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Dissertation Research Proposal

Dropsonde Observations of Intensity Changes in Tropical Cyclones

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Abstract

Forecasting the intensity of Tropical Cyclones (TC) remains one of the great unsolved problems in tropical meteorology and the ever lasting threat of these weather systems keeps motivating research to elucidate physical processes that intensify these storms. This study proposes the use of dropsonde observations to assess the role of inner-core processes in modifying the intensity of a TC. A relevant and well sampled storm will first be studied and described to relate dropsonde observations to the storm's intensity change, subsequently, dropsonde observations will be composited by the sign and magnitude of their respective changes in intensity. Several dynamic and thermodynamic metrics will be used to provide a generalized view of factors affecting intensity change with particular emphasis on the role of symmetry for intensity in TC. These results will be useful to modeling research groups or forecasting agencies to validate and improve existing models that forecast the intensity of TC.

Scientific Rationale

Tropical Cyclones (TC) are one of the most studied atmospheric phenomena as well as one of the most harmful ones. Every year, these weather systems cause economic and human impacts across the world, motivating scientists to be able to predict their track and intensity. To that end, research is concentrated in increasing our basic understanding of the physical processes that drive intensity changes with the premise that a thorough description of the forces in play will lead to better forecasts, thus, decreasing the socio-economic risk of these systems (Emanuel 1991, Gall et al. 2013). However, state of the art forecasts still lack the ability to predict rapid intensification and intensity changes in general (Rappaport et al. 2009, Rogers et al. 2006); for instance, the strongest hurricane on record, Patricia (2015), experienced an intensification process like no other (see Figure 1), currently holding the record of fastest intensification rate (Rogers et al. 2017). Figures 1 also illustrates that the statistical and dynamical models did a poor job forecasting the intensity change of this very dangerous record-breaking storm (Rogers et al. 2017).

There are several reasons for prognostic models not to accurately forecast intensity changes but, the most important one is the fact that the physical processes that intensify or weaken a storm are not fully understood (Braun et al. 2013, DeMaria et al. 2014). In fact, the organization and intensification of TC is still a very active field in theoretical tropical meteorology (Montgomery et al. 2015). This lack of understanding causes large spreads and disagreements between numerical models of convection and intensity of a TC.

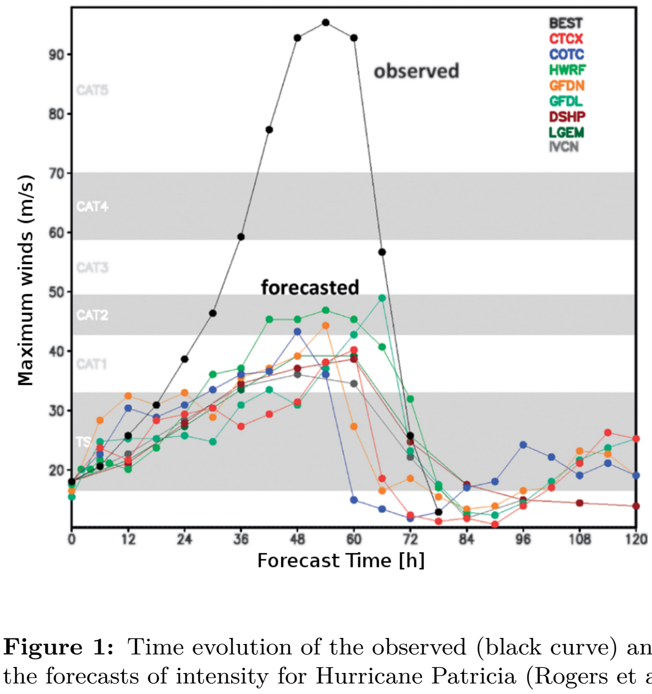

Figure 1: Time evolution of the observed (black curve) and the forecasts of intensity for Hurricane Patricia (Rogers et al. 2017).

The limited record of satellite observations and the inherent danger of sampling TC directly, *i.e.*, lack of reliable long-term observations, has greatly limited our capability to increase our understanding of these physical processes. In spite of these shortcomings, many studies (Hendricks et al. 2010, Cione et al. 2013, Kelley et al. 2004) have documented several mechanisms that enhance and intensify tropical cyclones, still, their scope and validity is restricted to particular cases and environments, thus, most studies have not been able to generalize processes and structures related to intensity changes in TC. A particular challenge relies on the vast possible processes that can affect the intensity of a TC, either large-scale environmental influence, air-sea interactions on the mesoscale or the smaller scale processes affecting dynamical internal features of the storm. Thus, the intensity of a TC becomes a function of a large combination of processes across all atmospheric scales.

Observations are one of the key tools in unraveling this conundrum (Rogers et al. 2006, Braun et al. 2013), in particular, the use of dropwindsondes (dropsondes for short) has proven to be effective for their vertical resolution and the long-term historical record of the over 20 years of storms that have allowed for multiple studies and their use has improved real-time forecasts (Wang et al. 2015, Gall et al. 2013). Dropsondes provide unique *in-situ* information about the eye, eyewall and the environment of a TC. The data collected by dropsondes thus provides a 3D sampling of TC by examining the thermodynamic and dynamic zonal and vertical features of a particular storm. Due to the long record and detailed information they provide, dropsondes are considered vital sources of data for both forecasters and researchers specialized in changes of intensity (Franklin et al. 2003).

This study is thus motivated by the need of observational insight to improve intensity forecasts, as such, dropsonde observations will be used to characterize a particular storm while suffering intensity changes and, secondly, dropsonde composites will be created for several storms in order to understand some dynamical and thermodynamical processes that drive intensity changes.

Background

Tropical Cyclone intensification is a very active area of research given the very large destructive potential of these systems across several ocean basins. However, the main dynamical theories developed since 1960 for genesis and development of TC have constantly been improved, debated and are still criticized repeatedly (e.g. Riemer et al. (2010), Montgomery et al. (2015)); this lack of agreement shows that our basic understanding of these natural phenomena still has room to improve.

The National Hurricane Center (NHC) and the National Ocean and Atmospheric Administration (NOAA) have thus declared a *priority* to improve our forecasting ability of intensity changes and, particularly, rapid intensification (Rappaport et al. 2009). Modelling, theory and observational work are required as an integral approach to fulfil this goal. While numerical model experiments have received a boost with increased computational capacity, the role of observations is still considered key to validate these models and provide physical insight on ongoing processes changing the intensity and track of storms (Braun et al. 2013).

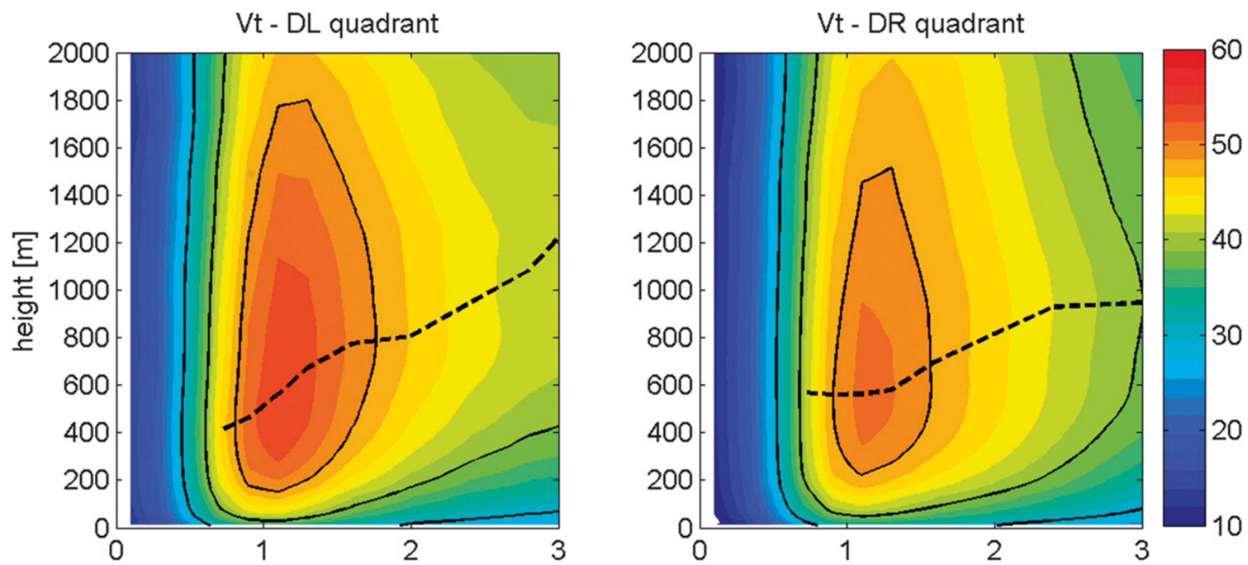

Figure 2: Tangential velocity for the dropsonde composite for the down-shear left and right quadrants oriented in a shear relative framework, the x-axis is a normalized (by the radius of maximum wind) distance scale, taken from Zhang et al. (2013).

One of the most important observational tools are dropsondes, these are scientific instruments launched from aircrafts, equipped with a parachute to delay its fall, a Global Positioning System (GPS) and a set of high-quality sensors. They have been used for over 20 years in the East Pacific and Atlantic Oceans by the Hurricane Research Division (HDR), the National Hurricane Center (NHC) and the US Air Force; these missions have sampled a wide range of storms across these two oceans, thus accounting for over 13,700 dropsondes from 1996 to 2012 (Wang et al. 2015).

This large dataset provides vertical information across several regions of TCs and reports relevant variables such as pressure, geopotential altitude, temperature, humidity and 3-D wind speed with a high precision location system to estimate the sonde's position during its descent. The vertical extent or height of the drop is limited by conditions within the storm and the research goals of the particular flight, thus, dropsondes have been launched from many altitudes, ranging from 2000 to 8000 m.

Dropsondes are now considered key in the study of TC for two main reasons, first, they provide *in-situ* data, unlike satellite observations, to forecast agencies in real time which has increased the accuracy of models, but also, dropsondes provided new information that increased our understanding of several dynamical processes and features of these weather systems. Moreover, research scientists flying on the aircraft usually decide when and where to launch a dropsonde, whether to sample the eyewall of a storm or the thermodynamic environment of a TC, which then means that dropsondes not only provide the most significant source of real-time data used for forecast models but they are also vital for subsequent posterior studies.

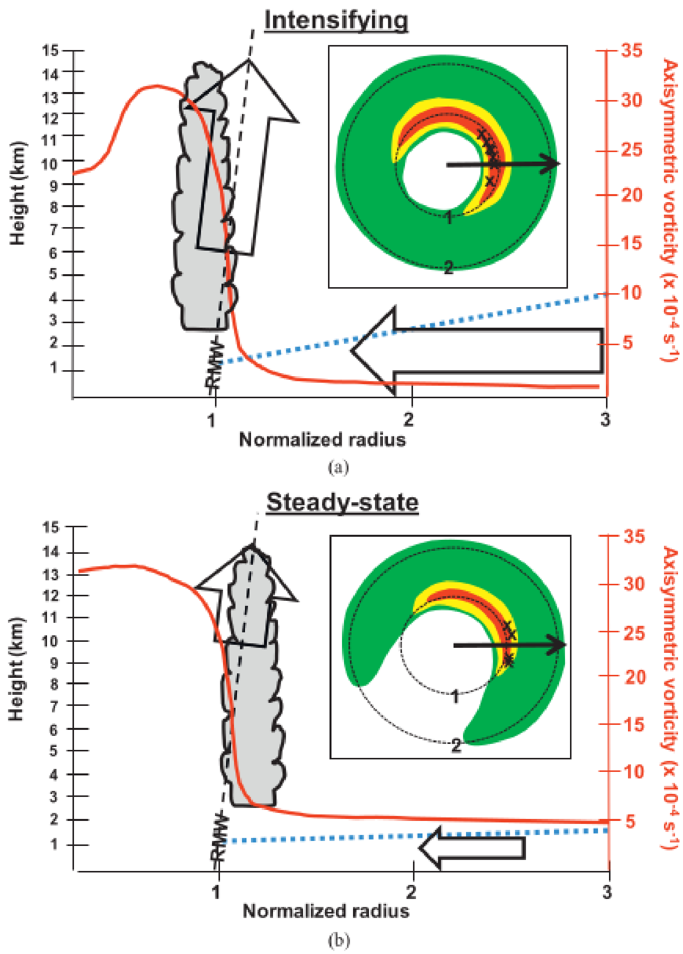

Figure 3: a) Intensifying and b) steady-state dynamical schematics from Rogers et al. (2013), showing the vorticity profile (red) and arrows relate the strength of winds. Plan views of reflectivity are also added and the Radius of Maximum Wind (RMW) is included.

Through the analysis of dropsondes several mechanisms relevant to the longevity and dynamics of a TC have been found. For instance, Houze et al. (2007) found evidence of the eyewall replacement mechanism based on the analysis of Hurricane Rita's dropsondes in 2005. Similarly, Zhang et al. (2013) made composites of a large set of available dropsondes to understand the relationship between the hurricane boundary layer asymmetries and the environmental vertical wind shear, finding differences of radial and tangential wind for different quadrants oriented to shear. Figure 2 shows the tangential velocity for different shear-relative quadrants with noticeable differences in the magnitude and distribution of the tangential speed depending on the quadrant, through this figure, Zhang et al. (2013) argued that symmetry, particularly shear-relative symmetry, should play a role in the intensification of TC.

Air-sea interaction is recognized as an important factor in TC organization and intensification (Montgomery et al. 2015, Emanuel 1991). Therefore, estimates of ocean surface fluxes, such as drag and momentum fluxes, are a very important metric that is related to changes in intensity since these fluxes are a measure of how the storm dissipates or draws energy. In particular, latent and sensible heat fluxes are important to maintain organized convection but, momentum and enthalpy fluxes could also prove to play a role and can be estimated from droponse profiles (Richter et al. 2016).

A number of TC were very sampled by dropsonde missions and, particularly those that suffered rapid intensification, have been thoroughly studied and described; for example, Earl in 2010 suffered two intensification processes that were very well sampled by the dropsonde coverage and Montgomery et al. (2014) were able to determine inner-core dynamical and thermodynamical dropsonde related metrics to the observed intensity changes, and even more so, to frame them in the context of their general paradigm for TC intensification (Montgomery et al. 2015) reaching the conclusion that Earl's intensification was caused by boundary layer and conventional vortex spin-up. A large number of other studies have been carried on a number of storms to study different influences on the observed intensity of a TC. Thus, dropsonde observations serve two purposes, the first is to aid studies of individual storms to characterize their lifecycle and secondly, dropsonde composites, such as Zhang et al. (2013), assess mean or statistical differences in a wide range of metrics such as updraft speed, potential vorticity, etc.

Other examples of observational studies, that have not used dropsondes, have also gathered storms as composites, particularly by their observed intensity change. For example, Rogers et al. (2013) registered differences between intensifying and steady-state storms using the flight-level Doppler radar dataset (see Data section) recovered at several flight missions by NOAA. The end result of this study was a diagram that illustrates (figure 3) the fact that intensifying storms posses a stronger and deeper inflow layer as well as stronger updrafts. The need to understand intensity changes has motivated an intensive line of study covering a wide range of relevant factors, while studies used buoy data to highlight air-sea interactions (Cione et al. 2013) others used satellite data to assess the environmental large-scale influence (Harnos et al. 2011) and the effect that the height of convection and tall precipitation cells (Kelley et al. 2004) has on intensity changes. A relevant note is that the aforementioned studies composited and binned their different datasets by intensity change to generalize their results and remarks.

One of the main goals of analyzing intensity change observations is to provide information to aid and improve our forecasting ability, for these purposes, Kaplan et al. (2010) developed a rapid intensification index that is based on environmental factors or *predictors* to relate environmental and storm-related features to statistical or probabilistic functions of a given intensity change to occur. Through the use of satellite and buoy observations, the probability of rapid intensification of a given TC is estimated based on the historical observed record of environmental influences and observed intensity changes. In other words, Kaplan uses environmental historical predictors to assess the likelihood of a storm experiencing rapid intensification.

In short, the intensity of TC has been studied in observational work through two main different approaches: first, the analysis of available observations of individual storms to describe the lifecycle of the storm through physical processes that explains the observed intensity, such as Montgomery et al. (2014). Secondly, the analysis of observational composites addressing mean differences between different categories (Zhang et al. 2013, Rogers et al. 2013). However, there is a lack of studies that composite dropsonde observations by intensity change, unlike with satellite Kelley et al. (2004), buoy Cione et al. (2013) and other existing observational datasets there is no understanding of the differences in dropsonde observations between different storms undergoing distinct changes intensity. Due to the relevant 3D information that dropsonde provides, we consider that a study that separates dropsonde composites by intensity change and presents the dynamical differences, if any, would certainly be of interest to modelling and forecasting agencies.

Objectives

Questions

1. Which internal processes can be observed to cause a storm's intensity to change?

2. How is the storm's symmetry linked to intensity changes?

Specific objectives

1. Characterize a storm that underwent intensity changes and was well-sampled over time.
   (a) Determine the dynamical and thermodynamical differences in the storm lifecycle while undergoing different intensity changes.
   (b) Relate these differences to inner-core processes to explain the observed intensity changes.
   (c) Assess the role of symmetry in the lifecycle of this storm.
2. Create dropsonde composites of TC divided by their changes in intensity, *i.e.*, assign dropsonde measurements to a given intensity change category (weakening, intensifying and steady-state) and identify the main differences in physical processes and metrics between the composites.
   (a) Determine the most and the least important factors in the intensity changes observed in the dropsonde coverage.
   (b) Assess the role and importance of symmetry for intensity changes.
   (c) Generalize the results and summarize them in a schematic (see figure 3).

Methodology and approach

Data

There are three main sources of data for this study:

- The dropsonde dataset by Wang et al. (2015) from 1996-2012 is the most complete existing record and has been through a number of quality controls and post-processing algorithms. This will be increased through the inclusion of the 2012-2016 observations from NOAA historical dropsonde record. These dataset then includes the processed data recovered from three different aircrafts (GIV, P-3.43 and P-3.42 as depicted by NOAA) and two different models of dropsondes.
- *Best track* is a well-known dataset that includes the track and intensity of any storm for the Pacific and Atlantic Basins every 6 h, made available by NOAA.
- *Flight level* data refers to the recorded observations taken by the aircraft *in situ* measurements (Vigh et al. 2015). Roughly, this dataset reports the Stepped Frequency Microwave Radiometer (SFMR) measurements of a Hurricane wind field, the dual-Doppler radar reflectivity observations and other possible instrumentation reports on-board for each of the flights conducted by NOAA. This dataset can also provide the track of a storm as well as a first approach to the RMW.

Data manipulation and analysis will be carried out in the free-software programming tools: Python and Julia.

Methodology

Objective 1

The dropsonde dataset will be surveyed to locate a storm that underwent several intensity changes and was well-sampled over time. Dropsonde observations will, first, be separated by the different sampling periods [1] to observe the storm's progression, then, they will be placed in a cylindrical coordinate system relative to the storm (e.g. Zhang et al. 2013, Montgomery et al. 2014), for this purpose, the best track and flight level data will be used as the best possible approximations to the storm's track.

[1] A sampling period is defined as a 4 hour period where a given aircraft sampled the storm via the use of dropsondes.

This will create a time series for the location of the centre of the storm which, in turn, will be used as the centre of the cylindrical coordinate system for any given dropsonde measurement.

A series of dynamical and thermodynamical variables will be estimated for this storm to address objective 1a), for example, the circulation around the storm, the convective available potential energy (CAPE) (Smith & Montgomery 2012) and the wind reduction factor, to name a few. Subsequently, the role of symmetry (objective 2c) will be analyzed in the calculated metrics (see figure 2) by separating the coordinate space into quadrants. This is traditionally computed by identifying the shear [2] directions at a given time and subsequently, locating a given dropsonde measurement relative to that shear direction. For this purpose, several databases that offer environmental wind shear direction and magnitude are available.

After performing these computations and analyzing the results, the storm's intensity history, *i.e.*, the development of the intensity of the storm over time will be related to the estimated metrics and with the help of produced plots, a physical explanation for the observed intensity changes and lifecycle of the TC will be given with particular emphasis on the role of symmetry, thus addressing the objective 1b) and completing the aims of the first objective of this study.

Objective 2

Subsequently, the second objective will be pursued by compositing TC by their intensity change, for this, only TCs that are considered to be well-sampled over time will be used, specifically, if dropsondes are available in three or more sampling periods and each sampling period contains at least 10 dropsondes in a 250 km radius. Well-sampled storms will then be subdivided by intensity change using the *best track* dataset and the classification of Harnos et al. (2011), which categorizes changes in wind speed ΔV (measured in knots kt) over a 24 h period as follows:

- Rapid intensification: $\geq$+30 kt/24h.
- Intensifying: $\geq$+10 kt/24h.
- Steady state: $\Delta V \leq$+10 kt/24h $\wedge \Delta V \geq$-10 kt/24h.
- Weakening: $\leq$ -10 kt/24 h.

After binning TCs into these categories, the storm track will be used to transfer all dropsonde data to storm-relative coordinates in a cylindrical coordinate system. The mean of the measured variables, such as wind speed or temperature, will be computed for each category to compare and contrast possible differences. In particular, similar metrics used for the first objective will be used, for instance, radial and azimuthal wind speeds (Zhang et al. 2013), convective available potential energy (CAPE) (Smith & Montgomery 2012), etc.

Richter et al. (2016) used the thermodynamic and wind profiles given by the dropsondes to estimate bulk surface fluxes of enthalpy, momentum and sensible and latent heat. In this novel methodology, the mean gradient of any quantity (for example wind speed) is solely based on the surface flux of that quantity and the height. In other words, by determining the slope of u, using wind as an example, and plotting it against the logarithm of z and estimating other parameters as surface roughness it is possible to estimate surface drag coefficients and fluxes. Determining the role of these fluxes, and comparing them, will be in place with objective 2a), pointing out the relative relevance of air-sea interaction to other dynamical features encompassed in this study.

In the assessment of environmental influences relevant for rapid intensification, Kaplan et al. (2010) statistically determined the most important features. Similarly, to fulfil objective 2a), after the computation of the previously stated metrics, an assessment will be made of the most and least influential metrics, *i.e.*, what variables are observed to present the largest or smallest (if any) differences between composites, this serves the purpose of highlighting the relevant physical processes for changes in intensity.

[2] Kaplan et al. (2010) defined shear as the vector difference between wind speed located at 200 and 800 hPa.

Furthermore, the analysis of symmetry and contribution of localized regions of the storm, objective 2b), is addressed by further subdividing the observations by region (eye, eyewall, etc.) or by shear-relative quadrants, this will provide information on the role of symmetry and particular regions of the TC relevant for intensity changes, this will be most useful if any given area of the storm shows a greater impact in intensity changes.

The results of the previous approach will elucidate possible physical mechanisms that drive intensity changes and more importantly, allow to generalize the results as indicated by objective 2c). For this purpose, these results will be shown in a summarizing diagram (such as figure 3), that will illustrate the main physical processes and properties that drive intensity changes in a clear and precise way to convey the main physical insight provided by this study.

To finalize this study, there exists the possibility of creating an intensity change index, this index could provide the probability of a given storm to suffer a given intensity change based on the results of this study and the observations of the storm available at the time. Different approaches could be taken for this purpose: a simple statistical prognostic tool, such as that of Kaplan et al. (2010).

Programme of research

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Individual storm data recollection	X	X						
Computation of dynamical and thermodynamical metrics	X	X	X					
Plan views and axis-symmetrical sections of individual storm plots.		X	X					
Symmetry study of individual storm		X	X	X				
Creation of composites		X	X	X				
Calculate cylindrical wind components for each composite			X	X				
Composite fluxes, circulation and other metrics				X	X			
Shear-relative subdivision				X	X			
Assessment of most and least important features					X	X		
Summary plots and schematics					X	X		
Write thesis						X	X	X

Outcome and Wider Implications

TC intensification, and changes of intensity in general, is considered a fundamental line of study given the complexity of the physical processes that drive intensity changes as well as the socio-economic impacts of intense TCs. Further research is needed to validate intensity forecasts and provide new insight into prognostic models. The use of dropsondes will certainly play a major role for this purpose given the unique information that they provide (Wang et al. 2015, Gall et al. 2013).

Immerse in this context, this study is relevant given that it will show the main differences in inner-core features, observed by a large number of dropsonde measurements, that drive intensity changes and, even if no significant differences are found, this would still be useful information since it would point out that other factors and variables not considered by this study could have a larger influence over TC intensity. Either way, this study will bridge the gap in our understanding of what processes are important and how do they actually contribute to any given intensity change observed. For instance, Zhang et al. (2013) and Cione et al. (2013) have argued that symmetry has a key role in the intensity of a TC and this study's results will test this hypothesis by analyzing how are inner-core thermodynamical and dynamical metrics different in several regions of the TC and how does symmetry affect these changes.

This study will complement existing knowledge and work done on intensity changes, given that, unlike studies focusing on the environmental variables, dropsondes have the advantage of sampling dynamical and thermodynamical variables in the eye, eyewall and surroundings of TC which makes this study novel and capable of validating model's representation of inner-core dynamics. This information will not only aid to the validation of models but it can also, ideally, be directly used by forecasting agencies and could be incorporated into their forecasting algorithm. If the intensity change index proofs to have moderate forecasting ability then, this index should also be provided to forecasting agencies to test its range of applicability in real-time forecasts.

If applicable, some insight given by this study could be made available to the dropsonde developers and organizations (NOAA, NASA and USAF) to point out further possible research and launch sites. For instance, if a particular region of a TC seems to be relevant for intensity changes, then, it would be in the interest of these organizations to perform a thorough sampling (by launching more dropsondes in this location) of this region and test if these data, when fed to real-time prognostic models, enhances the intensity forecasts.

The results of this project in the form of a set of summary plots and a schematic will be presented to the scientific community in the next Royal Meteorological Society Student Conference as well as to individual scientists from the Met Office studying intensity changes or complement currently ongoing research of rapid intensification at the University of Leeds. The outcome of this study will aid both scientific and operational groups concerned with gaining new insight of the drivers of TC intensity.

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