APE, principalmente no inverno. Entretanto, o conjunto de equações proposto por Johnson (1970) é desenvolvido para um sistema de coordenadas isentrópicas e, como notado por Vincent e Chang (1973), esse fator acaba acarretando em uma série de simplificações indesejadas (como assumir que a contribuição de aquecimento diabático é negligenciável), de modo a inviabilizar o uso desta formulação como diagnóstico para o balanço de energia.

Vincent e Chang (1973), então, a partir das contribuições apresentadas por Smith (1969), desenvolve um sistema de equações, em coordenadas isobáricas, para os balanços de APE e K, para um sistema aberto na atmosfera a partir de um referencial semi-Lagrangiano. Neste trabalho, a APE é particionada na APE do estado de referência para esta determinada região e duas componentes representando as contribuições barotrópicas e baroclínicas para a APE da região delimitada. Não obstante, no balanço de APE, surge um termo relacionado com o movimento das fronteiras no referencial semi-Lagrangiano e a respectiva advecção de massas de ar com diferentes propriedades através das fronteiras.

A formulação apresentada por Vincent e Chang (1973) foi utilizada por Edmon e Vincent (1979) para analisar o ciclo energético do Furacão Carmen (1974). Porém, somente em Brennan e Vincent (1980), também interessados na energética do Furacão Carmen, que a análise do ciclo de energia proposta por Vincent e Chang (1973) foi apresentada utilizando uma formulação particionada em componentes zonais e turbulentas. O trabalho de Brennan e Vincent (1980) é, então, o primeiro oferecer um conjunto de equações regais, aplicáveis a uma área limitada na troposfera, onde APE e K são particionadas em suas componentes zonais e turbulentas. Entretanto, Brennan e Vincent (1980) optam pelo uso da tradicional abordagem euleriana para a análise energética.

Não obstante, Brennan e Vincent (1980) oferecem uma nova interpretação para os termos $B\Phi_Z$ e $B\Phi_E$. Menciona-se que estes são resultado do trabalho exercido pelas componentes zonais e meridionais do vento contra a pressão atmosférica, nas fronteiras do domínio computacional. Assim como em Oort (1964), os termos de fricção não são calculados diretamente, mas sim estimados à partir do balanço energético. Além disso, Brennan e Vincent (1980) mencionam que os resultados obtidos para $B\Phi_Z$ e $B\Phi_E$ são excepcionalmente grandes e irreais. Isso é devido ao fato de que pequenos erros no campo de altura geopotencial podem resultar em grandes erros nestes termos. Sendo assim esses termos foram combinados junto com os termos de dissipação (D_Z e D_E) e calculados como resíduos do balanço de K_Z e K_E, formando assim os termos RK_Z e RK_E. O ciclo energético revisado a partir deste avanço pode ser encontrado na Figura 2.15.

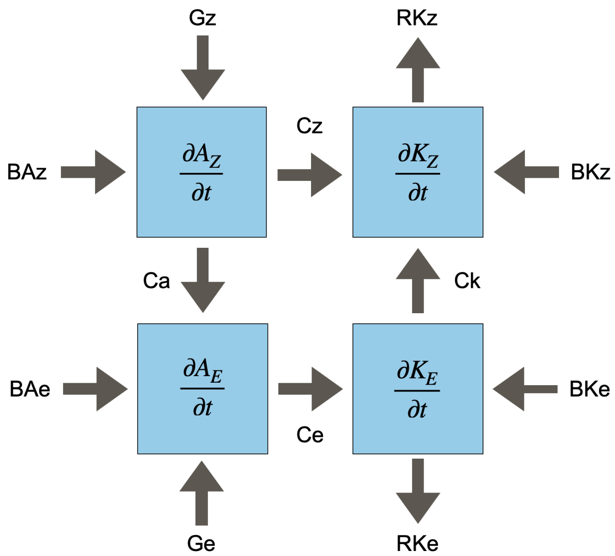

Figura 2.15: Ciclo Energético tal como formulado por Lorenz (1955), após os avanços de Brennan e Vincent (1980). Neste, os termos de fronteira $B\Phi_Z$ e $B\Phi_E$ são unidos com os termos de dissipação D_Z e D_E, de modo a compor os termos residuais K_Z e K_E.

A nova formulação apresentada, então, é a seguinte:

$$\frac{\partial A_Z}{\partial t} = -C_A - C_Z + G_Z + BA_Z \tag{2.14}$$

$$\frac{\partial A_E}{\partial t} = C_A - C_E + G_E + BA_E \tag{2.15}$$

$$\frac{\partial K_Z}{\partial t} = C_K + C_Z + BK_Z + RK_Z \tag{2.16}$$

$$\frac{\partial K_E}{\partial t} = -C_K + C_E + BK_E + RK_E \tag{2.17}$$

de modo que:

$$RK_Z = B\Phi_Z + D_Z \tag{2.18}$$

$$RK_E = B\Phi_E + D_E \tag{2.19}$$

Robertson e Smith (1983) utiliza a formulação apresentada por Brennan e Vincent (1980) para domínios de área limitada, desenvolvendo uma nova formulação apenas para o termo A_E. Para isso, o autor parte da formulação de APE para um domínio limitado apresentada por Smith et al. (1977), combinando-a com a primeira lei da termodinâmica para as derivativas eulerianas das formulações de APE e A_Z. Dese modo, a formulação final do balanço de A_E acaba por ser substancialmente diferente dos trabalhos apresentados, com o surgimento de um novo termo associado a mudanças no campo de pressão referencial e resultando em diferenças na formulação do termo C_A. Tal linha de raciocínio se deve ao fato dos autores estarem interessados em avaliar, através do uso de modelagem numérica, o impacto de processos úmidos no desenvolvimento - e, consequentemente, na energética - de ciclones extratropicais. Entretanto, tal desenvolvimento faz o que certos termos do balanço energético acabem sendo dependentes de integrais em coordenadas isentrópicas, resultando em dificuldades computacionais.

Interessado no estudo da energética de um evento de ciclogênese no Golfo de Genoa, no Mar Mediterrâneo, Michaelides (1987) propõe mais um avanço na formulação do ciclo energético. Neste trabalho, o autor, tal como Brennan e Vincent (1980), mencionam a questão de os termos $B\Phi_Z$ e $B\Phi_E$ apresentarem resultados irreais. Sendo assim, os autores optam por considerar além dos termos de resíduo RK_Z e RK_E (conjunto de equações 2.14 e 2.18), um termo (ϵ) representando erros numéricos resultantes das estimativas dos termos em 2.18. O mesmo é feito para os termos de geração G_Z e G_E. A representação esquemática proposta encontra-se na Figura 2.16. Desse modo, o autor utiliza o conjunto de equações dado por:

$$\frac{\partial A_Z}{\partial t} = C_K - C_A + BA_Z + \Delta G_Z \tag{2.20}$$

$$\frac{\partial A_E}{\partial t} = C_A - C_E + BA_E + \Delta G_E \tag{2.21}$$

$$\frac{\partial K_Z}{\partial t} = C_K - C_Z + BK_Z - \Delta R_Z \tag{2.22}$$

$$\frac{\partial K_E}{\partial t} = C_E - C_K + BK_E - \Delta R_E \tag{2.23}$$

Onde:

$$\Delta R_Z = B\Phi_Z - D_Z + \epsilon_{KZ} \tag{2.24}$$

$$\Delta R_E = B\Phi_E - D_E + \epsilon_{KE} \tag{2.25}$$

$$\Delta G_Z = G_Z + \epsilon_{GZ} \tag{2.26}$$

$$\Delta G_E = G_E + \epsilon_{GE} \tag{2.27}$$

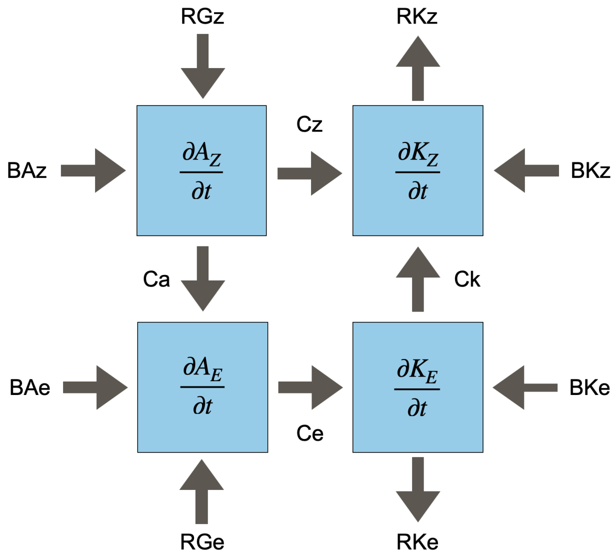

Figura 2.16: Ciclo Energético tal como formulado por Lorenz (1955), após os avanços de Michaelides (1987). Neste, erros numéricos resultantes das estimativas dos balanços são incluídos dentro dos termos de resíduo.

Em Michaelides et al. (1999) o autor apresenta um avanço na teoria proposta em Michaelides (1987), onde a formulação para o cálculo da energética é explorada para áreas limitadas usando tanto um referencial euleriano, quanto um semi-Lagrangiano. Neste caso, é avaliado o ciclo energético no desenvolvimento de um caso de ciclogênese no mediterrâneo a partir dos dois referenciais distintos. O autor ainda apresenta uma discussão detalhada do processo de derivação realizado em Michaelides (1987) e das implicações em utilizar referenciais distintos. É mencionado que a maioria dos estudos opta pelo uso da abordagem euleriana para a análise energética em áreas limitadas na atmosfera. Nesta abordagem, o domínio espacial selecionado para a realização dos cálculos deve ser grande o suficiente para acomodar todos os estágios de desenvolvimento do sistema, levando em conta seu deslocamento espacial e as mudanças de tamanho envolvidas. Entretanto, a opção pelo uso dessa metodologia resulta em limitações na interpretação dos resultados. Isso se dá ao fato de que, ao determinar uma área de tais dimensões, o cálculo da energética inevitavelmente acaba por agregar circulações sinóticas adjacentes, não refletindo assim apenas a energética da circulação de interesse.

Uma representação desta problemática é demonstrada na Figura 2.17. Nesta está representada o domínio computacional selecionado para o estudo da energética de um ciclone com gênese em uma região costeira, próxima à uma região de topografia elevada.

Esta é uma situação análoga à ciclogênese na região costeira do Sudeste do Brasil, por exemplo (Reboita et al., 2010; Gramcianinov et al., 2019, e.g). Neste caso, o domínio computacional deve abranger tanto a região costeira (fase de vida inicial do ciclone), quanto a região oceânica adjacente (fase final da vida do sistema). Após o ciclone avançar sobre o oceano, em seus estágio de desenvolvimento finais, circulações de mesoescala estabelecem-se próximas às regiões costeiras, como por exemplo, movimentos ascendentes relacionados ao aquecimento da superfície e convecção relacionada a interação da brisa marítima com a topografia local. Ou seja, a interpretação da energética do domínio de área limitada acaba por ser comprometida, dado que há processos dentro do domínio que influenciam nos valores de APE e K - e consequentemente, nos termos de conversão, fronteira, dissipação e geração - computados para o domínio.

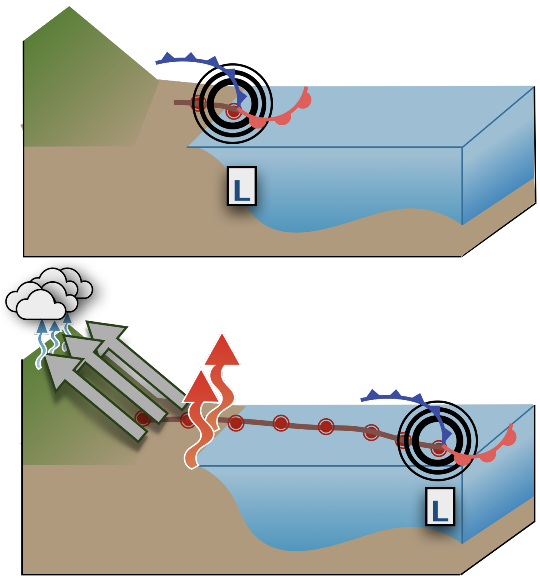

Figura 2.17: Ilustração representativa dos problemas relacionados à análise do ciclo energético utilizando um referencial euleriano. A imagem de cima representa um ciclone em formação próximo ao continente, enquanto que a figura debaixo representa o mesmo sistema em estágios tardios de desenvolvimento.

Apesar das limitações do método euleriano, Michaelides et al. (1999) discute que o uso de um referencial puramente lagrangiano para estudar ciclones extratropicais acarretaria em grandes dificuldades metodológicas. Isso pois, para tal, o sistema de interesse teria de ser rastreado em um espaço tridimensional isolado de outras circulações, utilizando variáveis conservativas específicas para as massas de ar contidas nele. Porém, ciclones extratropicais envolvem massas de ar de origens distintas (polar e tropical), e esse fator influencia em suas características conservativas. Além disso, para que o sistema seja isolado de circulações espúrias.

Desse modo, Michaelides et al. (1999) argumenta que a solução que balanceia uma aplicabilidade prática do método, mas que minimiza o efeito de circulações adjacentes na energética, é a abordagem quase-Lagrangiana. Nesta, similarmente ao que foi proposto por Vincent e Chang (1973), são utilizados múltiplos domínios fixos para diferentes instantes de tempo, de modo a seguir o sistema de interesse. Porém, diferentemente de Vincent e Chang (1973), nas formulações de Michaelides et al. (1999) não aparecem termos relacionados com o deslocamento das fronteiras do domínio computacional. Por fim, os autores comparam os resultados de ambas as metodologias (euleriana e quase-lagrangiana) e demonstram ambas podem apresentar resultados bastante diferentes, a depender dos termos analisados, discutindo que o uso do método euleriano, inclusive, dificulta comparações entre diferentes estudos, dada as contribuições dos sistemas adjacentes na energética. Assim, o mesmo conclui que o método semi-lagrangiano constitui uma metodologia mais robusta para a análise energética de sistemas ciclônicos. O autor ainda comenta que, devido ao fato da abordagem semi-Lagrangiana não utilizar um volume computacional fixo, não é possível realizar as derivadas locais dos termos de energia em relação ao tempo. Logo, o uso desta abordagem não possibilita fechar o balanço de energia de forma completa. Entretanto, não é apresentada uma argumentação completa a respeito desse tema.

O presente trabalho baseia-se nesta formulação apresentada por Michaelides et al. (1999). A formulação completa é apresentada na Seção 2.4.2, acompanhada da interpretação física de cada termo do ciclo energético. Enquanto isso, a descrição dos métodos computacionais empregados para o cálculo do LEC encontra-se na Seção 3.3.

2.4.2 Ciclo de Lorenz: Formulação Matemática e Interpretação Física

- Mostrar as formulações matemáticas utilizadas, baseadas em Michaelides (1987); Michaelides et al. (1999), oferecendo uma interpretação física e dinâmicade cada termo e, inclusive, através de diagramas didáticos, qunado possível.

2.4.3 Lorenz Energy Cycle applied to cyclonic systems

- Mostrar exemplos de estudos que empregam o LEC para ciclones e os resultados obtidos, e.g.: Veiga et al. (2008); Dias Pinto e Rocha (2011); Michaelides (1987);

Michaelides et al. (1999); Muench (1965); Brennan e Vincent (1980).

- Ao final, oferecer uma síntese dos resultados obtidos, já indicando possíveis padrões possíveis na energética de ciclones

Capítulo 3

Métodos

3.1 Fluxograma de atividades

- Fluxograma demonstrando os passos metodológicos e como se encaixam em cada pergunta de pesquisa

3.2 Bases de dados utilizadas

- ERA5
- Tracks do Atlântico Sul (base de dados da Carolina)
- CHIRPS
- QUICKSCAT
- OISST

3.3 Cálculo do ciclo energético

- Programa de calculo do LEC (Github) e procedimentos adotados para os cálculos

3.4 Determinação dos padrões energéticos

- Padronização da duração dos sistemas através do ciclo de vida
  - Cyclophaser
- Diagrama de fase (Lorenz Phase Space)

- Cálculo da PCA dos termos
- Método K-means

3.5 Descrição do MPAS-A

- Visão geral do modelo
- Descrição do núcleo dinâmico e discretizações numéricas
- Malha adotada e estrutura de grade (horizontal e vertical)
- Opções disponíveis de parametrizações físicas

3.6 Desenho experimental das simulações

3.6.1 Testes de sensibilidade: Furacão Catarina

- Desenho dos experimentos
  - Combinações de parametrizações físicas e de cumulus
  - Duração de cada set de experimentos (3 períodos de 48h cada)
- Inicialização do modelo
- Estrutura de grade adotada (horizontal e vertical)

3.6.2 Experimentos com SST

- Casos escolhidos
- Pertubações adotadas

Capítulo 4

Life cycle of cyclones in South America

Capítulo 5

Southwestern Atlantic Cyclones Energetics

- Aqui, estou na dúvida se não seria bom criar um capítulo (ou uma seção?) para falar do ciclo de vida dos ciclones, visto que os sistemas serão normalizados a partir disso, havendo diferentes configurações de ciclos de vidas, por exemplo.
- No caso, pensei em criar um capítulo para o ciclo de vida, apresentando os mapas espaciais de modo a indicar que a metodologia utilizada é válida e corresponde ao esperado pela literatura de climatologia de ciclones (ao mesmo tempo em que adiciona novas informações). Entretanto poderia acabar ficando desconexo com os objetivos da tese.
- A alternativa seria apenas incluir como uma seção neste capítulo aqui, de modo que eu indique apenas as configurações de ciclones detectadas pelo programa e mostre alguns exemplos para aferir confiabilidade aos resultados, mas poderia acabar ficando desconexa das outras seções.

5.1 Características gerais

- Estatísticas gerais da energética dos sistemas
- Compósitos para alguns termos, para diferentes fases do ciclo de vida
- Mostrar diagrama de fase para todos os casos

5.2 Padrões energéticos

- Resultados das componentes principais

- Clusters identificados pelo K-means
- Resultados dos padrões energéticos

5.3 Limitações, aplicações e passos futuros

- Limitações: metodologia semi-lagrangiana deve ser interpretada como snapshots (relacionando com Muench (1965))
- A formulação adotada apenas permite a seguinte interpreteção: contribuição para energética global e não a energética individual de cada sistema
- Contextualizar a energética como ferramenta para determinação objetiva das causas eficientes e finais dos ciclones (diagramas do Hart estão relacionados com causas formais e materiais - os trabalhos complementam-se)
- Estudos de caso? (e.g. ciclones extratropicais clássicos formados no sul da ARG, ciclones bomba formados em LA-PLATA, ciclones subtropicais formados em SE-BR e, ciclones tropicais Anita, Iba, 01Q.

Capítulo 6

Modelagem numérica

6.1 Testes de sensibilidade: estudo de caso com Furacão Catarina

- Objetivos: 1) determinar qual conjunto de parametrizações de microfísica e cumulus apresentam os melhroes resultados para o Catarina 2) determinar o impacto de diferentes escolhas na energética dos sistemas

6.1.1 Comparação da pressão mínima em superfície e posição do sistema

6.1.2 Precipitação acumulada

6.1.3 Ventos em superfície

6.1.4 Energética

6.2 Experimentos com pertubações no campo de SST

6.2.1 Interação oceano-atmosfera

6.2.2 Ciclo energético

Capítulo 7

Conclusões

Conclusões do trabalho e/ou perspectivas

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Apêndice

Apêndice A

título do apêndice 01

A.1 *subtítulo 01*

Apêndice B

título do apêndice 02