Evolution of Tropical Cyclones in North Atlantic mid-latitudes

A Reanalysis of 1987-2003

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June 27, 2014

Abstract

Tropical cyclones may undergo a major transition in their structure when they encounter circumstances that do not support the tropical structure of such a cyclone. This is called extratropical transition (ET). However, ET can take place in a number of different ways. To gain insight in these different ways of phase transition, this study uses a relatively high-resolution reanalysis dataset called MERRA and categorizes all tropical cyclones between 1987 and 2003 based on their thermal symmetry and core nature. The study also review the trajectory these tropical cyclones follow throughout the mid-latitudes. Generally, tropical cyclones that enter mid-latitudes follow a curved path from different places in the tropics towards the East American Coast, along which they tend to turn eastward along the Gulf Stream and when the influence of the westerlies becomes important. The amount of tropical cyclones that enter the mid-latitudes correlates well with the amount of tropical cyclones in general ($r = 0.77$), although it does not correlate well with the amount of cyclones that enters Europe ($r = 0.46$). Six different categories of phase cycles are found. 1) Tropical cyclones that undergo almost no transition. Cyclones going through this phase cycle are generally weaker in pressure and winds and do not reach far north. 2) Tropical cyclones that become thermally asymmetric while retaining their warm lower core. These are relatively strong and reach far north. 3) Tropical cyclones that become thermally asymmetric and then grow cold. Their tracks are close to the East American coast and are relatively strong. 4) Tropical cyclones whose core cools down and then start developing the asymmetric structure of an extratropical cyclone. These cyclones are highly variable in strength and track. 5) Tropical cyclones that seclude a shallow warm core after having had the extratropical characteristics of asymmetry and a cold-core nature. These cyclones are relatively strong and generally come far north. 6) Tropical cyclones that seclude a deep warm core after having had a shallow warm seclusion. These cyclones penetrate farthest north and are the strongest in pressure and winds.

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1 Introduction

1.1 Preface

Cyclones in the North Atlantic play an important role in the transport of heat and moisture and they can have severe consequences for the finances, food production and even housing within countries. Understanding these phenomena and predicting them is therefore of great importance. Among the cyclones present in the North Atlantic, two kinds of cyclones, inter alia, can be distinguished: *tropical* and *extratropical* cyclones. These two cyclone types have different characteristics. While extratropical cyclones arise in mid-latitudes and generally stay there, tropical cyclones originate from low latitudes and often move pole ward. This means that many tropical cyclones encounter rather different environmental characteristics than the ones that they originated from. Literature states that these cyclones may undergo a transition in their structure, gaining other (extratropical) characteristics (Hart, 2003) (Hart & Evans, 2001) (Evans & Hart, 2003) (Klein et al., 2000). This process is called *extratropical transition* (ET) and may take place in different ways with respect to the changes of the core structure. There have been developed several methods to describe these different ways (Hart, 2003) (Matano & Sekioka, 1971a) (Matano & Sekioka, 1971b) (Beven, 1997). This thesis will use the methods of Hart (2001) focused on the core structure to gain insight in what kind of transitions can be found in the North Atlantic. This is done by looking at observation-based (reanalysis) data of the period 1987-2003. To introduce the topic, the existing knowledge and literature on ET will be shown in the following section.

1.2 Theoretical Background

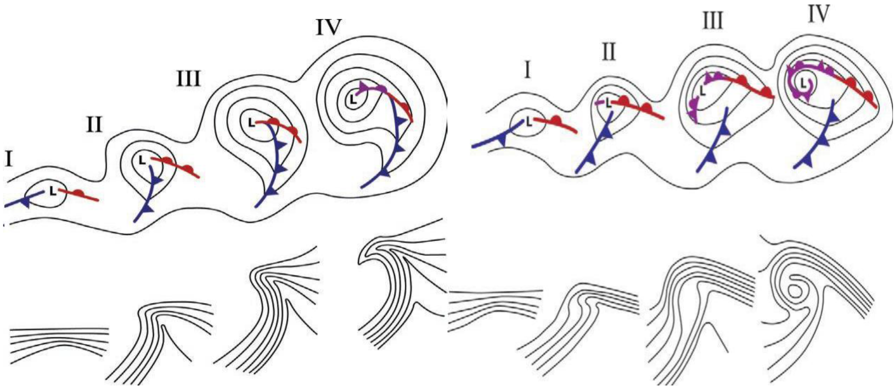
1.2.1 A brief Climatology of Tropical cyclones and Extratropical cyclones

The genesis of a tropical cyclone has been debated a lot (Gray, 1968). Kuo et al. (1964) state that the evolution of tropical cyclones consists of three stages. First of all an infant (cold-core) stage starting with pre-existing large-scale perturbations such as easterly waves (in the North Atlantic). This is followed by a more or less rapidly developing transitional stage in which the instability is holding for over a day and the lower level convergence and rising motion in the center starts. The surface pressure in the center drops and wind speeds start to increase. The cyclogenesis of tropical cyclones is concluded by a mature warm-core vortex stage, in which the system is called a tropical storm when it reached wind speeds of at least 18 m s^{-1}. Hurricane status is attained when wind speeds exceeded 33 m s^{-1}.

Six important conditions for tropical cyclones to be formed and maintained are high sea surface temperatures (Ooyama, 1969), atmospheric instability (and moist convection), moisture availability, pre-existing near-surface disturbances (Kuo, 1964), low levels of vertical wind shear and a strong enough Coriolis force (i.e. not near the equator) (Nelson, 2012).

When tropical cyclones enter mid-latitudes, they come across regions with high temperature gradients. These areas contain locations of baroclinic instability (basically areas with strong temperature gradients), which are the birth-ground for extratropical cyclones. There are two conceptual models on the life-cycle of extratropical cyclones: the Norwegian model and the Shapiro-Keyser model. The Norwegian model is associated with the view on fronts as being discontinuities in the temperature field (Schultz et al., 1998).

Along a frontal boundary, an initial wave disturbance can develop into a cyclone. This development is further aided by the existance of a jet streak. *Jet streaks* are local wind maxima within a *jet stream*, which are narrow air streams with relatively high wind velocities meandering around the globe. Jet streams are in close proximity of strong temperature gradients, which means jet streaks



(a) (b)

Figure 1: Conceptuals model of the genesis of an extratropical cyclone according to the (a) Norwegian model and the (b) Shapiro-Keyser model. The upper figures show the positions of the fronts, the geopotential height minimum (denoted by L) and isobars. The lower figures show the positions of the isotherms.

are, too. In the Northern Hemisphere, jet streaks often have warmer air south and cooler air north of them. Because of the vertical cross-frontal circulations that arise near the entrance and the exit, air masses near the surface at the entrance of the jet move southward and air masses near the surface at the exit of the jet move northward. Because of this wave, a warm front in the east moves northward and a cold front in the west moves southward (Fig. 1a I). As cold fronts move faster than warm fronts do, the cold front catches up with the warm front, creating an occlusion front. This will form a hook-like figure of isotherms ('bent back warm front'), which is visible in the bottom part of Fig. 1a IV. In advance of the cold front, an area of polewards moving warm moist air slopes up which is called the *warm conveyor belt*. The *cold conveyor belt* is positioned in advance of the warm front, wrapped around the hook-like figure.

The second important model on the life-cycle of extratropical cyclones is the *Shapiro-Keyser model* (see Fig. 1b). The main difference with the Norwegian model is that in the Shapiro-Keyser model, the cold and warm fronts do not remain in touch in the low pressure center, but the cold front propagates into the warm area, perpendicular to and separate from the warm front (see Fig. 1b II). This is called *frontal fracture*, which does not appear in the Norwegian model. A characteristic *frontal T-bone* arises after the frontal fracture. As can be seen in Fig. 1b, an occluded front will still arise near the center of the low pressure. This is due to the wrapping up of the thermal wave (Schultz et al., 1998). This leads to the trapping of warm air in the core of the storm (wrapped by the cold conveyor belt), which is called *warm seclusion*.

Both of the models are associated with the evolution of a frontal nature, which creates asymmetry in the temperature and precipitation fields. This in contrast with tropical cyclones. There are more differences between tropical and extratropical cyclones. These are shown in Tab. 1. Besides the difference in thermal symmetry, the difference in thermal nature of the cyclone's core is an important difference, too. While tropical cyclones have a (tropospheric) warm core, extratropical cyclones generally have a (tropospheric) cold core. An exception to the latter can be found in cases of warm seclusions, that have a warm lower core. The term "warm core" refers to the core being relatively warmer than its environment at the same pressure surface.

Table 1: Important differences between tropical and extratropical cyclones (Mass, 2014).

Tropical cyclones	**Extratropical cyclones**
Non-frontal	Frontal
Wind maximum close to the cyclone center	Wind maximum removed from the center
Wind maximum in lower troposphere	Wind maximum in upper troposphere
Warm core	Cold core (baroclinic)
Energy source is latent heat release	Energy source is zonal potential energy
Symmetric in precipitation	Asymmetric in precipitation: left of track
Originates above high surface temperatures	Originates in baroclinic instable areas

1.2.2 Extratropical transition

Although, as is visible in Tab. 1, the differences between tropical and extratropical are significant, no less than 46% of all (Atlantic) tropical cyclones since 1950 underwent a transition in which they attained many characteristics of extratropical cyclones and partly lost their tropical nature (Hart & Evans, 2001). As is already mentioned, this process is called *extratropical transition* (ET).

Matano and Sekioka (1971) proposed the idea that a tropical cyclone in the mid-latitudes could either (1) form a complex system by interaction with a pre-existing front, in that way inducing an extratropical cyclone, (2) form a compound system by interaction with a pre-existing extratropical cyclone or (3) passing over a front without significant interaction. Another conceptual model on ET has been proposed by Hart (2001) in the form of a phase space concept. Three parameters are used in this phase space. The first concerns the thermal symmetry of the cyclone, using the effect of the temperature on the geopotential height differences in the proximity of the cyclone. The other two indicate whether the core is warm or cold in two different layers (900-600 hPa and 600-300 hPa), calculated by the vertical derivative of the maximal geopotential height gradient within an area of 500 km (based on the assumption of thermal wind balance). With these parameters, the cyclone's symmetry and core nature could be described. Klein et al. (2000) suggested a new conceptual model viewing ET as a two-stage process (see Fig. 2. With a modification of Jones et al. (2003) these stages are the *transformation stage* and the *extratropical stage* (or *reintensification stage* in Klein et al., 2000). Agusti-Panareda et al. (2004) added a third stage prior to these two in their study of *Irene* (1999): the *tropical stage*. Not all tropical cyclones enter all three stages (Agusti-Panareda et al., 2004).

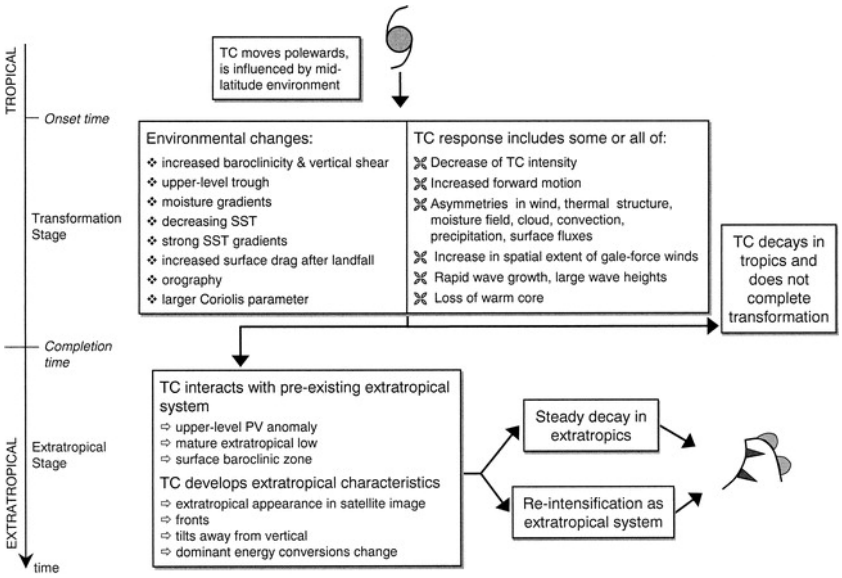


Figure 2: Schematic view on the classification of extratropical transition as described by Klein et al. (2000) and Jones et al. (2003). The onset and completion times correspond to the definitions of Evans and Hart (2003). Figure from Jones et al. (2003).

The *tropical stage* contains the development and life cycle of the storm as a tropical depression, storm or hurricane. The tropical cyclone then moves poleward into areas with different characteristics. If they remain on sea, they could encounter strong vertical shear, increased baroclinity, meridional humidity gradients, decrease sea surface temperatures (SST), strong SST gradients and the effects of an increased Coriolis parameter. Some make landfall and may, along with some of the changes just mentioned, also encounter orography, increased surface drag and the effects of reduced surface fluxes. The *onset time* is the time at which the influence of these new environmental conditions starts to become significant. In the literature, the exact definition of this point in time has been debated. Among the different definitions, Hart (2003) proposed using the conceptual model on core symmetry and nature (Hart & Evans, 2001) that the onset time is at the time at which the thermal symmetry parameter exceeds a certain level, i.e. the cyclone becomes thermally asymmetric (Klein et al., 2000, uses the same basis for the definition of the onset time). It marks the end of the tropical stage and the beginning of the transformation stage.

The transformation stage consists of the merging or interaction of the cyclone with an extratropical system (or upper-level trough) or at least the interaction of the cyclone to its new environment. During the ET, the tropical cyclone generally has an increased translation speed. The position of favorable regions for the transition varies: early and late in the season it is mostly between 30°-35°N and at the peak of the season it is often at higher latitudes (40°-50°). ET mostly happens in September (Hart & Evans, 2001), a result that is probably closely linked to the peak of the Hurricane season itself (which is September, too). In the early stages of ET, the cyclone tends to weaken first (Hart & Evans, 2001), this is in many cases to some extent due to the interaction between the cyclone and an upper-level trough, as the latter is associated with high vertical wind shear. The decrease in intensity of the cyclone will also depend on the inner-core convection evolution by the environmental changes (Jones et al., 2003). The interaction of tropical cyclones with the increased vertical shear in mid-latitudes includes the vertical tilt of the cyclone and thus the asymmetry in temperature and vertical motion. The magnitude and direction of the tilt depends on the strength of the shear and the strength and size of the tropical cyclone (Jones et al., 2003). It is modeled by Ritchie and Elsberry (2001) that strong vertical shear erodes the upper-level potential vorticity (PV) anomaly, together with the downshear tilt of the mid- and lower-level PV anomaly. Two processes have been discussed by Jones et al. (2003) to be mechanisms by which the interaction between a tropical cyclone and an extratropical system lead to the modification of the extratropical system. First the adiabatic interaction between the PV of a tropical cyclone and that of a mid-latitude jet and second, the influence of diabatically modified PV on the mid-latitude circulation. In the development of a extratropical system (as described above), increased frontogenesis leads to a strengthening of (adiabatic) frontal circulation and more latent heat release, which results in a nonlinear positive feedback (Jones et al., 2003). It is suggested that surface fluxes (of heat and moisture) also play an important role in the preconditioning of the environment into which the cyclone is moving: to allow for latent heat release during the development of the extratropical system (Jones et al., 2003). However, latent heat release is not the driving force for extratropical cyclones, which baroclinic instability and the potential energy. The kinetic energy for the ET in specific originates from cross-isobaric flow to lower pressure (potential energy from pressure gradients) and horizontal flux convergence of kinetic energy from the surrounding region. Summarized, important changes to the tropical cyclone during an ET are the loss of organized convection in the inner core, the increase in translation speed, the loss of upper-level outflow circulation, frontogenesis (a comma-shaped cloud pattern), asymmetry in the precipitation (moisture) and temperature fields and the expanding of the gale force winds area (Hart & Evans, 2001). Other changes are the loss of the typical high-cloud canopy over tropical cyclones and the exposure of the low-level circulation center. Hart (2003) defined ET in his phase space analyses to be the increase in thermal asymmetry and cooling of the upper and lower core. To order the many different effects of ET, ET is divided into three steps by Klein et al. (2000) as shown in Fig. 3, each of which has its own dominating effects.

The extratropical stage may contain the decay or the reintensification of the cyclone. About half of the ETs (Hart & Evans, 2001) reintensify. Most storms that reintensify originated from the deep tropics (Hart & Evans, 2001). It is stated that this might suggest that storms that have the most purely tropical origins and are the strongest (climatologically) are the most likely to undergo reintensificaiton after their transition. Around 50% of the post-transition intensity change variability can be described by the transit time a tropical cyclone requires to enter the region of baroclinic instability after leaving the tropically supportive region. (Hart & Evans, 2001). Both weak and strong cyclones can reintensify, but weak cyclones need to have a smaller transit time. A main feature in this stage is increased frontogenesis with a well-defined warm frontal region. The cold baroclinic core may stay, but in some cases a warm seclusion may occur (as described above) in this stage. Latent heat release and energy surface fluxes may remain important.

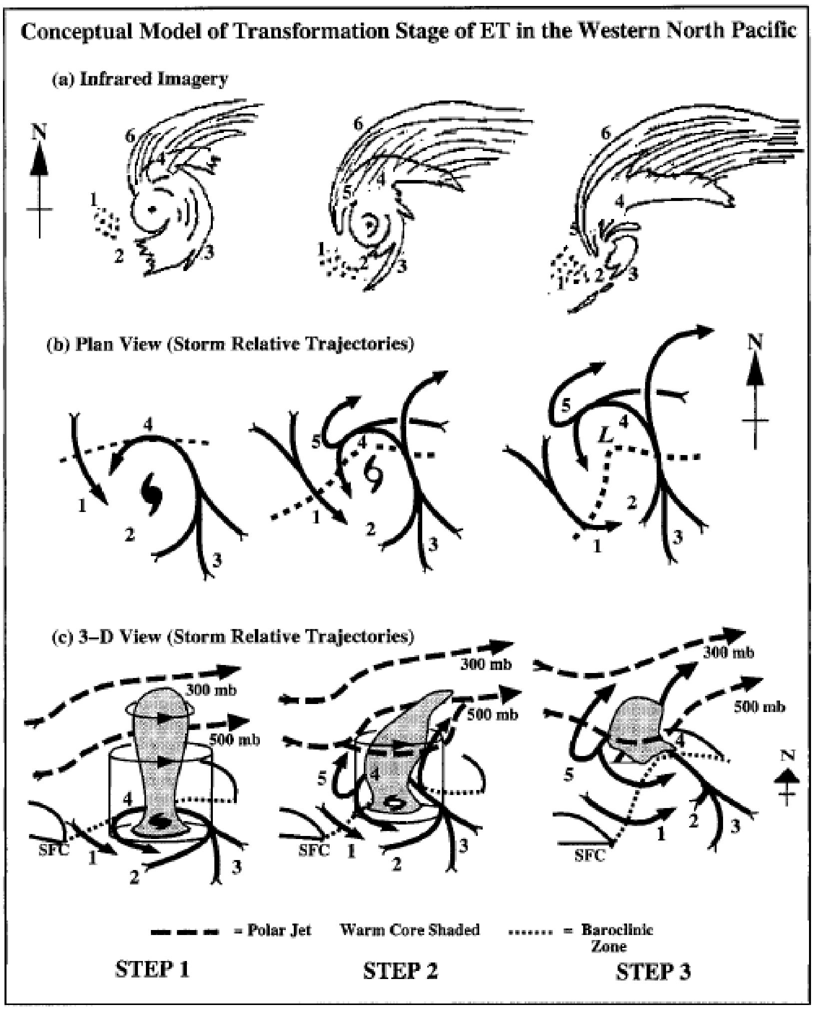


Figure 3: Conceptual model of the transformation stage of ET as proposed by Klein et al. (2000). Numbering is as follows: 1) environmental equatorward flow of cooler, drier air, 2) decreased convection in the western quadrant in step 1, extending to the southern quadrant in steps 2 and 3, 3) environmental poleward flow of warm, moist air is ingested into tropical cyclone circulation (maintaining convection in the eastern quadrant resulting in asymmetric distribution of precipitation), 4) ascent of warm, moist inflow over tilted isentropic surfaces due to baroclinity, 5) ascent producing cloudbands wrapping westward and equatorward around the storm center and the eyewall convection is being erosed by dry-adiabatic descent near the circulation center, 6) cirrus shield with a sharp cloud edge. Figure from Klein et al. (2000).

1.3 Target of the thesis

There is much literature on hurricanes reaching Europe (e.g. Haarsma et al., 2013), on hurricanes in general (e.g. Gray, 1984), on extratropical transition in general (e.g. Hart, 2001) or on cyclones in general (e.g. Hart, 2003). Categorizations of extratropical transition have been made as described above. However, a complete overview of the ET in the North Atlantic has been hampered by the lack of reliable data. The limitations concern the relatively low temporal and spacial resolution. However, in this thesis a new reanalysis data set MERRA (see section for details) with sufficient temporal and structural resolution is used, which allows for better analysis of the ET. This thesis focuses on the group of tropical cyclones that enter the mid-latitudes and provides insight in the evolution of these cyclones. Therefore, the main question that will be treated in this thesis is the following:

How do tropical cyclones that enter mid-latitudes evolve in structure and in their path?

This is a rather broad question and two aspects to the answer of this question will be discussed in this thesis. The first aspect concerns the core structure of the tropical cyclone and can be described by the following subquestion:

Subquestion 1. *How do the thermal symmetry and the warm-core structure of tropical cyclones evolve when they enter mid-latitudes?*

As has been discussed above, Hart (2001) suggested a way of describing the structure of cyclones by creating a phase space based on three parameters: one concerning the symmetry of the cyclone and the other two indicate whether the core at particular heights is warm or cold using thermal wind. This is argued to be a complete set of parameters to create a successful phase space and therefore by definition describe the different phases and transitions a cyclone encounters concerning its core structure. The second aspect that will be treated in this thesis concerns the trajectory of these cyclones and is contained in the following subquestion:

Subquestion 2. *What is the general trajectory of tropical cyclones that enter the mid-latitudes and is there a correlation between these trajectories and the evolution of their core structure?*

It is well-known that when a tropical cyclone undergoes ET, its survivability increases due to the adaptions made to its environment (Jones et al., 2003). Vertical wind shear and lower surface temperatures are generally less detrimental for extratropical cyclones than they are for tropical cyclones. Moreover, the driving force for tropical cyclones changes if they undergo ET. That is why it is interesting to see what the effect is of different evolutions of cyclone core structures on their path.

2 Data and Methods

2.1 Data

2.1.1 Reanalysis

Reanalysis is way of creating data sets for climatological research. Using an (observation based) initial state the process of *data assimilation* starts, which is done in analysis cycles. These cycles consist of the combining of observations with the output of a numerical model. This is considered to be the best estimate of the system at a particular location, taking into account errors in both the data and the model. These analysis cycles are done for every timestep. Reanalysis then uses such a analysis system to reprocess observations in the past. This makes it possible to make the right interpolations and work with high spatial and temporal resolutions. Another advantage is that is an incorporation of many observations into one stable system, which would be nearly impossible for an individual to collect and analyze separately. An important limitation of reanalysis is that they are not pure observations and that this has its influence on the output in the form of spurious variability or trends.

2.1.2 MERRA data

The data used for the reanalysis originates from the MERRA reanalysis model of the Global Modeling and Assimilation Office (GMAO), which is an institude of NASA[1]. MERRA is an abbrevation for the Modern-Era Retrospective analysis for Research and Applications. The MERRA system is conducted with version 5.2.0 of the GEOS-5 ADAS with a 0.66°x 0.5°x 72 vertical layers model configuration. The MERRA data is from 1979 to the present, but for this thesis the years 1987 through 2003 will be analyzed, which is a total of 17 years. As this thesis is specified to the North Atlantic, the reanalysis is only done on data with 100°W-40°E and 0°N-90°N. There are two specific products used from MERRA. This is because both 10 m wind data with small timesteps was needed (for the purpose of accurate tracking of cyclones) and high vertical resolution was needed (for the purpose of calculations for the analysis of the structure of cyclones), which were two criteria that were not included into one single product.

The product with the high vertical resolution is called `inst6_3d_ana_Np`, which includes 42 of the 72 vertical layers. Following Hart et al. (2003), a resolution of 50 hPa per layer is taken from 1000 to 200 hPa (so 1000 hPa, 950 hPa, etc.), resulting in the use of a total of 17 vertical layers. The product has four timesteps per day (00, 06, 12 and 18 GMT) (in the sequel the timestep will be called Δt). Variables that are used from this product are sea-level pressure in Pa (slp, 2D), geopotential height in m (h, 3D), air temperature in K (T, 3D), eastward and northward wind component in m s^{-1} (u and v, 3D) and specific humidity in kg kg^{-1} (q_v, 3D). The product with 10 m wind data at small timesteps is called `tavg1_2d_slv_Nx`. The variables used from this dataset are slp and 10 m u and v vectors. The timestep Δt equals 1 hour.

2.2 Programming Methods

Several considerations are done in the programming of software that could read the MERRA data (contained in netcdf files) to get output that could be analyzed well: a database of cyclones that meet certain criteria, containing their track, pressure and structural evolution.

[1]For details, see http://gmao.gsfc.nasa.gov/merra/

2.2.1 Cyclone detection

To investigate the cyclones, they first need to be found in the reanalysis data (MERRA). This was done by first calculating the total wind speed $V = \sqrt{u^2 + v^2}$ at 10 m height and searching for all grid points were $V \geq 14$ m s^{-1}. The limit of 14 m s^{-1} is intentionally chosen below the limit of the first category of hurricane status, which is 33 m s^{-1}. Because the high wind speeds are not measured continuously, the choice of 20 m s^{-1} is preferable to get an better view of the path and pressure evolution of the cyclone. To counter the doubling of storms due to the fact that one cyclone naturally gives more than one grid point whose wind speed exceeds the given limit, the maximum wind speed is searched for and all of the earlier mentioned grid points within 10°range of this maximum are deleted. The maximum is saved and removed and the procedure is done again. The center of a cyclone is (in this thesis) defined as the position of the lowest pressure within 10°range of a wind maximum. To remove double storms, all 'pressure minima' that have a lower pressure within a range of 10°are deleted. In favor of the tracking system that will explained below, the pressure minima (or *cyclone locations*) positioned at latitudes $<$ 4°or $>$ 86°or longitudes $<$ -96°or $>$ 36 are removed, too. This is allowed because these storms are not of interest to this thesis.

2.2.2 Cyclone tracking

To track cyclones, the given pressure minima will be automatically linked to a past pressure minimum if the past pressure minimum was within 10°range. It will first look for such a past pressure minimum one time step back (at time $t - \Delta t$ with $\Delta t = 1$ h), and if there is no such point found, it will search a second step back ($t - 2\Delta t$), etcetera. This search ends after searching in 16 time steps back. In some cases, some corrections had to be done manually. Examples of these cases are when cyclones are fused or when a cyclones was following the track of nearby other storm. These corrections are based on horizontal θ_E (equivalent potential temperature) and p fields. The θ_E fields indicate the presence of baroclinic instability, which plays an important role in cyclogenesis of extratropical cyclones. The p fields (together with θ_E) indicate the presence of cyclone centers. All cyclone center data points are divided into seven categories based on their maximum wind speed. The categories are normally chosen according to the Saffir-Simpson hurricane wind scale. However, this scale uses peak wind speed from values averaged over ten minutes, which results into higher wind speeds than when the average over an hour is used (as it is in this thesis). This is why is chosen for the Beaufort wind scale as shown in Tab. 2, analogous to Haarsma et al. (2003).

Table 2: The Beaufort wind scale, used for the categorising of the cyclone data points.

Class	Description	Wind speeds
$\leq$B7	Near gale, high wind (or weaker)	≤ 17.1 m s^{-1}
B8	Gale	17.2-20.7 m s^{-1}
B9	Strong gale	20.8-24.4 m s^{-1}
B10	Whole gale, storm	24.5-28.4 m s^{-1}
B11	Voilent storm	28.5-32.6 m s^{-1}
B12	Hurricane force	≥ 32.7 m s^{-1}

Note that when although barely any winds of class B12 are measured, this does not mean that there are only few hurricane force winds present in the reanalysis data. The hourly averaging just reduces the wind speeds. Another comment on the tracking of the storms should be made. The reanalysis data is from August 1st to November 30th, which means that for a cyclone that propagates from July 25th to August 5th, only half of it will be recorded. These kind of storms will still be used in the analysis if horizontal p and θ_E fields confirm that it has a tropical origin (i.e. it originated having a symmetric and warm-core structure).

The cyclone tracks were checked on whether they passed through Europe, as defined analogous to Haarsma et al. (2013): Norway (60°N-70°N, 0°E-15°E), the North Sea (50°N-60°N, 3°W-8°E), Western UK (50°N-60°N, 3°W-15°W) and the Gulf of Biscay (43°N-50°N, 0°W-15°W).

2.2.3 Cyclone Structure

To describe cyclone structure, there are a number of important parameters. Both the strength of the warm-core structure of a tropical cyclone and the cold-core structure of an extratropical cyclone should be quantified, together some kind of description of the tilt of the cyclone. The latter is important because cyclones go through different states of development (formation, occlusion, intensification, etc.). Accordingly, cyclone structure can be described well with the Hart variables (Hart, 2003). The first of these three variables is cyclone thermal symmetry B, which is a measure of the symmetry of the cyclone (and indirectly its baroclinity). To calculate B, one uses the difference of geopotential height averages over two semicircles with a radius of 500 km around the cyclone center. The choice of 500 km is analogous to Hart et al. (2003), in which the authors state that within the range of 250-1000 km, the consequences for the analysis are not significantly changed (the amplitude changes slightly and the sign does not change at all) and that it is large enough so that it generally includes the convergent circulation of tropical cyclones but small enough to not include external factors. To calculate how many grid points away from the center 500 km was, latitude (θ) and longitude (ϕ) degrees needed to be transformed into kilometers, which is calculated using basic geometry. However, at higher latitudes, the width in degrees longitude of the 500 km radius increases. This dependency has been accounted for using nine 10°-bands of latitudes. The fact that this approximation is rather bad for latitudes higher than 75°is not a problem, as the cyclones we consider in this thesis generally do not come higher than that value. Knowing that $\Delta\theta = 0.5°$and $\Delta\phi = 0.667°$between grid points, the circle of 500 km radius around the cyclone center can be constructed in the used grid. To calculate B, this circle is divided into two semicircles, which is done by taking the direction of the propagation of the cyclone center as the line of demarcation. This is illustrated in Fig. 4.

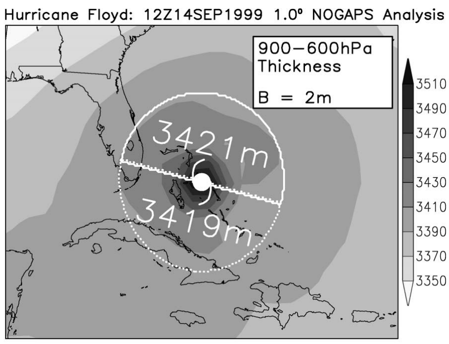


Figure 4: Example of the semicircles made to calculate cyclone thermal symmetry B, in this case for hurricane *Floyd* in 1999. Figure retrieved from Hart et al. (2003).

The direction (or angle) of propagation of a cyclone center is calculated using the relative position of the particular cyclone center to its (temporally) closest recorded past location (which is often 6 hours back). In this calculation north is called 0°, east is 90°, etcetera. This leads to the following equation to calculate the direction of the propagation α in radians:

$$\alpha = \arctan(\frac{\phi_0 - \phi_{-1}}{\theta_0 - \theta_{-1}}) \quad (1)$$

where subscript 0 refers to the present cyclone center, and -1 refers to the past location it is compared to. Note that when $\alpha > 90°$, (say 135°), it is recorded wrong (in the case of 135°, it is -45°), because the sign of the argument in the arctangents does not change by the choice of whether the denominator or the numerator is negative. This is accounted for using a case distinction. If the cyclone was standing still, the propagation direction is recorded as `NaN` (Not a Number). After the creation of the semicircles (using a dummy matrix with elements containing their angle relative to the center), B is calculated by the following formula (which is its definition) (Hart, 2003):

$$B = h(\overline{Z_{600\text{ hPa}} - Z_{900\text{ hPa}}}\,|_R - \overline{Z_{600\text{ hPa}} - Z_{900\text{ hPa}}}\,|_L) \quad (2)$$

where h is an integer of value +1 for Northern Hemisphere (which is always the case in this thesis), and -1 for the Southern Hemisphere, Z is the geopotential height and the subscripts R and L indicate the semicircles right and left of the propagation direction, respectively.

The second ($-V_T^L$) and third ($-V_T^U$) Hart variable describe the core structure. It is based on the idea that in the case of a cold core, the magnitude of the vertical derivative of the cyclone geopotential height (and thus geostrophic wind magnitude) above the surface cyclone center is positive (as the geostrophic wind increases due to vertical shear from the thermal wind balance), while the vertical derivative of the geopotential height above a cyclone center that is warm decreases with height (vice versa). Two tropospheric layers are examined to gain insight in the core structure: 900-600 hPa and 600-300 hPa. To calculate $-V_T^L$ and $-V_T^U$, the cyclone height perturbation (in the sequel called ΔZ) has to be calculated first (per specific pressure level):

$$\Delta Z = Z_{max} - Z_{min} \quad (3)$$

where Z_{max} and Z_{min} are the maximum and minimum geopotential height at a specific pressure level, respectively. The variables $-V_T^L$ and $-V_T^U$ are, then, calculated as follows:

$$-|V_T^L| = \left.\frac{\partial(\Delta Z)}{\partial \ln p}\right|_{900hPa}^{600hPa} \quad (4)$$

$$-|V_T^U| = \left.\frac{\partial(\Delta Z)}{\partial \ln p}\right|_{600hPa}^{300hPa} \quad (5)$$

where p is pressure. To get the average value of ΔZ over the specified pressure ranges, a linear regression fit of the ΔZ and $\ln p$ data is made (the angle of this linear function is used as the derivative of ΔZ to $\ln p$). The vertical resolution (in p) for both variables is 50 hPa. This method is analogous to Hart (2003).

2.3 Processing Methods

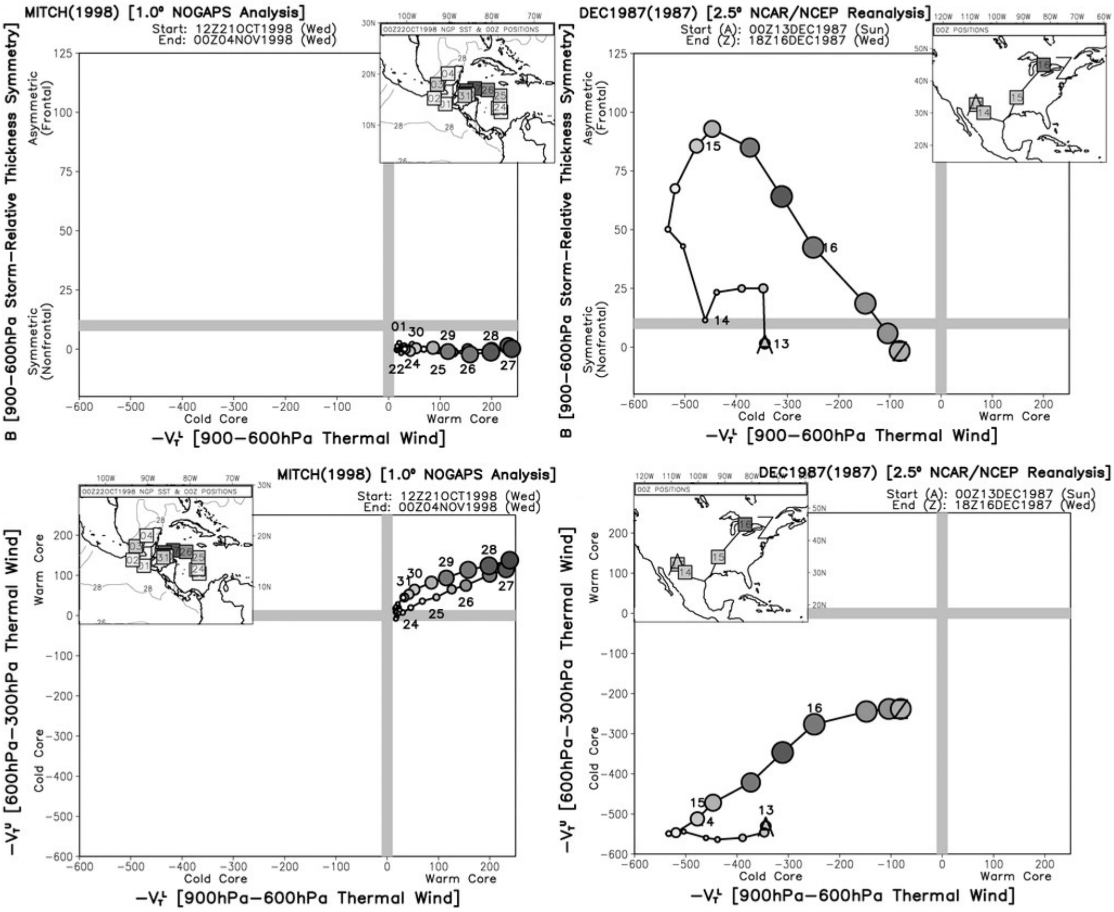
So far only methodology on the programming is explained. The following section contains methodology on the analysis of the data.

2.3.1 Analysis of cyclone structure

To analyse cyclone structure, B, $-V_T^L$ and $-V_T^U$ are used. As described by Hart et al. (2003), B is a measure of the symmetry of a cyclone. Near-zero values of B indicate a thermally symmetric (or tropical) character, while high values indicate an thermally asymmetric character (which is often extratropical). This can be seen in the formula of B: if B is almost zero, the averaged geopotential differences of the two semicircles is small, but if B is high, the averaged geopotential difference in the right semicircle is (much) more than in the left semicircle. This indicates cold air left of the cyclone track (for the Northern hemisphere, as everything in this thesis) and warm air right of the cyclone track. Thus the advection downstream will be warm and upstream the advection will be cold when B is positive. This is the case in extratropical cyclones. The threshold for determining whether the cyclone is symmetric or asymmetric is 10 m as this is the convenience and argued by Hart et al. (2003) and Hart (2001).

As is mentioned, $-V_T^L$ and $-V_T^U$ indicate whether the core is warm or cold at the specific layer. When the value of $-V_T^L$ or $-V_T^U$ are positive, the core at that layer is warm (which is the case in tropical cyclones), and when they are negative, it is cold (which is the case in most extratropical cyclones). This analysis is based on the fact that the cyclone height perturbation (ΔZ) is proportional to the geostrophic wind, and the derivative to p then basically is an expression for a scaled thermal wind magnitude, which is naturally positive in the case of a warm core (and negative in the case of cold core). This is why the threshold between warm and cold is chosen to be at 0. Generally, $-V_T^L$ has a greater magnitude in warm cores and $-V_T^U$ in cold cores (Hart, 2003). The two may differ in sign in the case of transitioning cyclones.

To analyse cyclone structure, phase space diagrams (in the sequel called *Hart diagrams*) are made for each cyclone that is to be analysed. For every cyclone, this analysis consists of two figures, one with B plotted against $-V_T^L$ and the second with $-V_T^U$ plotted against $-V_T^L$. Two examples of cyclone phase diagrams are shown in Fig. 5.



(a) (b)

Figure 5: Examples of Hart diagrams of (a) a tropical cyclone (Mitch) in 1998 and (b) an extratropical cyclone in 1987. The timesteps are (a) $\Delta t = 12$ h and (b) $\Delta t = 6$ h. Figures retrieved from Hart et al. (2003).

A distinction can be made between conventional (non-transitional, or single phase) cyclone evolutions and unconventional (transitional or multiple phase) cyclone evolutions. The distinction is well visible in Hart diagrams as conventional cyclone evolutions do not (explicitly) cross the threshold values of $-V_T^L$ (or $-V_T^U$) = 0 and $B = 10$ m and unconventional cyclones do cross them. It should be mentioned that a categorization of cyclone structure transitions will be made in the results section (Ch. 4) as this is a result in itself.

Note that although it is according to Hart (2003) that cyclone phase cycles can be fully described with just the Hart variables B, $-V_T^L$ and $-V_T^U$, this might be arguable. The following categorization is solely based on these phase space diagrams, which means that it could be the case that a storm that is categorized as a warm seclusion by its Hart diagrams is in fact not a warm seclusion, but only behaves like one. It is beyond the scope of this thesis to validate the completeness of the Hart variables.

2.3.2 Criteria storms to be analyzed

Using data collected by the methods as described above, a database of storms with their structure characteristics is made. However, many of these storms are not the kind of storms this thesis focuses on, e.g. polar lows or tropical storms without any form of structure transition. The target of this thesis is to compare cyclone evolution cycles of tropical cyclones in the reanalysis with those in EC-EARTH. To specify of storms that will be analyzed in this thesis, a number of criteria is created (for clarity purposes: if in the sequel is spoken of *recorded storms*, cyclones that meet these criteria are meant):

1. The cyclone has data points at latitudes lower *and* higher than 37.5°N.
2. The cyclone has at least datapoints over a period of 3 days.
3. The cyclone is of Beaufort class B8 (see for details Tab. 2).
4. The cyclone does not have a conventional extratropical cycle (an example of such a cycle can be found in Fig. 5b).

The motivation for the first two is that this thesis focuses on tropical storms that undergo a phase transition and the mentioned latitude levels indicate a first-order transition area. The third criterium is to assure that the cyclones have a tropical origin. The fourth is to record only cyclones that have had some time to evolve at all and the fifth criterium is to remove cyclones from the dataset that are too weak to show any cyclonic structure or evolution.

3 Results

This section is divided into two main parts. First of all the results on important general characteristics of the recorded storms will be given, containing information about the amount and frequency of tropical storms entering the extratropics, together with the trajectories they follow. Secondly, the results of the analysis of the structure of the cyclones will be given, together with a categorization of tropical storm phase cycles (i.e. the path they take in the phase space as proposed by Hart, 2003).

3.1 General characteristics

3.1.1 Frequency

To get an general overview of how many tropical cyclones were recorded in the data and how many reached Europe, independent of their thermal symmetry and core nature, Fig. 6 is shown.

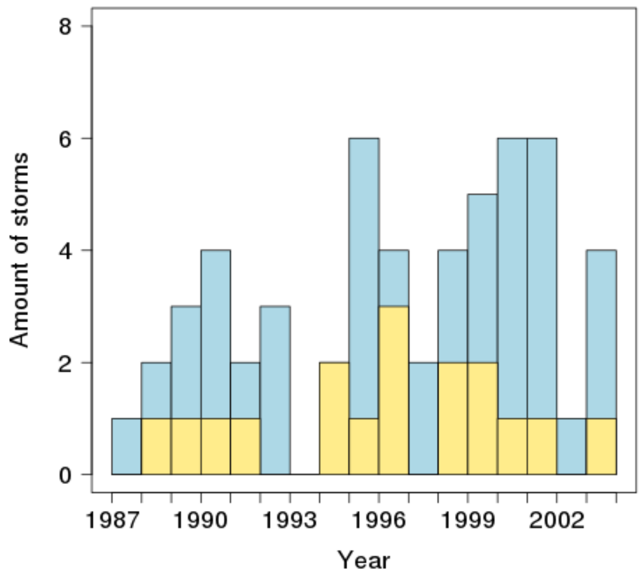


Figure 6: Amount of tropical cyclones entering latitudes higher than 37.5°N plotted annually (blue) and amount of these cyclones that also reached Europe (yellow).

The average amount of tropical cyclones recorded per year is 3.24 cyclones per year with a standard deviation of 1.86. Temporal evolutions in five year means are calculated and showed no significant increase. Approximately 31% of the storms tracks passed through Europe. No strong correlation has been found between the amount of tropical cyclones that entered the mid-latitudes (blue in Fig. 6) and the part of these cyclones that also reached Europe (yellow in Fig. 6), as the correlation coefficient equals 0.46.

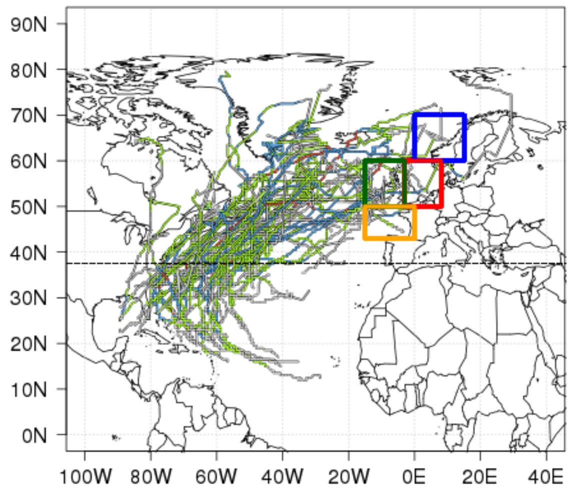
3.1.2 Tracks

The trajectories of the cyclones (independent of their phase cycle) in the period 1987-2003 are shown in Fig. 7a, together with a frequency plot in Fig. 7b showing which storm paths are used most.

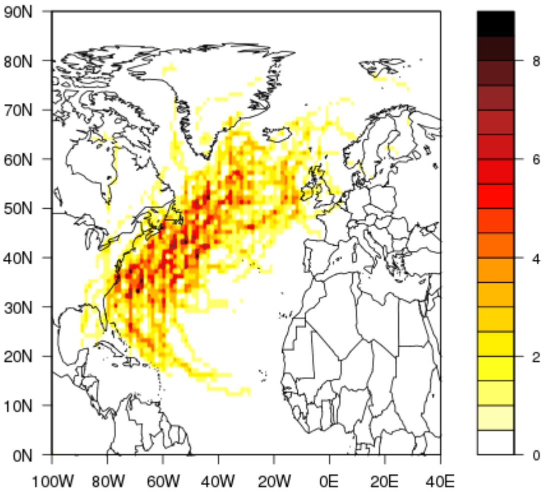
The tracking program finds the first datapoints of the tropical cyclones mostly in the areas of the Gulf of Mexico, near the Caribbean Islands, more in the direction of Cape Verde or even some at higher latitudes of about 25°-30°N. In the lower latitudes, an area of high cyclone frequency can be distinguished near the Caribbean Islands near 70°W, 25°N. Throughout Fig. 7b, several separate tracks can be distinguished to be used much, such as the ocean-crossing around 45°N and several parallel bands of trajectories along the East American coast. The general tendency is that they move along a curved path and cross the ocean either completely directed towards the east, or directed towards to northeast. Most cyclones die out before that, as is displayed in Tab. 3, which shows the amount of cyclones that reaches particular areas in Europe. A final note on Fig. 7a is that it is visible that the cyclones that do cross the ocean, bring along strong winds compared to their not-crossing counterparts.

Table 3: Percentage of recorded cyclones reaching specific locations in Europe, being the areas of Norway (blue, 60°N-70°N, 0°E-15°E), the North Sea (red, 50°N-60°N, 3°W-8°E), Western UK (dark green, 50°N-60°N, 3°W-15°W), Gulf of Biscay (orange, 43°N-50°N, 0°W-15°W).

Region	**Percentage (amount)**
Norway	3.6% (2)
North Sea	7.3% (4)
Western UK	23.6% (13)
Gulf of Biscay	10.9% (6)
Not reached Europe	69.1% (38)



(a)



(b)

Figure 7: Maps showing (a) the tracks of recorded storms and (b) the storm frequency (in amount of storms per gridbox of 1°by 1.33°). Thick-lined colored rectangles show the areas of Norway (blue, 60°N-70°N, 0°E-15°E), the North Sea (red, 50°N-60°N, 3°W-8°E), Western UK (dark green, 50°N-60°N, 3°W-15°W), Gulf of Biscay (orange, 43°N-50°N, 0°W-15°W). The colors of the storm tracks indicate wind speed magnitude, according to the Beaufort Scale: grey corresponds to Beaufort 7 green to Beaufort 8, blue to Beaufort 9, violet to Beaufort 10 and red to Beaufort 11. The horizontal dashed line shows the position of the zonal of 37.5°N.

3.2 Classification of phase cycles

As has been described, only tropical cyclones that enter latitudes higher than 37.5°N are recorded. However, the evolution of the structure of these tropical cyclones still varies greatly amongst each other. In this section a categorization is made, dividing the different kinds of transition cycles that are found in the reanalysis. This classification is based on the analysis of the phase space diagrams of each individual cyclones as proposed by Hart (2003). Three main classes have been seen in the data, all divided into two subclasses (making a total of six categories). They are illustrated with examples and figures of the phase space diagrams. The conventional cyclone names of most of the used examples are determined comparing their tracks and time series with a hurricane archive[2].

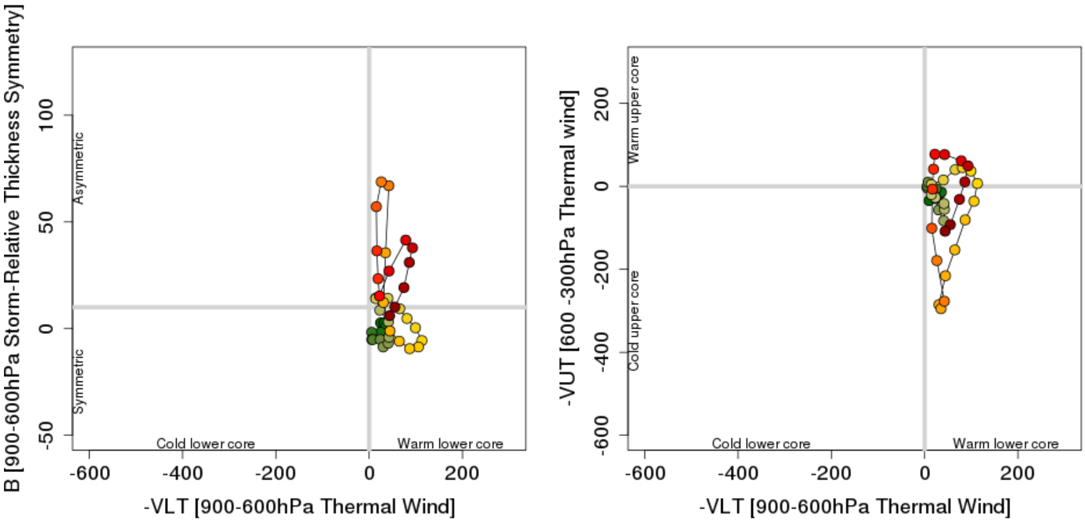
3.2.1 Minor phase transitions

The term 'minor phase transition' applies in this thesis to the tropical cyclones that do not lose their lower warm core (or only just before they fade). There are still many forms of this seen in the reanalysis. Some became asymmetric, and then evolved towards symmetry again. Others only intensified greatly and then faded after some weakening. A distinction can be made between tropical cyclones that kept a their conventional deep warm core, and tropical cyclones that lost this deep warm core or already had a shallow warm core when they entered higher latitudes. The term *long-lived* is chosen for the reason that the tropical cyclones keep this warm-core structure for the significant part of their lives.

Long-lived shallow warm core

As has been described, these kind of tropical cyclones keep a shallow warm core. They fade before they can transit significantly into a cold-core cyclone. These cyclones are also called 'hybrid' cyclones, as they have the warm-core nature of a tropical cyclone, together with the asymmetric nature of an extratropical cyclone. For the clarity purposes, their phase evolution will be called *long-lived shallow warm core*, pointing out the shallowness of their prevailing warm-core. An example of this is Hurricane *Helene* from 1988. This remarkably strong storm in the end of September made it all the way to over 70°N across Iceland, but kept a warm core at lower levels, which is visible in Fig. 8 (for details on the analysis of these phase space diagrams, the reader is invited to read section 2.3.1 or the caption of Fig. 8). In general, just before these cyclone fade, there is often some slight asymmetry development visible. Their phase cycle can be distinguished by prolonging positive values of $-V_T^L$, and often negative values of $-V_T^U$, while B might oscillate between positive (which by definition indicates thermal asymmetry) and negative to near-zero values (which by definition indicates thermal symmetry).

[2] http://www.wunderground.com/hurricane/hurrarchive.asp

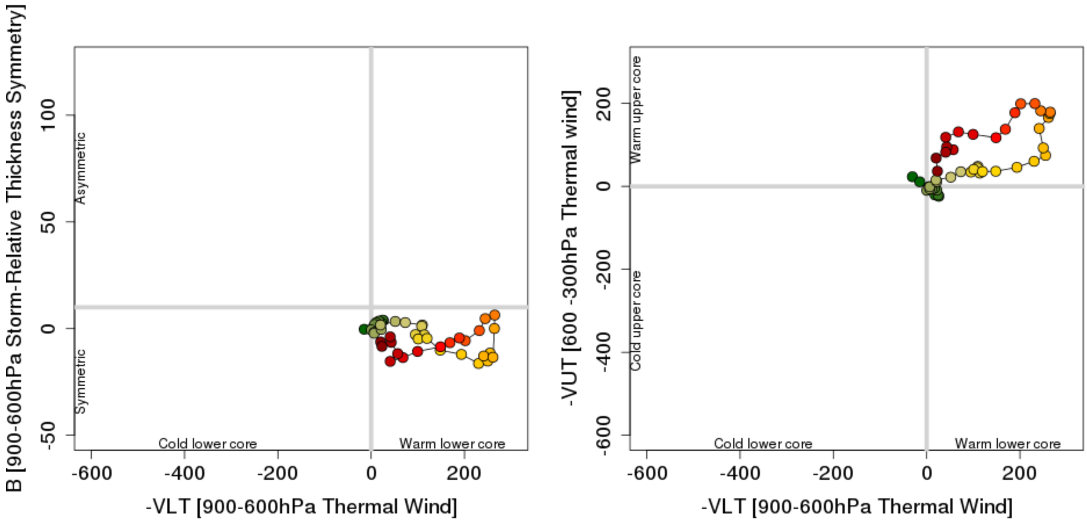


(a) (b)

Figure 8: Phase space diagrams of Hurricane *Helene* (1988), an example of a tropical cyclone that undergoes only minor phase development, keeping only a lower (shallow) warm core. (a) Thermal symmetry B against lower thermal wind $-V_T^L$, where $B > 10$ m indicates thermal asymmetry and $B < 10$ m indicates thermal symmetry while $-V_T^L > 0$ indicates a warm lower core and $-V_T^L$ < 0 a cold lower core. (b) Upper thermal wind $-V_T^U$ against lower thermal wind $-V_T^L$ showing a warm core in the upper and lower layer for positive values, respectively, and a cold core in the upper and lower layer for negative values, respectively. The phase of the cyclone evolves temporally starting at the green dots evolving towards the red dots. A running mean of 18 hours is used.

Long-lived deep warm core

In contrast with the just described shallow warm core cyclones, some tropical cyclones do not only keep a lower warm-core, but also an upper one. This is what is called in this thesis *long-lived deep warm core* cyclones. Theses phase cycles might include some intensification while keeping their warm-core structure, visible in the form of increase in positive values of $-V_T^L$ and $-V_T^U$. B tends to be below zero for this kind of phase cycles, indicating the symmetry of these kind of cyclones. An example is of these is Hurricane *Bonnie* of 1998, shown in Fig. 9. The intensification is clearly visible in these figures.



(a) (b)

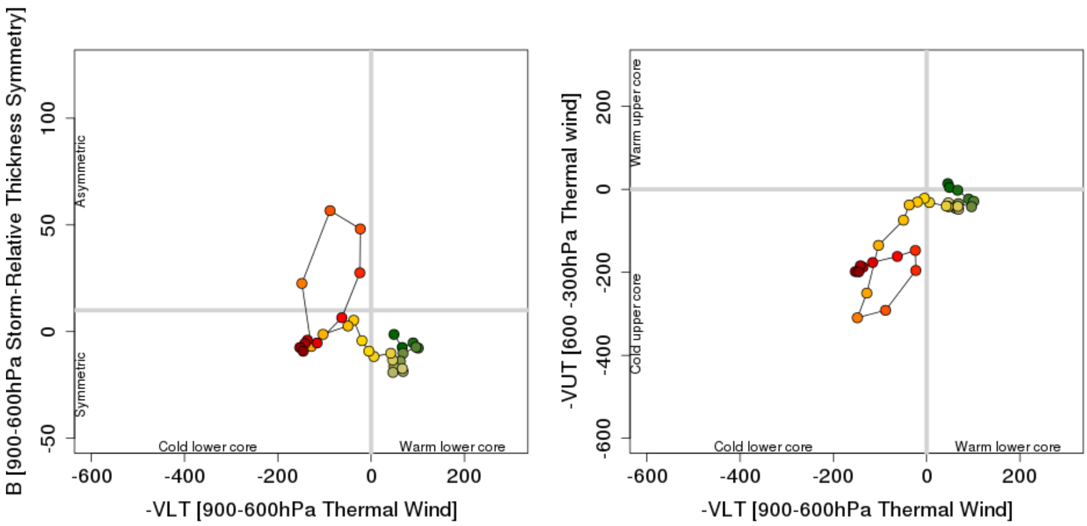
Figure 9: Phase space diagrams of Hurricane *Bonnie* (1998), an example of a tropical cyclone that undergoes barely any phase development, keeping a deep warm core. For further details see the caption of Fig. 8.

3.2.2 Cold-core extratropical transition

These categories concern the extratropical transition of the warm core to a cold core. The reanalysis resulted in the formulation of two different phase cycles for this. The classical path (as described in Hart (2003)) is called *shear transition* here, where clear asymmetry is measure before the lower core is cooled down, while in the *cold-surface transition*, the lower layer cools down ($-V_T^L$ becomes negative) as the first sign of transition.

Cold-surface transition

As described, this phase cycle can be recognized by the cooling of the lower core. Often this happens after a long trajectory where $-V_T^U$ has long become negative. When the core is cold at the lower layer, too, it starts acting like an extratropical cyclone, rapidly becoming asymmetric. It is interesting to note that this phase cycle is clearly the most apparant in the data (30% of all cyclones follow a transition path like this). An example of these storms is *Earl* from 1998, whose upper layer cools down very quickly and keep its symmetric structure until its lower core is cold, too.



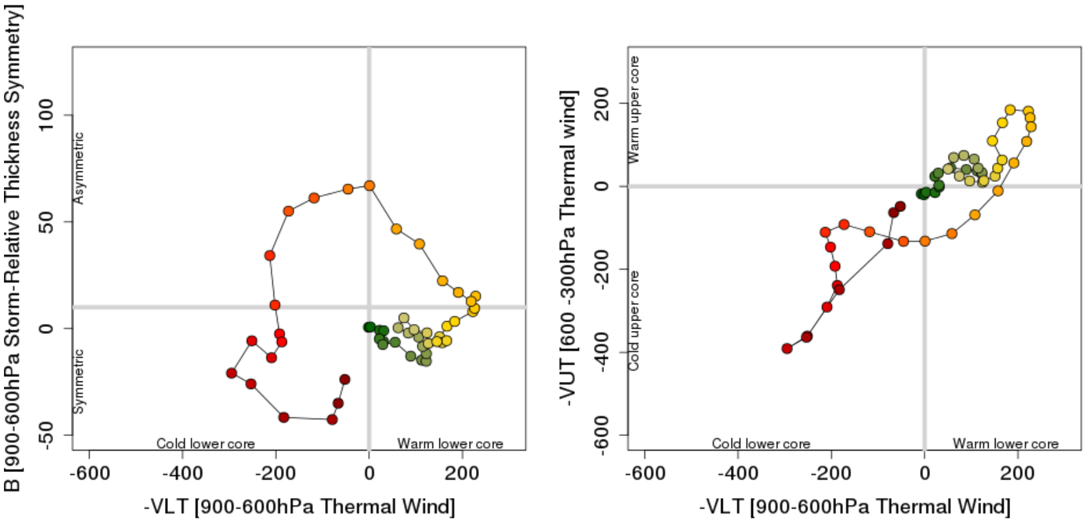
(a)

(b)

Figure 10: Phase space diagrams of Hurricane *Earl* (1998), an example of a tropical cyclone that undergoes extratropical transition while its core remains a symmetric structure until it is cold in both layers. For further details see the caption of Fig. 8.

Shear transition

This conventional extratropical transition cycle is recognized by its reversed U-shaped phase space diagram of B and $-V_T^L$ and the transition of a warm symmetric core via a warm asymmetric core towards a cold asymmetric (or after that even symmetric) core. An example of a cyclone that had this type of phase cycle is *Floyd* (1999), as shown in Fig. 11, where the expected transitions are clearly visible. It shows a feature that many of these cyclones show: after the strong cooling throughout the whole column, it starts warming a little again, while still classified as a cold core.



(a) (b)

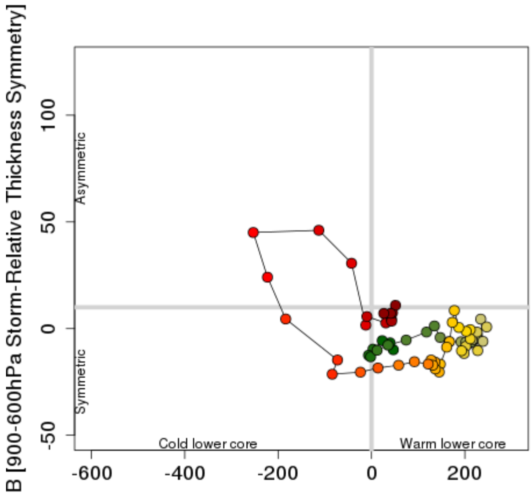
Figure 11: Phase space diagrams of Hurricane *Floyd* (1999), an example of a tropical cyclone that undergoes conventional extratropical transition, where vertical wind shear made the cyclone asymmetric before its core cooled down. For further details see the caption of Fig. 8.

3.2.3 Warm secluding extratropical transition

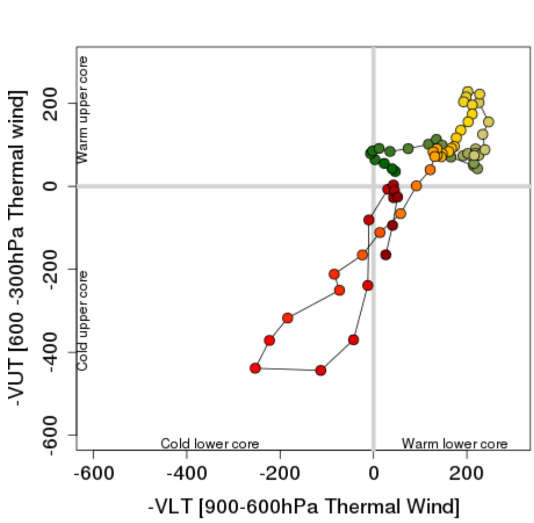
As has been described, warm seclusions are cyclones that underwent extratropical transition but attained a warm core again. For clarity purposes, these categories only include cyclones that during their ET attained a cold core first before the warm seclusion. The distinguishing between shallow warm seclusions and deep warm seclusion is important because of the difference in strength. The most extreme storms are generally deep warm seclusions. That is, storms with the strongest reintensification. Cyclones that transit as shallow warm seclusions have a high variability in physical characteristics.

Shallow warm core seclusion

Shallow warm core seclusions can be distinguished from cold-core extratropical transitions by having a shallow warm core after having had a cold-core, which is clearly visible in the example *Gabrielle* of 1989, shown in Fig. 12. They may also first appear as an extratropical cyclone, but at some point gain clear positive values of $-V_T^L$.



(a)

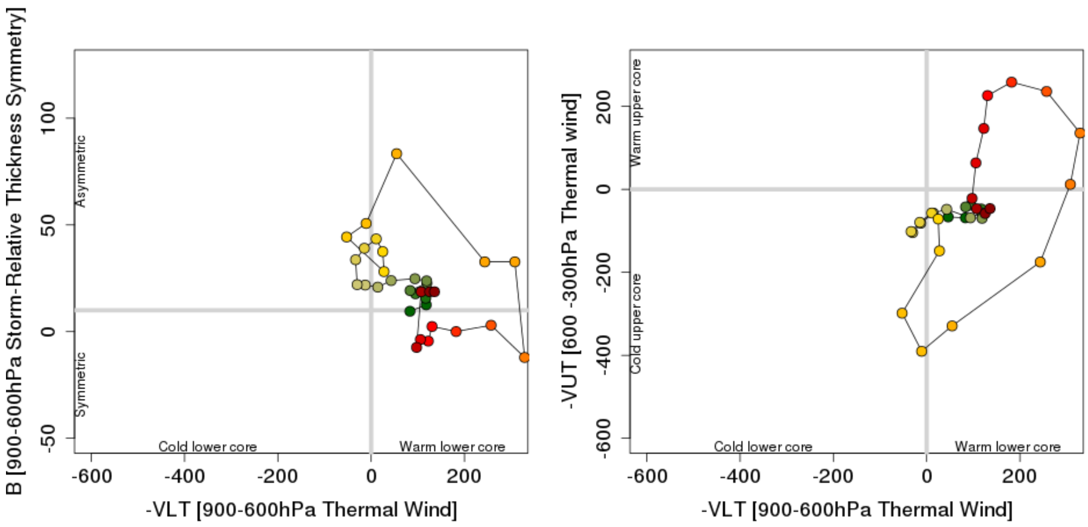


(b)

Figure 12: Phase space diagrams of Hurricane *Gabrielle* (1989), an example of a tropical cyclone where warm air is secluded in its core at lower levels. For further details see the caption of Fig. 8.

Deep warm core seclusion

As been said, the most extreme storms in the North Atlantic follow a cycle with a *deep warm core seclusion*. Asymmetry may appear in these kind of storms, as they initially might have follow a classical cold-core extratropical transition, but after having been cold, the lower core of the storm warms up again and subsequently the warms up the upper core. An example of a deep warm core seclusion from 1989 is given in Fig. 13.



(a) (b)

Figure 13: Phase space diagrams of a Hurricane from October (1989), an example of a cyclone that developed a deep warm seclusion together with strong reintensification. For further details see the caption of Fig. 8.

3.2.4 Different categories compared

A general observation is none of the cyclones that are recorded show a status of $-V_T^L < 0$ and $-V_T^U > 0$, which basically means that either the both parts (300 hPa - 600 hPa and 600 hPa - 900 hPa) are classified as warm-cores or only the lower part of a cyclone is warm. Never only the upper part. This might sound trivial, but it is interesting that in the various kinds of phase evolutions we see in tropical cyclones, the upper core is always the first to become cold.

Characteristics specified per category are shown in Tab. 4. It shows the percentages and appearance amount of the specific types of phase cycles in the total amount of cyclones, together with the percentage of the storms in that class that reaches Europe and the average pressure minima of these phase cycle categories.

Table 4: Percentage and amount of recorded cyclones for every type of cyclone phase transition. Note that not all storms that are recorded in the tracking system, were also recorded in the program that was needed for the analysis of the structure, so the total amount represented here is not the total amount of cyclones whose tracks are recorded (which is presented between brackets). The pressure values shown are minima per single whole track (i.e. one minima per storm), averaged over the storms per category.

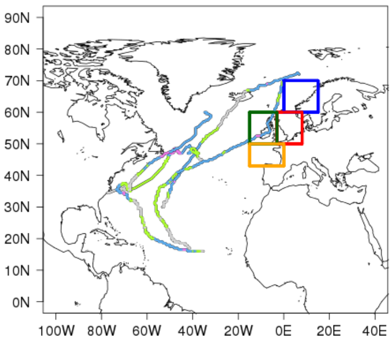
Type of phase transition	% **of total**	**Amount**	% **Europe**	$\overline{p_{min}}$ **(hPa)**
Minor phase transition	*26%*	*13*	*30.8%*	*970.6*
Long-lived shallow warm core	8%	4	25%	964.4
Long-lived deep warm core	18%	9	33.3%	973.4
Cold-core extratropical transition	*42%*	*21*	*28.6%*	*970.9*
Cold-surface transition	30%	15	33.3%	968.9
Shear transition	12%	6	16.7%	976.0
Warm secluding extratropical transition	*32%*	*16*	*31.2%*	*959.2*
Shallow warm core seclusion	20%	10	40%	967.2
Deep warm core seclusion	12%	6	16.7%	946.0
Total	100%	50 (55)	31%	967.9

Concerning the amount of each category, cold-core extratropical transition dominates with 42% of the total. As a subcategory, long-lived shallow warm core phase cycles are the least, with only 8% of the total.

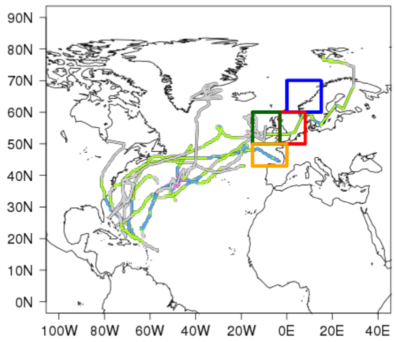
The results of the pressure minima show that deep warm core seclusions are significantly the strongest, followed by long-lived shallow warm cores (hybrid storms) and shallow warm core seclusions. The cold-surface transition storms are highly variable in pressure minimum which makes their mean value of 968.9 hPa not very representative.

Considering the tracks of the different categories, there are a few observations to be made, based on the results displayed in Fig. 17. Note that the dataset only contained 55 storm tracks, which means that the statements based on these results are only first indications.

First of all, the long-lived deep warm core cycles seem to reach weaker winds in higher latitudes and do not penetrate far north. Furthermore, deep warm core seclusions penetrate deep north and many of them do not follow the conventional path eastward, toward Europe. Shear transition ('classical' extratropical transition) tracks are mostly situated at a rather small distance to the East American Coast.



(a)



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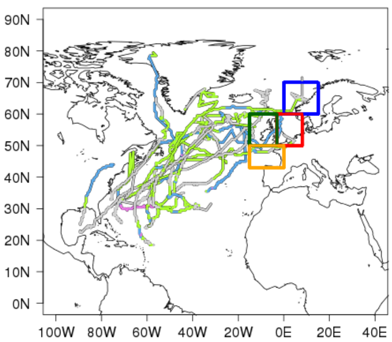

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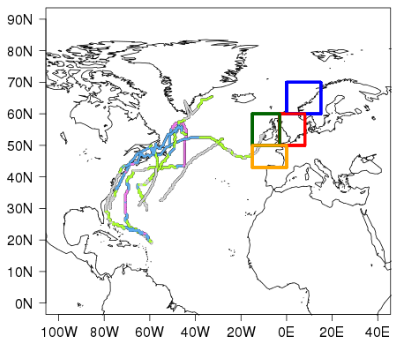

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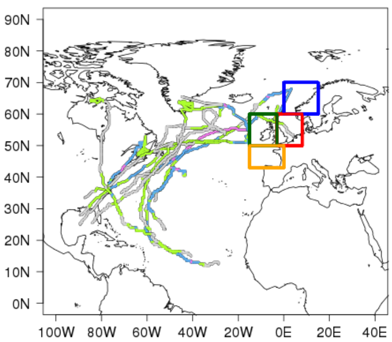

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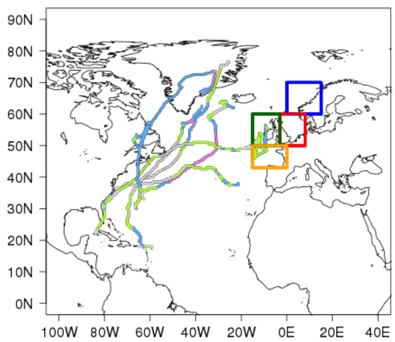

(f)

Figure 14: Tracks of the recorded tropical cyclones sorted by category: (a) long-lived shallow warm core, (b) long-lived deep warm core, (c) cold-surface transition, (d) shear transition, (e) shallow warm core seclusion and (f) deep warm core seclusion.

4 Discussion

This chapter has three subsections. First of all the general characteristics of the recorded tropical cyclones will be discussed, such as their amount and tracks. In the second part, the phase cycle categorization will be discussed and the physical aspects of every category. The hypothetical relation between trajectory and category will be discussed. Then, in a the third part, a review of these results is made in the light of results of Hart (2003) and Haarsma (2013) will be made. In the final section of this chapter, the limitations of the methods used in this thesis will be discussed, together with some general uncertainties of the statements done.

4.1 On General characteristics

4.1.1 Frequency

To compare the amount of tropical cyclones that enter the mid-latitudes with the total amount of tropical cyclones, these are shown together in Fig. 15. The correlation coefficient between the total amount of tropical cyclones and the amount that enters the mid-latitudes is calculated to be 0.77, while as described in the previous chapter, the correlation coefficient between tropical cyclones that enter mid-latitudes and the part of them that reaches Europe is 0.46. This could mean that (noting that statistics on a 55-sized sample is not always sound) there is no specific process behind the reach of tropical cyclones to the mid-latitudes, which might just be a roughly constant fraction of the tropical cyclones in total. But there might be another process behind the reach of these cyclones toward Europe. This could support the idea that the phase cycles of tropical cyclones (which are perhaps not statistically constant but dependent on many different meteorological circumstances) partly determines whether tropical cyclones reach Europe. The reason for the variation in the amount of tropical cyclones in general is beyond the scope of this thesis.

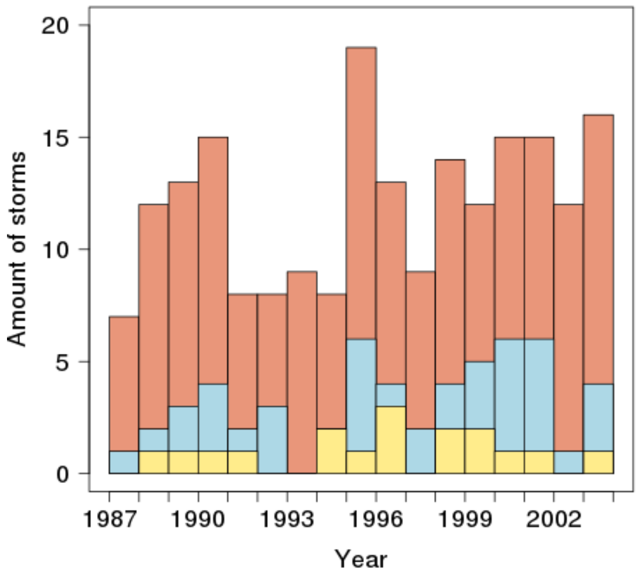

Figure 15: Amount of tropical cyclones per year (red), the part of these cyclones that enters the mid-latitudes (blue) and the part of these cyclones that reaches Europe (yellow). Data of the total amount of tropical cyclones is gained from NOAA.

4.1.2 Tracks

The tracks generally start at four different locations, either in the Gulf of Mexico, near Cape Verde (or a bit west of it), near the Caribbean Islands and sometimes somewhere at higher latitudes. This is as expected, as most tropical cyclones will originate at places with high sea surface temperature (i.e. low latitudes and large sea basins).

The separate parallel bands might be a result of general winds or warm ocean currents. The general curved path of the cyclones is probably due to the fact that they are subject to westerlies at higher latitudes and easterlies at lower latitudes. The fact that the Gulf Stream is mainly on this road makes it the ideal way of crossing the ocean (although diabatic processes do not dominate in extratropical cyclones), see Fig. 16.

4.2 On the phase cycle categorization

As already said, the upper layer of a cyclones (300 hPa - 600 hPa) is always the first to cool down. This is easily explained as the warm-core structure is dependent on surface heat fluxes, which means that in the case of a colder environment, surface heat fluxes do not penetrate far enough to keep the upper core warm. Another reason for the earlier cooling of the upper core is asymmetry, because in the case of extratropical behavior, the cyclone tends to tilt into the colder area, which makes the upper core subject to colder air.

Apart from this detail, the major result of this thesis is the categorization of phase cycles. These will be discussed and suggestions for explanations of the observations will be done.

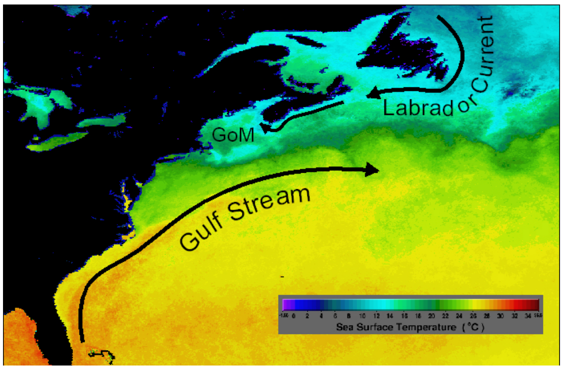

Figure 16: Map showing sea surface temperatures and the location and direction of the Gulf Stream, the Labrador Current and the Gulf of Main. Sea surface temperatures are 32 day composites from July 4 to August 4 2003. Figure received from the Aqua-MODIS SST.

4.2.1 Minor phase transitions

The fact that there are cyclones reaching latitudes over 37.5°and keeping a warm core is rather remarkable as one would expect that the colder air and baroclinicly unstable areas (through making the cyclone asymmetric) would change to core into a cold one. The explanations for the appearance of these phase cycles is different for shallow and deep warm cores.

Cyclones that had a phase cycle as from the long-lived shallow warm core ('hybrid') category basically had a strong combination of characteristics from both kinds of cyclones: the frontal asymmetric nature of extratropical cyclones and the warm core of tropical cyclones. This means that the cyclone now has two main driving factors: both baroclinity and surface heat fluxes, which makes it live longer and deepens it (which is visible in the relatively low value of $\overline{p_{min}}$, 964.4 hPa).

The long-lived deep warm cores are some of the weakest cyclones (typically Beaufort 7 and 8 in the areas above 37.5°N), which is as expected. The fact that they keep their tropical nature generally means that they do not reintensify as they do not interact with pre-existing extratropical systems nor develop extratropical characteristics (which are the two criteria for reintensification through extratropical transition, as stated by Klein et al. (2000)). Another aspect is that some of these cyclones could be recorded in the dataset while they are dying, and simply only have been tropical because they were mainly located in the tropics. Abrupt submission of deep symmetric warm core storms (tropical cyclones) to relatively very cold and baroclinic environment may perhaps have a rather destructive effect on the cyclone. This could be the reason why the tropical cyclones following this phase cycle that did come far, followed the Gulf stream eastward towards Europe and few to none of them went further north than 55°N. Extratropical transition might be more probable if the cyclone has some time to gradually adapt to its environment. This, however, is a matter for future research. These storms might be dependent on the presence of warm ocean surface at latitudes higher than 37.5°N, as deep warm core structures generally depend on high sea surface temperatures. So these storms could be explained by looking at ocean surface currents. The intensification in the core heat that many of the long-lived deep warm core cycles show (mainly taking place below the 37.5°boundary), points out general tropical intensification, based on increased surface heat and moisture fluxes and the resulting latent heat release through convection of this warm, moist air (Hart, 2003). This way not only the lower core heatens up ($-V_T^L$ increases), but also the upper core ($-V_T^U$ increases).

4.2.2 Cold-core extratropical transition

Extratropical transition could start with the presence of an upper-level trough, or without the presence of one. This could be an explanation for the two different kinds of ET that are visible in the dataset. Because when there is a trough nearby, the ET might be much quicker than in the case of the absence of a (notable) pre-existing system. The cooling of the lower core might take some time, so in the case of the interaction with a trough, the downward cooling is slower than the tilting (and asymmetrizing) of the cyclone.However, in the absence of a trough (or shear in general), land or cold surface temperatures are the cause of the weakening of the cyclone's tropical structure. In this case, $-V_T^L$ might decrease more rapidly than $-V_T^U$ (Hart, 2003), but anyway the core becomes cold while the system does not directly become asymmetric. This is exactly what is the difference between shear transitions and cold-surface transitions: while the first is based on the interaction with a trough or strong wind shear, the latter is based on cyclones moving into the land or colder sea surface temperatures.

Further general differences are hard to point between the two as the assessment of whether shear or colder surfaces was a driving force behind the extratropical transition is hard to make, because this is dependent on the position of the location of baroclinic instable areas, the presence of warm (or cold) ocean waters (and therefore the time of the year) and the strength of the cyclone itself when it encounters these features. It does seem, however, that shear transition is less apparant in the data than cold-surface transition is. The reason for this is unknown, although it might have something to do with the fact that colder surfaces are always encountered at some point when cyclones turn northward, but shear or frontal areas that are strong enough to make the cyclone become asymmetric in structure is not always present in a storm's path.

Pressure minima are highly variable for both cyclone types in this dataset, and so is their reach towards Europe, which is why it is hard to state something based on these results. However the tracks of shear transition cyclones are remarkably close to the East American Coast. Much closer, for example, than those of long-lived shallow warm core cyclones (see Fig. 17). The reason for this difference could be that this is exactly the path of the Gulf stream, which provides high sea surface temperatures because of which the tropical cyclones can hold on to their lower warm core for a longer while, but quickly become asymmetric through interaction with nearby baroclinic instabilities (which eventually may cool the lower core anyway).

4.2.3 Warm seclusions

The most obvious result is are the relatively low pressure levels of these kind of storms. This is mainly because of their ability to reintensify strongly after their transition. As has been described in the introduction, prior to the seclusion of a warm core, extratropical transition takes place, but then because of the formation of a frontal T-bone (as described by the Shapiro-Keyser model) warm air that was ahead of the cold front is trapped in the center. This process is not dependent on the domination of diabatic processes as surface fluxes or convection although they may enhance it (Hart, 2003). That is what could be the physical reason behind the greater strength of deep warm seclusions compared to shallow warm seclusions, as it could be expected that in deep warm seclusions, diabatic processes are more important which means that they contribute to the deepening of the storm. This could only be the case if the cyclone is over sufficiently warm water. However, as the colder air in higher latitudes makes it hard for even the strongest storms to convect surface heat into its upper layer, the upper (deep) warm seclusions could also be a result of the lowering of the tropopause in the case of extreme storms. This lowering introduces warm stratospheric air and therefore warms the upper layer (Hart, 2003).

Statistics about the percentage of warm seclusion storms arriving in Europe are not very robust as the amount of these storms is relatively low. Interesting to see is that many deep warm seclusions are more directed towards Greenland and Iceland instead of Europe. The reason for this is unknown and perhaps this fact is more a result because of the small sample-size than a representation of the reality. It could be that a deep warm seclusion forms more easily if the cyclone is separated from the strong temperature gradients along the polar jet.

4.3 Comparison with literature and EC-Earth

Concerning the tracks of the tropical cyclones, an interesting comparison could be made with Haarsma et al. (2013), which ran simulations from EC-Earth. A first important note is that the EC-Earth output had a frequency of 3 hours, which is lower than the tracking for the purpose of phase analyses (6 h), but higher than the tracking for the purpose of investigating trajectories and wind speed (1 h). Furthermore, EC-Earth has a higher resolution (25 x 25 km) than the reanalysis data of MERRA has (0.5°x 0.67°). Another important note is that these (six member ensemble) simulations are specifically for the period 2002-2006 and only cyclones that reach Europe are considered, which according to the statistics in Tab. 4 contain mainly long-lived shallow warm core, cold-surface transition and shallow warm core seclusion cycles. The tracks of extreme storms (Beaufort 12 in Haarsma et al., which is perhaps comparable to Beaufort 10-11 in this thesis because of resolution issues) could be compared the same origin (which is in both cases variable) and the same parallel three paths could be discovered together with the optimum near the Caribbean islands. Note that in Haarsma et al. (2013), the Beaufort 12 wind frequency is plotted instead of cyclone frequency.

Concerning the phase cycle categorization, a comparison could be made with the paper of Hart (2003). In this paper, a similar survey of examples of cyclone life cycles is made. An important difference is that he did not exclude cyclones of (pure) extratropical origin in his dataset, which was done for the creation of the dataset for this thesis. This naturally meant that he did also encounter pure extratropical life cycles and cold- to deep warm-core transitions. The latter is basically a form of tropical cyclogenesis, but instead of being formed like a regular tropical cyclone, it is formed by the conversion of a occluded cold-core cyclone (or from a frontal wave). Hart (2003) also did not make a clear distinction between shallow and deep warm seclusions (which in this dataset showed different characteristics) and between cold-surface and shear extratropical transition (which in this dataset did also not show clear different characteristics apart from their life cycle). Hart (2003) did however mention the existence of these categories but did not describe their structure as distinct.

Focusing specifically on the types of extratropical transition that are mentioned in this thesis (shear and cold-surface transition), a comparison with Evans and Hart (2003) could be made. The main difference to point out here is that they defined extratropical transition to be starting when the cyclone starts to become asymmetric, which is not the case in this thesis, as here extratropical transition is stated to also be able to start without any symmetry changes. Perhaps this is a matter of terminology.

4.4 Limitations of the methodology

There are quite a number of limitations on the methodology, which is why these are divided into a few subsections, of which the first contains limitations regarding the tracking program, the second contains remarks on the phase space analyses and the third contains some general notes.

4.4.1 Regarding the tracking program

The detection program is based on maxima in wind speed. When the wind speeds higher than a certain threshold (14 m s^{-1}) are found, only the highest in a region are recorded and the lower wind speed points are not (see section 2.2.2 for details). This could mean that when there are actually two small cyclones close to each other, only one of these cyclones is recorded in the program.

Furthermore, the tracking program itself is only based on location: it connects cyclone points at times by checking whether they lie near each other. The problem with this is that it could be that they are actually two different cyclones. However, most cyclones are checked manually on this matter. A way of solving this in the future could be by making the tracking system dependent on the propagation of the storm compared to its previous location, this way a first guess could be made of where the location of the cyclone in the subsequent time step will be, making the tracking system more accurate.

4.4.2 Regarding the phase space analyses

When calculating the parameters for the phase space analyses (thermal symmetry and thermal wind), using the right value of the propagation of the cyclone is crucial. However, in the merging of cyclones (which is often the case in extra-tropical transition), the propagation of the first cyclone could be quite different than the propagation of the second cyclone. If the merge takes a timestep or two, the values of the Hart variables in the extra-tropical transition are not representative for the thermal symmetry. However, if one of the two merging storms is dominating (and the other is absorbed), the values might be much better. The latter often happens when a well developed hurricanes enters a baroclinic zone, such as *Irene* (1999) did.

Another problem with the determination of the propagation is that the time resolution is 6 hours, in which the propagation could be altered to be significantly different than what is calculated as in this thesis. This (and the limitation described above) could be resolved in the future by making its propagation not only dependent on its past location, but also on its future location, and using hourly data (so that 10 m wind could be used for other purposes) and taking the point 3 hours before present, and 3 hours after present for the propagation. Then the gap between datapoints used is smaller than 6 hours, but it is large enough to still gain insight in the mean progapation of the storm (instead of high variance in the angle of the propagation due to small timesteps).

For the purpose of calculating the Hart variables, a second tracking program is used based on wind measurements at 1000 hPa. To ensure related results between the 10 m tracking and the tracking used for the Hart variables, the 10 m tracking could have been used by taking a datapoint every 6 hours and calculate the Hart variables by using these locations in the other dataset (with high vertical resolution, which is needed for the calculation of these variables).

A limitation of the dataset of cyclones used in this thesis could be that July is not considered. Many literature studies (e.g. Hart et al. 2001) do use this. As July also contains tropical storms, this could result in a more general insight in their evolution in the extratropics. However, in July, the temperature gradient throughout the extratropics is lower which means that baroclinic instabilities will be weaker.

5 Conclusions

5.1 Summary

Conclusively, it can be said that tropical cyclones that enter the mid-latitudes may undergo at least six distinguishable phase cycles when looking at thermal symmetry and the upper and lower core nature. Generally, they follow the curved path lead by easterly and westerly winds with arguably some influence of the Gulf Stream. The number of cyclones that enter the mid-latitudes does not significantly correlate with the amount of cyclones that reaches Europe, which could mean that the reach of Europe is determined by something else, like the phase cycle of the specific cyclone. These include, together with their main characteristics:

1. Tropical cyclones that undergo almost no transition (long-lived deep warm core cycles). Cyclones going through this phase cycle are generally weaker in pressure and winds and do not reach far north.
2. Tropical cyclones that become thermally asymmetric while retaining their warm lower core (long-lived shallow warm core cycles). These are relatively strong and reach far north.
3. Tropical cyclones that become thermally asymmetric and then grow cold (shear extratropical transition cycle). Their tracks are close to the East American coast and are relatively strong.
4. Tropical cyclones whose core cools down and then start developing the asymmetric structure of an extratropical cyclone (cold-surface extratropical transition cycle). These cyclones are highly variable in strength and track.
5. Tropical cyclones that seclude a shallow warm core after having had the extratropical characteristics of asymmetry and a cold-core nature (shallow warm seclusion cycle). These cyclones are relatively strong and generally come far north.
6. Tropical cyclones that seclude a deep warm core after having had a shallow warm seclusion (deep warm seclusion cycle). These cyclones penetrates farthest north and are the strongest in pressure and winds.

5.2 Future research

Concerning the knowledge gained from the results of this thesis, there are a number of new topics and questions that are suggested for future research. A first suggestion could be made concerning the results from this thesis. They could be improved and extended in more than one way. The tracking system could be more sophisticated, as there many uncertainties connected to the methodology (as described earlier). Another welcome addition to the current results are identifying categories of phase cycles using more than just the Hart variables of thermal symmetry and thermal wind. Suggested variables could be equivalent potential temperature θ_E and potential vorticity.

Another suggestion for future research is checking whether reintensification takes place for different categories. Warm seclusions are expected to have reintensification after their extratropical transition, but is this also true for cold-core extratropical transition? In the process of making this thesis, a reintensification index was added to each storm manually to get an idea of how many storms reintensify, but this assessment was quite subjective and the difference between *re*intensification and intensification is difficult when there is no clear definition of the point of extratropical transition. Due to these reasons, reintensification differences between phase cycle categories was ignored. However, one definition of the so-called *onset time* (start of extratropical transition) is given in Klein et al. (2000), so when made strictly numerical, this could be a suggestion for future research.

Concerning the field in general, it might be interesting to compare the tracks per category and the categories themselves to simulations from for example EC-Earth, to check whether (high-resolution) models simulate these structure transitions well.

Another suggestion for future research is concerning the dataset, as only tropical cyclones have been researched now. However, extratropical cyclones might also have some kind of structure evolution throughout their lives. Although extratropical cyclones generally do not change in driving factors (except for warm seclusions and hybrids storms perhaps), there may be structure differences between extratropical cyclones coming from the Labrador Sea and extratropical cyclones originating from 35°N.

6 Acknowledgements

I would like to thank my supervisor at the KNMI, Rein Haarsma for the opportunity to do an internship at the KNMI and the many ways in which he supported the creation of this thesis. I would also like to thank my supervisor at the University of Utrecht, Aarnout van Delden. Furthermore I would like to thank my friends and family for all the support.

Appendices

A Tracks of Examples

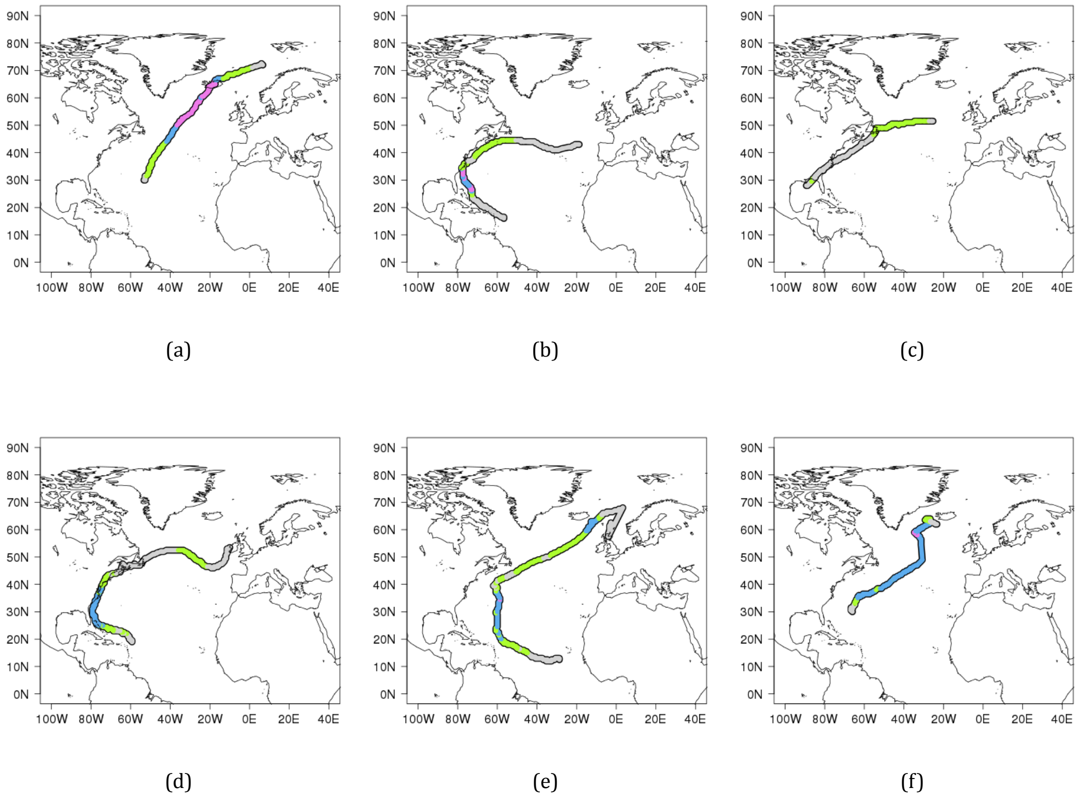

Figure 17: Tracks of the examples of tropical cyclones used in section 3.2: (a) *Helene* from 1988 (long-lived shallow warm core), (b) *Bonnie* from 1998 (long-lived deep warm core), (c) *Earl* from 1998 (cold-surface transition), (d) *Floyd* from 1999 (shear transition), (e) *Gabrielle* from 1989 (shallow warm core seclusion) and (f) a tropical cyclone from October 1989 (deep warm core seclusion).

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