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MRes Climate and Atmospheric Science

Literature Review

Inner-core drivers of intensity in Tropical Cyclones

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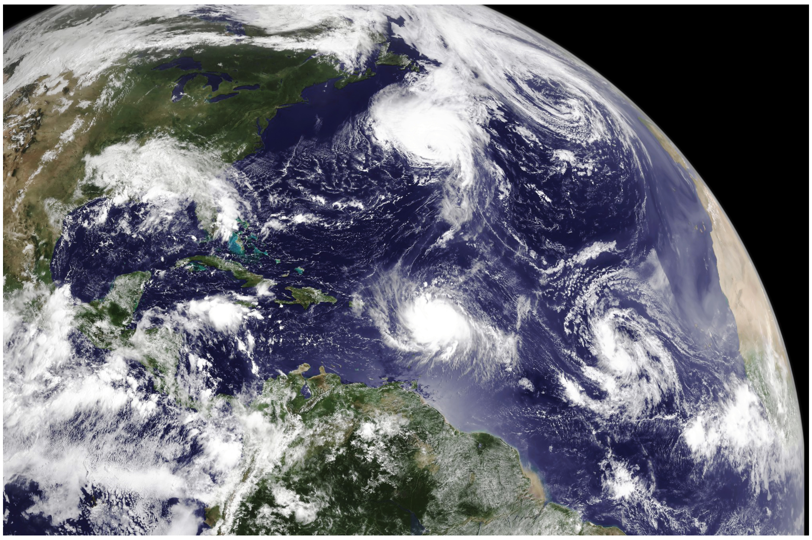

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Abstract

Dynamical forecast models of Tropical Cyclones need to represent both large and small scale processes to have skill in predicting intensity changes. While forecast models reproduce large-scale features to a relatively good degree, small scale processes associated with the inner-core are far from understood and are poorly represented. This paper presents, first, a short a review of the available observational datasets for Tropical Cyclone studies and, then, a summary of the main drivers of intensity in or near the inner-core. This review mainly comprises boundary layer processes, air-sea interaction, thermodynamical constraints and eyewall processes. Sea-surface surface temperature is the main component of air-sea interaction and it influences the organization and destruction of Tropical Cyclones but it does not affect sudden changes of intensity and it is not associated with the rate of intensification. The boundary layer affects the rate of inflow and the properties of the air that undergoes deep convection, therefore it can spin-up the vortex circulation causing intensification or ventilate the eyewall and weaken the storm. Deep convection inside the inner-core precedes episodes of rapid intensification and, thus, observing bursts of deep convection can forecast intensity changes. Observational studies found asymmetries in the configuration of Tropical Cyclones, particularly, asymmetries imposed by the shear vector that were associated with intensity changes. The review suggests the need for a composite study of the dropsonde dataset where observations are binned by intensity change in order to estimate differences in dynamical flow, temperature and moisture distribution and convective metrics between composite sets.

1 Introduction

Tropical Cyclones (TCs) are organized convective systems that have a horizontal scale of ~ 100 km, a vertical scale of $10 - 20$ km and a lifetime of several days and even weeks (Montgomery & Smith 2017). In addition, these weather systems are characterized by a cyclonic circulation, very strong winds ($50 - 200$ km hr^{-1}), torrential precipitation and storm surges that cause severe damage to infrastructure and human lives (Moore et al. 2017). TCs are also important to the energy budget due to their meridional transport of heat across the ocean (Emanuel 2001). The intensity of TCs is determined by both minimum sea-level pressure and maximum sustained horizontal winds at 10-m altitude. Based on these meteorological values, TCs are categorized (for the East Pacific and Atlantic Basins) as tropical depressions, tropical storms or within 5 sub-categories of hurricanes (Saffir-Simpson Scale) (Montgomery & Smith 2017).

A wide range of scales is required to properly define the structure of a TC, but, in short, TCs have a low-pressure centre with a warm core and relatively low winds, an eyewall with vertical velocities reaching 50 m s^{-1} and a large band of clouds surrounding the eyewall in a spiral-like structure. TCs are affected by Earth's rotation, due to the Coriolis effect, causing them to generate a vortex circulation (Montgomery & Smith 2017).

The physical characteristics and socio-economic implications of TCs have motivated scientists to understand the physical processes that organize and develop these storms (Emanuel 1991, Rogers et al. 2006). Moreover, in order to mitigate the impacts on society of TCs, forecasting agencies and research groups provide the population of vulnerable regions with early alert systems based on prognostic tools or forecasts. These forecasts provide an outlook or prediction of the track and intensity of a TC for a given time period. In spite that these forecasts have been ongoing for a long time, only track forecasts have shown a substantial increase in accuracy (Rappaport et al. 2009). Although intensity forecasts have shown some signs of improvement (DeMaria et al. 2014), evidence suggests that forecasting sudden changes of intensity is still outside of our predicting capabilities (Rogers et al. 2017). Improvement of track forecasts can be attributed to enhancements in large-scale circulation models and their representation of the environment of TCs (Rappaport et al. 2009, Nystrom et al. 2018), whereas the lack of improvement in intensity forecasts is caused by poor representations of inner-core processes (Nystrom et al. 2018, Braun et al. 2013). For this reason, this literature survey will mainly address processes associated with the inner-core and not environmental control variables.

Paradigms or paradigm theories refer to global or large-scale theories that explain the organization and development of the aforementioned TC typical structure (Emanuel 1986, Riemer et al. 2010). Since paradigms theories mostly explain larger-scale dynamics, the discussion of these theories is beyond the scope of this review but several papers provide a detailed account of this topic (Emanuel 1991, Riemer et al. 2010, Montgomery & Smith 2017). Even though they are not directly addressed by this review, proper links to paradigm theories are made when the observations and arguments refer to them.

Finally, while literature regarding observations is the main component of this paper, some modelling results are also used to compare or support observational evidence.

The Masters of Research project entitled "Dropsonde Observations of Intensity Changes in Tropical Cyclones" focuses on understanding the main drivers of intensity in the region of the inner-core that can be observed by the dropsonde coverage. In this context, this literature review will provide first, a very short survey of the available methodologies and instrumentation used in sampling TCs and, second, a summary of existing literature regarding inner-core processes and how they are associated with metrics of TC intensity.

2 Observational Datasets

Observations in atmospheric science, and particularly for extreme weather systems, have a key role to evaluate and validate numerical models as well as to test new theories and provide a novel insight. However, the inherent danger and impracticality associated with in-situ measurements of these systems has tampered with the resolution and techniques that provide data in this environment (Smith & Montgomery 2012, Emanuel 1991). In recent years, several new techniques and breakthroughs have improved our ability to sample these storms and new data has been important to the current progress in forecasts (DeMaria et al. 2014, Gall et al. 2013). Since this review is primarily based on observational studies, this section presents a short introduction to observational datasets used in TC studies. The majority of observations of TCs can be classified as aircraft associated measurements, satellite and buoy information, with a minor contribution from surface observations.

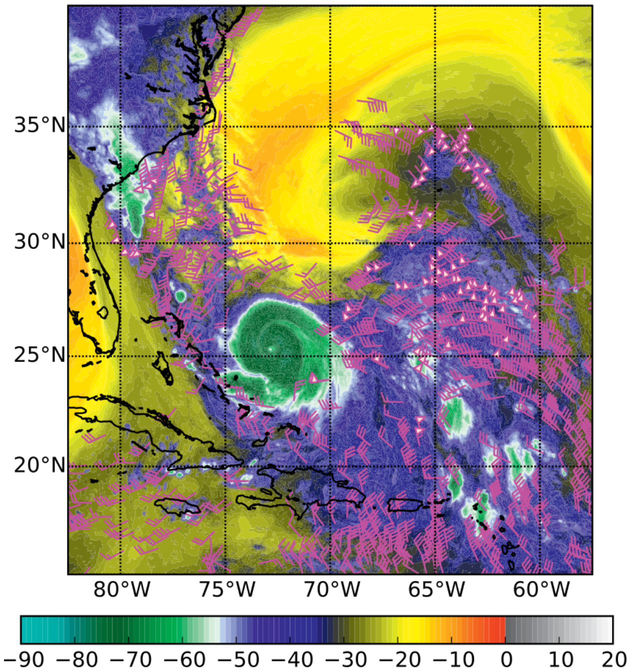


Figure 1: GOES13 observations of water vapour brightness of Hurricane Joaquin on Oct 10, 2015, taken from Doyle et al. (2017). As part of the GOES network, GOES13 was located at a key position viewing the East Pacific Basin, the Gulf of Mexico and the Caribbean.

The National Oceanic and Atmospheric Administration (NOAA) provides public observational data of TCs including a track record going back to the nineteenth century. NOAA has teamed with the US Air Force (USAF) and the National Aeronautics and Space Administration (NASA) to organize short field campaigns and plan long-term strategies for obtaining novel and better observations with increasing resolution and improved measurement techniques (Houze Jr et al. 2006, Braun et al. 2013, Rogers et al. 2006, Doyle et al. 2017).

Satellite information of TCs dates back to the early 1970s (Dvorak 1975), where one of the first meteorological satellites provided information on how TCs evolved over time and, particularly, how intensity changed over time. This is now known as the *Dvorak technique* and it is used to estimate the intensity of a TC using satellite observations. Since then, constant improvements (DeMaria & Kaplan 1999) have been made on retrieval techniques and resolution so that currently, satellite observations are a major factor in determining the intensity of TCs all over the world and their information is fed directly into forecast models (DeMaria et al. 2014).

The long-term record (20-30 years) and relatively high horizontal resolution ($\sim 1 - 5$ km) of satellites enable long-term studies but their poor vertical ($\sim 250 - 500$ m) and temporal resolution can impair their sampling of the inner-core region. For these reasons, satellites are primarily used to identify statistical characteristics of the environment of TCs (Kelley et al. 2004, Franklin et al. 2003). The greatest disadvantage of some satellites is that, depending on their orbit, they do not monitor continuously the same region, therefore, the temporal resolution while sampling a particular TC might be quite poor (several days between measurements).

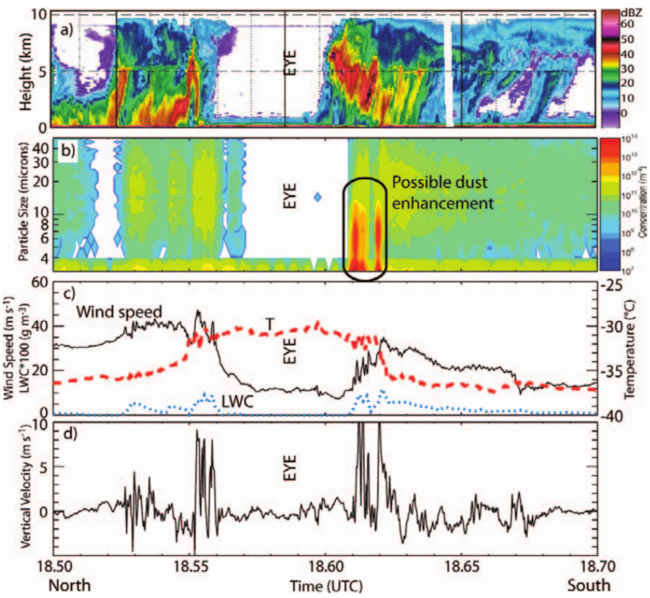
Figure 1 illustrates the information that satellite instruments can provide, the water vapour image of Hurricane Joaquin gives a sense of the cyclone size as well as of the precipitation large-scale structure. As part of the GOES network, GOES13 provided with a long record of water vapour images of TCs in the Atlantic Basin. These images provided a proxy for intensity since the water vapour organization accounts, in a sense, for the intensity of the TC (Doyle et al. 2017).

Weather station networks have been deployed over land and ocean (buoys), these stations provide meteorological data with a high temporal resolution (*half-hourly sampling*) and when on land can also have a high spatial resolution ($\sim 10km$). These stations are primarily used to validate numerical models estimates of sea level winds and pressure (Kaplan et al. 2010). While the use of these observations only provides individual points in a grid and no vertical information, they can become important in determining the intensity of TCs (DeMaria et al. 2014). For instance, Hurricane Patricia's track and intensity were corrected through the use of surface observations. Initially, Patricia was reported to have made landfall as a category-5 major hurricane, in the Saffir-Simpson scale, but later surface analyses showed that the actual intensity of Patricia as it crossed through Jalisco, Mex., corresponded to a category-4 Hurricane (Rogers et al. 2017, Kimberlain et al. 2016).

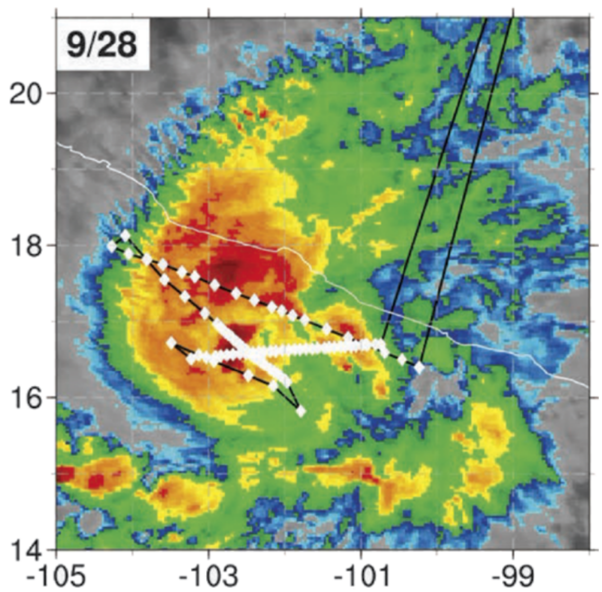
Buoy observations are able to provide estimates of surface fluxes between the ocean and atmosphere through measurements of meteorological variables on sea-level. This is now known as the tropical cyclone-buoy database (TCBD) and it provides long-term (40-50 years) records of sea-surface temperature (SST), moisture and temperature profiles for TC studies with a relatively fine resolution ($\sim 10km$) on an hourly basis (Cione et al. 2013).

The study of TCs through aircraft observations has been in use for several decades. NOAA, NASA and the USAF have conducted hundreds of flights on the Pacific and Atlantic Basins and other agencies also sample TCs in other basins (Wang & Wu 2004). Recent improvements have allowed flights to conduct both *onboard* quality observations and to launch disposable *dropwindsondes* or dropsondes (Franklin et al. 2003). Remote sensing instruments have been equipped onboard aircraft deployed by the aforementioned agencies. These instruments sample along the flight tracks, providing data that is usually denominated as *flight-level data* (Rogers et al. 2006, Braun et al. 2013).

Dropsondes are scientific instruments designed in the early 1990s by NASA and NOAA to provide detailed sampling of vertical profiles along specific parts of TCs such as the eye, the eyewall or the



(a)



(b)

Figure 2: Flight-level observations of a) Hurricane Earl and b) Hurricane Patricia. Subfigure a) shows a time series of radar reflectivity, cloud droplet number, wind speed and temperature and vertical velocity, from upper to lower panels, respectively, taken from Braun et al. (2013). Subfigure b) is a plan view of radar reflectivity (colour contours), along with dropsonde launch location (white dots) and flight track (black solid lines), taken from Doyle et al. (2017).

environment and to improve estimates of surface wind speed (since this metric is directly related to the intensity) (Franklin et al. 2003). In over 20 years of campaigns, over 14,000 dropsondes have been launched in TCs of different intensities and undergoing different lifecycles (Wang et al. 2015).

Figure 2 shows the wide range of observations that are taken *on-board* by these remote sensing instruments. From the transect of Hurricane Earl depicted in figure 2a), the eye can then be depicted as the zone with low radar reflectivity and low cloud droplet number, high temperature and significantly low horizontal and vertical wind speeds. Figure 2b) illustrates the intense dropsonde coverage that some regions of a TC may have, whereas other regions are with low or without coverage as well as the typical cross-leg pattern of the flight itself (black solid line). Dropsonde and flight-level data are assimilated in real-time by forecast models (Nystrom et al. 2018) and the use of these observations is an important part of the increased accuracy in current forecasts (DeMaria et al. 2014, Wang et al. 2015).

3 Drivers of intensity

A considerable amount of processes and scales influence the structure and intensity of TCs. The impact of large-scale dynamics over TC intensity is relatively better understood than smaller-scale features (Hendricks et al. 2010, Harnos et al. 2011) since large-scale processes have been observed for a longer time and are relatively well resolved by numerical simulations (Kaplan et al. 2010). Ocean heat content, low-level moisture, vertical wind shear and large-scale vorticity are examples of these larger scale factors and they are part of the *predictors* in the statistical forecasting algorithms, such as the Statistical Hurricane Intensity Prediction Scheme (SHIPS) (DeMaria & Kaplan 1999) and the Rapid Intensification Index (Kaplan et al. 2010). Other synoptic relevant features are the distance of a TC to a landmass, the interaction between the cyclone and a low or high-pressure system and the impact of atmospheric waves (Montgomery & Smith 2017).

Since most of these mentioned large-scale processes mainly influence the track of a TC and are secondary for sudden changes of intensity (Hendricks et al. 2010, Doyle et al. 2017), this literature review mostly encompasses inner-core processes associated with TC intensity changes. First, this section overviews air-sea interaction since it is the main driver of heat fluxes between the atmosphere and ocean, then, a survey of the impact of the boundary layer upon TC intensification. Similarly, this section discusses thermodynamic constraints upon TC intensity presenting evidence on how convective bursts can be related to rapid intensification. The final driver of intensity in this section refers to eyewall processes with particular emphasis on eyewall replacement cycles. While environmental wind shear has a well-established role in being detrimental to a TC structure in the large-scale sense (DeMaria & Kaplan 1999, Kaplan et al. 2010, Montgomery & Smith 2017), on a smaller scale it is not trivial to assess how shear affects TC intensification, section 3.5 will elaborate on this particular topic as the final section of this review.

3.1 Air-sea interaction

Observations show that most TCs weaken when they make landfall since they disconnect from the ocean, their source of heat, emphasizing the requirement of a relatively warm ocean to generate, organize and maintain TCs (Montgomery & Smith 2017, Emanuel 2001). This section will elaborate on the relation between the atmosphere and the ocean and how this interaction impacts the development of TCs and sudden changes in intensity.

The three main components of the interaction between the ocean and the atmosphere are SST, the state of the atmosphere (depicted by the temperature and moisture profiles) and the wind speed (Emanuel 1986). These features, in turn, determine the fluxes of entropy, enthalpy, heat and momentum between air and sea (French et al. 2007, Richter et al. 2016). A detailed description of the distribution and magnitude of these fluxes in the inner-core and the boundary layer of the TCs remains an unsolved problem (Cione et al. 2013).

Recent studies were able to compute momentum and moisture fluxes using buoy observations (French et al. 2007) and enthalpy and drag fluxes using dropsonde data (Richter et al. 2016). These measurements have proven that, first, air-sea fluxes do not increase linearly with wind speed but, in turn, level-off for large wind speeds. Secondly, the radial distribution of enthalpy and entropy fluxes within the boundary layer determines the amount of buoyant energy that is convected into upper parts of the atmosphere, thus completing the transport of energy between sea surface and upper atmosphere (Emanuel 1986, 1991).

The maximum potential intensity of TCs has long been associated with SST (Emanuel 2005) and a wide range of statistical and dynamical models use SST as a predictor or important variable to determine changes of intensity, for instance, SHIPS and the Rapid Intensification Index. Hendricks et al. (2010) used data from re-analysis products and the Tropical Rainfall Measuring Mission (TRMM) observations to do composite analysis and investigate the statistical differences of SST between bins of intensity change. They found that SST is not crucial to determine the rate of intensification for both the Atlantic and Pacific Basins and it is only statistically different between the weakening and the intensifying storm composites (see figure 3). The interpretation of this result is straight-forward since most weakening storms are often found in cooler waters at higher latitudes whereas intensifying storms are usually in warmer waters that allow them to develop and thrive.

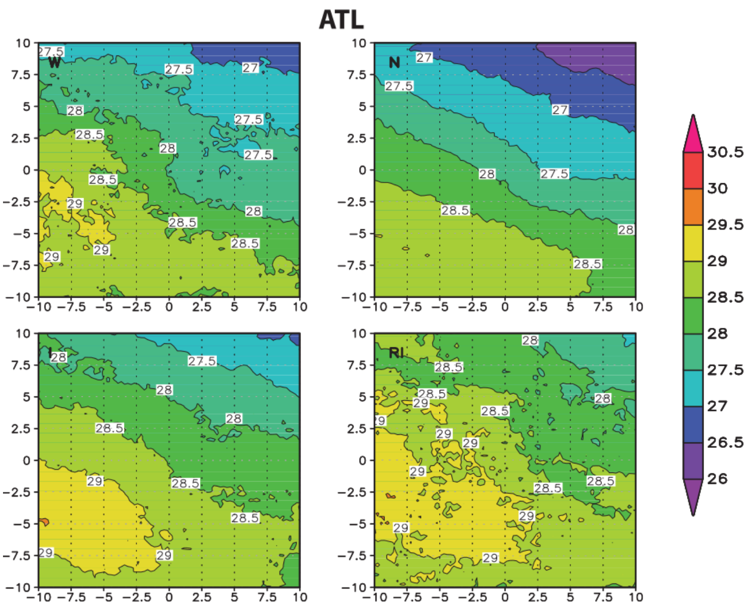


Figure 3: Composite analysis of mean SST for weakening (upper left), neutral (upper right), intensifying (lower left) and rapidly intensifying (lower right) TCs in the Atlantic Basin, taken from Hendricks et al. (2010).

Figure 3 shows an increase in SST ranging from the weakening to the intensifying composites but no difference between intensifying and rapidly intensifying composites. Several examples illustrate that a warmer ocean generally causes intensification and a cooler ocean is detrimental to TC intensity. For instance, Hurricane Patricia found an abnormally hot region in the East Pacific which, in addition to other factors such as scarce low-level shear, developed Patricia to become one of the strongest TCs of all time (Rogers et al. 2017).

A study conducted by Cione et al. (2013), similar to that of Hendricks et al. (2010), related buoy observations to TC composites, categorizing observations in bins of intensity change. This study aimed to understand how surface conditions of moisture, equivalent potential temperature (θ_e), shear and SST change under the different intensity change regimes. The results suggested that intensifying TCs are found in drier environments ($\sim$ 1g/kg less moist than weakening composite) but SST conditions were not different (to a statistically significant level) between weakening and intensifying storms. These findings are at odds with those presented by Hendricks et al. (2010) but this can be attributed to the different observational datasets that they used (satellite vs buoy observations). While satellite information has greater spatial resolution and coverage, buoy observations have a better temporal resolution (see section 2).

The Wind-Induced Surface Heat Exchange (WISHE) paradigm argues that a feedback mechanism exists between wind speed and the moisture flux from the ocean surface towards the atmosphere (Emanuel 1986, 2005). This paradigm suggests that the main driver of the intensity is air-sea interaction, through WHISHE's feedback mechanism. Recent observations of surface fluxes and surface equivalent potential temperature θ_e suggest that intensification can be independent of air-sea fluxes driven by wind stress (Montgomery et al. 2009, Riemer et al. 2010, Montgomery et al. 2015) and other drivers, such as the boundary layer (section 3.2) might be more influential.

While SST poses a lower and upper limit in the required temperature for the formation and the maximum potential intensity of TCs, respectively, recent results, like the studies of Hendricks et al. (2010) and Cione et al. (2013), reveal that SST can be considered more of an environmental control variable than a main driver of intensity. This supports the argument that the conundrum of TC intensity requires the assimilation and understanding of a complex set of processes across many scales (DeMaria et al. 2014, Doyle et al. 2017) and intensity changes cannot easily be attributed to any individual process (Cione et al. 2013).

A gap in our understanding of air-sea interaction is that estimates of surface fluxes, made by French et al. (2007) and Richter et al. (2016) were not directly associated with the change of intensity of the sampled TC. In other words, while their work sets the tone for further research using their methodology to estimate surface fluxes, their results are limited to the calculation of the fluxes and were not concerned with studying their possible differences between weakening and intensifying storms. According to the WISHE paradigm, intensifying TCs should noticeably show larger fluxes of momentum, enthalpy and entropy when compared to a weakening sample.

3.2 Boundary layer processes

The Tropical Cyclone Boundary Layer (TCBL) encompasses the adjacent section of the atmosphere to the surface that is affected by friction between the air and ocean surface (Smith & Montgomery 2010, Kepert et al. 2016). This layer has a general structure comprising low-level inflow, a depth between 500 and 1000 m (Zhang et al. 2011) and it modifies the intensity of TCs by determining the radial distribution of absolute angular momentum, moisture and vertical motion (Smith & Montgomery 2010). Due to the very strong winds in this layer, sampling in this region is considered dangerous and therefore, observations of the TCBL are scarce. The most reliable source of information in this region is provided by the dropsonde profiles.

The characteristic structure and properties of the TCBL can be divided into two main categories: the mixed or thermodynamical TCBL and the dynamical TCBL or inflow layer. The former is defined as the region where the potential temperature (θ) remains constant due to mixing processes (Zhang et al. 2011, Kepert et al. 2016), whereas the latter has its origin in the frictional disruption of gradient wind balance near the surface (Zhang et al. 2013). The dynamical TCBL height was studied in a composite analysis of dropsondes and was found to be higher than, and can be twice as high as, the mixed TCBL (Zhang et al. 2011). Kepert et al. (2016) argued that the dynamical or inflow layer is a better proxy for the TCBL height that models should use since the mixed TCBL is affected by moist processes and it is highly dependent on the radial advection of potential temperature.

Figure 4a) illustrates the radial inflow observed as a low-level jet of air converging towards the centre of the vortex, with the maximum value, for this particular composite studied by Zhang et al. (2013), found outside the radius of maximum wind (RMW). The correspondent tangential wind structure, shown in figure 4b) shows the maximum wind to be within 600-1000 m in altitude. Figure 4a) also shows that the maximum inflow decreases in height as the distance to the centre decreases, a feature that had already been encountered by previous studies, for instance, Schwendike & Kepert (2008) while studying the wind structures of Danielle (1998) and Isabel (2003) were able to observe this radial variation of TCBL height in both dropsonde observations and model output.

Several studies have investigated the role of the boundary layer in the intensification of particular TCs (e.g. Montgomery et al. 2014, Raymond & López Carrillo 2011), their results show that the TCBL height and TCBL structure determine to a large extent the inflow of air that is then convected through the eyewall. In the specific case of Hurricane Earl in 2014, Rogers et al. (2015) found that Earl intensified due to a mixing of the eye and eyewall and strong inflow of air converging absolute angular momentum that feed into the eyewall ascent.

The *boundary-layer spin-up* mechanism argues that TC intensify and thrive mostly as a result of a spin-up of the vortex enhanced by the boundary layer (Riemer et al. 2010, Smith & Montgomery 2010, Montgomery et al. 2015) . This spin-up is caused by two main processes, first, the conventional spin-up triggered by an inflow of air above the boundary layer conserving absolute momentum, and second, the boundary layer spin-up which refers to the inflow of air within the boundary layer that materially conserves both momentum and equivalent potential temperature θ_e (Montgomery et al. 2009, 2014).

This paradigm was put to a test using observations in Hurricane Earl and Montgomery et al. (2014) argued that the maximum tangential speed exceeded the corresponding gradient wind, thus characterizing a layer of super-gradient flow just above the TCBL, and proved the propositions made by the boundary-layer spin-up paradigm. Through the analysis of momentum surfaces, Montgomery

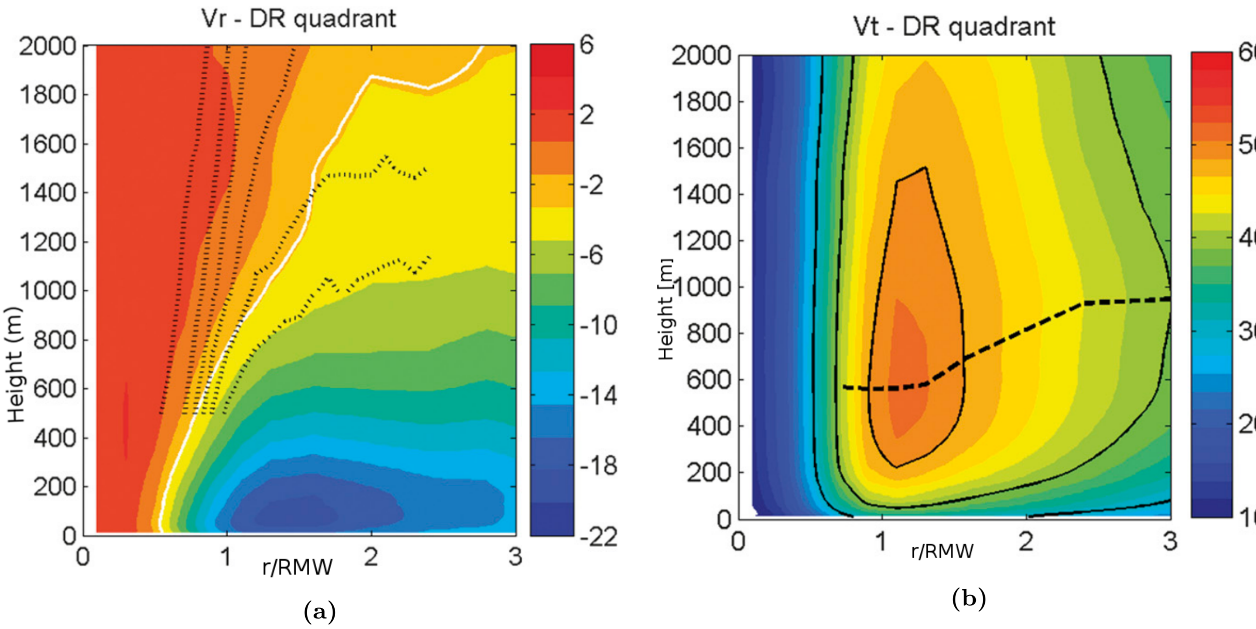


Figure 4: Radial a) and tangential b) wind speeds in axisymmetric radial-height cross sections for the down-shear right quadrant, the x-axis is normalized by the radius of maximum wind (RMW) and the white line differentiates inflow from outflow. The white line in a) shows the 10% inflow contour and the black lines refer to Doppler radar composite results. In b) the solid lines are 5 m s^{-1} contours and the dashed line represents the level of maximum tangential wind for every radius, from Zhang et al. (2013).

et al. (2014) suggested that Earl's intensification was due to the import of absolute momentum by the boundary layer, as proposed in the spin-up paradigm. The WISHE paradigm assumes that within the inner-vortex, gradient wind balance holds, however, the observations and remarks of Montgomery et al. (2014) suggest the opposite (super-gradient flow in Hurricane Earl), thus supporting the view that the boundary-layer spin-up mechanism provides a more accurate description of TC intensification.

The properties of the boundary layer structure determine the characteristics of the inflowing air into the eyewall region to a great extent. The TCBL can drive intensity changes through two main mechanisms, first, convergence of unstable air with relatively high angular momentum or high vorticity can promote the strengthening of a storm (Montgomery et al. 2014, Riemer et al. 2010, Raymond & López Carrillo 2011), second, inflow of dry, low entropy or low angular momentum air masses can promote a process called *ventilation* (explained in section 3.3) where the TC losses convective potential and spindowns, therefore weakening (Didlake Jr & Houze Jr 2013, Riemer et al. 2010).

The aforementioned studies have established that boundary layer processes can determine the rate of change in the intensity of TCs, however, the composites of Zhang et al. (2011, 2013) did not differentiate TCs by their intensity change, therefore not providing evidence of how inflow changes according to the subsequent changes in intensity. Similarly, Kepert et al. (2016) did not discuss if the mixing of the thermodynamic TCBL could be expected to be different under different intensity changes and what would the implications of this mixing be to weaken or intensify the storm.

Rogers et al. (2013) answered some of these questions by using composite analysis to determine statistical differences in the *flight-level* observations between intensifying and weakening storms. This study found than intensifying storms have stronger and deeper inflow as well as stronger ascent in the eyewall region than weakening storms. Although Rogers et al. (2013) explored the main physical differences between the two composites, they disregarded studying weakening storms and separating the rate of intensification by *intensifying* and *rapidly intensifying* storms. Another gap in the study of TCBL influence upon TC intensity is the depiction of state variables under different intensity composites. If the boundary-layer spin-up mechanism holds, then absolute momentum surfaces derived from the dropsonde coverage should show differences in intensifying and weakening storms, yet the evidence suggested by Montgomery et al. (2014) only included the study of one hurricane.

3.3 Thermodynamical constraints

A way to thermodynamically describe a TC uses the physical concept of a Carnot engine, which refers to a closed thermodynamic cycle (Emanuel 1991, 2001). In this model, a TC transports energy from the ocean to the atmosphere in the form of heat and moisture fluxes (Emanuel 1986). Since these fluxes are driven by differences in temperature and moisture, a TC in this model requires a warm ocean to thrive and intensify, as section 3.1 discussed. Although the Carnot engine does not provide the best representation of the TC, the fact that TC dynamics can be described by a purely thermodynamic argument highlights the importance that thermodynamic processes enforce in TC organization and development.

The two main thermodynamical variables of interest in TCs are temperature and moisture since they determine the transport of thermodynamic state variables as enthalpy or entropy while also determining the magnitude and direction of heat fluxes. Capturing the convective-scale thermodynamic processes is considered one of the great challenges of dynamical models to accurately forecast intensity changes (Harnos et al. 2011).

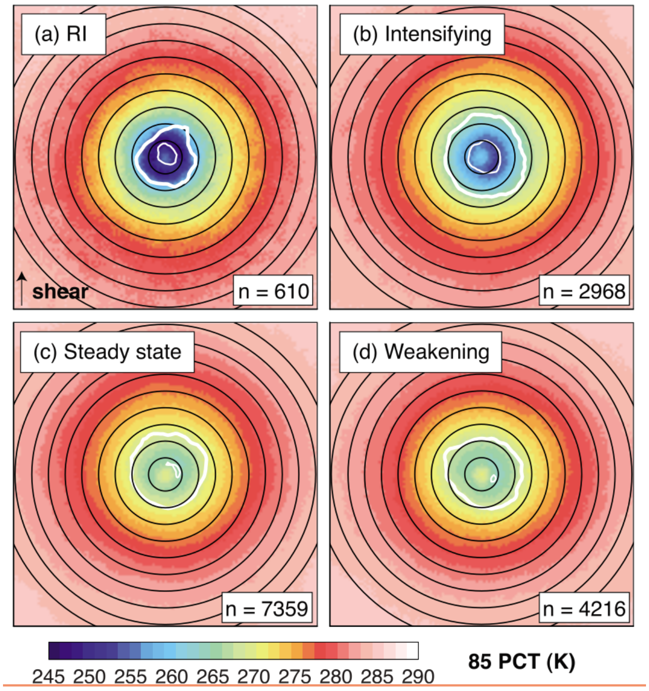


Figure 5: Polarization corrected temperature (PCT) contour plots for 4 intensity change composites, the sample size is observed in each panel as n and the while line contours the eye, from Harnos et al. (2011).

The core of a TC is characterized by being relatively warm, compared to outer regions of the system, and by having the greatest portion of ascent. The temperature distribution in TCs has been associated with intensity changes since temperature is a proxy for convective activity (Rogers et al. 2015). Figure 5 shows the temperature differences between intensity change composites (weakening, steady-state, intensifying and rapidly intensifying) observed using the Special Sensor Microwave Imager (SSM/I) from 1987-2008 and the TRMM Microwave Imager (TMI) from 1997-2008. The figure suggests an increasing trend in inner-core temperature ranging from rapidly intensifying (RI) towards the weakening composites as well as an asymmetric eyewall region in RI regions (Harnos et al. 2011). These results could be integrated into forecast algorithms that, using satellite information, can map the temperature distribution of a TC and identify possible intensity changes using these results.

Outside of the eyewall, stratiform precipitation can also influence the intensity of a TC, specifically, since *spiral rainbands* can produce ventilation, which is explained by the following mechanism. These spiral rainbands contain air that has cooled during the ascent and produced ice particles, moreover, these air masses also have weaker vertical velocities (ω) than the eyewall. In this regime of low ω, ice tends to fall from these regions, as precipitation occurs, latent heat is absorbed by falling hydrometeors, thus cooling the atmosphere (Didlake Jr & Houze Jr 2013). This descending cooling flow, denominated as downdraft, imports low-entropy [1] air into mid and low-levels of the TC. When these air masses are inserted into the TCBL, air is then converged back into the ascent region, yet, since this is low entropy or low-angular momentum air, this new inflow can weaken the storm, this process is referred to as *ventilation*.

Didlake Jr & Houze Jr (2013) found evidence of ventilation driven by stratiform precipitation in the outer rainbands of Hurricane Rita through the inspection of the *flight-level data* provided by the Rainband and Intensity Change Experiment (RAINEX) campaign (Houze Jr et al. 2006). Observations

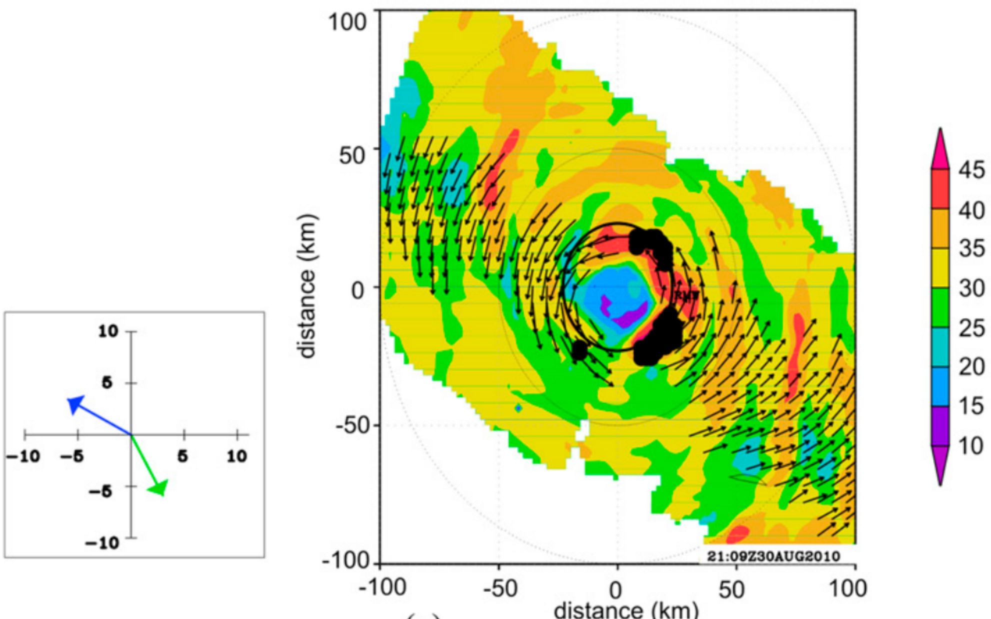
[1] In this context, entropy is defined as the amount of energy that is no longer available to perform work, therefore, low-entropy air masses are less capable of doing mechanical work, *i.e.*, the ascent is limited. The adiabatic processes of the Carnot engine are also called isentropic surfaces since entropy is conserved during these motions.

of reflectivity fields showed the development of stratiform rainbands downwind that through latent cooling produced both horizontal vorticity as well as the descending flow or downdraft. This downdraft was later associated with a weakening of Rita.

The Convective Available Potential Energy (CAPE) is an energy metric associated with the likelihood of extreme weather occurring since it is a measure of buoyancy and therefore, convection. CAPE is often used as a proxy for extreme cumulonimbus weather but it has its limitations when applied to larger-scale phenomena (Alfaro & Khairoutdinov 2015). In a similar way, while CAPE is very high in most regions of a TC there is no apparent association between CAPE estimates and intensity or intensity change (Montgomery et al. 2014, Stevenson et al. 2014). In particular, Smith & Montgomery (2012) studied the thermodynamic differences between developing and non-developing storms using the thermodynamic profiles measured by dropsondes in Hurricane Karl (developed storm) and Tropical Storm Matthew (non-developed storm). This study showed the evolution of CAPE over time of developing and non-developing TCs concluding that CAPE was not relevant, in their sample, to distinguish between intensifying and non-intensifying storms. Stevenson et al. (2014) also estimated CAPE from dropsondes in Hurricane Earl and found no particular feature in the CAPE field distribution.

Although the evidence presented by Smith & Montgomery (2012) and Stevenson et al. (2014) suggests that CAPE is not a good indicator of intensity change, the robustness of this conclusion can be challenged since their studies were based on small samples. A composite analysis of developing and non-developing CAPE measurements could be considered more conclusive. Moreover, other types of CAPE-related metrics have been found to have more skill in predicting intensification or longevity in convective systems, such a metric, for instance, Integrated CAPE (Alfaro & Khairoutdinov 2015), could be more differentiable between composite sets.

Localized regions of intense convection, also called *convective bursts* (CBs) (Stevenson et al. 2014, Rogers et al. 2015), are characterized by producing tall cells of convective movements that are driven by intense vertical velocities. CBs have been associated with episodes of rapid intensification and as much as 22% of all eyewalls contain at least one tall cell or convective burst (Kelley et al. 2004). These tall portions of ascent are observed by the retrieval of cloud top temperature from satellite's measurements, which is a very good proxy for cloud top height, therefore making satellites images able to capture the distribution and frequency of CBs.



(e)

Figure 6: Plan views of Hurricane Earl flight-level observations showing radar reflectivity (colour contours) and wind speed (black arrows). CBs are shown as black regions and the RMW is drawn as the black dashed lines. The left panel shows the motion (blue) and shear (green) vectors, from Rogers et al. (2015).

Kelley et al. (2004) used TRMM Precipitation Radar's long-term record and found statistical differences between intensity change composites in the frequency and height of tall convective towers, estimating a 71% chance of intensification in TCs with at least one extremely tall tower (cloud top height above 10 km). Similar results were presented by Jiang (2012) who found that three satellite-derived metrics of intensity were statistically different between slowly-intensifying and rapidly intensifying TCs, thus concluding that convective activity can be used as a proxy for rapid intensification. A difficulty in accurately assessing the distribution and occurrence of tall precipitation towers or convective activity from satellite measurements is the poor temporal resolution that satellites can have while sampling a TC, for instance, TRMM only captures a storm every 5 days.

The association between CBs and TC intensification was examined during the sampling of Hurricane Earl, where, the X-band tail Doppler radar on board the NOAA WP-3D aircraft conducted provided data on good temporal and spatial resolution of Earl while it underwent intensification (Braun et al. 2013, Rogers et al. 2015, Stevenson et al. 2014). Figure 6 shows the reflectivity field and the distribution of the convective bursts relative to the shear and motion vector for a particular time period. During the rapid intensification period, most of the CB activity remains inside of the RMW (as figure 6 illustrates) and this convective activity was stronger and more concentrated than during the non-intensifying periods. A dominant distribution of these convective structures relative to the shear-vector was related to the intensification process (this will be addressed in section 3.5). This relation of CBs and intensification had been addressed by Rogers et al. (2013) in their composite analysis of flight-level wind data where it was shown that, in general, intensifying storms have a larger concentration of CBs inside the RMW when compared to weakening composites.

Rogers et al. (2013, 2015) argued that CBs are not the cause of intensification but rather a proxy of expected intensification, *i.e.*, episodes of deep convection or CBs can be observed due to a preferential alignment of the vortex that motivates both CBs, deep convection and an intensification period. In other words, CBs can serve to forecast intensity changes but they are not the cause of intensification.

A wide range of processes in a TC are mostly thermodynamic or are related to a thermodynamic metric. Therefore, thermodynamic constraints such as heat fluxes or CBs must be accurately represented by forecast models of intensity in order to have some skill. Although a warm ocean can be considered the basic thermodynamic feature of a TC, observational evidence shows that processes associated with convection, as CBs, or precipitation, as rainband downdrafts, can influence and modify a storm's intensity to a larger extent than SST by itself. Dropsonde composites could be used to assess differences in intensifying and weakening storms in convective metrics such as core temperature, vertical wind speeds and frequency and distribution of large ascent (as a proxy for CBs), thus connecting and reinforcing studies mentioned in this section.

3.4 Eyewall processes

The eyewall is the ring-like region of highest vertical velocities that transports the energy of the ocean to the upper parts of the atmosphere through moist convection (Wang & Wu 2004). With the advent of new observations (such as those described in section 2) increased attention was put into the eyewall region (Rogers et al. 2006, Houze Jr et al. 2006) and extensive sampling of the eyewall was conducted in recent years. As a result, the eyewall replacement cycle was shown to be the most relevant process affecting the intensity of TCs in the eyewall region (Wang & Wu 2004, Houze et al. 2007, Didlake Jr & Houze Jr 2013).

The eyewall replacement mechanism occurs when on the outer edge of an existing eyewall a second outer eyewall is formed, thus, creating two regions of strong ascent and one region of inflow separating these two eyewalls, known as *the pouch* (Houze et al. 2007). Figure 7 illustrates the reflectivity structure in Hurricane Rita showing two eyewalls coexisting, separated by the dry pouch where some descent occurs. In this particular case, the new outer eyewall ascent appears weaker than the old inner eyewall. During the period shown by this figure, the storm halted its intensification cycle and weakened, however, as the outer eyewall contracted and the inner eyewall disappeared, Rita re-intensified.

Another example of a storm that underwent an eyewall replacement cycle was Hurricane Earl (Stevenson et al. 2014, Rogers et al. 2015); while undergoing rapid intensification Earl had an eyewall replacement cycle that, first, haltered the intensification and as the new eyewall contracted, Earl gained

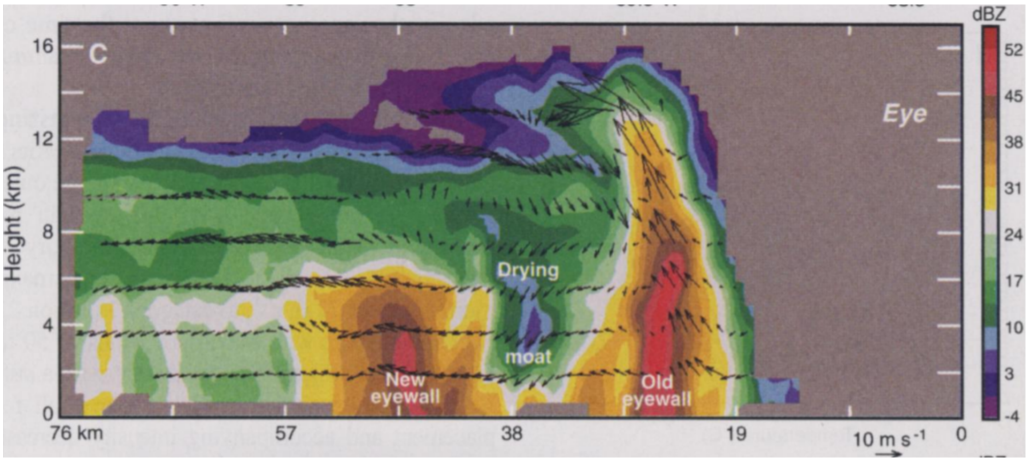


Figure 7: Flight level data observations of reflectivity (colour contours) and wind speed (black arrows) in Hurricane Rita, the moat, eye and eyewalls are labelled in white, the moat is observed as a dry zone between the inner and outer eyewall, from Houze et al. (2007).

intensity, just like Rita. Similar observations have been made in other storms, therefore showing that the eyewall replacement cycles can have an impact on the life-cycle and intensity of a TC.

Kepert (2013) provided an explanation for the existence of the eyewall replacement cycle arguing a boundary layer influence upon the vorticity field of the TC. Using three different numerical models, Kepert (2013) identified a positive feedback between the boundary layer influence on the vorticity field and convection that could explain the existence of the eyewall replacement cycles. This numerical study intertwines boundary layer, convection and eyewall processes for the intensification of TCs through the argument that boundary layer can influence convective and vorticity fields and generate eyewall replacement cycles.

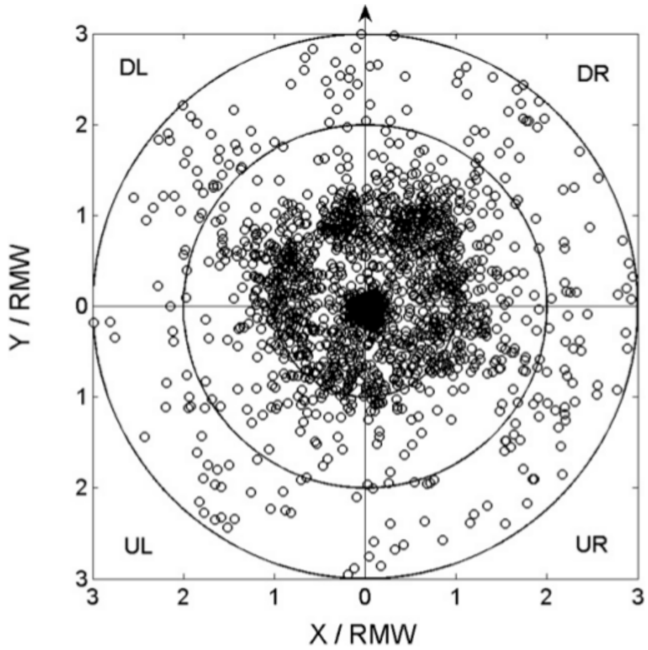
Eyewall mesovortices are another eyewall process related to TC intensification and they are that are un-related to eyewall replacement cycles (Wang & Wu 2004). These mesovortices a are observed as intense transitions of vorticity near the eyewall region of both weak and intense TCs (Li et al. 2013). Eyewall mesovortices can rotate around the centre of the storm (Braun & Wu 2007) and due to their intense local circulation these vortices can import high-entropy air into the ascent region in the eyewall. Montgomery et al. (2006) studied the impact of mesovortices on the maintenance of Hurricane Isabel (2003) and suggested that a TC intensity can be sustained solely through the transport of this air to the eyewall through mesovortices.

Eyewall replacement cycles are considered the primary driver of intensity related to eyewall processes (Wang & Wu 2004, Houze et al. 2007). The specific mechanisms that associate the formation of two eyewalls with weakening and the subsequent contraction are unclear, but the general sense is that during the eyewall replacement cycles the storm losses it intensity or, at least, stop the intensification process, followed by a re-intensification associated with the contraction of the outer eyewall (Wang & Wu 2004, Kepert 2013).

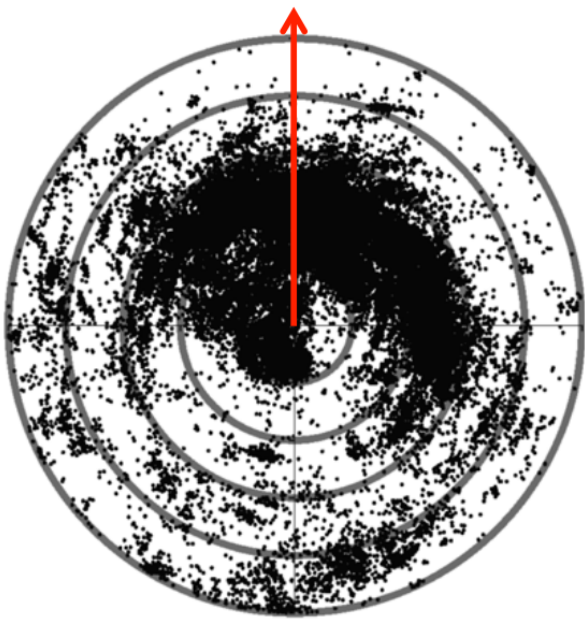
3.5 The role of symmetry for intensity changes

TCs are usually depicted as axis-symmetric organized systems, *i.e.*, they are azimuthally symmetric, therefore, most theoretical early models considered the dynamics of TCs to be only two-dimensional (Emanuel 1991), where only the distance from the eye and the height were the important coordinates to be described. However, as it has been stated in previous sections, asymmetries in several variables arise and these asymmetries are associated with intensity changes. The dominant asymmetric structure is imposed by the environmental vertical wind shear (Zhang et al. 2013, Montgomery & Smith 2017), *i.e.*, properties are asymmetric with respect to the shear vector, but other asymmetries may arise forced by the vorticity and moisture distributions (Zawislak et al. 2016).

Shear is the vector difference of wind speed between adjacent layers of the atmosphere and it is generally considered to be detrimental to TC organization and structure since strong vertical wind shear tends to decompose the vortex organization in the larger scale. However, in the small scale,



(a) Composite dropsonde distribution, both axes are normalized by RMW. The shear vector points northwards and the down-shear right (DR), down-shear left (DL), up-shear right (UR) and up-shear left (UL) regions are indicated in each quadrant, from Zhang et al. (2013).



(b) Lightning distribution in Hurricane Earl (2014), the shear vector is depicted by the red arrow in the down-shear direction and range rings are observed as solid circular grey lines and are drawn every 100 km. Taken from Stevenson et al. (2014).

Figure 8: Plan views of a) dropsonde and b) lightning distribution in a shear relative framework for a dropsonde composite and for a particular TC, respectively.

longevity and intensity of TCs were associated with asymmetric patterns in TC. Observations show that shear-relative asymmetries exist in temperature, moisture wind speed and precipitation (Cione et al. 2013) and these asymmetries are associated with intensity changes (Hendricks et al. 2010). For these reasons, some studies of intensity change re-organized their samples to be shear-relative.

For this purpose, the shear vector is oriented northwards and each data point is then located according to their relative position to the wind shear vector. Figure 8 illustrates this method of redistributing observations in a shear-relative framework. First, figure 8a) shows the shear-relative dropsonde distribution of the composite of Zhang et al. (2013) with a dominant distribution of the dropsondes inside the RMW and the slight dominance of dropsonde observed in the down-shear quadrants. Second, figure 8b) shows the lightning distribution in Hurricane Earl, where the down-shear section is dominant. Lightning distribution in Earl was considered as a proxy for convection, given that lightning occurs where ice and strong vertical velocities (ω) occur, both associated with deep convection (Stevenson et al. 2014).

An example of intensity differences in shear-relative frameworks was introduced in figure 4 where the radial wind is shown specifically in the down-shear right quadrant of Zhang et al. (2013)'s composite. This study found differences in the strength and distribution of both radial and azimuthal wind speeds in the vertical cross sections of all four quadrants of figure 8a). In other words, the dynamic flow around a TC is, generally, dependent on the relative position to the shear vector.

Another dynamical feature dependent on their relative location to shear is vertical wind speed. Dropsondes with extremely high ω, where the dropsonde itself stopped its descent and partially ascended, denominated *upsondes*, are observed in regions of extreme winds inside a TC. Stern et al. (2016) found that the frequency of upsondes is highly asymmetrical in a dropsonde composite. In fact, the occurrence of extreme updrafts when the motion of the TC was aligned with the shear vector was 10 times more frequent than when the motion was opposed to shear.

Moisture and convective metrics are also factors that have presented asymmetric features in shear-relative intensity change composites (Cione et al. 2013, Rogers et al. 2013, Harnos et al. 2011). In particular, Cione et al. (2013) observed a significant difference in surface specific humidity between intensifying ($18.8g/kg$) and weakening ($21g/kg$) composites for the down-shear quadrant measured by the TCBD. Zhang et al. (2013) also explored the differences in humidity in a shear-relative framework and found that the right hand quadrants, both down and up-shear, were moister than the respective left-hand quadrants. Due to the fact that Zhang et al. (2013) did not further sub-divide their samples by intensity changes, so no real comparison can be made with the study of Cione et al. (2013).

Convective bursts, described in section 3.3, frequency and distribution are a key parameter to predict TC rapid intensification (Rogers et al. 2015, 2016, Zawislak et al. 2016). Figure 6 shows a reflectivity plan view of Hurricane Earl where convective bursts are observed relative to the shear and motion vectors. The distribution of CBs throughout the intensification processes of Earl was predominantly found to the left of the shear vector (see figure 6) (Rogers et al. 2015), whereas lightning activity was located primarily down-shear (see figure 8b) (Stevenson et al. 2014).

In the study of Hurricane Edouard, Rogers et al. (2016) and Zawislak et al. (2016) found asymmetries in both the kinematic and the precipitation structure. Specifically, the precipitation structure was asymmetric when Edouard was in a steady-state and it shifted to symmetric when Edouard was undergoing rapid intensification. However, both periods showed increased precipitation in the up and down-shear left quadrants.

Even though Zhang et al. (2013) provided evidence that radial and azimuthal wind speeds differ in the dropsonde coverage when separated by shear-relative quadrants, they did not establish how these differences would change if the sample was further sub-divided by intensity change, like Cione et al. (2013) did for the buoy observations. Also, while asymmetries in individual storms (*e.g.* Hurricanes Earl, Rita, Edouard) have been extensively studied observing convective and precipitation parameters, there is no composite analysis of how these asymmetries affect intensity change in a more robust sense. This proposition would suggest the need for a comprehensive study to obtain global conclusions on how shear-relative asymmetry affects TC intensity and the dropsonde coverage can provide information on temperature, moisture and dynamical flow in a shear-relative framework.

4 Concluding Remarks

The advent of satellites and the introduction of onboard high-resolution instrumentation into research aircraft has provided unprecedented data of inner-core regions of TCs. Through a combination of all available observational datasets, research is now focused on understanding inner-core features and their association with TC intensification and weakening.

The complex interplay of processes around or in the inner core that affect the intensity of a TC was illustrated by this literature review. Air-sea interaction drives the fluxes of energy in the TC vertical circulation and thus can be seen as the engine of a TC, however, SST is most important to organize a TC but it observations suggest that it secondary to sudden changes of intensity, particularly rapid intensification. The TCBL determines the rate of inflow and the physical properties of air that is convected upwards by the eyewall region, thus it poses a dynamical and thermodynamical effect upon TC intensity. Several thermodynamic features are a good indicator of intensity change such as core temperature and CBs activity and distribution whereas the relation between other metrics, as CAPE, with intensity is unclear. Eyewall replacement cycles weaken TCs at first but then act to re-intensify the storm. Shear-relative asymmetries dominate characteristics such as CBs and lightning activity and they also pose a relatively important constraint in the dynamical flow.

This literature review has elucidated the main known mechanisms and observations of intensity drivers but it has also highlighted gaps in observational studies. Several examples were discussed where the observations were binned by intensity change (e.g. Harnos et al. 2011, Cione et al. 2013, Rogers et al. 2013) but none of them used the dropsonde coverage as their primary source of data. There is a need for a composite analysis of the dropsonde coverage where the observations are binned by intensity change to detail differences in sets for some of the metrics that were discussed in this literature review: CAPE, radial and tangential wind speed, upsonde frequency and distribution, core temperature and low-level moisture. Similarly, given the importance of shear-relative symmetry, such a dropsonde study should consider further subdividing the observations by shear-relative quadrants since most papers studied either intensity change composites or shear-relative symmetries but a combination of them is scarce in the literature presented here.

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