UNIVERSIDAD COMPLUTENSE DE
MADRID FACULTAD DE CIENCIAS FÍSICAS
Departamento de Física de la Tierra y Astrofísica

TESIS DOCTORAL

Cyclones with tropical characteristics over the northeastern Atlantic and Mediterranean sea: analysis in present climate and future projections

Ciclones con características tropicales sobre el Atlántico nordeste y el Mediterráneo: análisis en clima presente y proyecciones de futuro

MEMORIA PARA OPTAR AL GRADO DE DOCTOR

PRESENTADA POR

Juan Jesús González Alemán

Directores

Miguel Ángel Gaertner Ruiz-Valdepeñas
Clemente Gallardo Andrés

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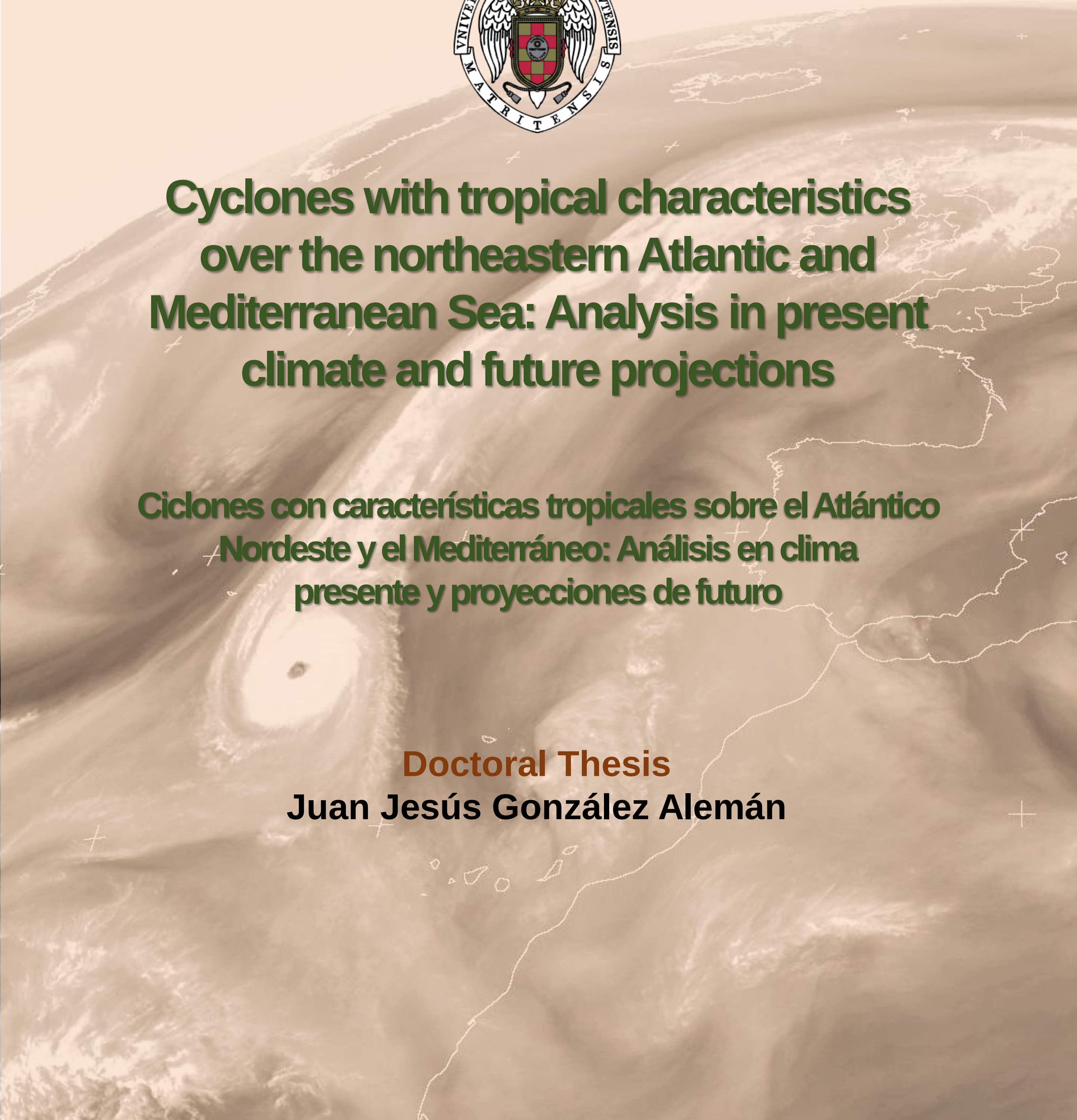
Doctoral Thesis

Juan Jesús González Alemán



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(Ciclones con características tropicales sobre el Atlántico Nordeste y el Mediterráneo: Análisis en clima presente y proyecciones de futuro)

MEMORIA PARA OPTAR AL GRADO DE DOCTOR CON MENCIÓN INTERNACIONAL
PRESENTADA POR

Juan Jesús González Alemán

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A todas las personas
que me han apoyado
durante todos estos años,
en especial a mi familia.

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Outline

Resumen

1. Introducción

Los ciclones con características tropicales son sistemas de bajas presiones que muestran características de ciclones baroclinos (o extratropicales) y ciclones diabáticos (o tropicales). Están situados en un continuo entre los extremos teóricos de ciclón. Ejemplos de este tipo de ciclones son los ciclones subtropicales (STCs, por sus siglas en inglés) que se forman en el Atlántico Nordeste, así como los "medicanes" en el Mediterráneo.

Las comunidades científica y operacional han puesto recientemente el foco sobre estos sistemas debido a su reciente reconocimiento como sistemas atmosféricos adversos. Están asociados con incertidumbre en la predicción y su relación con el cambio climático antropogénico (ACC) no está bien establecida, especialmente en el Atlántico Nordeste. Por tanto, esta tesis doctoral tiene como objetico mejorar el conocimiento de estos sistemas tanto en clima actual como en clima futuro, así como evaluar las herramientas con las que se pueden estudiar.

2. Objetivos

Los objetivos principales de la tesis son:

- Caracterizar los ambientes sinópticos que favorecen la formación de STCs en el Atlántico Nordeste y compararlos con los que se forman en el Atlántico Noroeste.
- Evaluar la capacidad de los modelos regionales climáticos al simular STCs, y obtener proyecciones en clima futuro en el Atlántico Nordeste.
- Testear una metodología de "clustering" o agrupación para el caso de un STC que sufre transición tropical (Huracán Alex, 2016) y que posteriormente interacciona con el flujo de latitudes medias en forma de transición extratropical (ET).
- Analizar cómo las diferentes características de los modelos regionales climáticos (acoplamiento, resolución y formulación del modelo) afecta a las simulaciones de "medicanes" en el Mar Mediterráneo.

3. Data y Metodología

Esta tesis usa datos procedentes de reanálisis (ERA-Interim, ERA-40), observaciones (NHC-HURDAT) y de simulaciones (CORDEX, ESCENA, EPS-ECMWF). Para identificar ciclones se usa un algoritmo de detección automática y para la selección de los ciclones con características tropicales, se utilizan los diagramas de fases de ciclones. Además, se utilizan distintas herramientas matemáticas de uso para la investigación y predicción meteorológica: anomalías climáticas, análisis de compuestos, test de hipótesis, agrupación, etc.

4. Resultados

Los resultados se dividen en 4 publicaciones científicas.

1. **Clasificación y análisis sinóptico de ciclones subtropicales en el Atlántico Nordeste (González-Alemán et al. 2015):** Los STCs en la cuenca del Atlántico Nordeste están asociados con un patrón sinóptico anómalo, caracterizado por una alta presión al norte de éstos, lo cual es una manifestación de una situación de baja aislada. Tienden a formarse cuando un ciclón extratropical se aísla de la circulación

de latitudes medias. Comparten características con los STCs que se forman en el Atlántico Noroeste, salvo que tienen una menor componente tropical, lo cual les hace asemejarse más a los ciclones extratropicales.

2. **Simulación de medicanes sobre el Mar Mediterráneo en un conjunto de modelos regionales climáticos: impacto del acoplamiento aire-mar y del aumento de la resolución (Gaertner et al. 2016):** Los modelos regionales climáticos (RCMs) generalmente no reproducen bien los "medicanes" observados en términos de caso por caso. Sólo los "medicanes" con mayor intensidad y duración se representan mejor. Los RCMs pueden usarse para estudiar "medicanes", pero la evaluación de éstos últimos debe hacerse en términos estadísticos. Una mayor resolución horizontal tiene un impacto sistemático positivo en la frecuencia de medicanes, pero la estimación de la intensidad no se mejora respecto a la baja resolución. La formulación en el modelo es más importante. El acoplamiento oceánico tiene en general un efecto limitado, pero lleva a un desplazamiento de la frecuencia de "medicanes" desde otoño hasta invierno. El efecto del acoplamiento puede, por tanto, depender de la capa de mezcla oceánica.

3. **Proyecciones de ciclones subtropicales en el futuro cercano por medio de un conjunto de modelos regionales climáticos sobre el Atlántico Nordeste (González-Alemán et al. 2017):** Los modelos climáticos globales (GCMs) no son capaces de resolver STCs, mientras que los RCMs introducen una mejora y son capaces de detectar la estructura híbrida de los STCs. Por tanto, los RCMs pueden usarse para obtener proyecciones de STCs en ACC, pero con cierta cautela. Los RCMs generalmente reproducen bien la frecuencia del STCs, pero con un cierto grado de incertidumbre, que depende de las características del modelo. Los primeros resultados muestran que el ACC podría reducir la presencia de STCs en el Atlántico Nordeste, principalmente debido a una menor presencia de ciclones extratropicales. Sin embargo, aparece cierta incertidumbre debido a que la tasa de conversión (de ciclones extratropicales a STCs) parece también estar afectada, especialmente en algunas simulaciones.

4. **Factores sinópticos que afectan a la evolución y predictibilidad del Huracán Alex (2016) en latitudes medias en una predicción por conjunto (González-Alemán et al. 2018):** La identificación de diferentes escenarios de evolución del Huracán Alex en latitudes medias ha resultado en una mejora de la información dada por las predicciones por conjunto. El análisis compuesto asociado a dichos escenarios o agrupaciones añade un mayor conocimiento sobre el papel jugado por los procesos en la escala sinóptica en variar la evolución de la estructura de Alex. Se sugiere de forma estadística que el frente frío y la cinta transportadora cálida asociados a un ciclón extratropical situado corriente arriba de Alex, determina la evolución de la estructura de Alex, por medio de modificar su interacción con una zona baroclina. Dependiendo de esta evolución, Alex pudo haber evolucionado como una ET de núcleo frio o una ET de seclusión cálida.

5. Conclusiones

Las principales conclusiones derivadas de esta tesis son:

- Los STCs en el Atlántico Nordeste se forman a partir de precursores extratropicales, como es el caso de una baja que se aísla de la circulación de latitudes medias del oeste, y tienen ciertas diferencias respecto a los STCs en el Atlántico Noroeste.
- Los RCMs pueden usarse para estudiar “medicanes”. Una mayor resolución puede mejorar la intensidad simulada, pero depende de la formulación del modelo. El impacto del acoplamiento oceánico puede depender de las características del océano como la capa de mezcla.
- Los RCMs también pueden usarse para estudiar STCs porque mejoran la información dada por los GCMs. Se proyecta que los STCs van a decrecer en frecuencia sobre el Atlántico Nordeste en general, sin ninguna variación aparente en su intensidad.
- La metodología de agrupamiento de trayectorias es adecuada para analizar fenómenos complejos como la interacción del Huracán Alex (2016) con el flujo de latitudes medias. Las diferentes formas en las que el huracán pudo haber evolucionado dependían del comportamiento de un ciclón extratropical corriente arriba y sus estructuras asociadas.

Summary

1. Introduction

Cyclones with tropical characteristics are low pressure systems showing characteristics of both baroclinic (extratropical) and diabatic (tropical) cyclones. Thus, they are within the continuum between the theoretical conceptual extreme of cyclones. Examples of these hybrid cyclones are subtropical cyclones (STCs) forming in the North Atlantic and medicanes of tropical-like cyclones in the Mediterranean Sea.

The scientific and forecasting community has recently focus on them due to their recognition as weather damaging systems. They are associated with uncertainties and their relationship with climate change is not very well understood yet. Especially in the northeastern Atlantic (ENA) there is little knowledge of them. Therefore, this thesis aims to add further insight into their characteristics on both present and future climate in Anthropogenic Climate Change (ACC) context, with an additional evaluation of the tools that can be used for studying them in both climates

2. Objectives

The main objectives of this thesis are:

- To characterize the synoptic environments that favour the formation of subtropical cyclones in the northeastern Atlantic basin and compare them with western subtropical cyclones.
- To evaluate the capability of regional climate models in simulating subtropical cyclones and obtain projections of them in a future climate change context in the northeastern basin.
- To test a clustering methodology for a subtropical cyclone that underwent tropical transition (Hurricane Alex in 2016), with a subsequent interaction with the midlatitude flow, and seek for synoptic factors that could modify this interaction.
- To analyse how different characteristics of regional climate models (coupling, resolution, and model equations) affect the simulation of medicanes in the Mediterranean Sea

3. Data and Methods

This thesis is based on: (I) reanalyses like ERA-Interim and ERA-40, (II) observations like NHC-HURDAT and (III) model simulations like CORDEX, ESCENA and EPS-ECMWF. An automatic cyclone tracking algorithm is applied in order to identify cyclones and the cyclone phase space is used to select only hybrid cyclones, i.e. cyclones with tropical characteristics. Several mathematical tools for climate and meteorological research and forecasting are also applied: anomalies, composites, hypothesis testing, path-clustering, etc

4. Results

Results are divided into four different scientific publications:

1. **Classification and Synoptic Analysis of Subtropical Cyclones within the Northeastern Atlantic Ocean (González-Alemán et al. 2015):** STCs over the

ENA basin are associated with an anomalous synoptic pattern with respect to climatology, characterised by a high pressure to their north, which is a manifestation of cut-off low situation. They tend to form when an extratropical cyclone is isolated from the westerlies. Eastern STCs share similar synoptic patterns with western STCs, but the latter are developed in a more tropical environmental (higher SSTs), which makes them more similar to tropical cyclones. On the contrary, eastern STCs are more similar to extratropical cyclones.

2. **Simulation of medicanes over the Mediterranean Sea in a regional climate model ensemble: impact of ocean–atmosphere coupling and increased resolution (Gaertner et al. 2016):** Regional climate models (RCMs) are not able to proper simulate medicanes on a case-by-case bases. Only those medicanes with highest intensity and duration are better represented. RCMs can be used to study medicanes, but the evaluation of medicanes in long regional climate model simulations should be then done statistically. Higher horizontal resolution has a systematic positive impact on the frequency of simulated, but their underestimated intensity in lower resolution is not corrected in most cases. Model formulation is more important. Air-sea coupling has an overall limited impact on medicane frequency and intensity, but it results in a seasonal shift of the simulated medicanes from autumn to winter. The effects of air-sea interaction on medicanes may thus depend on the oceanic mixed layer depth.

3. **Subtropical cyclones near-term projections from an ensemble of regional climate models over the northeastern Atlantic basin (González-Alemán et al. 2017):** Low resolution global climate models (GCMs) are not able to resolve STCS, while high resolution RCMs are effectively able to capture the hybrid structure of STCs and thus can be used to obtain ACC projections of STCs, but with some caution. When RCMs are nested in GCMs, the frequency of STCs is generally well reproduced although with some degree of uncertainty, depending on model characteristics. First results indicate that ACC could reduce the presence of STCs over the ENA basin, mainly due to a reduced present of extratropical cyclones. However, uncertainty arises since conversion rate (STCs per extratropical cyclones) seems to be also affected, especially in some simulations.

4. **Synoptic factors affecting the structural evolution and predictability in ensemble fore-cast of Hurricane Alex (2016) in the midlatitudes (González-Alemán et al. 2018):** The identification of different scenarios of development for Hurricane Alex in the midlatitude improve the information given by ensemble forecasts. The composite analysis associated with those different scenarios or clusters obtained added insight into the role played by synoptic scale features in the varying structural evolutions of Alex. The cold front and warm conveyor belt associated to a large extratropical cyclone upstream of Hurricane Alex, are statistically suggested to determine the structural evolution of Alex, through modifying its interaction with the baroclinic zone. Depending on this interaction, Alex could have evolved as a cold-core ET or as a warm seclusion ET.

5. Conclusions

The main conclusions of this thesis are:

- STCs over the ENA basin form from extratropical precursors, like an upper-level cold core low that isolates from the westerlies and have certain differences with respect to western STCs.
- RCMs can be used to study medicanes in long-term simulations. Higher resolution RCMs are preferred but it is not determinant. More important is the impact of air-sea coupled RCMs.
- RCMs can also be used in STCs, because they improve the information given by GCMs. STCs are projected to decrease over the ENA basin in future ACC context with no variations in their intensity.
- Path-clustering methodology is suitable for using complex phenomena like a Hurricane Alex (2016) in the midlatitudes. The different potential evolutions of Alex were determined to be cause by the different behaviour of an extratropical cyclone upstream and its attendant structures.

Preface

The birth of hybrid cyclones as a meteorological problem

The formation and life-cycle of cyclones have been studied for decades, being generally believed that the life-cycle of tropical cyclones (TC) was completely distinct from extratropical cyclones (EC). The literature has pointed out that tropical cyclones formed over warm water, gained intensity from wind-driven evaporation and the resulting latent heat release, and decayed over colder water or land (Charney and Eliassen 1964). On the other hand, extratropical cyclones formed within the middle latitudes, largely as a consequence of the baroclinic instability, i.e. temperature gradients and wind shear intrinsic to those latitudes, and then decayed as this instability was removed with occlusion (Bjerknes and Solberg 1922; Charney 1947; Eady 1949). Therefore, there were two seemingly well-defined types of cyclones with little acknowledgment of a grey continuous area between them.

This discrete separation between both types of cyclones was subsequently losing support as some unclassifiable cases were detected, and satellite imagery provided increased proof of more variability in the structure and evolution of cyclones. Tannehill (1938) and Pierce (1939) were probably the first authors to demonstrate the existence of a cyclone with mixed characteristics. They described the 1938 New England hurricane losing tropical characteristics and obtaining energy through baroclinic processes as it interacted with a baroclinic zone, with the result of a frontal structure appearing. The recognition of this system showed that cyclone energetics could change through its life-cycle. Later on, observations continued to indicate similar results, that is, initially tropical cyclones evolving to frontal structures (Knox 1955; Sekioka 1956a,b, 1957; Palmén 1958; Kornegay and Vincent 1976; Brand and Guard 1978). These studies demonstrated the fact that the transition between both types of cyclones could exist and that it was a gradual process. During this transition, the cyclone could have a hybrid phase that was not previously acknowledged.

There was also evidence for cyclones having partial characteristics of both tropical and extratropical cyclones (e. g. lower-troposphere warm core and upper-troposphere cold core). Simpson (1952) discusses the evolution of “Kona Storms” in the Pacific Ocean during winter, and states that they could originate either via occluded cyclones that had been isolated from the westerlies (with an associated anticyclone to the north) or via intrusion of an upper-level feature (cut-off cold low or a tropical upper tropospheric trough (TUTT) that induces baroclinic cyclogenesis at the surface). Ramage (1962) confirmed the hypothesis of Simpson (1952) that upper cold cutoffs are present in that type of cyclogenesis in the subtropics, performing a detailed case study of a subtropical cyclone over the Pacific. An important feature highlighted by Ramage (1962) is the persistence of subtropical cyclones, even when they are cut-off. He also argued that these hybrid cyclones were likely related to the Kona storms of Hawaii.

Later in the 1970s, these cyclones that were observed to show both baroclinic (extratropical) and diabatic (tropical) characteristics attracted the attention of the forecasting community (Hebert 1973). They were observed to simultaneously obtain their energy from both thermal differences in air masses (and upper-level disturbances) and organized convection. Some of them evolved into fully tropical cyclones while others retained hybrid characteristics during their entire life-cycle. Hebert and Poteat (1975) subsequently developed guidelines for diagnosing structural changes and intensity of subtropical cyclones from satellite imagery. This satellite recognition was implemented as a complement to the Dvorak technique (Dvorak 1975) for tropical cyclone classification. They not only argued that subtropical cyclones formed from upper cold cutoff lows, but also distinguished two sub-categories with low-level baroclinic origins: non-frontal lows which form east of upper troughs and frontal waves.

In the subsequent decade, processes known to be critical for tropical cyclone development were found to likely play a major role in extratropical cyclone development. Bosart (1981) illustrated that surface fluxes and convection had a crucial impact in coastal baroclinic cyclogenesis. His work not only diagnosed one major limiting factor preventing successful numerical forecasts of explosive cyclogenesis at that time, but also showed that mesoscale processes can significantly impact synoptic-scale cyclone evolution. Soon after, (Gyakum 1983a,b) explored the sensitivity of extratropical development to the intensity and vertical distribution of convective heating in a model, showing that baroclinic cyclogenesis was highly influenced by convective scale processes.

Higher-resolution models with more complex physics lead to an increase in forecast accuracy of explosive cyclogenesis in the 1980s. This fact allowed researchers to identify the strong role that mesoscale processes can play in extratropical cyclones development (Sanders 1987). As oceanic surface fluxes, convection and convective heating were shown to have a strong impact on extratropical cyclones, the possibility given to warm-core development within extratropical cyclones in extreme circumstances increased.

Succeeding research in the 1990s illustrated the possibility of extratropical cyclones acquiring warm-core over land, associated with a region of warm air trapped within the centre of the cyclone in case of an explosive development (warm seclusions). Such unconventional cyclones started to be deeply studied thanks to the increasing availability of higher-resolution satellite data and surface observations. The interest in them arose because their characteristics defied the conventional definition for extratropical cyclone development and structure (Bjerknes and Solberg 1922). Abundant attendant convection, wind field contraction, warm thermal anomaly in the centre and a lower-level vorticity maximum were observed in those “anomalous” extratropical cyclones (Bosart 1981; Gyakum 1983a,b; Kuo et al. 1992). As a result, Shapiro and Keyser (1990) proposed to add an alternative way of extratropical cyclone development to the conventional Norwegian cyclone model (Bjerknes and Solberg 1922). This development mode was mainly associated with intense extratropical cyclones because of their warm seclusion phase. The development of a warm seclusion in extratropical cyclones was shown to be produced by purely adiabatic processes (Reed et al. 1994), although diabatic processes could also play a role, by enhancing the end result (Gyakum 1983a,b; Kuo et al. 1992).

Also in the 1980s and 1990s, research into the changing structure in the evolution of tropical cyclones that move into the midlatitude flow, experiencing extratropical transition (ET), underwent a rebirth since previous studies in the 1940s-1950s. Most extreme cases of extratropical transition were found to be associated with the favourable capture of a deep warm-core cyclone by a deep cold-core trough, just downstream of the latter. The tropical cyclone then underwent the transition while moving ahead of the trough (DiMego and Bosart 1982a,b; Harr and Elsberry 2000; Harr et al. 2000; Klein et al. 2000). This process is mainly located over the western Pacific and North Atlantic basins and it has been shown that it is only likely to occur for a few months per year in the North Atlantic (Hart and Evans 2001).

On the other hand, a process in the opposite direction was later discovered in the 1990s. Warm-core or tropical cyclone formation in non-typical environments with baroclinic features was demonstrated by Bosart and Bartlo (1991), Montgomery and Farrel (1993), Bosart and Lackmann (1995), Beven (1997), Miner et al. (2000) Davis and Bosart (2001, 2002), and Davis and Bosart

(2003, 2004). There had been already some studies addressing the issue of tropical cyclones forming via baroclinic processes. Sadler (1976, 1978) had shown that some tropical cyclones formed from weakly baroclinic tropical upper tropospheric troughs (TUTTs) in the North Pacific. TUTTs are nowadays considered as upper troughs or vortices that frequently occur in the subtropical basins and result from fractures of thinning potential vorticity streamers occurring in conjunction with anticyclonic Rossby wave breaking events (when low potential vorticity (PV) air folds over high PV air; Martius et al. 2007). Bosart and Bartlo (1991) showed that tropical cyclone Diana (1984) was preceded by a baroclinic cyclone formed through midlatitude quasi-geostrophic (QG) processes, ahead of an upper-level cold low that formed via Rossby wave breaking. Subsequently, the cold-core baroclinic cyclone evolved into a warm-core diabatic cyclone. This process has been recently called tropical transition (TT) (Davis and Bosart 2003, 2004).

Apart from the North Atlantic, violent cyclonic storms that resembled tropical cyclones were started to be observed in midlatitude basins like the Mediterranean Sea, thanks to the advent of satellite imagery (Ernst and Matson 1983; Billing et al. 1983; Mayengon 1984). These subsynoptic vortices were notorious for inducing sudden changes in pressure and wind over the affected areas, although rarely attaining hurricane intensity. They often acquired tropical characteristics like a symmetric warm core with eye-like features and spiral bands (Ernst and Matson 1983; Reale and Atlas 2001; Jansa 2003). These tropical-like cyclones in the Mediterranean were later coined “medicanes” (MEDIterranean HurriCANES) by Emanuel (2005), who demonstrated the possibility of a tropical cyclone with hurricane structure being originated by an upper cold-core cutoff low.

Therefore, the classical sharp boundary to classify tropical cyclones and extratropical cyclones has been substantially weakened thanks to the emergence of numerous studies addressing unconventional cases that challenge such a classification. This has led to a change in the paradigm regarding cyclone’s structures. As a consequence, the focus is now on a more flexible approach toward a classification of the three-dimensional nature of cyclone structure. This new approach understands variability in cyclones as if there were a broad continuum between theoretical extremes of cyclones (extratropical and tropical cyclone), rather than a mutually exclusive set of cyclone types.

The majority of the observed cyclones seem to lie within the interior of this continuum (Beven 1997; Reale and Atlas 2001). Beven (1997) is thought to be the first author to suggest a phase space for classifying cyclones’ structures, in which cyclones would be defined by two characteristics: core temperature (warm to cold) and frontal nature. This work made a substantial step forward in this issue and provided motivation to pursue a more rigorous definition and analysis of cyclone phases. However, an objective, consistent approach was still needed. Partially inspired by Beven (1997), it was Hart (2003) who came up with a new objective method to classify cyclone’s structures, thoroughly analysing its suitability. Hart (2003) developed and objectively defined a three-dimensional cyclone phase space using the parameters of storm-motion-relative thickness asymmetry (symmetric/nonfrontal versus asymmetric/frontal) and vertical derivative of horizontal height gradient (cold- versus warm-core structure through thermal wind relationship). The life cycle of any cyclone can be analysed within this phase space, providing substantial insight into their structural evolution. An objective classification of cyclone phase can then be derived with this method, since it unifies the basic structural description of tropical, extratropical, and hybrid cyclones into a continuum phase space. This kind of diagnosis could not be done through examinations of conventional model fields. Thus, the cyclone phase space (CPS) developed by Hart (2003) has been substantially helpful for both the extratropical cyclone and tropical cyclone communities by allowing to understand the nature of the evolution of any cyclone either observed or forecasted by numerical models. In this way, the potential threat and intrinsic intensity forecast uncertainty associated with a given cyclone can be quantified and related to its structure.

Hybrid storms with ambiguous origins and/or structures forming over the ocean usually have been operationally classified as "subtropical cyclones". It is difficult to define objective criteria when classifying and forecasting subtropical cyclones, because of the complexity of measuring the extent of their tropical or extratropical characteristics. However, from the point of view of their impacts, there are no real distinctions between subtropical and weak tropical cyclones, as the weather produced by both is similar (Evans and Guishard 2009). Indeed, the evolution of subtropical cyclones into tropical cyclones could occur as part of the tropical transition process (Davis and Bosart 2003, 2004). Given their recognition as damaging weather system, subtropical cyclones were first given a distinct category in 1972, after some years of debate. At that time, the National Hurricane Center (NHC) started to launch watches and warnings of those systems for maritime navigation only. In 2002, this changed and NHC began to focus on them, and they were treated in the same way as tropical cyclones; subtropical cyclones were assigned names from the same list that tropical cyclones are named. This change was mainly motivated by the impact that subtropical cyclones were seen to make [e.g. Hurricane Karen during its subtropical phase; Stewart (2001)], similar to that of hurricanes. For years, the distinction between a subtropical and a tropical cyclone relied on the subjectivity of the weather forecaster and was mainly based on satellite images and ship data. Despite the recognition of their associated high impact, hybrid oceanic cyclones are still treated with a high degree of subjectivity in their identification and definition, although the CPS (Hart 2003) has substantially helped in this task. Nowadays, the CPS has become an important tool in the NHC for differentiating subtropical cyclones from extratropical or tropical cyclones (e.g. Blake et al. 2013).

There exist certain reasons why studying subtropical cyclones is important and interesting:

- The existent controversy in their definition
- The scarcity of their associated bibliography as they weren't recognized as damaging weather systems.
- Their inherent low predictability in numerical prediction models and forecasts in general. Their hybrid structure is a consequence of the "fight" between different forcings seeking for dominating the evolution of the system.
- Their high potential to become truly tropical cyclones or even hurricanes and therefore, make even greater impacts on humans and ecosystems.

In fact, related to the last point, the first-ever reported hurricane in the South Atlantic (Hurricane Catarina; Pezza and Simmonds 2005) was provoked by the transition underwent by a subtropical cyclone. Pezza and Simmonds (2005) found that more episodes like that could occur in the future due to anthropogenic climate change (ACC). Over the last fifteen years, certain notable cases of tropical cyclones or cyclones with tropical characteristics have also occurred in the northeastern Atlantic (e.g. Beven 2006; Franklin 2006; Blake et al. 2013, Blake 2016) and the Mediterranean Sea (Tous and Romero 2013; Miglietta et al. 2013) with impact over Iberian Peninsula or surroundings that have attracted the attention of the scientific community due to certain record-breaking characteristics. The interest of these events is due in part to an "unwritten" rule (mainly based on the present climatology) that tropical cyclones cannot be found over these regions. Hurricane Ophelia (2017) (Figure 1) is the last remarkable example of a subtropical cyclone which acquired fully tropical characteristics, even reaching hurricane category 3 (a supposedly unprecedented fact; first-ever reported over this region since reliable records are available, i.e. 1851). Therefore, the possibility of tropical cyclones appearing over these regions seems plausible, mainly thanks to the formation of subtropical cyclones that subsequently undergo tropical transition.

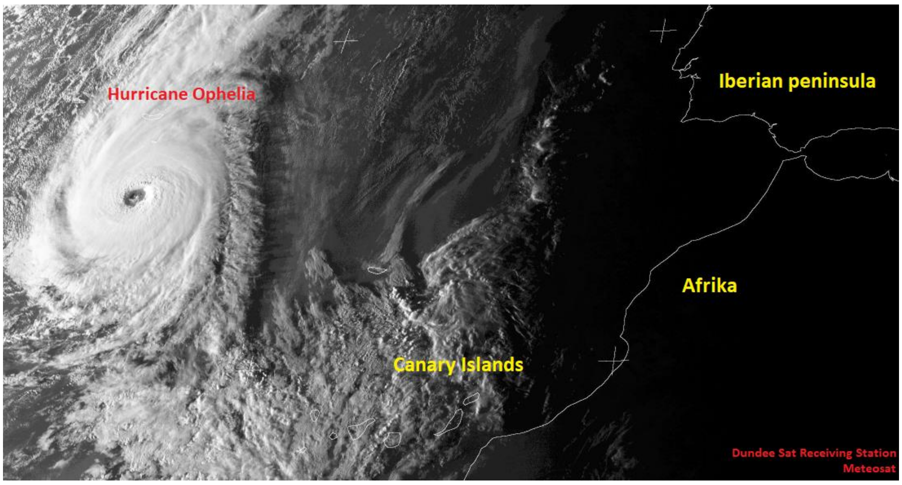

Figure 1. Satellite imagen (VIS channel) showing Hurricane Ophelia (2017) when it acquired category 3 hurricane south of Azores Islands. Source: Meteosat-Eumetsat and NERC Satellite Receiving Station, Dundee University, Scotland.

These facts could indicate two options. Either this anomalous appearance of cyclones with tropical characteristics is due to an improvement in observations and tools while in the past they were missed, or it is related to ACC. In this latter context, Haarsma et al. (2013) found a relationship between ACC and an increase in tropical cyclones affecting Europe using a high-resolution climate model (~25 km). Baatsen et al. (2015) further developed this issue. On the other hand, Liu et al. (2017) have recently projected tropical cyclone frequency increases over the eastern North Atlantic and decreases in the western North Atlantic, probably due to changes in the tropical cyclone genesis location. This is also associated with an increased frequency of these cyclones undergoing ET in the eastern subtropics of the Atlantic, implying increased TC-related risks in those regions. Liu et al. (2017) hypothesize about a more TC-favourable future climate causing this increased ET occurrence in the eastern North Atlantic. However, one must be cautious when considering this issue, as tropical cyclones have been reported affecting Spanish shores long time ago (Vaquero et al. 2008; Betencourt and Dorta 2010). Over the last years, there has been an increase in studies of these kind of cyclones, which is indicative of the importance that is acquiring this issue in the scientific community. Over the Mediterranean Sea, climate change projections show a decreased frequency of medicanes associated to an intensity increase (Cavicchia et al. 2014; Tous et al. 2016; Romera et al. 2017), but most of the available future climate change projections for medicanes have been performed either with uncoupled high-resolution atmospheric models or with lower-resolution air-sea coupled models.

As this work also deals with the analysis of the effect of ACC on hybrid cyclones, a brief review of the history of climate change science is provided below.

The development of anthropogenic climate change as a scientific issue

Anthropogenic climate change has become a very important issue in atmospheric sciences since it was addressed by the scientific community 30-40 years ago. The World Climate Conference of the World Meteorological Organization (WMO) concluded in 1979 that it appeared plausible that an increased amount of atmospheric carbon dioxide could contribute to a gradual warming of the lower atmosphere, with especial effect at high latitudes, such as polar areas (WMO 1979). It continued arguing that some effects on a regional and global scale would likely be detectable before the end of the 20th century and become significant before the middle of 21st century. In the same year, the United States National Research Council (NCR) concluded that when a double concentration of carbon dioxide (CO_2) in the atmosphere is assumed and statistical thermal equilibrium is achieved, the most realistic simulations at that time predicted a global surface warming of between 2°C and 3.5°C, with greater increases at higher latitudes (NRC 1979). They also mentioned that they were unable to find any overlooked or underestimated physical effects that could reduce or completely reverse the estimated global warming.

By the early 1980s, the slight cooling trend from 1945–1975 had stopped (Figure 2). Atmospheric aerosol pollution had decreased in many areas due to environmental legislation and changes in fuel use, and therefore it became clear that their known cooling effect was not going to increase substantially. At the same time, carbon dioxide levels were progressively increasing. Hansen et al. (1981) showed that the anthropogenic carbon dioxide warming should emerge from the noise level of natural climate variability by the end of the 20th century, and there was a high probability of global atmospheric warming in the 1980s. They also argued that there would be potential effects on climate in the 21st century, including the appearance of regions more prone to droughts in North America and central Asia as a result of shifting of climatic zones. Another dramatic projected effect would be the erosion of the West Antarctic ice sheet with a consequent worldwide rise in sea level, and the opening of the fabled Northwest Passage in the Arctic.

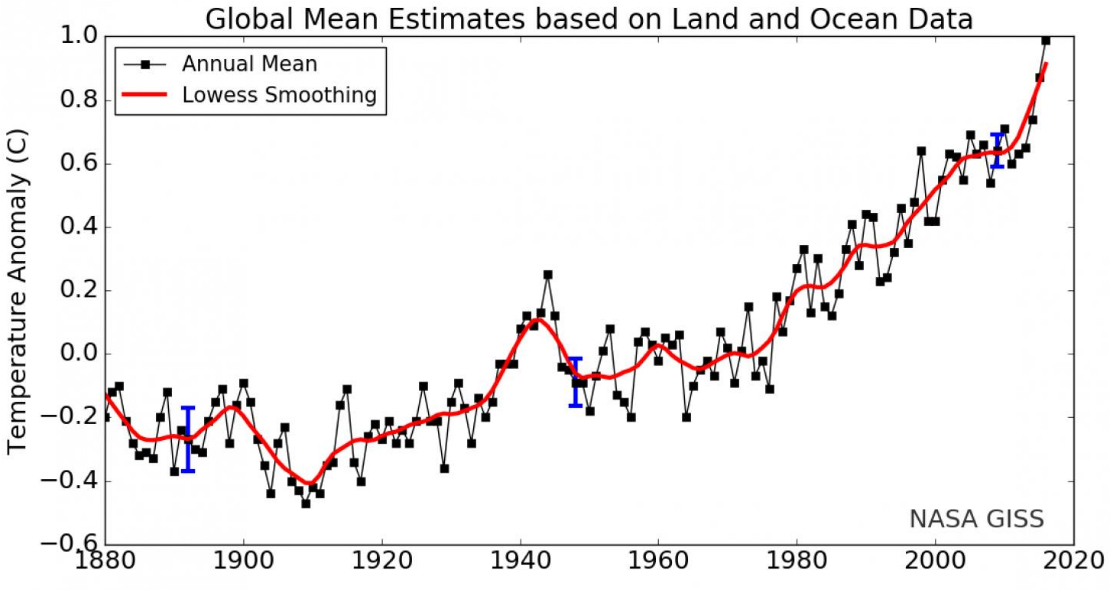

Figure 2. Global surface temperature evolution with time (1880-2016) as measured by National Aeronautics and Space Administration National Aeronautics and Space Administration Goddard Institute for Space Studies (NASA-GISS). Source: NASA-GISS's website.

Dansgaard et al. (1982) provided a context by revealing substantial temperature oscillations in the space of a century in the remote past deduced from Greenland ice cores drilled. The most prominent temperature change appearing in their record was associated with the violent Younger Dryas climate oscillation seen in shifts in types of pollen in lake beds all over Europe. With these results, it became evident that drastic climate changes were indeed possible within a human lifetime. Later on, ice cores drilled by Lorius et al. (1985) showed that atmospheric CO_2 and temperature changes in the past had shown similar evolutions, with both quantities increasing and decreasing together. This supported the CO_2-temperature relationship purely obtained through climate simulations, strongly reinforcing the emerging scientific consensus with (indirect) observational data. In addition, the findings by Lorius et al. (1985) pointed out to robust geochemical and biological feedbacks.

Two reports from the WMO started to point out that the problem was becoming critical. WMO (1985) concluded that greenhouse gases were expected to cause substantial warming in the 21st century, with some of this warming being already inevitable at that time. Shortly after, WMO (1989) concluded that atmospheric changes due to human pollution represented a major threat to international security and were already having harmful consequences over many parts of the globe. In that report, it also declared that the world would have to decrease its emissions (at least, 20% of the 1988 level) by 2005, something which clearly did not happen. Important breakthroughs in global environmental challenges occurred in the 1980s, when ozone depletion was mitigated by the Vienna Convention (1985) and the Montreal Protocol (1987), whereas acid rain was mainly regulated on the national and regional level, but legislation regarding carbon dioxide was not seeing any substantial change.

1988 was a key year on the issue, when the WMO established the Intergovernmental Panel on Climate Change (IPCC) with the support of the United Nations Environment Programme. The IPCC was created to provide policymakers with regular assessments of the current scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation. The IPCC continues its work until the present day and issues a series of Assessment Reports that describe the state of scientific knowledge at the time each report is prepared. Scientific developments are thoroughly summarized about once every five to six years in the IPCC Assessment Reports. They have been released in 1990 (First Assessment Report), 1995 (Second Assessment Report), 2001 (Third Assessment Report), 2007 (Fourth Assessment Report), and 2013 (Fifth Assessment Report). In their last report (IPCC 2014), the existence of a global warming (Figure 2) caused by human activity, that is, ACC, is showed to be widely accepted by the scientific community. They state:

"*Human activities are continuing to affect the Earth's energy budget by changing the emissions and resulting atmospheric concentrations of radiatively important gases and aerosols and by changing land surface properties. Previous assessments have already shown through multiple lines of evidence that the climate is changing across our planet, largely as a result of human activities.*"

Given this scientific consensus on ACC, this thesis also searches for possible alterations in the formation, frequency or intensity of cyclones with tropical characteristics. This is an important issue since knowing whether the northeastern Atlantic and Mediterranean Sea basin will experience an increase of those cyclones or not, could facilitate preparations for their impacts.

Motivation

The motivation of the present thesis first arose from the personal experience of the author when a subtropical cyclone affected the Canary Islands in 2010. During the last days of January 2010, an extratropical low started to behave atypically, showing tropical characteristics off the coast of Africa, a few hundred miles west-southwest of the Canary Islands. The storm formed from an isolated cold-core low that was wandering over the Atlantic and had developed a partial warm core. A respectable amount of heavy thunderstorm activity had built near the storm's centre, characteristic of a tropical storm. The low was over cool (21 - 22°C) water, far colder than the typical 26°C supposedly needed for a tropical storm to form. The low then headed towards the Canary Islands leaving strong winds and rain, with floods, and also impacting the Iberian Peninsula but with less intensity. Media focused on the system, calling it a tropical storm while the National Weather Service of Spain (AEMET) said that it was a typical winter storm. Given that the typical systems that affects the Canary Islands and surroundings are extratropical cyclones, the system stimulated the author's curiosity. The main questions arisen from this event were whether this system with tropical characteristics was exceptional or not and whether ACC could affect this type of cyclones or not. It is important to note that no studies were available on these issues so far.

The motivation also stems from the increasing concern of the scientific community and society about cyclones with tropical characteristics over the northeastern Atlantic and the Mediterranean Sea. The increased availability of improved tools for detecting them have made possible study them and that increasingly studies focus on this kind of cyclones. It is important to understand their dynamics and evolution in order to improve their forecasts in present climate. Another important issue is knowing if recent cases of such cyclones in the northeastern Atlantic are mainly being caused by ACC or if it is just natural variability. As have been shown, those cyclones even have the potential to develop into fully tropical cyclones. Therefore, another motivating question is whether ACC could also increase that possibility over those regions. In order to do this, it is also needed to evaluate the tools for projecting them in future climate. This thesis aims at providing knowledge on these issues. In the case of the Mediterranean Sea, this thesis aims at evaluating new improved tools available for projecting them.

The present work is structured as follows: The state of knowledge, on which this thesis is based, is described in Section I. The objectives of this thesis are detailed in Section II. Sections III and IV describe the data and methodologies used in this thesis, respectively. The main results are presented as a collection of scientific publications in Section V, and an integrative discussion of those results is provided in Section VI. Finally, the main conclusions and implications of the thesis follow Section VII, together with potential paths for future work that have arisen from this research.

I. State of Knowledge

In this chapter a review of the current state of knowledge of the theory which covers the topics investigated in this thesis is provided. With this aim, a review of the theoretical knowledge of cyclones is provided in Section I.1. In Section I.2 cyclone transitions are treated. And a review of the current knowledge on the relationship between cyclones and ACC is provide in in Section I.3.

1. Theory of cyclones

A cyclone is a synoptic-scale atmospheric system with a well-defined vertical structure. Air masses converge to its centre spinning counter clockwise around the low-pressure centre in the Northern Hemisphere, and clockwise in the Southern Hemisphere. In the Earth's atmosphere, there exist different types of cyclones depending on their features and the phenomena associated with them. These differences result from the differing physical mechanisms which cause them to form. A brief review of these mechanisms is provided below.

a. Thermal and dynamical structure

As a first approach, a simple and fundamental classification of cyclones is related to their thermal and dynamical structure. Based on this, a cold-core cyclone can be distinguished from a warm-core cyclone. These two thermal systems conceptually represent theoretical extremes within which all of the cyclones occurring in the atmosphere can be found.

Although cyclones are typically linked to the synoptic scale, some of these systems tend to show connections to the mesoscale (meso-alpha). This kind of cyclones, such as tropical and subtropical cyclones are greatly influenced by diabatic processes. However, observations show that they still retain synoptic-scale characteristics and the theory explained below can also be applied.

This description is based on the cyclones' structures. A cold-core cyclone will have a negative thermal anomaly within its core with respect to its surroundings in the horizontal plane, whereas a warm-core cyclone will have a positive thermal anomaly. This differing thermal structure affects its associated vertical distribution of the horizontal wind, and therefore results in a differing dynamical structure.

Given that the Rossby number

$$Ro = \frac{U}{fL} \quad (1)$$

reaches low values (Ro << 1) in the synoptic scale (U and L are, respectively, characteristic velocity and length scales of the phenomenon and $f = 2\,\Omega \sin \varphi$ is the Coriolis frequency, where Ω is the angular frequency of planetary rotation and φ the latitude), the hydrostatic and geostrophic approximations can be considered.

Hydrostatic balance is represented by

$$\frac{\partial p}{\partial z} = -\rho g \quad (2)$$

Where p is the air pressure, z is the geometric height, ρ is air density and g is the gravitational acceleration, or alternatively

$$dp = -\rho d\Phi = -\rho g_o dZ \quad (3)$$

Being Φ the geopotential, Z geopotential height and g_0 a constant value for g (standard gravity; 9.81 m s^{-2}).

Introducing the ideal gas law, and taking the integral, the end result is that the variation of the geopotential height, or thickness, between two isobaric surfaces is related to the temperature of the layer in a way such that:

$$\Delta Z = Z(p_2) - Z(p_1) = R\langle T\rangle ln\frac{p_1}{p_2} \quad (4)$$

being $\langle T\rangle = \frac{\int_{p_2}^{p_1} Tdlnp}{\int_{p_2}^{p_1} dlnp}$ the mean temperature of the layer.

In other words, the thickness of a given layer defined by two isobaric layers is proportional to its mean temperature. In addition, the symmetry of geopotential thickness fields of a cyclone will be similar to the symmetry of its thermal structure. Now, we will see how this thermal structure has an effect on the dynamical structure through its relation to the wind distribution.

To do this, we consider the geostrophic balance (as we are allowed in the synoptic scale)

$$\vec{V_g} = \frac{1}{f}\left(\hat{k}x\vec{\nabla}_p\Phi\right) \quad (5)$$

And taking into account an alternative expression for the hydrostatic equation

$$\frac{-\partial\Phi}{\partial p} = \frac{RT}{p} \quad (6)$$

where R is the ideal gas constant, we obtain the expression which relates vertical geostrophic wind shear to temperature, commonly referred to as thermal wind equation or balance:

$$\frac{\partial\vec{V_g}}{\partial lnp} = \frac{-R}{f}\hat{k}x\vec{\nabla}_pT \quad (7)$$

As thermal wind is defined by

$$\vec{V_T} = \int_{p_1}^{p_2} d\vec{V_g} = \vec{V_g}(p_2) - \vec{V_g}(p_1) \quad (8)$$

the end result, where we wanted to end up, is the equation

$$\vec{V_T} = \frac{R}{f}\left[\hat{k}x\vec{\nabla}_p\langle T\rangle\right]ln\frac{p_1}{p_2} \quad (9)$$

This expression allows us to obtain two clear conclusions:

- Thermal wind intensity is a function of the mean barometric temperature in a proportional manner.
- Thermal wind vector separates relatively cold (to its left) from warm (to its right) air masses.

Furthermore, a third conclusion can be inferred from considering also expression (8):

- Spinning geostrophic wind, and therefore real wind, increases with height in cold-core cyclones, whereas wind speed is greater at low levels than at high levels of the troposphere in warm-core cyclones.

By the same reasoning the circulation is anticyclonic above the non-divergence level in warm-core cyclones, while continues to be cyclonic in cold-core cyclones throughout the troposphere. To sum up, a cold-core cyclone deepens with height in the troposphere whereas a warm-core cyclone weakens, including even the presence of an anticyclone aloft in the upper troposphere. Figure 3 show a description of the distribution explained above.

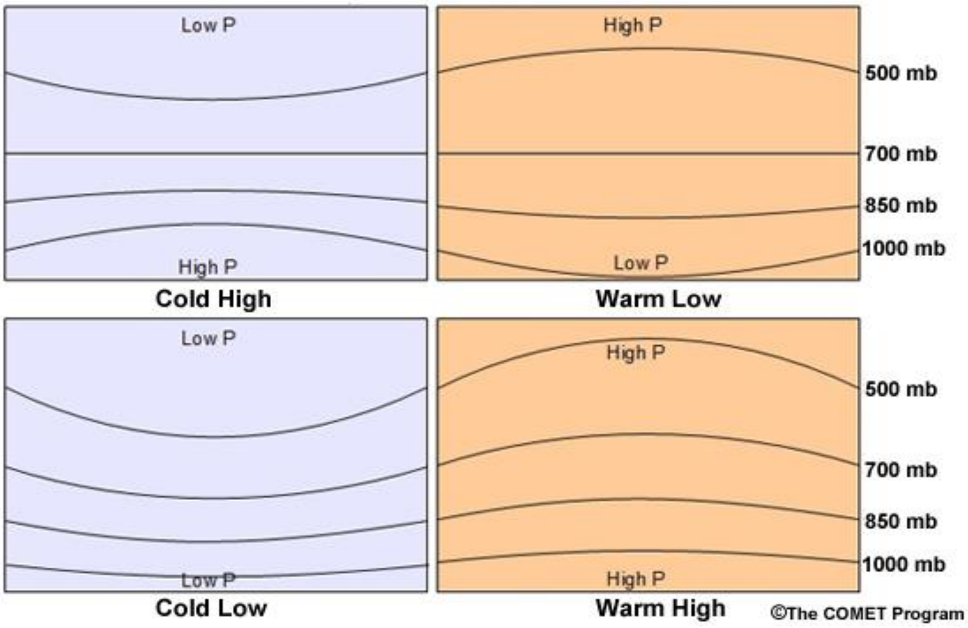

Figure 3. Schematic cross sections showing the relationship between surface pressure, temperature and pressure aloft in the different possibilities cyclone (as explained in the text) and anticyclone types. Source: The COMET® Website of the University Corporation for Atmospheric Research (UCAR).

In the atmosphere, two well-known classical instances of these conceptual extremes are observed. A typical cyclone which forms in the midlatitudes, i. e. an extratropical cyclone is a cold-core cyclone. On the contrary, a hurricane which form in low-latitudes, i. e. a tropical cyclone is a warm-core cyclone. Consequently, thermal wind is positive (negative) in extratropical (tropical) cyclones. This reasoning forms the basis for the development of the CPS (Hart 2003), which is one of the main tools used in this thesis and will be further explained in Section IV.

(i) Other features

Apart from the differences in their thermal and dynamical structure, warm- and cold-core cyclones can also be distinguished based on more characteristics arising when they develop, maintain, and interact with their environment. This is what causes them to have the above-shown different thermal and dynamical structure.

Cold-core cyclones obtain their energy from the baroclinic instability (Charney 1947; Eady 1949), i.e., from the horizontal thermal gradients in conjunction with vertical wind shear. This kind of environment is typical of midlatitudes and most of the cyclones developing in the extratropics (extratropical cyclones) are cold-core as a result. These phenomena can be explained through the quasi-geostrophic theory (Charney 1947) in a relatively simple manner. In contrast, warm-core cyclones energetic is fundamentally associated with deep convection and latent heat release in a barotropic environment (Charney and Eliassen 1964), with heat and moist (enthalpy) surface fluxes from warm oceans important role in determining their intensification (Emanuel 1986; Rotunno and Emanuel 1987). The warm ocean waters (typically in low-latitude regions) provide the energy source for the tropical cyclones. Latent and sensible heat fluxes from the ocean surface warm and moisten the tropical cyclone boundary layer. These fluxes, added to the potential energy, comprise the moist static energy of the air. A tropical cyclone intensifies when conversion of this moist static energy into kinetic energy occurs.

Therefore, a suitable environment for genesis and development of extratropical cyclones is hostile in the case of tropical cyclones, and vice versa. There still exist certain discrepancies relative to what is the actual mechanism that powers tropical cyclones as no global and definite theory has been developed equivalent to that of extratropical cyclones. This will be further explained when both types of cyclogenesis are addressed (cf. Section I.1.c).

Furthermore, observations show that wind speed rapidly decays in the horizontal plane from the centre in tropical cyclones, contrary to extratropical cyclones, where equal or even higher wind speed far away from the centre can be identified. Symmetry is another important and distinct feature of the theoretical extremes of cyclone that can be observed in the atmosphere. This characteristic is strongly linked and motivated by the atmospheric environment in which cyclones are formed and developed. Warm-core cyclones are vertically stacked with horizontal axisymmetric distribution of winds and temperature fields, whereas those fields in cold-core cyclones are asymmetric along with a vertically sloping structure. Due to this, satellite images (Figure 4) can be used to distinguish generally cold-core cyclones from warm-core cyclones. Extratropical cyclones are associated with frontal cloudiness structures (asymmetric), while tropical cyclones are associated with symmetric cloudiness patterns that tend to obtain a circular shape as the cyclone intensifies. Indeed, in a tropical cyclone's mature stage, the typical pattern is a ring of convective clouds surrounding a cloud-free eye located at the central minimum pressure or cyclone's centre associated with calm winds.

To sum up, cyclone types are determined by the environment within they are embedded, and the energy used to grow. Tropical warm-core cyclones take energy from diabatic heating and surface enthalpy fluxes within an barotropic environment. These processes play a secondary role in extratropical cold-core cyclones, as they strongly depend on horizontal thermal gradients and wind shear, which is associated with baroclinic environments. Based on the main ideas explained above, Figure 5 classifies cyclones depending upon their thermal structure (y axis) and frontal nature, i. e., symmetry (x axis). Extratropical and tropical cyclones are in opposite extremes, consistent with what has been mentioned, with hybrid cyclones (Section I.1.d) in the continuum between the theoretical extremes.

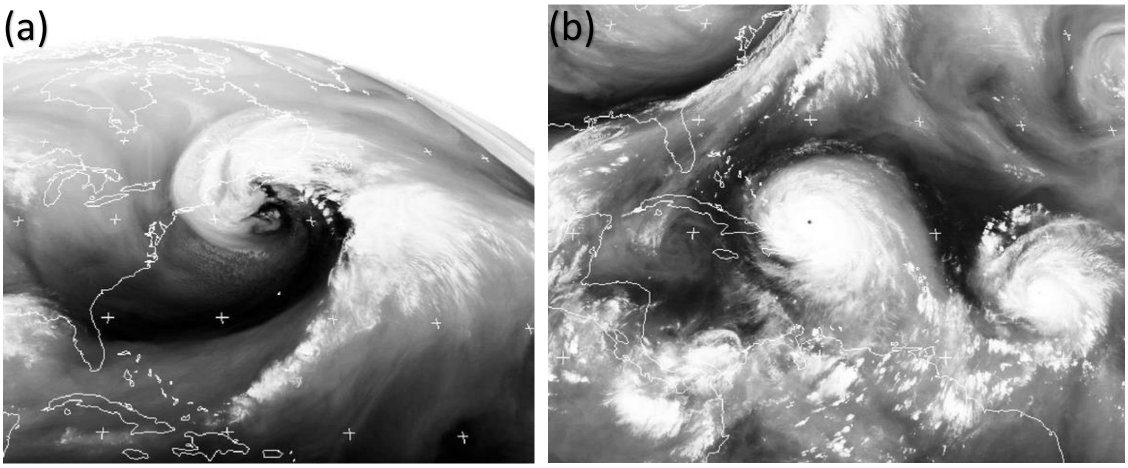

Figure 4. a) Intense extratropical cyclone developed on 26 March 2014. b) Intense tropical cyclone with hurricane structure developed on September 2017 (Hurricane Irma). Both images are from channel 5.8 - 7.3 µm (water vapor channel) GOES satellite. Source: Natural Environment Research Council Satellite Receiving Station, Dundee University, Scotland.

So far, the differing nature of cyclones in the Earth's atmosphere and their associated mechanisms or physical processes has been shown. At this point, it becomes necessary to elucidate the processes which cause them to form, in order to have a complete review of cyclones. These processes are referred to as cyclogenesis. Before this, conceptual models are presented in the next subsection to get further insight into their different structures.

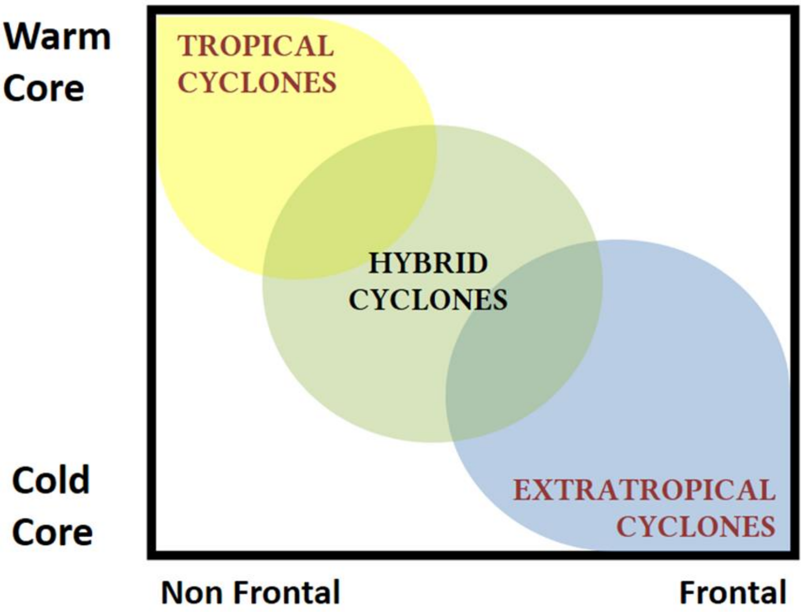

Figure 5. Schematic classification of atmospheric cyclones based on their thermal and frontal nature. Adapted from Beven (1997).

b. Conceptual models of theoretical cyclones

In order to gain insight into the theoretical knowledge that scientific community has on cyclones, in this section we will briefly see how all this knowledge can be summarized into conceptual models of the development and structure of both theoretical cyclones seen in the previous subsection. Conceptual models have been developed to facilitate the understanding of cyclones and their behaviour with the main aim of improving the task done by weather forecasters. It is important to use conceptual models in weather forecasting in order to facilitate this task. In this section conceptual models regarding the structure of both extratropical and tropical cyclones are introduced.

(i) Extratropical cyclones

The Norwegian cyclone model is the foundation of observational synoptic meteorology. In the early twentieth century, previous research and a mesoscale observing network were used to create a conceptual model for the structure and evolution of extratropical cyclones and their attendant fronts (e.g. Bjerknes and Solberg 1922).

Likely due to the success of the Norwegian cyclone model in explaining observed cyclones, Keyser (1986) found that "modern case studies illustrating occluded fronts and the occlusion process are virtually non-existent". A period of abundant research on extratropical cyclones that originated from the problem of forecasting explosive cyclone development identified by Sanders and Gyakum (1980) yielded new insights into occluded fronts and the occlusion process (e.g., Shapiro and Keyser 1990; Kuo et al. 1992; Schultz et al. 1998; Martin 1998a,b, 1999a,b; and Martin 2006). For instance, Shapiro and Keyser (1990) showed that extratropical cyclones could occlude in a different way from that of the Norwegian cyclone life-cycle. Therefore, nowadays two different conceptual models of cyclone surface evolution coexist in the literature. These are the Norwegian (Bjerknes and Solberg 1922) and the Shapiro-Keyser models (Shapiro and Keyser 1990). Both lifecycles have been well studied from theoretical (e.g. Simmonds and Hoskins 1978), numerical (e.g. Nielsen and Sass 2003), observational (e.g. Niemann and Shapiro 1993; Browning 2004), and climatological (Hoskins and Hodges 2002; Hoskins and Hodges 2005) points of view.

Further reading of extratropical cyclone research can be found in Holopainen (1990) and Shapiro and Grønås (1999).

Norwegian cyclone model

The Norwegian cyclone model describes the development of a cyclone evolving along a westerly flow. Weather conditions can be interpreted in a rapid and easy way by analysing fronts appearing in this model. Surface fronts are usually associated with the warm edge of either 850 hPa temperature gradient or potential temperature gradient fields. Figure 6 provides a schematic depiction of extratropical cyclone development according to the Norwegian model. The process is as follows:

1. A wave or front forms on the warm side of an extratropical jet, linked to a trough in the surface pressure field and a wave in the temperature field.

2. The wave intensifies as the low pressure deepens at the surface. Associated ascending motion generates clouds and precipitation and the upper trough, lying upstream of the surface low, also deepens.

3. The wave occludes as cold fronts move faster than warm fronts. When both fronts merge, they become an occluded front and the warm air region (between the cold ad warm front) starts to detach from the low center. The pressure stops falling and the jet stream passes over the occlusion point.

4. The disturbance disappears while the pressure rises because synoptic scale vertical motions cease, and a weakening occluded front remains.

It is important to note that cyclones form often families. Therefore, a new low could deepen within the cold front of an occluded cyclone and the process starts again, although not all early stage wave disturbances develop into cyclones. An extratropical cyclone will, on average, travel 1000-8000 km with the upper-level flow during its development, with a typical life span of 3-7 days.

However, one of the disadvantages of the Norwegian model is that it does not work properly outside westerly flows. For example, there exist low pressure systems developing over the Baltic Sea in summertime that are often accompanied by a non-occluding open wave (Lehkonen, n.d.). Another example are cut-off lows (Nieto et al. 2005) that reach subtropics. Cut-off lows develop when the amplitude of an upper-level Rossby wave increase, its trough stretches far south and finally breaks off from the basic flow (Rossby wave breaking). The result is a cold upper-level low, which will often gradually induce a surface low if it has sufficient cyclonic vorticity and a favourable stability environment below (Rossby penetration depth; Hoskins et al. 1985).

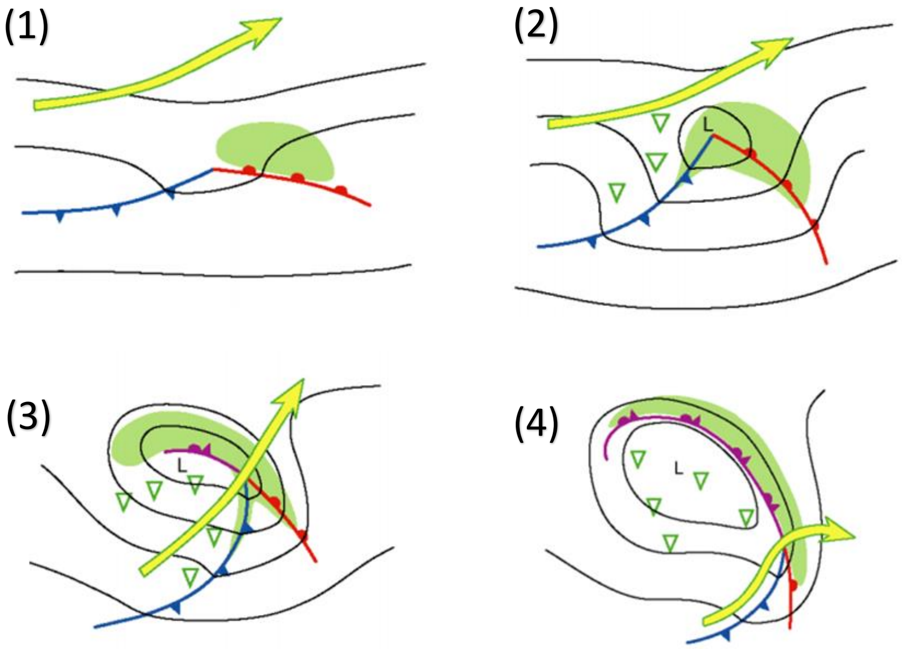

Figure 6. Schematic illustration of the cyclone development in the Norwegian cyclone model. See text for more details. From Lehkonen (n.d.).

Another flaw of this model is that it suggests that cyclones form along a pre-existing (polar) front that separates polar from tropical air masses throughout the depth of the troposphere. Nevertheless, subsequent work has proven consistently that cyclogenesis and frontogenesis nearly occur at the same time (Martín 2006). In this way, simple idealized simulations demonstrate that the development of fronts is a consequence, not a cause, of cyclogenesis (Martín 2006). Such a conclusion departs radically from the ideas that built the Norwegian model. However, baroclinic instability theory indicates that a substantial background vertical shear (associated with robust horizontal temperature contrast) is necessary in order for cyclogenesis to occur, a fact which supports the Norwegian model.

Therefore, despite the durability and longevity of the Norwegian cyclone model, their applicability needs to be continually reassessed. For instance, Schultz and Vaughan (2011) pointed out the need of rewriting the description of the occlusion process in textbooks by comparing the 90-yr-old Norwegian cyclone model to recent research results.

Shapiro-Keyser model

Shapiro and Keyser (1990) proposed a new conceptual model describing four distinct phases of extratropical cyclone life cycles that differs from the Norwegian one. This model arose from the study of powerful Atlantic cyclones. It is based on a combination of previous numerical modeling simulations (e.g. Gyakum et al. 1983ab; Kuo et al. 1990) and field experiment observations (Alaska Storms Program and The Experiment on Rapidly Intensifying cyclones over the Atlantic). This model has also been called the T-bone model. A new element in this model is that the warm front of the developing cyclone stretches backward at the same time when the cold front detaches from it. Shapiro and Keyser (1990) designated this extension of the warm front a "back-bent warm front", which has been also called “bent-back occlusion”. The occlusion process in the Norwegian model is associated with the warm sector becoming narrower and starting to disappear upward from the surface in the cyclone’s centre. The centre of the low starts to fill and its movement slows down. However, in the Shapiro-Keyser model, part of this warm sector is advected to the centre of the cyclone. When extratropical cyclones develop through this process they are associated with warm seclusion processes. Extratropical cyclones undergoing this process had been unofficially known since the 1940s, but only when numerical simulations made it possible to study them more closely, the focus on them increased.

The development of a disturbance into a Shapiro-Keyser cyclone model is shown in Figure 7, and compared to the Norwegian model for easier understanding:

(I) The initial disturbance begins as a wave in the polar front. Frontal cyclone formation in this model also starts from a long boundary region of different air-mass characteristics, i.e. a baroclinic zone. However, in this case the cold front starts to propagate perpendicularly to the warm front as the time passes.

(II) The temperature gradient weakens near the centre of the cyclone, just in the polar side of the cold front. The temperature gradient accompanying the warm front simultaneously intensifies, and a temperature gradient also forms upstream of the low, causing the warm front to stretch behind the low. Note that the warm front is nearly perpendicular to the cold front, hence the term T-bone.

(III) The cold front detaches from the warm front, i.e. the previous weakening of the temperature gradient becomes a frontal fracture. The cold front has fractured near the cyclone centre. Contrary to the Norwegian model, both fronts never encounter each other.

(IV) The warm front develops backward (in storm-centred coordinates) with its rear part rapidly coiling and wrapping up the cyclone. The result is a bent-back warm front. This bent-back front prevents the cold air from coiling just around the centre of the low, which is moving eastward, thus provoking warm air secluded from the warm sector, to be present in the cyclone centre. This latter process is called a warm seclusion.

The heaviest precipitation is found on the cold side of the bent-back front. Warm core seclusions have been found to form temperature gradients of approx. 7° K with respect to the cold side of the encircling bent-back warm front. This relatively warm and moist air in the cyclone centre may exist for several days (Shapiro and Keyser 1990). Mesoscale bands of hurricane force winds have been observed on the cold side of the seclusion (Browning 2004; Browning and Field 2004; Parton et al. 2009; Baker 2009). These bands of strong winds are associated with rapidly descending air with typical strong, gusty winds near the end of the bent-back front. This is usually associated with a feature called "sting-jet" or "poisonous tail of a cyclone" (Grønås 1995; Browning 2004; Schultz and Browning 2017). This life cycle model has been recently extended by Hewson (2009) to include a new feature called "diminutive frontal waves", often associated with small cyclonic windstorms. One of the differences between the two models is that the Norwegian cyclone model occlusion involves air originating from the warm sector whereas the occlusion involves air within the baroclinic zone on the north side of the cyclone in the Shapiro-Keyser model. Cyclones following this model suffer considerable dynamical structure changes during short time periods of several hours, where an upright tower circulation is generated (Rossa et al. 2000).

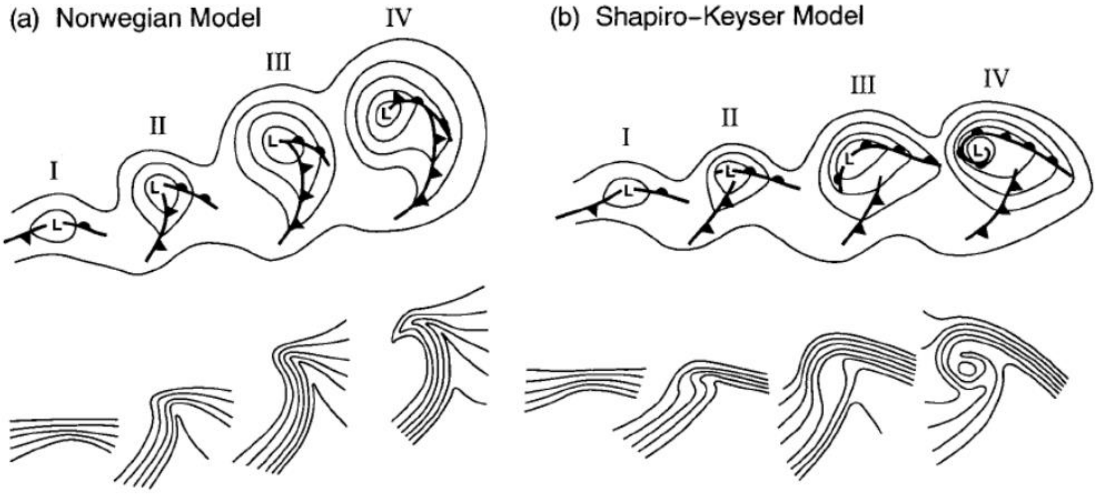

Figure 7. Schematic illustration of the development of a cyclone into the (a) Norwegian model and (b) the Shapiro-Keyser model. Pressure field and fronts' evolutions are represented in the upper row and thermal field evolution in the lower row. See text for more details. From Schultz et al. (2008).

The influence of the basic flow

From Figure 7, it can be deduced that the Norwegian cyclone model describes a cyclone lifecycle which is mainly meridionally-oriented, with a long, strong cold-front and a shorter and weaker warm front. On the other hand, a Shapiro-Keyser cyclone is zonally-oriented with a strong warm-front and relatively weak cold front. These differences have been attributed to the environment within which the cyclone is embedded (e.g. Shapiro and Keyser 1990; Shapiro et al. 1999; Schultz et al. 1998; Schultz and Zhang 2007; Davies et al. 1991; Thorncroft et al. 1993).

Schultz et al. (1998) demonstrated that both types of development are provoked by different setups of the basic flow. They showed that Shapiro-Keyser cyclones are more frequent under confluent upper-level areas, whereas Norwegian cyclones tend to develop under a large-scale diffluent flow (exit regions of the extratropical jet core). When a low-pressure system arrives in a diffluent ridge with a large amplitude, the low stretches meridionally. This results in a strong meridional cold front and a weak warm front development, undergoing an occlusion consistent with the Norwegian model. This development is typical in westerly flow for cyclones located in the eastern parts of the North Atlantic Ocean, where the exit region of jet streams is often found. On the contrary, if the low arrives in a confluent zonal flow with weak amplitude, then it stretches zonally, resulting in a strong, zonal warm front and a weak cold front. Such a cyclone would then develop following the Shapiro-Keyser model. In this case, the cyclone finally develops a warm seclusion via the bent-back warm front and the detached cold front. This development is usually found in the western parts of the North Atlantic Ocean, which is often the entrance region of jet streams. However, Shapiro-Keyser development can also change as it progresses and start following the classical Norwegian model if the low travels over the Atlantic from an upper-level confluent region into a diffluent one.

Conveyor belts

Another method to describe the structure of extratropical cyclones through conceptual models is by using the conveyor belts features. This conceptual model was presented by Carlson (1980) and examines cyclones based on Lagrangian coordinates, where the coordinate system is fixed to the cyclone centre and thus air flows are studied in relation to the cyclone.

Conveyor belts are relatively narrow air flows that travel along isentropic surfaces. They offer a perspective on the clouds and precipitation associated with cyclones that differs from the quasi-geostrophic model (cf. Section I.1.c). They can be considered as a group of air parcels originating from a common source region that moves with the atmospheric flow. In this way, this conceptual model provides a three-dimensional way of looking at a cyclone's surface air-masses. Conveyor belts are useful for highlighting important atmospheric processes that can be advantageous for making forecasts. They can also provide the forecaster with insight in understanding the three-dimensional structure of the atmosphere. An illustration of these conveyor belts is shown in Figure 8.

There are three types of conveyor belts as defined by Carlson (1980):

- Warm conveyor belt (WCB; relatively high wet-bulb potential temperature (θw) values). It is the main injection of warm and moist air that feeds the extratropical cyclone. It streams poleward where the warm sector (between the cold and the warm front) of the cyclone is located, with a movement parallel to the cold front. As the warm conveyor approaches the warm front, it begins to ascend. The area with the strongest ascending motions over the warm front is associated with strongest warm air advection. As this air ascends it moves away from the cyclonic centre. Cloudiness and precipitation within the cyclonic region are mostly related to the humid and rising air in the warm conveyor belt. It has been also proposed (cite The COMET Program), that warm conveyor belts split into two branches in occluded cyclones (as shown in Figure 8).

- Cold conveyor belt (CCB; relatively lower θw values). It is located north of the warm front, along the general path of the system and originates in the relatively cold air poleward and east of the centre of the cyclone. The CCB initially flows westward below the WCB just above the surface toward the centre of the low, where it then ascends at the tip of the warm and cold fronts, eventually turning anti-clockwise to become part of the westerly upper air flow. The CCB transfers air from the cold sector ahead of the warm front into the cyclone. Schultz (2001) proposed the definition of two CCB, although in strong, deepening cyclones there is only a cyclonic CCB. There are clear boundaries between the CCBs in lows with well-defined and strong warm fronts, which are wider and less definite when the warm front is weak.

- Dry conveyor belt (DCB; lowest θw values). Unlike the warm and cold conveyors, which are originated at the surface, the dry conveyor forms at altitude (from the high troposphere/low stratosphere). It then flows downward behind the cold front while moving equatorward. This conveyor is associated with relatively deep layer of low relative humidity. As it descends west of the upper level trough, it can spread out, part of it flowing up and over the warm/occluded fronts and the other part behind the surface cold front. The DCB is important in the cyclone environment for maintaining a strong temperature contrast across the cold front.

Estimating relative vertical motions is needed in order to define conveyor belts. A conveyor belt's airflow generally slants along isentropic surfaces. Warm conveyor belts ascend, dry conveyor belts descend, and cold conveyor belts may do both, but they tend to ascend on average.

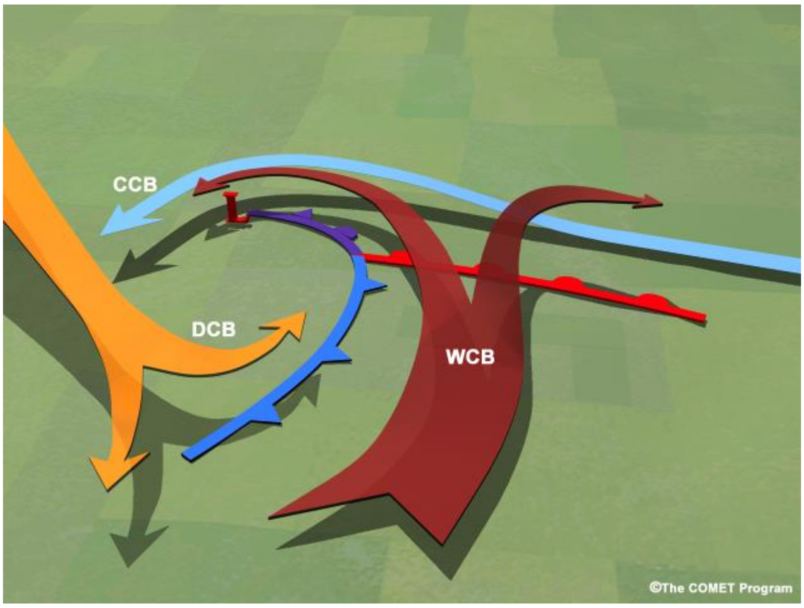

Figure 8. Schematic illustration of the warm (WCB), cold (CCB) and dry (DCB) conveyor belts associated with the structure of a mature extratropical cyclone. See text for more details. Source: The COMET® Website of the UCAR.

(ii) Tropical cyclones

Given a favourable environment (cf. Section I.1.c), an incipient disturbance in the tropics may organize into a tropical cyclone. Maintenance of these favourable environmental conditions for tropical cyclogenesis could lead to further organization and intensification. This process will be further seen in Section I.1.c. If the tropical cyclone continues to intensify it reaches a stage where it acquires a highly symmetric structure. Relatively few tropical cyclones reach this status. Intensification to a severe tropical cyclone generally requires that the storm remains over the open ocean, although there are some exceptions.

If a tropical cyclone moves into a hostile environment it will either decay or undergo extratropical transition (cf. Section I.2.a). A hostile environment is characterized by either strong vertical wind shear, relatively cold ocean temperatures, dry air intrusion, or landfall (cf. Section I.1.c). Cool sea surface temperatures (SSTs) and strong shear are typical of a midlatitude environment, which explains why this region is generally hostile for favourable tropical development, although sometimes it is not (Section I.2.b). Such a hostile environment may unbalance the storm so that it ceases to be self-sustaining.

When a tropical cyclone has reached its mature stage, a few structural elements can be identified, which are common to all tropical cyclones and could form a conceptual model (The COMET Program 2017). A (i) boundary layer inflow, (ii) eyewall, (iii) cirrus shield, (iv) rain bands, and (v) upper tropospheric outflow can be found in all tropical cyclones, and if the storm become more intense, a (vi) clear central eye increasingly becomes visible from satellite (Figure 9).

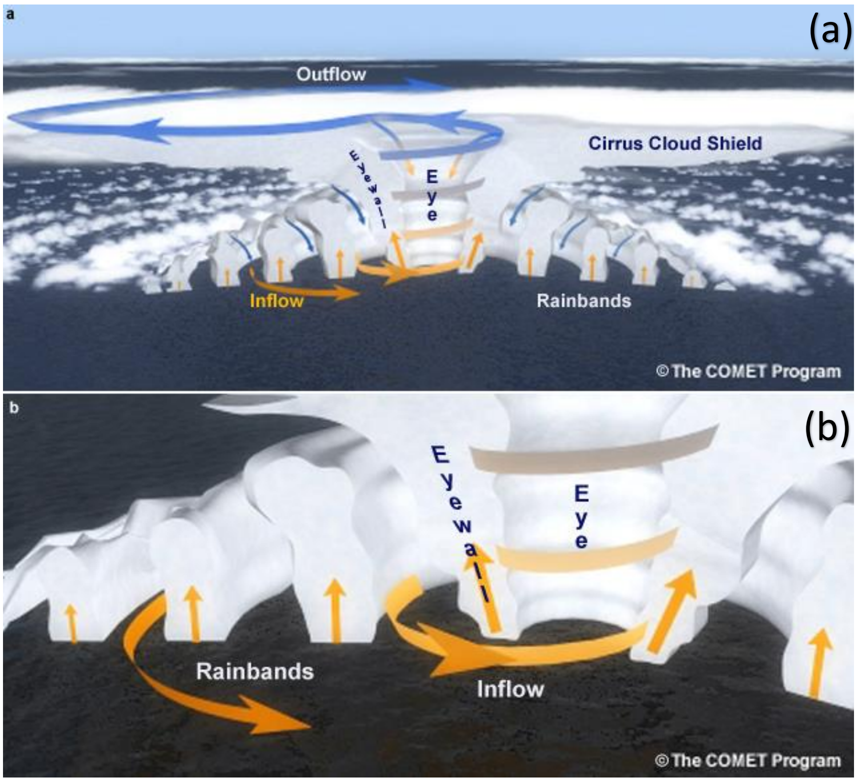

Figure 9. (a) Illustration of the conceptual model of the main structural elements of a mature tropical cyclones. Notice the (i) boundary layer inflow, (ii) clear central eye, (iii) eyewall, (iv) cirrus shield, (v) rainbands, and (vi) upper tropospheric outflow. (b) Close-up view of the boundary layer flow in the tropical cyclone. Source: The COMET® Website of the UCAR.

In a mature tropical cyclone, the wind flows inward cyclonically at lower levels, spiraling upward where deep convection is located (the central eyewall or the spiral rainbands), and spiraling outward aloft, just at the top of the troposphere. The clear region just in the centre of a mature tropical cyclone is known as the eye. It is characterized by relatively calm or light winds and the lowest surface pressure of the system can be found there. For a tropical cyclone in steady state, subsidence in the centre occurs to compensate for the air rising in the convection region, due to mass conservation. The clear eye in the centre appears because of this descending air motion. In weaker storms, the eye may not be evident from visible and infrared satellite images.

An organized band of thunderstorms immediately surrounds the storm centre or eye. This region of deep convection is the eyewall and is associated with the presence of the strongest winds, just on the inner flank. A clear indication of the intensification a tropical cyclone is the appearance of a clear eye with eyewall vortices and further development of an asymmetric eye, which then resymmetrizes. Overshooting convection into the stratosphere is usually seen in the eyewall, which results from an enhancement of convection due to thermal instability.

Convergence in the cyclonic boundary layer flow occurs due to surface friction, which slows the winds above the surface. This cyclonic flow spirals into the eyewall and forces (dynamically-driven) convection. The existence of a frontal zone between the moist inward frictional flow and the dry subsiding air flowing outwards from the eye enhances convergence just under the eyewall. Air ascending in the eyewall then comes from both differently characterized regions. On the other hand, convection in the rainbands can be weakened due to lower to mid-tropospheric drier air entrained above the boundary layer (Frank 1977), which tends to converge moving to the cyclone center. The image of the rainbands spiraling around the eye is one of the most recognized satellite signatures of tropical cyclones.

c. Cyclogenesis

Cyclogenesis is the process by which a low-pressure region is created, develops into a closed circulation, i. e., a surface cyclone, and subsequently intensifies. Cyclogenesis is considered to be finished once the resulting structure has become self-sustaining, i.e., is able to maintain itself without the help of an external forcing or its environment. Cyclogenesis is often regarded as the intensification of the cyclone since its initial state. This intensification is often measured in terms of the drop in the sea-level pressure following the cyclone centre. This semi-Lagrangian negative pressure tendency is associated with an increase in the low-level geostrophic vorticity. Therefore, cyclogenesis can be similarly considered as a process which produces low-level vorticity. As low-level vorticity production necessitates the presence of divergence and vertical motions, cyclogenesis is thus triggered by vertical motions that become self-sustained once the cyclone is formed. In order to explain why cyclogenesis occurs, we have to focus on what is provoking those vertical motions and what cause them to become self-sustained without the help of external forcing after some time.

As we have already seen, differing cyclones are governed by distinct dynamics and hence the genesis of extratropical cyclones is different from that of tropical cyclones. Therefore, extratropical cyclogenesis must be distinguished from tropical cyclogenesis.

(i) Extratropical cyclogenesis

Extratropical cyclones develop through the baroclinic instability. Baroclinic instability theory (Eady 1949) is based on the linearization of the dynamic equations and the calculus of the natural modes of the system. When the basic flow is unstable, the natural frequency of the modes has an imaginary part, which turns into an exponential development, i.e., the development of a cyclone. The energy source for baroclinic instability is the potential energy associated with the environmental flow. The situation of an equator to pole temperature gradient on the rotating Earth has potential energy associated with it. This energy that may be extracted by the baroclinically growing disturbances through conversion to kinetic energy. A thorough explanation of this phenomenon is provided in Martin (2006).

Assuming that the flow in the mid-latitudes is zonal and follows the thermal wind balance, isobars and isotherms are parallel in the upper troposphere. When the basic flow is perturbed by a (Rossby) wave disturbance, meridional movements are generated in the flow. These movements bring warm advection downstream of the trough's axis and cold advection upstream of the trough's axis [cf. Figure 8.5 in Martin (2006)]. If the general system with temperature gradient ends up in a state of less potential energy (Figure 10), some of the potential energy turns into kinetic energy. This happens if both cold and warm temperature anomalies intensify, thus increasing kinetic energy derived from potential energy of the waves which then results in intensification of the wave because the flow has become unstable. Low and high pressures in the mid-latitudes are wavelike phenomena. To sum up, when Rossby waves are growing in the atmosphere, cold air moving downwards and equatorward displaces the warmer air moving poleward and upwards (Figure 10).

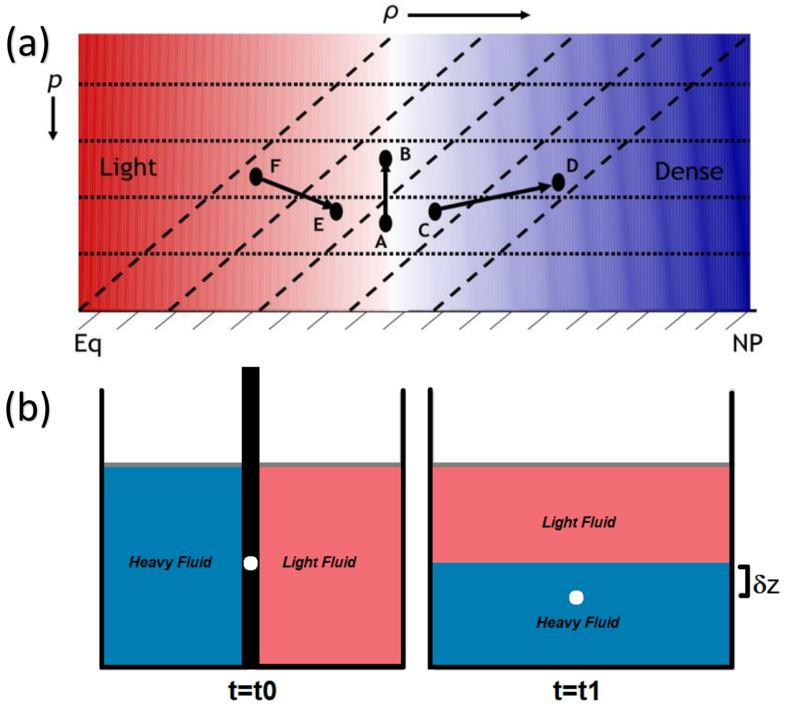

Figure 10. a) Schematic illustration of sloping convection. Surfaces of constant pressure are illustrated by the dotted lines and surfaces of constant density by the dashed lines. From Simpson (2010). The only possible spontaneous movement in the free atmosphere is C-D, which releases potential energy. b) Fluids of different densities separated horizontally in a container by a dividing wall (thick black line) at t= t0. The white dot represents the height of the centre of gravity of the two-fluid system. At t = t1, after the divider has been removed, the height of the centre of gravity of the fluid system has been lowered by an amount δz. This process illustrates why potential energy is released in a process like C-D in a). Adapted from Martin (2006).

Extratropical cyclogenesis may be elegantly explained through the quasi-geostrophic (QG) theory, which basically relies on the interaction of two equations and the phenomena or process which they represent. The use of QG dynamics and equations for the development of extratropical cyclones can be considered as another way of analysing the baroclinic instability, based on interpretable equations that can be easily calculated in synoptic meteorology. It explains and summarizes the development of cyclones embedded in the baroclinic instability. QG theory relies on an assumption that can be made on the mid-latitude synoptic-scale flow. This underlying simplifying assumption is based on the fact that geostrophic balance (in the horizontal) and hydrostatic balance (in the vertical) are the fundamental balances which constrain the behaviour of the mid-latitude atmosphere on Earth. As we have seen above, these two separate balances are combined in the thermal wind balance.

Given known expressions for Newton's second law, mass continuity and energy conservation, expressed for atmospheric motions in terms of the equation of motion, continuity equation and the thermodynamic equation, respectively, appropriate simplifications of these relationships can be made to develop a simple system of equations. This system can be then exploited to gain physical insight into the nature of the mid-latitude weather systems and extratropical cyclogenesis. Given those equations we could explain the physical sequence of events that characterize the adjustment of the mass and temperature fields to a canonical extratropical cyclogenesis event.

This set of equations are the geopotential tendency (10) and omega equations (11):

$$\left(\nabla^2 + \frac{{f_0}^2}{\sigma}\frac{\partial^2}{\partial p^2}\right)\chi = -f_0\overrightarrow{V_g}\cdot\nabla\left(\frac{1}{f_0}\nabla^2\Phi + f\right) + \frac{{f_0}^2}{\sigma}\frac{\partial}{\partial p}\left[-\overrightarrow{V_g}\cdot\nabla\left(\frac{\partial\Phi}{\partial p}\right)\right] \quad (10)$$

$$\left(\nabla^2 + \frac{{f_0}^2}{\sigma}\frac{\partial^2}{\partial p^2}\right)\omega = \frac{{f_0}^2}{\sigma}\frac{\partial}{\partial p}\left[\overrightarrow{V_g}\cdot\nabla\left(\frac{1}{f_0}\nabla^2\Phi + f\right)\right] + \frac{1}{\sigma}\nabla^2\left[\overrightarrow{V_g}\cdot\nabla\left(\frac{-\partial\Phi}{\partial p}\right)\right] \quad (11)$$

where $\chi = \frac{\partial\Phi}{\partial t}$ is the geopotential tendency and $\sigma = S_p\,\frac{R}{p}$, being S_p the static stability parameter for the isobaric coordinate system ($S_p = \frac{-T}{p}\frac{\partial\theta}{\partial p}$). T and θ are the temperature and potential temperature of the air, respectively.

Nearly all cyclogenesis events derive from a precursor in the upper-level disturbance in the flow. In the case of extratropical cyclogenesis, this disturbance is associated with Rossby waves. Rossby waves are the most important weather features occurring in the mid-latitude atmosphere. If equations (10) and (11) are applied to a Rossby wave in the upper-level flow in conjunction with the typical strong low-level thermal gradient often associated with the midlatitudes, extratropical cyclogenesis can be explained in a simple manner.

Considering that Rossby waves provoke a similar wavy disturbance in the geopotential height field, one can infer its interaction with vertical wind once there is sufficient low-level thermal gradient. Then, regions of both general ascending and descending wind will be generated, thus creating cyclones and anticyclones, by decreasing or increasing the pressure at surface (through mass conservation), respectively.

Given a synoptic wave as shown in Figure 11, the first term on the right side of equation (10) causes the wave to move to the east with respect to the background flow. The second term represents the intensification of the upper-level troughs and ridges due to the geostrophic thermal advection change with height. This change is mainly based on the fact that isotherms are basically parallel to height contours in the upper and middle levels of the troposphere, while this condition is not met at low-levels (isotherms tend to cross height contours).

In equation (11), the first term on the right side is associated with generalized rising (sinking) air motion downstream (upstream) of the trough due to the change with height in geostrophic advection of relative vorticity. This change is provoked by the phase differences between the upper-level wave and the lower-level wave. At the same time, the second term is identified with generalized rising (sinking) air motion downstream (upstream) of the trough associated with the differing geostrophic thermal advections. This rising and sinking air is often referred to as secondary circulation (ageostrophic). This secondary circulation is then the causal mechanism of low-level production of positive (negative) vorticity and upper-level divergence (convergence). This low-level production ahead of the trough causes surface pressure to drop and a cyclone to form downstream of the trough as a result.

On the other hand, the interaction between both equations (10) and (11) is what describes the feedback between both phenomena mentioned above and the intensification and self-sustaining of the cyclone. Once the secondary circulation is formed with its respective cyclones and anticyclones at surface, positive (negative) thermal advection is intensified downstream of the cyclone (anticyclone). Due to the cold air advection upstream of the cyclone, and considering the second term of omega equation (11), rising air motion is intensified above the cyclone. In addition, the change with height of this thermal advection (stronger at surface) causes the trough to deepen, based on the second term of equation of the geopotential tendency (10). This feedback makes the cyclone at surface be self-sustained without the help of its environment and the cyclone is said to be formed as a result. The same reasoning is applied to anticyclones downstream (upstream) of ridges (troughs).

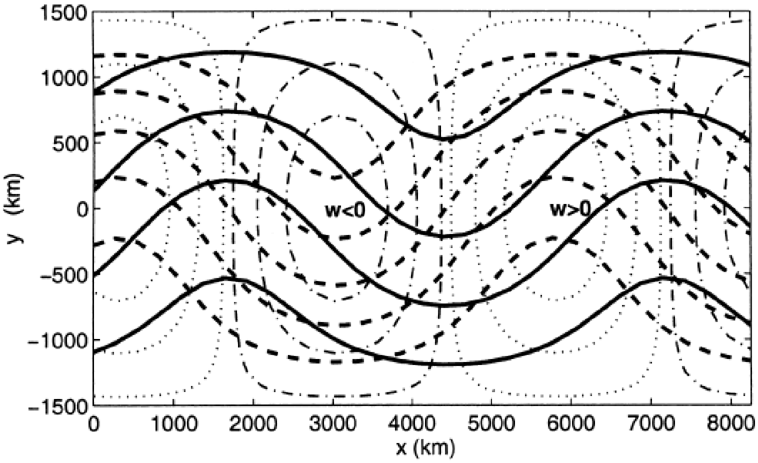

Figure 11. Schematic illustration of a Rossby wave pattern. 500-hPa height contours (solid lines), isotherms (dashed lines), and vertical motion field (w > 0 dash-dot lines, w < 0 dotted lines) for a developing synoptic-scale system. Upward motion occurs where vorticity decreases moving left to right along an isotherm, and downward motion occurs where vorticity decreases moving left to right along an isotherm. From Holton (2004).

(ii) Tropical cyclogenesis

The genesis of tropical cyclones has been considered as one of the most important unsolved problems in atmospheric dynamics and climate (Hendricks et al. 2004; Emanuel 2005). As outlined by Dunkerton et al. (2009), the problem of tropical cyclogenesis in the real atmosphere is challenging. They argue that the problem still remains unsolved after decades of research because scientist have not had in situ observations of genesis available as they mostly tend to occur over remote tropical oceans. The available observations are mainly associated with operational efforts to better forecast mature storms treating land regions. Therefore, it has been difficult to adequately model critical processes thought to be involved in warm-core cyclogenesis or at least to compare simulations with observations. In this section, a brief review on the updated knowledge of the complex problem of tropical cyclone genesis and intensification is provided. For further reading, the reader is referred to Montgomery (2016a,b) and Montgomery and Smith (2017).

Despite operational centres requiring a consistent definition to decide when a tropical cyclone has formed, this is not always the most helpful method for explaining what is physically occurring within the storm. In the context of this thesis, a physically-based definition is more appropriated. Thus, a tropical cyclone will be said to have formed once it is self-sustaining, as in the case of extratropical cyclogenesis. This means that the system is independent of the external environment, i.e. it does not need external forcing to remain a coherent system or even to intensify, although external forcing might enhance or weaken the favourable evolution of the cyclone. For example, if the system is still an incipient tropical disturbance, it will require external forcing to be sustained.

The NHC defines a tropical cyclone as "a warm-core non-frontal synoptic-scale cyclone, originating over tropical or subtropical waters, with organized deep convection and a closed surface wind circulation about a well-defined centre. This definition does not require any wind threshold, but it is required for intensity classification, e.g. tropical depression as a tropical cyclone with maximum sustained surface winds of less than 17 m s^{-1} (34 kt, 39 mph) and, in the Atlantic and eastern Pacific basins, a "tropical storm" as a tropical cyclone with surface winds between 17 m s-1 and 33 m s-1. For more information on operational classifications of tropical cyclones, the reader is referred to the NHC's glossary (NHC 2018).

However, a universally accepted definition of tropical cyclogenesis does not exist. For example, Ritchie and Holland (1999) define genesis as: "the series of physical processes by which a warm core tropical-cyclone-scale vortex with maximum amplitude near the surface forms". Nolan et al. (2007) requires a wind speed threshold of 20 m s^{-1} to define genesis onset. In the context of this thesis' section, tropical cyclogenesis will be referred to as the first stage of a tropical cyclone, which means the formation of a tropical depression. Therefore, intensification is a later stage where the cyclone intensifies beyond the tropical depression stage. However, there is an emerging view which is considering genesis and intensification as part of the same process, as we will see below, thus making unnecessary a precise definition of cyclogenesis based on the attainment of specific wind thresholds.

Contrary to midlatitude or extratropical cyclogenesis, tropical cyclogenesis is fostered by abundant deep convection which is arranged around a central point of minimum pressure without the need of baroclinic environments. Therefore, tropical cyclogenesis generally occurs within a barotropic environment, and thus, baroclinic instability can be neglected. In contrast to baroclinic cyclogenesis, no complete mathematical theory which explains the formation of tropical cyclones have been developed yet. However, after more than fifty years, several environmental factors have been established for tropical cyclogenesis to occur.

Necessary conditions for tropical cyclogenesis

Most of these conditions arisen from an early work done by Gray (1968) and have been revisited over the last decades. These conditions are generally necessary but not sufficient, i.e. the fact that they are met does not guarantee tropical cyclone formation. Therefore, research continues to seek for a physical (and mathematical) explanation of tropical cyclogenesis as we will see later in deeper detail.

Tropical cyclones do not develop instantaneously, but they need some weaker tropical disturbance to provide a promising environment in which the tropical cyclone can develop. This incipient disturbance can be substantially asymmetric. The favourable environment associated with the initial disturbance must satisfy all of the (six) necessary conditions. Each condition plays a physical role in preconditioning the environment for cyclogenesis. They may be summarized as the environment's ability to support deep convection in the presence of a low-level absolute vorticity maximum.

Such incipient disturbances are frequently present in tropical ocean basins during their respective tropical cyclone seasons, but relatively few finally become tropical cyclones. This incipient disturbance can come from different sources, depending on the region of the world, and can have different formation pathways. In the Atlantic Ocean, the most common disturbance is associated with the monsoon, which is confined to West Africa. Easterly waves are often present in that region and are influenced by local convection and mesoscale systems that initiate near the Aïr Mountains, Jos Plateau, and Guinea Highlands. They later move out to the ocean and some of them persist and can successfully develop into tropical cyclones. Another source of Atlantic tropical cyclogenesis is subtropical cyclones (cf. Sections I.1.d and I.2.b).

In order for an environment to be favourable for tropical cyclogenesis, it must feature:

1. Warm ocean waters (of at least 26.5°C) throughout a sufficient depth (unknown but at least ~50 m). Warm waters are necessary to provide thermal energy. This limit is presently being questioned (Mctaggart-Cowan et al. 2015), focusing instead on the more important differences in temperatures between low-levels and upper-levels.

2. An unstable atmosphere cooling fast enough with height, fostering convective activity. Convection releases the heat stored in the ocean waters needed for the tropical cyclone development. This is related to the previous point (Mctaggart-Cowan et al. 2015).

3. Relatively moist layers near the mid-troposphere (~5 km). Dry mid-levels could impede the continuous development of convection.

4. A minimum distance of around 500 km from the equator. This is needed for Coriolis forces to be enough for providing a background rotation. Systems can form in regions near the equator if they have sufficient local rotation, but these are infrequent events.

5. A pre-existing disturbance near the surface with sufficient vorticity and convergence (i.e. inflow). Tropical cyclones are generally not observed to form spontaneously, but they require a weakly organized system with those characteristics. The low-level vorticity maximum reduces the local Rossby radius of deformation by focusing the convective heating locally (The COMET Program 2017).

6. Low vertical wind shear of the horizontal wind, typically less than 40 km/h from surface to tropopause. If wind shear has larger values, it tends to disrupt the organization of the convection in the core of the cyclone. In addition, high wind shear values do not permit latent heat released to be concentrated above the surface low centre. However, wind shear could have a positive role in some circumstances, e.g. in the baroclinic development of subtropical precursors (e.g. Guishard et al. 2009) or intensifying storms in a marginal thermodynamic environment like in the case of TUTTs (Reasor et al. 2004). In the latter case, storms must already be sufficiently intense to survive the initial disruption of their convection by the vertical wind shear, which explains why wind shear is considered to have an overall negative effect on tropical cyclogenesis.

These conditions are frequently met but no tropical cyclone forms. Due to this, tropical cyclogenesis continues to be under controversy. What differentiates cases where tropical cyclogenesis occurs when those conditions are met and cases where tropical cyclogenesis does not occur is still under question. Tropical cyclogenesis cannot be treated as extratropical cyclogenesis because its occurrence does not only depend on the synoptic scale but on multiple scales. Thus, the problem is more complex. The environmental factors highlighted in the previous section represent the large- and synoptic-scale end of the spectrum.

The problem of tropical cyclone genesis and intensification

The main objective of researching on the genesis of tropical cyclones is to improve tropical cyclone forecast. This kind of forecasts remains difficult due to the relative lack of good quality data, operational forecast numerical models' errors, and the existence of competing theories for explaining processes involved in the organization of a cluster of thunderstorms into an intense convective vortex (Tory and Frank 2010).

Two main theories for explaining genesis have arisen in the last two decades. The first one is related to a downward spin up of the vortex and includes two variations.

- Variation 1: Ritchie and Holland (1993, 1997) argued about the existence of two mid-level vortices originating from the stratiform region nearby mesoscale convective systems. These features interact and create an area of enhanced cyclonic vorticity that appears to grow downwards. If the merged circulation extends to the surface, it will lead to a spin-up of an organized system that can ultimately result in an intense convective vortex.

- Variation 2: Developed by Bister and Emanuel (1997). Unlike the model of Ritchie and Holland (1993, 1997), it is assumed the existence of a single mesoscale convective vortex (called "mesoscale convective vortex embryo"). The development of a cool, moist environment resulting from stratiform rain (evaporation) serves as the incubation region for the formation of the intense warm-core cyclonic vortex, through downward transportation of cyclonic vorticity to the surface. This leads to an increase of near-surface winds which in turn increases surface moisture fluxes and induce convection via destabilization. Development of deep convection induces low-level convergence and vorticity stretching, thereby increasing the low-level

> tangential winds which serves to “ignite” an amplification process [the wind-induced surface heat exchange (WISHE) mechanism; see below].

However, some questions have arisen regarding these theories. One is about the dynamics of the pre-amplification process (Tory and Montgomery 2006), which is related to absolute angular momentum conservation reasoning. Another is about concerns on the assumed air-sea interaction feedback as an amplification process (Raymond et al. 2011; Smith and Montgomery 2012; Montgomery and Smith 2012; and Wang 2012).

These “top down” viewpoints have been challenged by a new view of genesis in recent years (called “bottom-up”), which is related to an emerging view of the genesis and intensification process as the same phenomenon (next subsection). Verification of this emerging bottom-up theory for tropical cyclone genesis was one of the aims of two recent field experiments called Tropical Cyclone Structure 2008 (Elsberry and Harr 2008) and PRE-Depression Investigation of Cloud systems in the Tropics (Montgomery et al. 2012). This theory recognizes a new element: the presence of deep cumulus convection in the form of “vortical hot towers” (VHTs; Hendricks et al. 2004; Montgomery et al. 2006). These VHTs act to concentrate and spin-up relatively large areas of near-surface vorticity. Another new element is a moist region of cyclonically recirculating flow in a low/mid-tropospheric layer that moves along with, e.g. a parent easterly wave (Dunkerton et al. 2009; Montgomery et al. 2012). This means that locally-favourable recirculation regions that could produce a tropical cyclone are generated within synoptic-scale precursor disturbances in the lower troposphere.

These viewpoints described above are not necessarily mutually exclusive and have provided advancement in understanding genesis, but more research remain is still needed to determine what pieces of the theories best fit observations.

As mentioned above, if the environment is favourable, the incipient disturbance may organize into a tropical cyclone (or operationally, a tropical depression). If these beneficial conditions are maintained, the tropical depression can intensify to the tropical storm or even hurricane stages. In such a favourable environment, warm ocean waters are then believed to provide the energy source of the tropical cyclone. Heat and moisture fluxes and the potential energy comprise the moist static energy of the air, which is then transformed into kinetic energy through convection, allowing the cyclone to intensify. This phenomenon is strongly dependent on convective processes and their interaction with the larger scale circulation (e.g. Marks and Shay 1998), which makes it difficult to study. For instance, the interaction of environmental vertical wind shear with the tropical cyclone is believed to be a major cause of uncertainty in intensity forecasting (e.g. Riemer et al. 2010; Tang and Emanuel 2010). When studying intensification of tropical cyclones, it is presumed that the initial vortex has become established over the ocean and has maximum spinning winds near the surface as a result of some genesis process.

Several theories have tried to explain the intensification process of a tropical cyclone, each having considerable popularity during its time. The most popular ones are the Convective Instability of Second Kind (CISK paradigm; Charney and Eliassen 1964; Ooyama 1964; Carrier 1971); the cooperative intensification paradigm (Ooyama 1969, 1982; Willougby 1990, 1995) and the thermodynamic air-sea interaction instability paradigm (Rotunno and Emanuel 1987; Emanuel 1989; Emanuel et al. 1994; Emanuel 1997, 2003; Holton 2004). These most stablished theories of tropical cyclone intensification are based on axisymmetric reasoning. A fourth theory has been emerging thanks to the use of more recent cloud-resolving numerical model simulations (Nguyen et al. 2008; Montgomery et al. 2009; Smith et al. 2009; Fang and Zhang 2011; Nguyen et al. 2011; Gopalakrishnan et al. 2011; Bao et al. 2012; Persing et al. 2013). This theory has been called “rotating convective paradigm” and suggests that the nature of the spin-up process is intrinsically non-axisymmetric and that there is a need for a modified view of the axisymmetric considerations of the intensification process. These paradigms are reviewed and compared by Montgomery and Smith (2014). Their main conclusion is that the only model able to properly capture the behaviour of intensifying tropical cyclones in three dimensions is the rotating convective model, where storm intensification is dependent on key parameters pertinent to the convective-vortex phenomenology. The main aspects of the different intensification theories are now explained.

More than half of a century ago, several studies had pointed out the substantial importance of oceanic enthalpy (heat and latent) fluxes in powering tropical cyclones (Riehl 1950; Kleinschmidt 1951; Riehl 1954; Malkus and Riehl 1960; Ooyama 1969). This was consistent with the fact that tropical cyclones were observed to develop only over oceanic regions where heat fluxes were relatively high, mainly due to higher sea surface temperatures. In addition, tropical cyclones were observed to decay generally over land even in unstable atmospheric environments containing abundant moisture.

Later on, Charney and Eliassen (1964) argued that tropical cyclones initially intensified mainly thanks to convection organization (CISK). The main idea was that tropical cyclones intensified using energy from the moist available potential energy of a conditionally unstable atmosphere. This process describes a positive feedback cooperation between deep convection (in the form of cumulonimbus clouds) and a larger scale vortex. Convection-associated latent heat released favours a warm thermal anomaly within the cyclonic region, which in turn causes convergence, bringing more heat and moist to the cyclone centre and leading to convection intensification. At this point, the cycle starts again. One of the important aspects of this theory is that surface fluxes are not needed to explain tropical cyclones deepening. In the cooperative intensification paradigm (Ooyama 1969), the representation of latent heat release is more sophisticated.

However, Emanuel (1986), echoing the earlier works where fluxes were taken into account (Riehl 1950; Kleinschmidt 1951), proposed instead that ‘‘the intensification and maintenance of tropical cyclones depend exclusively on self-induced heat transfer from the ocean’’. Therefore, in the reasoning of Emanuel (1986), ambient conditional instability plays essentially no role, and energy powering tropical cyclones derive exclusively from surface enthalpy fluxes. A key word in this theory is ‘‘self-induced’’, which stands for the idea of winds associated with the tropical cyclones driving the surface enthalpy fluxes that in turn power it. That is why the process has since been called ‘‘wind-induced surface heat exchange’’.

As mentioned above, the evaporation of water from the underlying ocean was soon recognized as the energy source for tropical cyclones but received little attention later. However, WISHE theory of Emanuel (1986), refocused attention on the key role of air-sea interaction in the intensification process. This theory would place latent heat release in deep convective towers in a secondary role for vortex amplification, i.e. no longer as ‘‘driving mechanism’’. Certain tropical cyclone’s features could be understood in terms of a simple time-dependent, axisymmetric model in which the latent heat release was implicit (Emanuel 1989). In addition, Rotunno and Emanuel (1987) argued that convective available potential energy within the cyclone environment was unnecessary for intensification.

The WISHE air-sea interaction instability paradigm for vortex intensification describes a multistep evaporative-wind feedback process of tropical cyclone intensification, where there is a two-way connection between near-surface wind speed and the evaporation of water from the underlying ocean, with wind speed and thermodynamic disequilibrium governing the evaporation rate. WISHE is an amplification mechanism that supports an intensifying tropical cyclone; a positive feedback process involving surface sensible and latent heat fluxes, ultimately manifested as continuous latent heat release within the convective clouds, which is responsible for the system to intensify. The WISHE mechanism is deeply entrenched in meteorological descriptions of the tropical cyclone intensification process (e.g. Holton and Hakim 2012) and continues to be the widely accepted theory for explaining tropical cyclone intensification in textbooks, didactic material, and the peer-reviewed literature (Montgomery et al. 2015). This mechanism is often presented as a finite-amplitude instability which requires some independently generated precursor disturbance (such as an easterly wave) for it to begin. Once this instability starts to act, the tropical cyclone would act as a ‘‘heat engine’’, i.e. it has been considered as the essential mechanism for tropical intensification. However, it is evident from a recent number of works (e. g. Montgomery et al. 2009, 2015) that the wind dependence of surface fluxes is not necessary for the intensification of tropical cyclones at least in the prototype problem.

Emanuel’s work was important because it highlighted the necessity of surface moisture fluxes in tropical cyclone intensification, but Montgomery et al. (2015) found many shortcomings in the connections between these fluxes and other elements of the intensification process. They state: “a careful examination of some of the interpretations of Emanuel’s theory exposes ambiguities or contradictions regarding the pertinent physical processes of WISHE”. For instance, WISHE was deduced first without explicit consideration of downdrafts (Rotunno and Emanuel 1987). The effects of downdrafts on intensification process have been refinements of the envisaged development process. Molinari et al. (2004) also argue about this issue. They wrote: ‘‘*The wind-induced surface heat exchange (WISHE) theory of Emanuel (1986) and Rotunno and Emanuel (1987) has continued to be refined (e.g., Emanuel 1989, 1997). The essence of the theory has remained the same, however: the pre-hurricane vortex must be of finite amplitude to develop, axisymmetry and slantwise neutrality are assumed, and development occurs basically as a feedback between surface wind speed and speed-dependent surface moist entropy flux. The WISHE-based developing hurricane contains no cold downdrafts nor strongly buoyant updrafts, and no asymmetric convection*’’. Montgomery et al. (2015) also provides several corrected misconceptions about the WISHE mechanism that currently are being taught to atmospheric science students and tropical weather forecasters.

The work of Montgomery et al. (2015) was also motivated by the linkages proposed by Miyamoto and Takemi (2013) between near-surface tangential wind speed and surface enthalpy fluxes during the rapid intensification phase in the simulation of a convective vortex. The results of the experiments designed (using a state-of-the-art cloud model with capped wind speed in the latent and sensible heat fluxes) by Montgomery et al. (2015) demonstrate that the linkage inferred by Miyamoto and Takemi is not causal but merely incidental. With support from Montgomery et al. (2009), these results refute the prior view that WISHE is the essential and dominant mechanism of tropical cyclone intensification, in the idealized problem that historically has been used to underpin the paradigm. However, Zhang and Emanuel (2016) demonstrated that WISHE feedback strongly influences both the rate of development and the ultimate intensity achieved by storms in idealized environments, and even may make the difference between development and non-development (more realistic) cases under less favourable conditions (e. g. wind shear).

Additionally, it is possible that the early stages of tropical cyclone development are powered or strongly influenced by interactions among radiation, clouds, and water vapor, similar to what happens in nonrotating self-aggregation of convection (e.g., Khairoutdinov and Emanuel 2013).

A more complete framework for tropical cyclone intensification is currently being developed, which includes rotating convection as an element of the intensification mechanism. The inclusion of rotating convection is starting to be considered as necessary to describe and understand the simulated development process occurring in three-dimensional models and that of real storms (Montgomery and Smith 2014; Mongomery et al. 2015). As mentioned at the beginning of this subsection, a last non-asymmetric theory to explain tropical cyclone intensification is emerging (Nguyen et al. 2008; Montgomery et al. 2009; Smith et al. 2009; Bui et al. 2009; Fang and Zhang 2011; Persing et al. 2013). This new rotating convective paradigm focuses again the attention on convection phenomena occurring within the cyclonic region. The first three intensification theories (CISK, Ooyama’s and WISHE) considered a simple tropical environment at the initial temporal point, where the flow is axisymmetric, with no uniform flow or vertical shear. This quiescent environment has served historically as the prototype configuration for understanding basic aspects of the intensification mechanism, without considering strong interactions with the storm environment. In the rotating convective paradigm, the initial stage also involves a quiescent environment, in which a circularly symmetric, cloud-free, cyclonic initial vortex of finite amplitude (i.e. at or below tropical storm strength) is embedded. There is a three-dimensional representation of explicit moist convection, and explicit air-sea transfer of momentum and latent and sensible heat (Nguyen et al. 2008).

Unlike the first three paradigms, the rotating convective paradigm is intrinsically three-dimensional. The dynamics in this paradigm is forced by the averaged eddy momentum and eddy heat fluxes (and their divergence, etc..) in an azimuthally averaged field, contributing to amplifying the tangential winds of the vortex (Persing et al. 2013). The work of Persing et al. (2013) suggest that limitations for understanding the intensification process (and their attendant phenomenology of axisymmetric convective rings) arise in previous studies when using strictly axisymmetric models. However, adopting an axisymmetric viewpoint of this process is a proper approach as Smith et al. (2009) and Persing et al. (2013) discuss. Further reading on this issue can be found in Montgomery and Smith (2014), where similarities and differences of the intensification paradigms are deeply discussed.

Emerging unified theory of cyclogenesis and intensification

Despite the historical separate view of tropical cyclogenesis with respect to tropical cyclone intensification, which have been always considered as different stages (e.g. Frank 1987; Emanuel 1989; McBride 1995; Karyampudi and Pierce 2002; Tory and Frank 2010), there is an emerging unified view, on the basis of the theoretical and observational evidence, where the differentiation between tropical cyclogenesis and intensification appears unnecessary (Kilroy et al. 2017). This idea is related to a new way of considering tropical cyclones as vortex spin up by vortical convection in a favourable tropical environment, instead of viewing them as the manifestation of a finite amplitude instability or the result of some triggering mechanism.

This theory describes a local amplification of vertical vorticity due to convection developing within a vorticity-rich environment. The main reason supporting this theory is the fact that this amplification by vortex tube stretching (conservation of angular momentum) is independent on the strength of the updraught and the depth of convection (Wissmeier and Smith 2010; Kilroy and Smith 2012), with the vortical remnants lasting longer than the convection phenomena that provoked them at first stage. There exists a subsequent upscale energy cascade associated with the quasi two-dimensional aggregation of the vertical remnants. Some of these remnants will intensify further by subsequent convective episodes.

In this process, an increase in the relative circulation occurs as a result of the amplification and aggregation of vorticity within the region where convection is embedded. An increase in surface moisture fluxes simultaneously occurs as the circulation intensify. However, in this case moisture fluxes are not required to continuously increase with surface wind speed, as otherwise would be expected in the WISHE mechanism. Instead, the boundary layer pseudo-equivalent potential temperature (θe) would increase as long as the atmosphere just above the surface remains unsaturated with respect to saturation at the given sea surface temperature. Another requirement would be that the positive entropy flux from the ocean must overcome downward advection of low θe from regions above the boundary layer (Montgomery et al. 2009; Montgomery and Smith 2014). The end result is a boundary layer θe that will continue to rise towards the limit value of saturation, causing air parcels to acquire sufficient potential energy for them to ascend within the warmed troposphere created by prior convective events.

This unified view would be consistent with the arguments discussed long ago by Ooyama (1982). He argued that the formation of a tropical cyclone is a series of events, arising by chance from quantitative fluctuations of the normal disturbances (with the probability of further evolution increasing as the process continues), rather than being triggered by a special mechanism or mechanisms (discontinuous change in the normal course of atmospheric processes). The climatological and synoptic properties of the environment would not then directly provoke the genesis but may alter the probability of its happening. According to this view, the statistical uncertainty could be decreased by better physical understanding of the mesoscale dynamics of organized convection. The work of Montgomery and Smith (2014) is recommended for further understanding aspects of the emerging unified view of genesis and intensification.

The strengthening of the circulation, i.e. the amplification of the azimuthally-averaged tangential wind field, occurs within a region of favourable conditions, which has been called "marsupial pouch" (Figure 12; Montgomery et al. 2012), from the viewpoint of a protected area from which a tropical cyclone could arise. The pouch would provide thermodynamic and kinematic conditions favourable for tropical cyclogenesis similar to those outlined in the six necessary conditions above. Seedling vortices associated with cumulus convective activity are protected in this region, from the adverse effects of vertical and horizontal shearing deformation and from the lateral entrainment of dry air. These favourable conditions allow the circulation to strengthen through synoptic-scale horizontal convergence, while vortex tubes (convective activity) are drawn inwards and amalgamated near the so-called "sweet spot", i.e. the potential final convective vortex. This process is explained by the so-called "marsupial paradigm" (Montgomery et al. 2012).

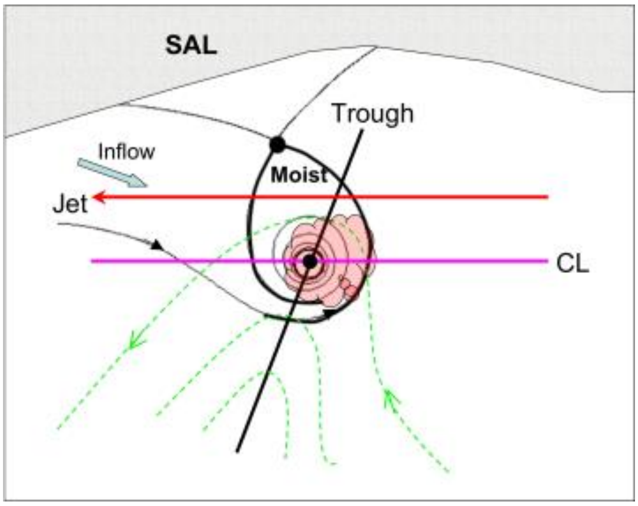

Figure 12. Cartoon of the marsupial pouch of tropical cyclogenesis associated with African easterly waves. The dashed green contours depict the horizontal wind currents of the easterly wave in the earth-based reference frame in the lower atmosphere, which is usually open with an inverted V pattern. The solid black curves delineate the approximate boundary of the marsupial wave pouch as viewed moving with the easterly wave. The pouch tends to protect the moist air motions inside from the generally hostile environment, such as dry air associated with the Sahara Air Layer (SAL) that flows westward from the African Sahel. Once the "joey" has attained sufficient spin within the pouch they can exist on their own and leave the mother pouch usually moving northward relative to the mother wave. The thick purple line [critical layer (CL)] and black line represent the critical latitude and the trough axis, respectively. The intersection of the critical line and the trough axis pinpoints the center of the pouch, which is the preferred location for tropical cyclogenesis (Wang, Montgomery and Dunkerton 2009). Figure caption and source from Montgomery (2018).

An alternative view is that diabatic heating released in the vortical convective systems have an aggregate effect that leads to a system-scale inflow in the lower troposphere. This axisymmetrically dynamically balanced inflow forces a meridional overturning (toroidal) circulation thanks to the summed effect of diabatic heating, boundary layer friction and related eddy fluxes of heat and momentum (Bui et al. 2009). When the boundary layer of the system-scale circulation has become well established, this inflow causes approximately conserved azimuthal-mean absolute angular momentum to converge above the frictional boundary layer, which spins up of the azimuthal-mean tangential winds. This increase of winds above the boundary layer leads to an azimuthal-mean radial inflow increase within the boundary layer (e.g. Smith et al. 2009), which subsequently provokes convergence of moist air enriched by surface fluxes from the ocean surface and ultimately feeds the deep convection. During this latter process, the boundary layer has also a dynamical impact on the spin-up process, by exerting a progressive control on the vortex evolution as the system-scale rotation amplifies.

d. Hybrid cyclones

As seen above, cyclones can be classified as warm-core or cold-core, with tropical and extratropical cyclones being the archetype of each one, respectively. These theoretical descriptions usually fail when applied to the observed atmosphere. There are many cyclones which do not meet those criteria but have a mix of those conceptually extreme features. In reality, there exists a continuum of cyclones between the tropical and extratropical cyclone (Hart 2003). This kind of cyclones are often referred to as hybrid cyclones.

Over the last 15 years, there has been a great increase of studies focusing on hybrid structures thanks to the advent of finer resolution tools. Due to this, hybrid cyclones with tropical characteristics have been analysed in regions outside of the tropics (where typical tropical cyclones form). Subtropical cyclones, Mediterranean tropical-like cyclones or medicanes, polar lows, warm seclusions or cyclone transitions are examples of hybrid cyclones. Those systems are important not only because of their peculiarities, low frequency and poor forecasts, but also because of the impact on the public. More importantly, certain hybrid cyclones have a high chance of becoming tropical cyclones in a subsequent stage, thus having a potential to produce large damage and economical losses.

Hybrid cyclones have energetics and structures of both tropical and baroclinic cyclones. Based on Figure 5, hybrids would be characterized by having a hybrid thermal structure (lower-tropospheric warm core and upper-tropospheric cold core) with accompanying frontal structures which often are really weak. One type of hybrid cyclones which is the focus of the thesis is the subtropical cyclone. As stated in the Introduction section, a lot of debate has arisen regarding its definition and potential damage, mainly due to the fact that the scientific and forecasting community did not focus on these cyclones until not much more than a decade ago. Although subtropical cyclones can be relatively readily distinguished from extratropical and tropical cyclones, their definition if often subtle.

(i) Subtropical cyclones

A typical case of a hybrid cyclone in the North Atlantic is a subtropical cyclone (STC; Evans and Guishard 2009; Guishard et al. 2009). STCs develop from both tropical (diabatic) and extratropical (quasi-geostrophic) processes. This combination causes the cyclone to bear a hybrid thermal structure in its core, consisting of a positive thermal anomaly at low levels (typically from 900 to 600 hPa) and a negative thermal anomaly at upper levels (600-300 hPa). Through thermal wind arguments, a weak wind speed signature at midlevels is expected as a result. Apart from the North Atlantic, STCs have been also studied in other regions such as the South Atlantic (Evans and Braun 2012; Gozzo et al. 2014), central Pacific (Otkin and Martin 2004), and Tasman Sea (Holland et al. 1987; Browning and Goodwin 2013).

STCs typically are a subsequent stage of an incipient low which is formed through QG processes. They begin to develop low-level warm core due to diabatic processes from deep convection, and frontal structures tend to disappear. STCs differ from ordinary baroclinic cyclones in that they develop in environments with little low-level baroclinicity in conjunction with diabatic processes. STCs develop in environments where positive vorticity is present in lower levels (originate from baroclinic processes) in conjunction with environments with low static stability. This kind of interaction is similar to that observed during extratropical and tropical transitions (Section I.2), but often occur during a period of time that is long enough while midlatitude westerlies are not affecting it.

STCs typically have only a weak lower-tropospheric warm-core structure because there is the lack of sustained convection near the cyclone core. This displacement of convection from the cyclone centre is often due to the existence of a weak frontal structure within the cyclone, forced by mesoscale ascent away from the centre. A large radius of maximum winds is associated with these cyclones, which is more typical of extratropical cyclones than of tropical cyclones. The transformation of a subtropical cyclone into a fully tropical cyclone only occurs if convection near the cyclone core is developed and maintained. Satellite imagery can be used to diagnose this conversion, although it can be difficult to forecast since the evolution within numerical models is often subtle and poorly characterized using conventional analyses. This is because the development of a full-tropospheric warm core implies that the potential cyclone intensity change, being more governed by convective processes, resulting in a more complex predictability with substantially more amplitude than was the case prior to warm core transition.

As the research focus on STCs is recent, there are still some inconsistencies regarding their definition. From an operational point of view, the NHC consider these cyclones as (NHC 2018): *"A non-frontal low-pressure system that has characteristics of both tropical and extratropical cyclones. Like tropical cyclones, they are non-frontal, synoptic-scale cyclones that originate over tropical or subtropical waters, and have a closed surface wind circulation about a well-defined center. In addition, they have organized moderate to deep convection, but lack a central dense overcast. Unlike tropical cyclones, subtropical cyclones derive a significant proportion of their energy from baroclinic sources, and are generally cold-core in the upper troposphere, often being associated with an upper-level low or trough. In comparison to tropical cyclones, these systems generally have a radius of maximum winds occurring relatively far from the center (usually greater than 60 n mi), and generally have a less symmetric wind field and distribution of convection".* If the subtropical cyclone has maximum sustained surface wind speed [using the United States (US) 1-minute average] of 33 kt (38 mph or 62 km/hr) or less, it is called subtropical depression. Subtropical Storm is reserved for a subtropical cyclone in which the maximum sustained surface wind speed (using the US 1-minute average) is 34 kt (39 mph or 63 km/hr) or more.

However, in the academic context, the definition of STC does not focus on fronts. Instead, the focus is on its hybrid structure. Based on the definition proposed by Guishard et al. (2009), for a cyclone to be subtropical it must: *"attain gale-force winds (17 m s^{-1}) on the 925-hPa surface at some time during its life cycle; exhibit a hybrid structure, determined by the CPS (Hart 2003) criteria of* $-V_T^L > -10$ *and* $-V_T^U < -10$*; persist in its hybrid form for at least 36 h; attain gales in the 20°–40°N latitude band; and become subtropical (i.e., attain hybrid structure) within 24 h if identified first as a purely cold- or warm-cored system".*

When this definition is contrasted with the operational STC datasets (Guishard et al. 2009), it is obtained that the STCs contribute to 12% of TC in the current NHC Hurricane Dataset (HURDAT); this is equivalent to about 1 in 8 genesis events from an incipient STC disturbance. In addition, there are 144 STCs identified that are not presently in HURDAT and a reclassification (as not STCs) of 65 existing storms in HURDAT. 197 out of 597 storms (33%) in the combined database are STCs. An additional class of hybrid storm is that of a 'frontal hybrid' (Beven, personal communication) that is characterized by organized moist convection in the presence of surface frontal zones, but this hasn't been further developed.

The socioeconomic impact of these cyclones could be similar to that of tropical storms. Despite their low frequency of occurrence, STCs pose a significant challenge to weather forecasters due to the high economical losses and security damage associated to them. They cause important warm-season forecasting problems for subtropical locations such as Bermuda and the south-eastern United States because they can rapidly acquire of gale-force winds close to land.

They are also often associated with poor forecast. Finer scale processes like convective processes and turbulent fluxes, which are still not resolved in typical global operational forecast models, are critical to subtropical and tropical cyclogenesis. On the other hand, forecast tracks and intensity of typical extratropical cyclones tend to be more accurate, due to more robust steering patterns in the mid-latitudes and predominance of synoptic processes governing it. Hence, development of extratropical cyclones is easier to forecast than subtropical cyclogenesis. In this context, the transition to subtropical cyclones is also less predictable as it is a convective-related phenomenon. Once a storm reaches its subtropical phase, the strength of the surface cyclone will mainly depend on the organization of the convection. Thus, it could be stated that the same difficulty arises when forecasting intensity change in a subtropical storm as in a tropical storm. As long as global forecast models increase their resolution and include better representation of finer scale processes, forecast of subtropical cyclones will improve.

Kona lows had been considered as subtropical cyclones in the North Pacific (Simpson 1952; Ramage 1962). Morrison and Businger (2001) found a presence of a cut-off upper cold low associated with the development of a Kona low in February 1997. Otkin and Martin (2004) suggest that a region of substantial number of subtropical cyclones in the Pacific may have been missed in the work of Simpson (1952), because it focused only in an area centred on the Hawaiian Islands. They found a maximum of subtropical cyclone formation between October and November, which clearly mismatch the January maximum found by Simpson (1952). Composite analyses from Otkin and Martin (2004) indicate that Kona lows are typically associated with the isolation from the westerlies of a surface cyclone in the subtropics, with the presence of an upper-level trough, a surface baroclinic zone, and a predominant northeastward movement of the surface low.

It is worth highlighting that the transition of Kona lows into fully tropical cyclones is not mentioned in neither of those works. Therefore, it seems reasonably to consider the possibility of subtropical cyclones in the North Pacific having differences from those of the North Atlantic in their evolution, despite similar structure and origin. This is supported by the fact that there are many examples of tropically transitioning subtropical cyclones in the North Atlantic.

One of the most extensive surveys on subtropical cyclones is Roth (2002), which resulted in a database of 218 subtropical storm candidates in the North Atlantic basin over a period of fifty-one years (1951-2001). He showed that potential Atlantic subtropical cyclones have occurred in every month of the year, but with a maximum frequency of development between September and November (51 % of all cases). However, the study lack of objective criteria to identify subtropical cyclones, as the method was to select all storms that the NHC (subjectively) had considered as subtropical, subjectively checking surface and upper air analyses, and observations including ship reports and aircraft reconnaissance.

Evans and Guishard (2009) were the first authors who attempted to develop objective diagnostic and identification criteria of STCs (see academic definition above), based on an analysis of 18 cases occurred in the western North Atlantic basin during the 1999-2004 hurricane seasons. This first analysis helped them to develop a subsequent 45-year (1957-2002) climatology of STCs for the North Atlantic based on European Centre for Medium-Range Weather Forecasts Re-Analysis 40 (ERA-40), where a total of 197 STCs were identified (Guishard et al. 2009). Around 60% of the 197 ST formed over SST in excess of 25 °C in a region of weak static stability, with a mean environmental vertical wind shear at formation of 10.7 m s^{-1}, a magnitude generally considered to be unfavourable for tropical cyclogenesis. They also explored the potential mean environment for development and found that seasonal evolution in the location and frequency of STC formation corresponds well to the changing region of overlap between SST > 25 °C and Eady growth rate (a measure of baroclinicity) of 0.1 day^{-1}.

Idealized simulations in a baroclinic channel model with full condensation heating effects (Davis 2010) demonstrated the baroclinic component of STCs. By supporting moist baroclinic instability, the resulting cyclones, identified as STCs, occurred in deep westerly wind shear but were almost devoid of lower-tropospheric baroclinicity. Those STCs were clearly distinct from baroclinically dominated secondary cyclones that also form at relatively low latitudes in the simulations. STC formation prevailed in environments featuring weak upper-level jets and strong surface easterlies. If westerly jets became stronger and/or horizontal shear weaker, the situation was reversed, with the midlatitude baroclinic wave affecting the ultimate intensification of the subtropical cyclone.

From a weather forecasting point of view, there exist several tools and meteorological fields that can help the forecaster to identify this kind of cyclones. González-Alemán et al. (2016) attempted to address this issue by meteorologically characterizing a subtropical cyclone developed in the northeastern Atlantic basin in 2010.

(ii) Polar lows and medicanes

Apart from STCs, there exist more examples of hybrid cyclones in the North Atlantic and Mediterranean Sea. Polar lows (Rasmussen and Turner 2003) and MEDIterranean hurriCANES (medicanes) or tropical-like cyclones (Rasmussen and Zick 1987; Reale and Atlas 2001; Emanuel 2005) are two accepted examples of mesoscale maritime extratropical cyclones that can physically emulate tropical cyclones at certain point (Emanuel and Rotunno 1989; Emanuel 2005). Most of those formations could be considered as solely hybrid cyclones, but a respectable amount of them can finally acquire a pure tropical or hurricane structure. Both types of cyclones can pose serious societal and ecological threat to the affected islands and coastal regions as well as open seas-related activities. Two impressive visual examples of a medicane on satellite images are shown in Figure 13.

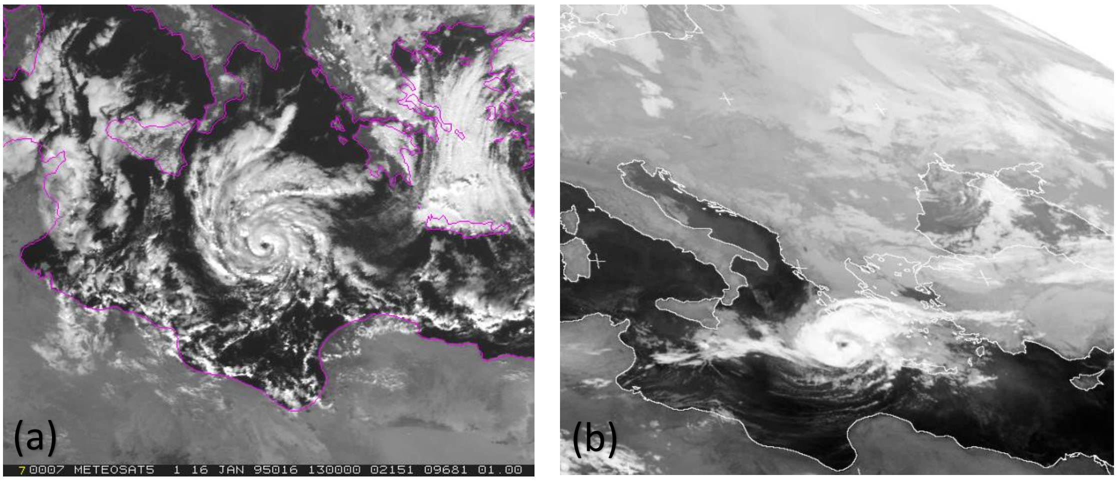

Figure 13. Satellite images of two examples of medicanes or tropical-like cyclones in the Mediterranean Sea. a) January 1995 case and b) October 2016 case. Source: EUTMESAT-Meteosat and NERC Satellite Receiving Station, Dundee University, Scotland.

Polar lows are maritime mesocyclones (radio of ~100-500 km) that form at high latitudes associated with intense surface heat fluxes from the ocean within cold outbreaks. They mostly form during cold seasons, when cold air outbreaks maximize the air-sea temperature contrast over ice-free waters. Polar lows can develop over any ocean basin in both the Northern and Southern Hemisphere, given such a high latitude. The scientific community has focused mostly on North Atlantic polar lows that are often found in the Norwegian and Barents Seas (e.g. Noer et al. 2011). Polar lows typically have mixed dynamics from both baroclinic sources and surface fluxes, where the development of convection seems to be important for an intense polar low to rapidly develop (Renfrew 2003). Fore et al. (2012), among others, showed these mixed dynamics of polar lows through the use of high-resolution numerical simulations. They found that surface heat fluxes start to play an increasingly important role while the cyclone transitions to a WISHE-governed system. This is why they have been referred to as Artic “hurricanes” (Emanuel and Rotunno 1989); because they often show moist convection organized in spiral cloud bands and surrounding a warm-eye structure, forming an eyewall where the maximum surface wind speeds are found.

Medicanes or tropical-like cyclones (Reale and Atlas 2001; Emanuel 2005) could be considered similar processes as polar lows, but occurring in the Mediterranean Sea, since they both have similar physical mechanisms involved in their genesis and development. These subsynoptic warm-core vortices are associated with steep changes in pressure and wind over the affected areas, although they rarely attain hurricane intensity (~33 m/s). The Mediterranean basin is recognized as one of the main cyclogenetic areas in the world (Pettersen 1956; Hoskins and Hodges 2002; Wernli and Schwierz 2006), with much of the high impact weather (notably strong winds and heavy precipitations) associated to cyclonic structures (e.g. Jansà et al. 2001). Cyclones over the Mediterranean Sea can range from synoptic to mesoscale in size and are modulated baroclinically, orographically or diabatically. Important orographic features surrounding the Mediterranean Sea have been identified to have a relevant impact on them (e.g. Martín et al. 2007). Despite the relatively low latitude of the Mediterranean region, some baroclinically formed cyclonic systems have also reached the category of ‘meteorological bombs’ (Conte 1986; Homar et al. 2002).

The occasional formation of hurricane-like mesoscale cyclones over the Mediterranean Sea have been evidenced by satellite images (Figure 13) and meteorological reports from ships and coastal regions (Ernest and Matson 1983; Reale and Atlas 2001; Jansà 2003), leaving hazardous impacts over populated areas. However, the statistical record of these systems has limited reliability and sample size, given their maritime characteristics, small size, infrequent occurrence, and the lack of reconnaissance missions (as those commonly undertake in Atlantic hurricanes). These systems are nearly axisymmetric and possess convective cloud bands wrapped around a cloud-free central eye (Figure 13), with a typical size of their associated cloud clusters on the order of 300 km in diameter. The convectively-generated vortex is confirmed by the strong gradient present in the cases showing a most tropical-like structure. As an example of the damages associated to medicanes, the island of Mallorca was affected by a system formed on 1 October 1986 near the Algerian coast, which moved northwards, with associated strong winds (higher than 50 kt) and estimated damage of >5 million € (García-Legaz and Valero 2013). More recently, another intense medicane formed on 8 November 2011 between Mallorca and Corsica (Miglietta et al. 2013). Some authors have considered medicanes as a subclass of polar lows (Businger and Reed 1989).

There are some studies available in the literature that have analyzed the environments in which these cyclones develop (e.g. Rasmussen and Zick 1987; Pytharoulis et al. 2000; Tous and Romero 2013), while other works have analyzed, by means of numerical simulations, the most influential factors on their development and trajectory (e.g. Homar et al. 2003; Tous et al. 2013; Miglietta et al. 2013). There have been also studies attempting to relate the effect of ACC on medicanes (Gaertner et al. 2007; Walsh et al. 2014; Cavicchia et al. 2014; Romera et al. 2017). The main common results are a decreasing frequency but increasing intensity. This latter issue will be further addressed in Sections V and VI.

(iii) Warm seclusions

Another example of hybrid cyclones in the North Atlantic are warm seclusions. A warm-core seclusion is the mature stage of an intense marine extratropical cyclone, usually associated with explosive deepening, strong surface winds, and mature structure of low-level warm core as conceptualized within the above-shown Shapiro-Keyser model (cf. Section I.1.b).

The warm seclusion stage (Shapiro and Keyser 1990) often has structural features reminiscent of major tropical cyclones. They show an eye-like region of calm air at the cyclone center within a barotropic lower warm-core structure. This region is surrounded by hurricane force winds along a bent-back warm front. Most of these cyclones are associated with periods of explosive intensification or deepening (Sanders and Gyakum 1980), some of them being a result of non-linear dynamical feedbacks associated with latent heat release (Raymond 1992). Numerical simulations during the 1960s (e.g. Eliassen and Raustein 1968) of amplifying baroclinic waves had already shown surface frontal structures that differed from the Norwegian frontal-cyclone model. Indeed, wave simulations with Eady (1949) adiabatic (excluding latent heat and surface fluxes processes) model had showed previously frontal processes that had not been described before, which included the formation of a bent-back warm front and the formation of a warm-core frontal seclusion at the mature phase of the cyclone. Later on, the existence of these processes was supported by model simulations of the Queen Elizabeth II storm of 1977 (Anthes et al. 1983; Kuo et al. 1990) which included boundary layer physics and latent heat processes at higher resolutions.

Sanders and Gyakum (1980) observed that some maritime extratropical cyclones intensified in an anomalously rapid way. They classified those cyclones as "meteorological bombs" if their central pressure dropped (geostrophically adjusted) by 1 millibar per hour for a period of 24 hours. They were most often observed along the western basins of North Pacific and North Atlantic during the cold-season, where and when extratropical cyclones can take maximum advantage of highly favourable baroclinic available energy and benefit from surface fluxes, thanks to the location of the Gulf and Kuroshio currents, to produce convection and release huge amounts of latent heat. Numerous works in the 1980s confirmed Sanders and Gyakum (1980) observations from both observational and modeling viewpoints (Roebber 1984; Rogers and Bosart 1986; Sanders 1986; Gyakum et al. 1989; Roebber 1989).

There was an increasing concern because both idealized and realistic numerical simulations of extratropical cyclogenesis and development failed to reproduce the classical Norwegian cyclone-frontal occlusion structure (Bjerknes and Solberg 1922). Therefore, Shapiro and Keyser (1990) proposed an alternative conceptualization which summarized many of the aspects of marine cyclogenesis that did not appear in the classical Norwegian cyclone (cf. Section I.1.b). Those features were mainly the development of frontal fracture and warm-core seclusion. For instance, the powerful warm seclusion from the ERICA field program intensive in 1989 provided considerable observations to validate numerical experiments against the Norwegian cyclone lifecycle paradigm.

The development of the warm-seclusion phase of a Shapiro-Keyser extratropical cyclone could occur through purely adiabatic processes (Reed et al. 1994), although earlier studies (Gyakum 1983a,b; Kuo et al. 1992) showed that diabatic effects could be important for enhancing this adiabatically driven warm-seclusion development. Later on, the suitability of the Shapiro-Keyser extratropical cyclone development model was confirmed by detailed field experiment observations from aircraft and numerical simulations (e.g. Neiman et al. 1993, 1998; Neiman and Shapiro 1993; and Wakimoto et al. 1995).

We have seen so far the differing conceptually extreme cyclones developing in the Earth's atmosphere. Their distinct nature has been analysed based on a thermal and dynamical description, and how they form through different mechanisms, resulting in cyclones with different observable and visible features. However, between these conceptually extreme cyclones, there exists a continuum within which hybrid cyclones can be identified. Indeed, they can evolve into one or another type. This phenomenon has been called "transition". Cyclones undergoing extratropical and tropical transitions are also considered as hybrid cyclones, but as they are part of a transition process they are addressed separately in the next section.

2. Cyclone transitions

Figure 5 showed a conceptual diagram of classification of different types of cyclones from the early work of Beven (1997). This diagram is useful for outlining a simple conceptual idea; the existence of a continuum in the spectrum of observed cyclone types. From such an idea arises the concept of transition, since there is no physical constraint in the free atmosphere to prevent one given type of cyclone from transforming into other different type one or from having hybrid characteristics. As mentioned in Section I.1.c, the structure and energy source of tropical cyclones is completely different from those of extratropical cyclones.

As seen in the Introduction section, past works had already dedicated thoughts to the fundamentals of the idea many decades ago. From this viewpoint, the tropical and extratropical transitions are two possible cases of transition occurring in the atmosphere, leading from one extreme to another in the spectrum, while they often show characteristics of hybrid cyclones. Transitions are frequently associated with extreme weather development, with the associated social and biological impacts being of very significant concern (Pezza 2008).

a. Extratropical transitions

Extratropical transition (ET; Jones et al. 2003; Evans et al. 2017) is a process by which a tropical cyclone loses its warm-core and symmetric nature and gradually acquires characteristics typical of cold-core asymmetrical cyclones, ending up as a pure extratropical cyclone. One of the most hazardous stages of tropical cyclones is the ET. This stage does not necessarily occur in all tropical cyclones, but it is only likely in those substantially moving northward to midlatitude regions. Only a subset of tropical cyclones complete ET and become fully extratropical, although even if they are only beginning their ET, they can already produce damage [e.g. Hurricane Sandy (2012) (Galarneau et al. 2013)].

In their ET stage, tropical cyclones are influenced by midlatitude atmospheric patterns by providing, e. g., sufficient forcing from upper-level troughs (Wang et al. 2012; DiMego and Bosart 1982; Hart and Evans 2001; Klein et al. 2000). When this process happens, the system gradually loses its tropical characteristics and becomes extratropical, its deep warm-core structure vanishes and becomes shallow, simultaneously being deformed in shape and less symmetric in circulation, convection, and humidity, ultimately resulting in a cold-core, asymmetric structure that includes the development of surface fronts (Evans and Hart 2003; Klein et al. 2000). The cyclone develops a westward and poleward tilt with height. As this process progresses, convection is suppressed near the centre. This transformation during the ET process often results in an expanded area of damaging winds and heavy rainfall, which can produce extreme waves, flooding and mudslides (Klein et al. 2000; Hart and Evans 2001; Jones et al. 2003; Evans and Hart 2008). The main risk of this phase is associated with the cyclone being able of possessing hurricane-force winds extended to a wider region. This evolution occurs as the tropical cyclone moves poleward into an increasingly baroclinic environment, which is characterized by the aforementioned temperature and moisture gradients as well as increased vertical wind shear, reduced sea surface temperature (SST), and an increasing Coriolis parameter. This environmental change is detrimental for tropical cyclone development, but it can otherwise change the TC structure if baroclinic conditions are favorable. Klein et al. (2000) proposed a three-dimensional conceptual model of the transformation stage of ET that describes how 30 cases evolved into an incipient, baroclinic low in the western North Pacific Ocean. This is shown in Figure 14 (see caption for detailed description).

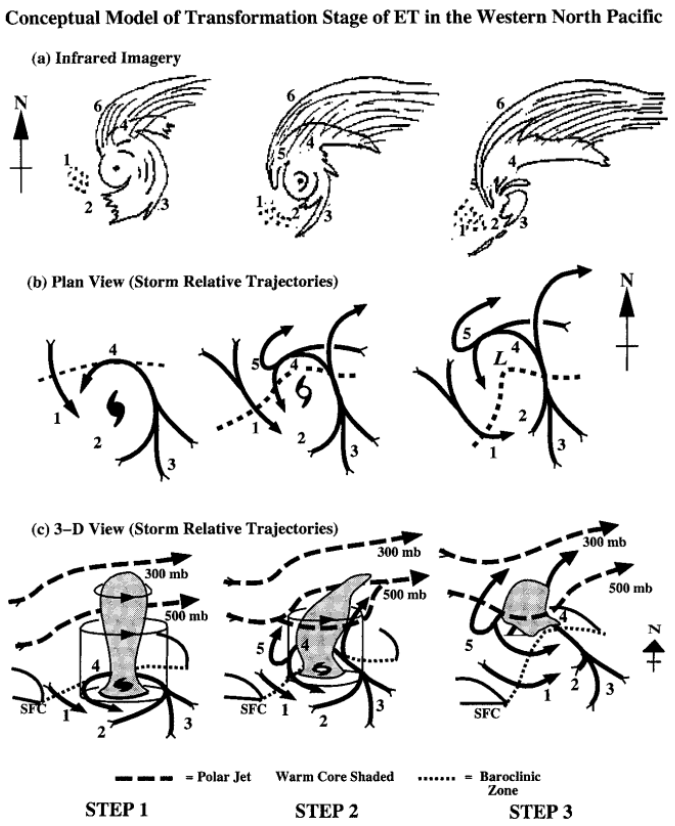

Figure 14. Conceptual model of transformation stage of ET in the western North Pacific, with labelled areas as follows: 1) environmental equatorward flow of cooler, drier air (with corresponding open cell cumulus); 2) decreased tropical cyclone convection in the western quadrant (with corresponding dry slot) in step 1, which extends throughout the southern quadrant in steps 2 and 3; 3) environmental poleward flow of warm, moist air is ingested into tropical cyclone circulation, which maintains convection in the eastern quadrant and results in an asymmetric distribution of clouds and precipitation in steps 1 and 2; steps 2 and 3 also feature a southerly jet that ascends tilted isentropic surfaces; 4) ascent of warm, moist inflow over tilted isentropic surfaces associated with baroclinic zone (dashed line) in middle and lower panels; 5) ascent (undercut by dry-adiabatic descent) that produces cloudbands wrapping westward and equatorward around the storm centre; dry-adiabatic descent occurs close enough to the circulation centre to produce erosion of eyewall convection in step 3; 6) cirrus shield with a sharp cloud edge if confluent with polar jet. Figure and caption from Klein et al. (2000).

Over the North Atlantic, the most typical trajectory of tropical cyclones undergoing ET is outlined by a storm recurving over the western basin and heading northeastward (Hart and Evans 2001). Therefore, the coastal Atlantic areas most likely to be impacted by a transitioning tropical cyclone are the northeastern United States and the Canadian Maritimes (1-2 storms every year) and western Europe (1 storm every 1-2 years) (Hart and Evans 2001).

Extratropical transition involves interactions across a wide range of spatial (tropical cyclone core to baroclinic trough) and temporal (convective to synoptic) scales. This presents a substantial challenge to the representation of these complex dynamic and thermodynamic processes in numerical weather prediction models, while imperfect representation of the initial conditions compounds the problem (e.g. Jones et al. 2003). Extratropical transitions events also often reduce downstream predictability by triggering or modifying Rossby wave train development, thereby propagating forecast uncertainty into regions far from the ET event (e.g.

Harr et al. 2008). ETs have been also found to generate hazards downstream [e.g., Hurricane Katia (2011) (Grams and Blumer 2015)].

b. Tropical transitions

Tropical transition (TT) is the process by which a cold-core cyclone loses its asymmetrical nature and gradually acquires characteristics typical of warm-core symmetrical tropical cyclones, ending up as a pure tropical cyclone. It is just the opposite sense of ET in the cyclone transformation path. TTs have received much attention during the last decade since Davis and Bosart (2004) defined this process. In addition, deep warm-core polar lows or medicanes (cf. Section I.1.d) are formed through this mechanism.

Tropical cyclones are not phenomena exclusive of the tropics. Influential studies of Palmén (1948), Gray (1968), and DeMaria et al. (2001) showed that the environmental conditions deemed favourable for tropical cyclogenesis are frequently observed at tropical latitudes. However, environmental conditions can become favourable for tropical cyclogenesis in locations out of the tropics. Hess et al. (1995) and Elsner et al. (1996) showed that baroclinic processes intervened at early stages in the development of almost 50% of all North Atlantic tropical cyclones. McTaggart-Cowan et al. (2008) further explored this idea and showed that three types of baroclinic genesis pathways, acting prior to North Atlantic tropical cyclogenesis during 1948-2004, could be differentiated. A global climatology of tropical cyclogenesis (McTaggart-Cowan et al. 2013) showed that the majority of tropical cyclones which form poleward of 25°N (25°S) in the Northern (Southern) Hemisphere during 1948-2010 developed nearby an upper-tropospheric disturbance in a baroclinic environment. The frequency of formation of those tropical cyclones varied across and between individual ocean basins. This is likely associated to the frequency of upper-level disturbances reaching these regions from the midlatitudes (Wernli and Sprenger 2007). Bentley et al. (2017) farther developed this association and found that STCs that undergo TT could be separated into one of three categories based on the upper-tropospheric features associated with their formation: 1) cutoff lows, 2) meridional troughs, and 3) zonal troughs. Cyclone-relative composites revealed in that work that ~61% of the categorized those events were linked to anticyclonic wave breaking. While forecasters have been aware of this mechanism of tropical cyclogenesis for some time (Guishard 2006), it is only recently that the frequency of occurrence of such genesis has been documented for the North Atlantic (Davis and Bosart 2003, 2004; Bentley et al. 2016).

Tropical cyclone development from baroclinic origin is preceded by diabatically enhanced turbulent momentum fluxes that act to homogenize the wind profile leading to rapid vertical wind shear decrease. The vertical PV redistribution due to convection results in upper-level PV depletion within the environment of the developing tropical cyclone (e.g., Hulme and Martin 2009a,b; Galarneau 2010). The TT (Davis and Bosart 2003, 2004) process describes a TC developing from a cyclone formed in the presence of an upper-tropospheric disturbance in a purely baroclinic environment at the very first moment. While the TT is ongoing, the initial extratropical cyclone often exhibits some characteristics reminiscent of an evolving marine extratropical cyclone in the Shapiro-Keyser model (i.e. bent-back warm front and warm seclusion; Shapiro and Keyser 1990; Neiman and Shapiro 1993; Schultz et al. 1998; Hulme and Martin 2009a,b; Cordeira and Bosart 2011; Bentley and Metz 2016).

During the first stages of the process, a region of upward motion is produced by vertical wind shear in a baroclinic environment (quasigeostrophic forcing; Suctcliffe 1947; Trenberth 1978), which in turn focuses deep moist convection and diabatic heating. Later on, a vertical transport of PV and momentum redistributes PV due to differential diabatic heating released by deep convection (e.g., Hoskins et al. 1985; Davis and Emanuel 1991; Raymond 1992; Stoelinga 1996; Campa and Wernli 2012). This in conjunction with the divergent outflow in the upper troposphere provokes a reduction in vertical wind shear, i.e., the initially baroclinic environment becomes more barotropic. The initial trough or upper-level low supporting the baroclinic cyclogenesis weakens and the system start to acquire a warm-core structure through latent heat release. This subsequently causes an environment setup that favours and/or allows an intensification of the stacked surface cyclone through air-sea interaction processes (Emanuel 1987; Davis and Bosart 2004; Bentley and Metz 2016). During the transformation period, the system often has structure of STCs, which could indicate us that STCs are in reality cyclones in a never-ending TT process.

Davis and Bosart (2004) indicated that the occlusion process in cyclones undergoing TT is distinct because it is driven by diabatic heating and advection arising from its secondary circulation, whereas the classical occlusion in pure extratropical cyclones is driven by quasi-horizontal advection by the swirling flow around the cyclone. They also separated TT cases based on the amplitude and structure of the precursor disturbance: strong extratropical cyclone (SEC) and weak extratropical cyclone (WEC). The distinguishing factor between these archetypes is that in SEC cases, extratropical cyclogenesis produces a surface cyclone already capable of WISHE (Emanuel 1987), whereas in WEC cases, the baroclinic cyclone is an organizing agent for convection which is later fed by WISHE. They also mention the possibility of the bent-back structure associated with occlusion occurring prior to TT, with enhanced rainfall upshear from the surface low (the upshear direction based on a synoptic-scale average). This is particularly efficient for eliminating the vertical shear over the cyclone centre (displacing upper-level PV gradients through upper-level PV dilution due to latent heat release, as shown by the conceptual model in Figure 15. This bent-back idea was further supported by Hulme and Martin (2009a,b), who noted the presence of convection to the west and southwest of the surface cyclone in TT events (SEC cases). This occurred at the time of frontogenesis and upper-level PV deformation, which suggests that diabatic heating contributes significantly to the TT process consistently with its role in extratropical occlusion (Posselt and Martin 2004). Far from improving the distinction of TTs, they also argued that their results support the idea of TTs being a substantially similar process as the occlusion process in ordinary marine extratropical cyclones, with the key distinctions being that the convection is stronger, and the initial upper-level feature is weaker in TTs. Therefore, TTs of SEC precursors follows the canonical midlatitude cyclone life cycle, where upshear convection favours or induces the TT by organizing processes. Due to the important role played by convection, it is suggested that TT is encouraged whenever extratropical occlusion occurs over relatively high SSTs.

The formation of a warm-core in oceanic extratropical cyclones has been mainly linked to air-sea interactions (more importantly sensible heat fluxes) (e.g., Bosart and Bartlo 1991; Neiman and Shapiro 1993; Cordeira and Bosart 2011). Cordeira and Bosart (2011) showed, through Lagrangian trajectory analysis, that the warm seclusion and subsequent TT process of the ‘‘Perfect Storm’’ (1991) in the northwestern North Atlantic was associated with the isolation of air parcels near the cyclone centre. These air parcels were warmed in the lower troposphere via sensible heating from the underlying relatively warm Gulf Stream. Studies have revealed that tropical cyclones resulting from the TT process occur over SSTs below the traditional threshold of 26.5°C for tropical cyclogenesis (e.g. Palmén 1948; Gray 1968). For instance, Mauk and Hobgood (2012) highlighted the potential for tropical cyclogenesis in the northeastern Atlantic to occur over relatively cold SSTs, in environments characterized by reduced stability. Indeed, McTaggart-Cowan et al. (2015) proposed a revision of the SST threshold for tropical development in baroclinic environments characterized by the presence of an upper-tropospheric disturbance. This feature could lower the height of the dynamic tropopause and steepens the stability lapse rates, which facilitates the development of deep convection that catalyses TT. These kinds of development were noted with the advent of satellite imagery, although they are not frequent due to the difficulty for the climatological atmosphere to set up a synoptic pattern introducing an extratropical cyclone over sufficiently warm sea surface temperatures and low wind shear.

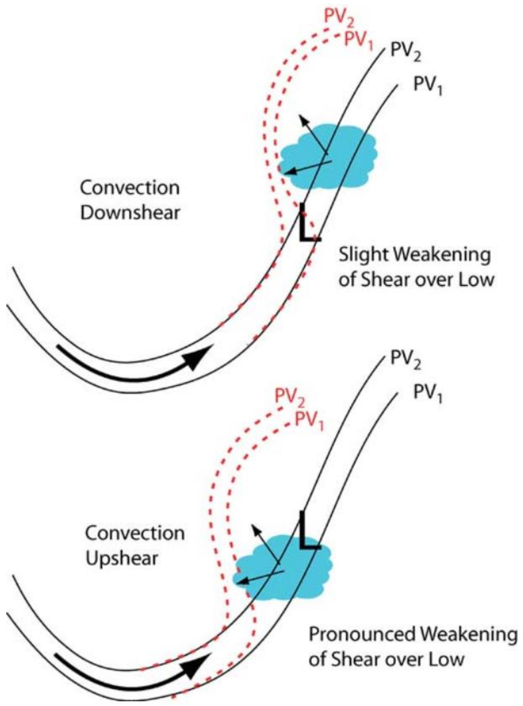

Figure 15. Schematic illustration showing the effect of convection (blue area) (top) downshear and (bottom) upshear, relative to a surface low ("L"). Small arrows indicate divergent motion near the tropopause. Large arrow indicates flow within upper-level jet. Solid lines are two initial PV con- tours (PV2 > PV1), and red dashed lines indicate positions of the same contours after deep convection has developed. Figure and caption from Davis and Bosart (2004).

The TCs forming via TT have been documented in many basins where tropical cyclogenesis events climatologically occur, such as the western North Atlantic (e.g., Moore and Davis 1951; Bosart and Bartlo 1991; Bracken and Bosart 2000; Davis and Bosart 2001; McTaggart-Cowan et al. 2006a; Evans and Guishard 2009; Guishard et al. 2009; Hulme and Martin 2009a,b), the western North Pacific (e.g., Wang et al. 2008), and the western South Pacific (e.g., Garde et al. 2010; Pezza et al. 2014). On the other hand, they have also been shown to form in basins where tropical cyclogenesis events are extremely rare, including the eastern North Atlantic (e.g., Case 1990; Franklin 2006; Beven 2006; Blake 2016), eastern North Pacific (Bentley and Metz 2016), the western South Atlantic (e.g., Pezza and Simmonds 2005; McTaggart- Cowan et al. 2006b; Evans and Braun 2012; Gozzo et al. 2014), and the Mediterranean Sea (medicanes or Mediterranean tropical-like cyclones; cf. Section I.1.d).

Mauk and Hobgood (2012) analysed tropical cyclones that formed in the northeastern Atlantic under high wind shear and low SSTs environments. 20 TCs were included between 1975 and 2005. Results showed that 17 out of 20 were developed from non-tropical disturbances and 3 from tropical waves. The interest of this study was that those TCs were formed in environments far from the typical stablished environments suitable for tropical development. For those 17 systems, sea surface temperatures are cooler than 26°C and stability analysis suggests that convection was shallow. It was obtained that wind shear was lower for the 850-300-hPa layer, unlike the 850-200-hPa layer usual in other cases. The capability of these TCs to survive was suggested to be due to the fact that late-season tropical cyclones in this region are shallower in vertical extent than typical tropical cyclones, which reduces the impact of strong wind shear in the 850-200-hPa layer.

Despite subtropical transitions not addressed in the literature, they could be considered as part of the tropical transition process, specifically the first stage when the cyclone starts to acquire tropical characteristics. Once the subtropical transition is completed, the cyclone would have subtropical structure and could continue its tropical transition to a tropical cyclone, remain subtropical until the end or die as a weak extratropical cyclone. To sum up, it could be said that subtropical cyclones are unfinished tropical transitions, or in other words, subtropical cyclones are extratropical cyclones which start their transition into tropical cyclones but never achieve a final stage of a pure tropical cyclone. Therefore, it is worth discussing how subtropical cyclones are formed in this section.

(i) Subtropical cyclogenesis

Apart from cyclogenesis of the two theoretical extremes of cyclones, a third type of cyclogenesis can be considered, which leads to the formation of a subtropical cyclone. Given that this process is much less analysed, an idealized and brief description is given below. As already seen in Section I.1d, subtropical cyclones are hybrids (cold-cored upper- and warm-cored lower-tropospheric thermal signatures) which tend to emerge from baroclinic developments in the presence of positive low-level vorticity over relatively warm SST or strong SST gradients.

Guishard et al. (2007) describe the subtropical cyclogenesis process, based on the geopotential and surface pressure fields, in their study of subtropical cyclones affecting Bermuda Islands, as follows:

The subtropical cyclogenesis begins with baroclinic cyclogenesis. As depicted in Figure 16a, a through embedded in the westerlies supports QG forcing and forms a surface cyclone as a result. This surface extratropical cyclone has its attendant cold, warm and occluded fronts. This trough subsequently begins to isolate from the westerlies associated with a Rossby wave breaking and forms a cut-off low (indicated by the X in Figure 16b), with the surface low occluding and the typical cloudiness band associated to the main baroclinic zone remaining. The system has become a subtropical cyclone, with a vertically-stacked structure more barotropic in nature. During this process, the whole cyclone's structure has decreased in scale from synoptic to nearly meso- scale in horizontal extent. At this stage, the system has developed a hybrid thermal structure due to the development of clusters of deep moist convection within the cyclonic region.

The behaviour of the hybrid structure of the cyclone will depend on what occur next, which could be divided into three different situations mainly depending on the behaviour of convection:

- The convection erodes the upper vorticity maximum. If the convection is enhanced, the lower warm core dominates the system and low-level convergence and deep convection begin to play a primary role, causing the system to become more tropical in nature. This may lead to a symmetric warm core extending upwards through upper troposphere, an upper anticyclonic outflow, and convection wrapped around the central low. The system has become a tropical cyclone and surface heat fluxes from the ocean begin to have a more important impact on the system behaviour (Davis and Bosart 2003, 2004; Hulme and Martín 2009a,b).

- The convection is suppressed: If convection is not sustained, the cyclone acquires a more extratropical nature. This could occur due to, e.g. relatively cold SST, or intrusions of dry air towards the cyclonic region, which weakens convection. In this case, the upper cold low starts to dominate the system and builds down to the surface (Hoskins et al. 1985), resulting in a less intense surface circulation than in the case of the tropical transition scenario. If the system remains cut off, it will disappear in several days. Loss of convection has resulted in the ultimate dissipation of the subtropical cyclone.

- Another trough interacts with the evolving system: The previously described two lifecycles best fit quasi-static lows, i.e. in the absence of another upper trough approaching. However, if the system begins to be under the influence of the steering flow of a new trough, thus becoming mobile, it will quickly transition to a fully extratropical low.

Tropical and subtropical transitions are more likely to occur if they spend longer periods as a hybrid cyclone since slow rates of movement are associated with less wind shear. If wind shear is present, the diabatic warming associated with the convection is disrupted, resulting in an impossibility for the warm core low to build from convective processes.

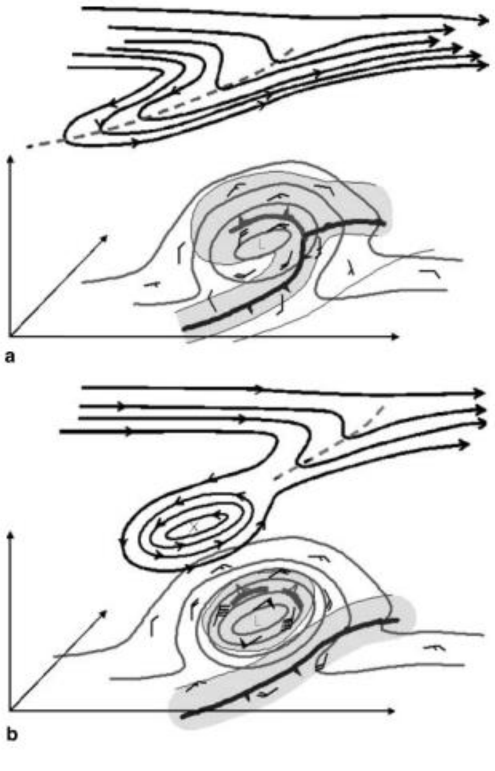

Figure 16. Conceptual schematic of subtropical cyclogenesis (see text for details). The evolution of a typical ST is illustrated in the schematic in Fig. 7. The initial baroclinic cyclogenesis is illustrated in panel (a) and the completion of transition to a subtropical cyclone is depicted in panel (b). Solid grey lines are surface isobars, with an L at the position of the central low pressure. Solid black arrows are upper streamlines, for example the 300 hPa flow. Surface fronts and wind barbs are marked in the conventional manner, and shading indicates the continuous cirrus shield associated with ascent. The dashed line is the upper trough axis. Figure and caption from Guishard et al. (2007).

3. Effects of climate change on cyclones

a. Effects on extratropical cyclones

Extratropical cyclones are major contributors to our everyday weather and usually have large societal and economic negative impact. Their associated phenomena such us high winds and heavy precipitation can result in windstorm damage, flooding, and coastal storm surge (Lamb 1991; Fink et al. 2009; Della-Marta and Pinto 2009; Liberato et al. 2013). On the other hand, extratropical cyclones play an important role in the water cycle (Hawcroft et al. 2012). They are important because many regions strongly depend on the precipitation produced by these systems for water supplies and livelihoods, such as agriculture. Extratropical cyclones are also an important component in Earth's climate system because they transport heat and moisture poleward from the equator reservoir, reducing the equator-pole temperature gradient (Oort and Vonder Haar 1976; Fasullo and Trenberth 2008). Therefore, it is vital to understand how extratropical cyclones characteristics (e.g. geographical distribution, frequency, intensity, etc.) might change in the ACC context for societies to adapt to it.

(i) Projections

The Fourth Assessment Report of IPCC summarized that increasing greenhouse gases will lead to ‘‘a poleward shift of storm tracks in both hemispheres that is particularly evident in the Southern Hemisphere, with greater storm activity at higher latitudes’’ (Meehl et al. 2007). Overall, there is a consensus that a general reduction in the number of winter extratropical cyclones will occur by the end of this century in association with a warming climate (e.g. Zappa et al. 2013).

However, there is an increasing evidence that this simple relationship may not be the best description of the response of the North Atlantic storm track to ACC. Regional changes may differ from this general trend (e.g., Schubert et al. 1998; Pinto et al. 2009; Colle et al. 2013). For example, an increase in the frequency of extratropical cyclones has been projected across the northeast North Atlantic, with climate model simulations showing that the storm track undergoes an eastward extension with a resulting increase of cyclones over the United Kingdom and central Europe during winter (Harvey et al. 2012; Zappa et al. 2013; Catto et al. 2011). This could enhance the windstorm risk and the economic loss potential over those areas, associated with cyclone activity (Pinto et al. 2007a; Della-Marta and Pinto 2009). In the Mediterranean Sea, climate models show a future reduction in the number of cyclones (Bengtsson et al. 2006; Lionello and Giorgi 2007; Raible et al. 2010), which could increase the appearance of droughts in this region. However, there exists some uncertainty as the spread in the model responses appears to be large (Ulbrich et al. 2008, 2009; Harvey et al. 2012). Furthermore, an increased cyclone activity off the East Coast of the United States was found by Colle et al. (2013) by the late twenty-first century.

In the North Atlantic, the projected changes in cyclone frequency have generally been related to changes in baroclinicity. The anomalous lower-tropospheric warming at high or polar latitudes, known as polar amplification, results in a decreased meridional equator–pole temperature gradient in the lower troposphere (Francis and Vavrus 2012). The development of cyclones is then hindered because of this reduction of baroclinicity since it causes extratropical cyclones to have less available potential energy to transform into kinetic energy. The end result is a reduction in the number of storms throughout the basin (e.g. Eichler et al. 2013). Another limiting phenomenon is the fact that the projected increase in waper vapor in a future warmer climate could result in more efficient poleward heat transport by extratropical cyclones. This suggests that a decrease in the number or strength of eddies (cyclones from a climate perspective) would be needed to move the same energy poleward (Zhang and Wang 1997; Bengtsson et al. 2006).

However, a projected ACC could also be positive for extratropical cyclone development. For example, synoptic activity could have a positive forcing from an enhanced warming of tropical upper troposphere, which strengthens baroclinicity aloft (Mizuta et al. 2011). Or the abovementioned regional increase of extratropical cyclones in the northeastern Atlantic, which may be caused by a minimum in sea surface temperature warming to the south of Greenland. This results in an enhancement of the temperature gradient and associated baroclinicity in that area (Carnell and Senior 1998; Bengtsson et al. 2006; McDonald 2011).

Because of the expected increase in moisture, using a sufficiently fine grid spacing is critical for modeling studies. Diabatic processes must be well resolved in order to better simulate extratropical cyclones in future climate. Due to this, coarser-resolution general circulation models have limitations when representing important aspects of extratropical cyclones, such us their intensity or associated frontal structures (Beersma et al. 1997; Bader et al. 2011; Willison et al. 2013). For instance, the above-mentioned increase in cyclone activity found off the East Coast of the United States for future climate, could be related to an enhancement of latent heat release in extratropical cyclone development, rather than an increase in environmental baroclinicity, as suggested for the northeast North Atlantic (Colle et al. 2013; Marciano et al. 2015). Another example of the criticality of this issue is Willison et al. (2013), where a stronger feedback between cyclone intensification and latent heat release in higher-resolution simulations was shown, which highlights the need for fine grid spacing to better resolve diabatic effects.

Another important issue is linked to intensity changes of extratropical cyclones, because an enhancement of cyclone strength has implications for densely populated areas, such as cities along the Atlantic Coast, the British Isles, and other areas of northwestern Europe. However, how the intensity of extratropical cyclones will change with a future climate still remains controversial (Bader et al. 2011; McDonald 2011; Feser et al. 2015).

One of the most comprehensive works on extratropical projections is Zappa et al. (2013). They investigated the response of North Atlantic and European extratropical cyclones to ACC in the global climate models from phase 5 of the Coupled Model Intercomparison Project (CMIP5). In contrast to previous multi-model studies, that work innovatively applies a feature-tracking algorithm to separately quantify the responses in the number, the wind intensity, and the precipitation intensity of cyclones. They found an increase in the number of cyclones in central Europe and a decreased number in the Norwegian and Mediterranean Seas in winter, whereas a reduction in the number of North Atlantic cyclones along the southern flank of the storm track is found during summer. Another important result is the decrease in the number of cyclones associated with strong winds as opposed to an increase in those associated with strong precipitation. The results are indeed confirmed under a higher-emission scenario, where the signals tend to be larger.

(ii) Uncertainties

Despite numerous studies addressing the issue of future changes in extratropical cyclones, more research is still needed as there exist uncertainties in the response of North Atlantic cyclones, due to the complex interaction between different physical drivers of those changes (Woollings 2010). Many factors intervene in the problem. For instance, changes in the baroclinicity of the mean state of the atmosphere or in the efficiency of baroclinic conversion (potential to kinetic energy) will most likely affect cyclone behavior (Hoskins and Valdes 1990; O'Gorman 2010). Another contributing factor is the atmospheric moisture content, which is a major driver of changes by altering baroclinicity. If latent heat release is increased in the warm sector of cyclones, cyclone development might be enhanced by generating additional available potential energy (Schneider et al. 2010; Laîne et al. 2009). However, an opposed effect is that the increased poleward and upward moisture fluxes also tend to reduce the zonal-mean baroclinicity, in such a way that cyclone development might not be favored (Held 1993). Other factors affecting the baroclinicity of the North Atlantic region are the polar amplification of global warming (Hwang et al. 2011), the expansion of the tropics (Fu et al. 2006; Lu et al. 2007), and the weakening of the meridional overturning circulation (Woollings et al. 2012).

A different source of uncertainty arises from the approach used to study extratropical cyclones in long-term numerical simulations. When studying extratropical cyclones, objective feature-tracking algorithms must be used since they are complex dynamical features and show diverse behaviour. This allows to track their trajectories and the number and intensities of cyclones could be quantified separately, with the aim of analysing their response to ACC. However, this method has only recently been possible to use since early multi-model datasets lacked high-frequency data. Either single-model studies based on tracking algorithms (e. g. Catto et al. 2011) or simple measures of storm-track activity on multi-model analyses (Yin 2005; Lambert and Fyfe 2006; Ulbrich et al. 2008; O'Gorman 2010) has been possible so far, but these approaches have limitations. For instance, limitations arise when different single-model studies use different tracking algorithms and cyclone intensity metric. Despite highlighting different aspects of cyclone behavior (Neu et al. 2013), it does not provide any information which can be objectively compared. Another simple approach like Eulerian measures of storm-track activity provide no direct clue on important quantities related to cyclones, such as intensity (or extremes) and number. To better address these uncertainties, studies using multi-models and multi-methods are recently appearing (Zappa et al. 2013; Flaounas et al. 2016; Lionello et al. 2016).

In addition, the way the intensity of the cyclone is measured also has uncertainty. Generally, studies which consider cyclone strength based on minimum central sea level pressure (SLP) or precipitation show a projected increase in extreme events (e.g. Lombardo et al. 2015). However, studies using vorticity, minimum SLP perturbation, or near-surface wind speed obtain a projected decrease in the strongest storms (e.g. Chang 2014). Champion et al. (2011) found an increase in extreme precipitation events but no significant change in vorticity or wind speeds.

Another approach is to analyse separately real storms or specific seasonal simulations occurring in actual climate and study their changes in different environments associated to future climate. In this context, Marciano et al. (2015) analysed 10 high-impact wintertime extratropical storms that affected the US East Coast in 1981-2010 and found that diabatic PV, precipitation, and low-level winds were enhanced in future climate and storm minimum SLP was reduced in future climate with respect to present climate. Willison et al. (2015) showed, through an analysis of 10 winter seasonal simulations in current and future climates, that an increase of eddy kinetic energy and 850-hPa eddy heat flux occurred over the eastern North Atlantic, being more prominent at higher resolutions. Willison et al. (2015) took a climate dynamics approach for investigating changes in the North Atlantic storm tracks rather than focusing on smaller, storm-scale features. They also found that storm-track response to global warming is amplified at the higher model resolution, and caution about using projections from coarse-resolution global climate models (GCMs). A limitation in the work of Marciano et al. (2015) is that it is focused on a specified and limited sample of storms. Future high-impact events might not be directly related to high-impact weather of the present.

Michaeli et al. (2017) tried to improve and expand on those previous works. Their intention was to apply a Lagrangian tracking algorithm to the simulations of Willison et al. (2015) and utilize a storm-relative composite analysis approach, as in Marciano et al. (2015), to investigate changes in storm-scale features. Changes in storm's structures and features do not necessarily correspond to changes in Eulerian quantities, such as eddy heat flux and eddy kinetic energy, that are otherwise of importance for the storm track and general circulation. In this case, this method provides more societally-relevant information. In addition, another departure from the analysis of Marciano et al. (2015) is that the model is free to choose which storms become the strongest and most significant in their impact. Michaeli et al. (2017) found enhanced extratropical cyclone activity in the northeast North Atlantic and off the US East Coast, but with changes in storm dynamics and the impacts associated with them, such as strong near-surface winds and heavy precipitation, becoming stronger and more frequent with warming.

As seen, the poleward shift of projected extratropical cyclones is a robust response across most models, but there is still no consensus on what the dynamical causes could be. Tamarin-Brodsky and Kaspi (2017) have recently presented a new perspective on this poleward shift. Based on a Lagrangian perspective of the storm tracks, they show a poleward shift in the genesis latitude of the storms, associated with the shift in baroclinicity, but also an increased latitudinal displacement of cyclonic storms. They argue that this increased latitudinal propagation in a warmer climate is caused by stronger upper-level winds and increased atmospheric water vapor.

b. Effects on tropical cyclones

In the case of the relationship of tropical cyclones to ACC, there is a fundamental difference with respect to that of extratropical cyclones; there is no climate theory for tropical cyclone formation. It cannot be confidently calculated the number of tropical cyclones likely to be produced in specific climate conditions. Although there has been a lot of progress in the formation and intensification problem itself, the links between tropical cyclone formation and climate are not well understood (cf. Section I.1.c). Understanding these fundamental connections is vital to improving the confidence of future projections of tropical cyclones. A brief updated is intended to provide here. Further information on this topic can be found in the review of Walsh et al. (2016).

The effect of ACC on tropical cyclones is a controversial scientific issue. The theoretical knowledge of the relationship between climate and tropical cyclones has greatly advanced. There has been a considerable improvement in understanding the association between the mean climate and the potential intensity. Potential intensity (PI; Tang and Emanuel 2012) is a measure of the theoretical maximum intensity that a tropical cyclone could achieve for given environmental conditions surrounding the cyclones, and it is closely related to the climate. On the other hand, climate models have improved in their ability to simulate present climatology of tropical cyclones and their interannual variability. This indicates that climate models are better capturing the key physical relationships which govern the relationship between tropical cyclones and climate. The horizontal resolutions of global climate models available to study tropical cyclones has decreased from 100-300 km range (CMIP5) to 10-50 km for the new generation of high-resolution models. Climate models are now able to simulate a realistic rate of global tropical cyclone formation, although simulation of the Atlantic tropical cyclone climatology remains challenging unless horizontal resolutions of less than 50 km are employed (Walsh et al. 2015).

The evidence that changes in the vertical circulation in the tropics appear to govern the tropical cyclone frequency has increased, as shown by recent studies (Held and Zhao 2011; Sugi et al. 2012; Zhao et al. 2013). In addition, low- to mid-tropospheric moisture content has also been considered as an important factor in tropical cyclone formation (Emanuel et al. 2008; Rappin et al. 2010). Nevertheless, the fact that mid-level moisture surrounding the environment of the incipient pre-cyclone disturbance plays an essential role in its formation, does not necessary imply that the climatological mid-level moisture content will affect climatological tropical cyclone formation in the same manner. For example, Bruyere et al., (2012) found that variations in the climatological mid-level atmospheric moisture content were not related to interannual variations in tropical cyclone frequency in the North Atlantic basin.

Analysis of the statistical relationship between climate and tropical cyclones is another line of research (Tippet et al. 2011; Emanuel and Nolan 2004; Emanuel 2010; Camargo et al. 2014). There have been recent advances in this issue through the use of the so-called genesis potential index (GPI; Menkes et al. 2012). However, numerous problems have been found, and further work on the contributions of various environmental parameters to tropical cyclone formation is needed. For instance, Bruyere et al. (2012) showed that the good reproducibility of statistical relationships in the Main Development Region east of the Lesser Antilles is missed when they are applied to the whole North Atlantic basin.

The thermodynamic theory of tropical cyclone maximum PI is well-stablished (e.g. Tang and Emanuel 2012), but it is still under investigation and refinement. Camargo et al. (2013) and Ting et al. (2014) found that PI's decreases caused by aerosol forcing largely cancelled PI's increases due to greenhouse gases, with the sharp increase in the PI observed in the last 30 years mainly dominated by multi-decadal natural variability. They argue that this natural variability is more effective in increasing PI than the contribution of SST increases related to climate change. However, Holland and Bruyere (2014) found that the observed increases in both global and basin fraction of intense hurricanes were associated with global changes arising from anthropogenic effects. On the other hand, changes in relative SSTs in the Atlantic basin over the 21st century under greenhouse gases forcing are uncertain (e.g. Knutson et al. 2013), and the impact of tropopause temperature trends on observed potential intensity changes appears unresolved (Emanuel et al. 2013; Vecchi et al. 2013; Ramsay 2013; Wang et al. 2014).

(i) Projections on frequency

A good synthesis of global and regional projections of future tropical cyclone climatology by 2081-2100 relative to 2000-2019 is provided by Christensen et al. (2013). In general, the consensus projection indicates a decrease in tropical cyclone frequency by approximately 5-30% but an increase in the intensity of category 4 and 5 storms by 0-25%, which is accompanied by an increase in tropical cyclone rainfall amounts by 5-20%.

In recent years, new studies have addressed the formation of tropical cyclones using high-resolution climate model simulations. Several models are now able to reasonably perform reliable simulations on this issue in most basin, except for the Atlantic, where it is still challenging (e.g. Tory et al. 2013a,b). However, Mei et al. (2014) indicated an improved ability to simulate Atlantic tropical cyclone formation. Most simulations continue to simulate fewer tropical cyclones in a warmer world, particularly in the Southern Hemisphere (e.g. Sugi and Yoshimura 2012; Tory et al. 2014). There are large biases in most CMIP5 models regarding the detection of tropical cyclones due to resolution. If models having an extremely poor tropical cyclone climatology in the present climate are excluded, there is a strong tendency for concluding that there will be a global reduction of tropical cyclones frequency in future climate.

A set of 19 experiments were included in Knutson et al. (2010) in order to conclude that the number of tropical cyclones in a warmer world is most likely to decrease. Christensen et al. (2013) had an increased availability of experiments (35) and concluded in the same line. Certain experiments included were obtained from Murakami et al. (2012a,b), where interesting results were obtained. Murakami et al. (2012a) found that the TC intensities simulated by the 20km resolution models with a different convection scheme are significantly different. Very intense tropical cyclones, similar to observations, were simulated by the Meteorological Research Institute atmospheric general circulation model (MRI-AGCM 3.2, the new version of the model) with a new convection scheme. If the same was performed with a previous version of the same model, the intensity of tropical cyclones is significantly underestimated. This indicates an interesting fact: the simulated intensity of tropical cyclones is not only affected by the resolution of the model but also depends significantly on the convection scheme. Murakami et al. (2012b) further examined systematically the impact of model physics and SST change patterns on global and regional TC frequency changes. From those works, it can be inferred that resolution, physics (convection scheme) and SST change patterns are the three major sources of uncertainty in the TC frequency change projections. Strachan et al. (2013) and Bell et al. (2013) also showed that the response of tropical cyclones to increased greenhouse gases depends on resolution, such that finer-resolution simulations show stronger decreases in the number of tropical cyclones.

The above-shown general projection of decrease frequency in future tropical cyclones has been challenged by Emanuel (2013), in which tropical cyclone numbers are projected to increase. This work uses a different method to study future tropical cyclones changes. Through the use of a dynamical downscaling technique, a constant “seeding” rate as representative of tropical disturbances is imposed under different climate conditions, and the “seeds” that successfully develop are then counted as tropical cyclones. In addition, Camargo et al. (2013) showed that some CMIP5 coupled models also project global future increases of tropical cyclone frequency in warmer climate, in contrast to the reduction of global tropical cyclone frequency projected by relatively high resolution stand-alone AGCMs. More disagreement arises when comparing projections in individual basins (Camargo 2013; Tory et al. 2014). For example, Murakami et al. (2013) found an important new result; the possibility of an increase in tropical cyclone frequency in the region near Hawaii.

Another way of studying future changes in tropical cyclones is through the analysis of changes in environments that favour their formation. Tang and Camargo (2014) showed that there is an increase in the seasonal ventilation index, which is a measure of the mixed influence of vertical wind shear, entropy deficit and potential intensity developed by Tang and Emanuel (2012). This implies less favourable conditions for tropical cyclogenesis or rapid intensification, in the majority of the tropical cyclone basins, with exception of the North Indian Ocean. Ventilation index changes are well correlated with changes in tropical cyclone frequency and intensification in the models. However, Camargo et al. (2014), using a high-resolution climate model, noted that tropical cyclogenesis indices that perform well in the present climate do not necessarily accurately reproduce the simulated future decrease in tropical cyclones. This decrease is only captured when modified indices, such as column saturation deficit (as humidity predictor) and the potential intensity (as thermodynamic predictor), are used.

Another relevant issue is whether there could be a change in the typical regions of occurrence of tropical cyclones in present climate with respect to future climate. Evans and Waters (2012) concluded from coupled models' analysis, that the threshold temperature for deep convection onset, which is often associated with regions where tropical cyclogenesis is favoured, is likely to increase in a warmer climate (see also Johnson and Xie 2010). This result implies that little change in future regions of cyclogenesis could happen, as the general increase in SSTs is counteracted by an increase in the future threshold temperature of deep convection. However, Dare and McBride (2011) examined all global individual tropical cyclone formation events from 1981 to 2008 and did not found any detectable shift of the threshold temperature toward a higher value. Lastly, Colbert et al. (2013) found an eastward shift in genesis location as well as a weakening of the subtropical easterlies in the North Atlantic in a warming climate.

Changes in tropical cyclones tracks is another critical issue. Using a statistical-dynamical modeling approach in the North Atlantic, Colbert et al. (2013) also found a decrease in tropical cyclones with westward tracks and an increase in those recurving in open ocean to the midlatitudes, mostly due to changes in the large-scale steering flow. Wang et al. (2011), using singular value decomposition (SVD) analysis in the western North Pacific, found that observed tropical cyclone track changes are associated with the leading SVD mode of global sea surface temperature warming and with related changes in large-scale steering flows.

(ii) Projections on intensity

After the pioneering work of Bender et al. (2010), climate models have been increasingly able to simulate the observed intensity distribution of tropical cyclones, thanks to the increasing resolution (e.g. Lavender and Walsh 2011; Murakami et al. 2012a; Manganello et al. 2012; Knutson et al. 2013; Yamada et al. 2014). Although higher resolution is still needed (Kanada et al. 2013), an increase in the frequency of the most intense tropical cyclones is projected by those models. The sensitivity of limiting hurricane intensity, i.e. the limit in the most intense hurricane that a given climate can produce, has recently been estimated to be about 8 m/s/K in the Atlantic basin, but this value is not reached in some recent high-resolution climate models (Strazzo et al. 2013), likely due to resolution issues. More supplementary information is needed. For instance, Christensen et al. (2013) noted that the number of very strong cyclones is usually more important for physical and societal impacts than typical measures such as mean intensity. On the other hand, Czajkowski and Done (2014), Done et al (2014) and Chang et al (2014) provided evidence that explicit inclusion of hurricane size and translation speed changes in projections studies is also important for predicting societal impacts.

A notable improvement in the representation of tropical cyclones in a global climate model was obtained by Murakami et al. (2015). Through the use of a new high-resolution Geophysical Fluid

Dynamics Laboratory (GFDL) coupled model [the High-Resolution Forecast-Oriented Low Ocean Resolution (FLOR) model (HiFLOR)], they investigated potential skill in simulation and prediction of tropical cyclone activity. Compared to previous version of the model (FLOR), a more realistic simulation of the structure, global distribution, and seasonal and interannual variations of tropical cyclones, as well as modulations induced by the Madden–Julian oscillation, was obtained in HiFLOR. Moreover, HiFLOR was also able to simulate and predict extremely intense tropical cyclones (those with Saffir–Simpson hurricane categories 4 and 5) and their interannual variations. This represented the first time a global coupled model has been able to simulate extremely intense tropical cyclones in a multicentury simulation and retrospective seasonal predictions.

Most of the high-resolution simulations addressing intensity changes in tropical cyclones have been performed using atmosphere-only climate model simulations, with SSTs coming from a coarser resolution coupled model. Therefore, the lack of full air-sea interaction in these simulations has raised questions about their realism, especially for intense tropical cyclones results where air-sea energy exchanges are strong. However, the limited number of studies using high-resolution coupled model simulations obtain similar results as the atmosphere-only GCMs. For instance, Kim et al. (2014), using the GFDL CM2.5 coupled model at ~50 km of resolution, found a strong link between decreases in ascent at mid-tropospheric levels and decreases in tropical cyclone occurrence in tropical cyclone formation regions. They obtain a substantial decrease (increase) in tropical cyclone numbers (in average tropical cyclone intensities) in almost all basins as a response of increased CO_2, like results from atmosphere-only models.

To sum up, many models have projected a lower frequency of tropical cyclones globally (e.g. Knutson et al. 2010), while other climate models and related downscaling methods have suggested some increase (e.g., Broccoli and Manabe 1990; Haarsma et al. 1993; Emanuel 2013). When it comes to individual basins, the issue becomes more concerning since for the Atlantic basin there appears to be little consensus on the future frequency of tropical cyclones (Knutson et al. 2010). Another disagreement comes from the relative role of forcing factors such as aerosols or increases CO_2 concentration. One reason for this disagreement could be merely related to statistical issues. As annual numbers of tropical cyclones in the Atlantic are relatively small, their identification is highly sensitive to the detection method used. In addition, projected responses of regional tropical cyclone frequency and intensity from downscaling studies (Knutson et al. 2007; Emanuel 2013) show a substantial spread. Given that there exist different projections of large-scale climate and differences in the present-day reference period and sea surface temperature depending on the dataset used, it is quite complicated to interpret the sources of uncertainty in tropical cyclone projections. A resulting question is whether this is caused by uncertainties in different large-scale forcing (e.g., Villarini et al. 2011; Villarini and Vecchi 2012; Knutson et al. 2013) or whether it is principally a reflection of the different methods and model characteristics [e.g. convective parameterizations (Kim et al. 2012) used]. Related to this is the changing ability of models to generate observed changes in tropical cyclone statistics when forced with a common forcing dataset.

Given the importance of the previous questions, a series of common idealized experiments were designed. Held and Zhao (2011), following Yoshimura and Sugi (2005), used the High Resolution Atmospheric Model setting up different kind of simulations with the purpose of determining whether responses were robust across them. Confirming earlier results of Yoshimura and Sugi (2005), Held and Zhao (2011) obtained in their simulation a decrease in tropical cyclone frequency of about 10% when CO_2 is doubled and an additional 10% when SST is increased by 2 K, resulting in a 20% reduction when both effects are present together. With respect to intensity, the average intensity of these cyclones increases when SST is increased, but it remains almost unchanged (or slightly decreased) when CO_2 is increased alone. When considering the frequency of the most intense cyclones, an increased intensity is obtained when SST is increased in isolation, but not in the case of CO_2.

An organized group project between scientist have been created to facilitate having results to answer those questions. The US Climate and Ocean: Variability, Predictability and Change (CLIVAR) established the Hurricane Working Group (HWG) to provide a synthesis of current scientific understanding of this topic. The work of Walsh et al. (2015) summarizes results of the HWG experiments (SST and CO_2 also changed separately) with a focus on tropical cyclone formation, reaching similar conclusions as, e.g., Held and Zhao (2011). Walsh et al. (2015) have found systematic differences between different experiment setups. A decrease in tropical cyclone frequency, like the decreases simulated by many climate models for a future warmer climate, is more likely in experiments where CO_2 is increased in isolation. Experiments where the combined effects of increasing CO_2 and SSTs are present also show decreases in cyclone frequency, but these tend to be less significant for models showing a strong tropical cyclone response to increased sea surface temperatures in isolation. They also propose further experiments that consider atmospheric-ocean coupling and variations in atmospheric aerosols.

II. Objectives

Considering the information presented in the previous Preface and State of Knowledge chapters, the main objective of this thesis is to add further insight into the existent knowledge on cyclones with tropical characteristics in the northeastern Atlantic and the Mediterranean basins, both for present and future climate. The objective is to focus on those issues that are still not well understood. These objectives are divided into four different targets, each one corresponding to a scientific publication included in the Results chapter. In this context, one important target are subtropical cyclones within the Northeastern Atlantic (target 1). No previous studies have focused on this kind of cyclones in that region. Another aim are medicanes in the Mediterranean Sea and the capability of regional climate models (RCMs) of simulating them (target 2) as well as subtropical cyclones with a view to their respective projections (target 3). The presented studies are the first ones in addressing their respective issues. Lastly, another objective arose from the anomalous evolution of a subtropical cyclone into a hurricane within the northeastern Atlantic basin, while this thesis was being developed. In order to exploit this opportunity, a novel methodology is tested and used to analyse its suitability for studying complex phenomena, both for operational forecasting and research purposes.

The questions addressed in this thesis are the following:

Target 1:

- Which common synoptic features are present when STCs evolve over the northeastern Atlantic basin (ENA)?
- What are the differences and similarities of those STCs with respect to STCs developing in the western North Atlantic?
- Under which conditions do ENA STCs occur? Could their forecasts be improved?

The answers to these questions are available in section V.1: Classification and Synoptic Analysis of Subtropical Cyclones within the Northeastern Atlantic Ocean (González-Alemán et al. 2015).

Target 2:

- Can observed medicanes be reproduced in climate-mode simulations on a case-by-case basis?
- Are RCMs able to reproduce the observed characteristics of medicanes?
- Are RCMs therefore useful for studying projections of medicanes?
- What is the impact of increased resolution on the simulation of medicanes in RCMs?
- What is the impact air-sea coupling?

The answers to these questions are available in section V.2: Simulation of medicanes over the Mediterranean Sea in a regional climate model ensemble: impact of ocean–atmosphere coupling and increased resolution (Gaertner et al. 2016).

Target 3:

- Are GCMs/RCMs able to simulate STCs? Can they be used to study ACC projections of STCs?
- Can they reproduce observed climatology of STCs?
- Will ACC affect the frequency and/or intensity of STCs in the ENA basin?

The answers to these questions are available in section V.3: Subtropical cyclones near-term projections from an ensemble of regional climate models over the northeastern Atlantic basin (González-Alemán et al. 2017).

Target 4:

- Is a recently developed path-clustering methodology suitable for improving ensemble forecasts of complex phenomena such as a hurricane in the midlatitude?
- Is the proposed methodology suitable for researching environmental causes behind different cyclone developments?
- If the last question is true, what was the role played by synoptic-scale processes in altering the (forecasted) evolution of Hurricane Alex (2016) in the midlatitudes?

The answers to these questions are available in section V.4: Synoptic factors affecting the structural evolution and predictability in ensemble forecast of Hurricane Alex (2016) in the midlatitudes (González-Alemán et al. 2018).

III. Data

The data sets used to carry out this thesis are described in this section. It is divided into two subsections following the different nature of the data: (1) reanalysis and observations; and (2) model simulations.

1. Reanalysis and observations

In this section two different reanalysis products and one additional observational data sets are described.

a. Reanalysis data

Reanalysis is a systematic approach to produce datasets that describe the “real” state of the atmosphere. These datasets are a very powerful and useful tool for climate monitoring and atmospheric research. They provide information of the past climate over the entire globe.

A reanalysis dataset is created through the use of an unchanging (or “frozen”) data assimilation system scheme and model configuration. The aim is to produce a homogeneous and dynamically consistent estimate of the climate state at each time step over the entire period which can be suitable for climate research. At each time step (6-12 hours) all available observations are ingested over the entire period being analysed. However, there is one component in this method which unavoidable does vary; the sources of the raw input data, i.e. the ever-changing observational network, including radiosonde, satellite, buoy, aircraft and ship reports. Currently, approximately 7-9 million observations are used at each time step.

Therefore, the resulting state of the atmosphere in reanalysis datasets at each location and time period is highly sensitive to the available observations. Climate variability over regions with higher spatial-temporal density of observations (e.g., Europe, North America, Eastern Asia etc.; cf. Fig. 1b) or downstream close to them (e.g. western North Atlantic) is better reproduced than in those areas where the model component plays a more important role in the data assimilation system to define the background state (e.g. over the oceans). In addition, artificial variability and spurious temporal trends can be produced due to the changing observation mix in the reanalysis. However, reanalysis datasets have proven to be rather useful when used with appropriate care.

As occurs with every tool used in atmospheric research, one must keep in mind advantages and limitations when using them. Positive points in favour of using them are that they are global data sets, with a consistent spatial and temporal distribution at least for 3 decades, with a substantial number of variables available. In addition, millions of observations are organized in a stable data assimilation system that otherwise would be nearly impossible for an individual to collect and analyse separately. This later fact has enabled the expansion of the number of works studying climate processes. However, limitations arise because there are observational constraints, and therefore reanalysis reliability can considerably vary depending on the location, time period, and variable considered, introducing spurious variability and trends (Trenberth et al. 2001). Importantly, diagnostic variables related to the hydrological cycle (e.g. precipitation and evaporation) should be used with extreme caution (Nigam et al. 2006).

Different reanalysis datasets are available for the scientific community: e.g., NASA MERRA (Rienecker et al. 2011); NOAA NCEP/NCAR reanalysis (Kalnay et al. 1996); NOAA 20th Century Reanalysis (Compo et al. 2011); ECMWF ERA-40 (Uppala et al. 2005); ECMWF ERA-Interim (Dee et al. 2011); JMA5 JRA-55 (Kobayashi et al. 2015), among others. Their differences are related to the horizontal and vertical resolution as well as time span coverage. This mainly depends on the computational sources available at each production centre and the optimum balance achieved between time period and resolution.

The reanalyses used in this thesis are the following:

(i) ERA-40

ERA-40 is a second-generation reanalysis from the European Centre for Medium-Range Weather Forecasts (ECMWF). The temporal window is 45 years of data (September 1957 to March 2002), with a spectral spatial resolution of T159 (~1.125°x1.125° in regular lat-lon grid), and 60 vertical levels from the surface up to 0.1 hPa. The data assimilation scheme is three-dimensional variational analysis (3D-Var). Uppala et al. (2005) provides further details about this data set. The data from the ERA-40 reanalysis are retrieved from the main repository of meteorological data at ECMWF, the Meteorological Archival and Retrieval System (MARS) at http://apps.ecmwf.int/datasets/. Data are available 4 times daily, daily and monthly in GRIB or NetCDF format.

(ii) ERA-Interim

ERA-Interim is a third-generation reanalysis from the ECMWF. It has a spectral horizontal resolution of T255 (~0.75°x0.75° in regular lat-lon grid), and 60 vertical levels from surface up to 0.1 hPa as in ERA-40. It includes data from 1979 up to now. The data assimilation scheme is based on a 12-hourly (00, 12 UTC) four-dimensional variational analysis (4D-Var), which is a great improvement with respect to ERA-40. The work of Dee et al. (2011) provides additional technical information about this data set. The data from the ERA-Interim reanalysis can be retrieved from the ECMWF's MARS archive as in the case of ERA-40. The data are available 4 times daily, daily and monthly in NetCDF or GRIB format.

b. Observations

(i) NHC-HURDAT database

HURicane DATabase (HURDAT; Jarvinen et al. 1984) contains all the information related to post-storm analysis of each tropical cyclone carried out by the National Hurricane Center (NHC) in its area of responsibility. The objective is to have an official assessment of the cyclone's history (Figure 17). This analysis uses all available observations, including those that may not have been available in real time, thus resulting in an improvement from real time analysis. In addition, NHC continuously conducts reviews of any past tropical cyclone analyses, and regularly updates the historical record to reflect changes introduced via the Best Track Change Committee (e.g. Hagen et al. 2012). Significant changes have been done since 2012 to the analysis of tropical cyclones and subtropical cyclones in the Atlantic basin. A new version called HURDAT2 (HURricaneDATa 2nd generation) has been developed. This new version includes non-synoptic (other than 00, 06, 12, and 18Z) best track times (mainly to indicate landfalls and intensity maxima), non-developing tropical depressions and best track wind radii. More information on this database can be found at http://www.nhc.noaa.gov/data/. In this thesis, HURDAT database was obtained by means of the International Best Track Archive for Climate Stewardship (IBTrACS) project (revision v03r01) (Knapp et al. 2010). The aim of the IBTrACS project is to create a global best track dataset from all the Regional Specialized Meteorological Centers in tropical cyclones, merging storm information from those centres into one product. More information on this project can be found at https://www.ncdc.noaa.gov/ibtracs/.

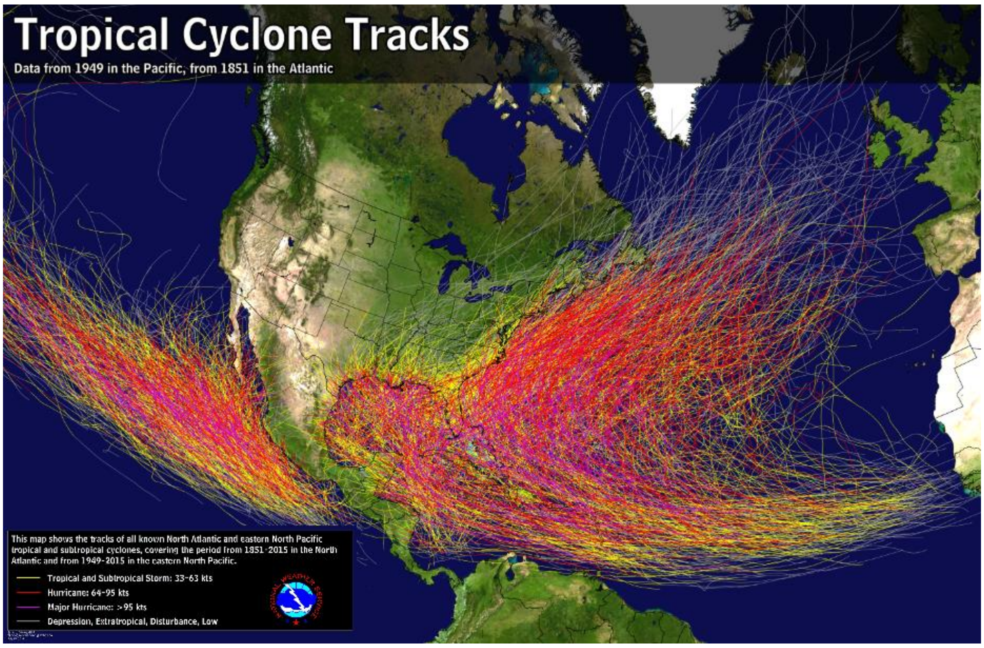

Figure 17. Historical tropical cyclone tracks as derived from HURDAT database. Source: NHC's website.

2. Model simulations

a. CORDEX initiative

The Coordinated Regional Climate Downscaling Experiment (CORDEX; Giorgi et al. 2009; Giorgi and Gutowski 2015) initiative focuses on advancing and coordinating the science and application of regional climate downscaling (RCD) through global partnerships. The main aims are to evaluate model performance and design a set of experiments to produce climate projections. Further information on this project can be found at http://cordex.org/.

GCMs can provide reliable information on how the climate of the earth may change in the future, on large scales regions possibly covering vastly differing landscape features with greatly varying potential extreme events. However, RCMs provide more relevant information for many vulnerable regions of the world. This is because they are applied over a limited area (driven by GCMs), in which much smaller scale extreme phenomena are better represented. In this way, RCMs support more detailed impact and adaptation assessment and planning. The impacts of a changing climate, and the adaptation strategies will take place on more regional and national scales, thus RCD plays a more important role.

Because RCD techniques are being increasingly used to provide higher-resolution climate information than is available directly from GCMs, it is important to appropriately apply them and understand their strengths and weaknesses. A global coordinated, international effort like CORDEX is able to objectively assess and intercompare various RCD techniques thus providing a means to evaluate their performance and provide a more solid scientific basis for an adequate use.

The choice of common RCMs' domains is important. The selection is based on physical issues, on considerations of resources needed for the simulations and on the availability of data from ongoing programmes. CORDEX domains encompass the majority of land areas of the world. In this thesis, a total of 29 model simulations from the Mediterranean and European domains (Med-CORDEX and EURO-CORDEX) have been used. The following list indicates the institution acronym, followed by the RCM used. The most relevant information for the purposes of this thesis is provided (coupled or uncoupled RCM; horizontal resolution in km; simulation periods):

- AWI/GERICS: REMO [uncoupled; 50, 25 and 18 km] and ROM [coupled; 50, 25 and 18 km (Sein et al. 2015)]. Simulation periods: 1982–2001 (50 km runs), 1978–2001 (25 km runs), 1975–2001 (18 km runs).
- CNRM: ALADIN5.2 [uncoupled; 50 and 12.5 km (Colin et al. 2010; Herrmann et al. 2011)] and RCSM4 [coupled; 50 km (Sevault et al. 2014)]. Simulation periods: 1979–2011 (ALADIN5.2 runs), 1980–2011 (RCSM4 run).
- ENEA: REGCM [uncoupled; 25 km (Artale et al. 2010)] and PROTHEUS [coupled; 25 km (Artale et al. 2010)]. Simulation period: 1982–2010.
- GERICS: REMO [uncoupled; 50 and 12.5 km (Jacob et al. 2012)] Simulation period: 1989–2008.
- GUF: CCLM 4-8-18 [uncoupled; 50 and 10 km (Rockel et al. 2008; Kothe et al. 2014)]. Simulation period: 1989–2008.
- IPSL-INERIS: WRF [uncoupled; 50 and 12.5 km (Vautard et al. 2013)]. Simulation period: 1989–2008.
- IPSL: WRF3.1.1 (uncoupled; 50 km [Skamarock et al. 2008; Flaounas et al. 2013; Stéfanon et al. 2014)] and WRF3.1.1-NEMO [coupled; 50 km (Brossier et al. 2015)]. Simulation period: 1989–2008.
- KNMI: RACMO22E [uncoupled; 50 and 12.5 km (van Meijgaard et al. 2012)]. Simulation period: 1989–2008.
- MET(Office): HadGEM3 [uncoupled; 50, 25 and 12.5 km (Moufouma-Okia and Jones 2014)]. Simulation period: 1990–2010.
- SMHI: RCA4 [uncoupled; 50 and 12.5 km (Kupiainen et al. 2011; Samuelsson et al. 2011)]. Simulation period: 1980–2010.
- UCLM: PROMES [uncoupled; 50, 25 and 12.5 km (Domínguez et al. 2010, 2013)]. Simulation period: 1989–2008.

b. ESCENA project

The ESCENA (Spanish acronym for 'scenarios') project was a Spanish initiative (2008–2012) which applied the dynamical downscaling technique, like CORDEX, to generate ACC projections based on an ensemble of RCMs. A difference with respect to CORDEX are the domains, which in ESCENA focus on the Iberian Peninsula and the Canary Islands. The ensemble of RCMs is composed of the models PROMES (from the Spanish 'PROnóstico a MESoscala', Mesoscale Forecast), WRF (Weather Research and Forecasting), MM5 (PSU/NCAR Mesoscale Model 5), and REMO (Regional Model) over a domain covering the Iberian Peninsula, the Balearic and Canary Islands and northwestern Africa, at 25 km resolution (cf. Jiménez-Guerrero et al. 2013 for more details on the RCMs). The GCMs used in ESCENA are ECHAM5-r2 (European Center HAMburg version 5), HadCM3 [Hadley Centre Coupled Model version 3; in two versions with different climate sensitivity: low sensitivity (HadCM3Q3) and high sensitivity (HadCM3Q16)] and ARPEGE-Climate version 3 (Action de Recherche Petite Echelle Grande Echelle, which means research project on small and large scales). The simulations cover both the present climate (historical simulations; 1951–2000) and future climate (scenario simulations; 2001–2050) period with different future greenhouse emission scenarios (A1B, B1, A2; IPCC 2001). Further information on this project is available in Jiménez-Guerrero et al. (2013) and Domínguez et al. (2013).

c. Ensemble prediction system from ECMWF

The ECMWF Ensemble Prediction System (EPS; Buizza 2006) is used in this thesis to apply the path-clustering methodology (cf. Section IV and Section V.4). Ensemble forecasts were created to quantify uncertainties arisen due to an imperfect knowledge of the initial conditions from observations and imperfect representation of atmospheric processes.

The ECMWF EPS aims at representing uncertainty in the initial conditions by creating a set of 50 different forecasts (members). Each member runs from slightly different atmospheric states that are close, but not identical, to the best estimate of the initial state of the atmosphere (the control). This control member is a lower resolution version of the deterministic forecast (Integrated Forecast System; ECMWF 2015). In addition, to quantify uncertainties arisen from an imperfect representation of the processes described by the model, slight model changes are also taken into account, using model formulations which are close, but not identical, to the best estimate of the model equations.

With this technique, forecast error can be analysed based on both model and initial conditions uncertainties. Forecast of a certain phenomenon, e.g. precipitation can thus be given in terms of probabilities just by counting the number of members that produces precipitation with respect to the total. Another application is the information on the atmospheric predictability. The divergence, or spread, of the 50+1 members (perturbed members plus control member) gives an estimate of the uncertainty of the forecast on a particular day (Figure 18). If the divergence is small, then the atmosphere is very predictable and thus the given forecast is reliable because it will fall somewhere in the narrow range of forecasts. When divergence is considerable, then the atmosphere is especially unpredictable. Changes in predictability on a daily basis is flow-dependent, thus they are intrinsic to the atmosphere's conditions and behaviour.

To sum up, probabilistic forecasts are aimed at both quantifying the probability of a specific forecast and the predictability of the atmosphere (forecast reliability). Therefore, they give useful information that otherwise is not present in deterministic forecasts. Having information on uncertainties in forecasts allows to make better informed decisions.

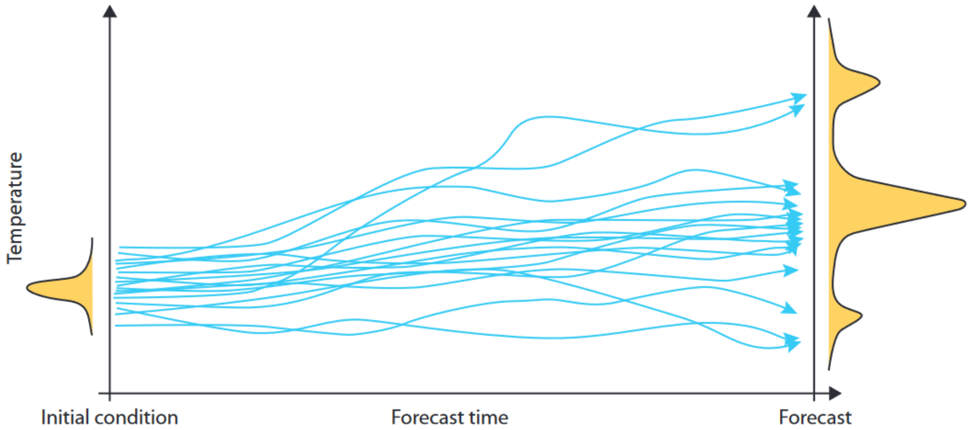

Figure 18. Divergence or spread in temperature at a given point on the Earth forecasted by an EPS. Source from ECMWF's website.

IV. Methodology

1. Data processing

The data processing techniques performed in this thesis are described below.

a. Calculation of standard deviation

The standard deviation of a set of numbers is a measure of the dispersion (σ) in their distribution with respect to their mean value (μ). It is computed by:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)}$$

$$\mu = \frac{1}{N}\sum_{i=1}^{N} x_i$$

where x_i are a set of N values having equal probability.

b. Calculation of anomalies

The analysis of anomalies is key in climate variability diagnosis to carry research on climate issues. The anomaly of a given variable (A) can be calculated with respect to its temporal ($\overline{A_t}$) or zonal average ($\overline{A_z}$):

$$A'_t = A - \overline{A_t}$$

$$A'_z = A - \overline{A_z}$$

Only temporal anomalies are used in this thesis. Variables such as geopotential height can be studied from a climate perspective during specific periods of time, compared to their climatological values. Additionally, anomalies can be standardized by dividing each value of the timeseries by the standard deviation of the whole timeseries in order to obtain a better idea of its abnormality. The period chosen as basis for the climatology is also important when calculating anomalies, since it can greatly affect the results. For instance, temporal means are usually associated with seasons or months in order to remove the signal of the seasonal cycle from the anomaly. If a given phenomenon mainly occurs over winter, then it is more appropriated to study its abnormality by only considering winter averages but not annual averages.

c. Calculation of composites

Composites are calculated as the arithmetic mean of a given set of meteorological fields. In some cases, the composites are computed only for anomalies. Composites are useful for elucidating the characteristics of a certain phenomenon. For example, by averaging meteorological fields when a specific phenomenon occurs, one could statistically (with a significance analysis; cf. Section IV.2) obtain or conclude what meteorological variables play a major role in it and what kind of patterns favour it. Obviously, there must be an underlying physical theory as a base for interpreting results from composites.

d. Path clustering

Path clustering is aimed at grouping trajectories within a space. A technique, whereby path-clustering using regression mixture models (Gaffney et al. 2007) is applied to forecasts in ensemble forecasting, has recently been applied (Don et al. 2016; Kowaleski and Evans 2016). In this thesis, path clustering is applied to forecasted trajectories of cyclones in the cyclone phase space (cf. Section IV.b and Section V.4).

Path clustering consider information over a given period, thus exploiting the spatiotemporal nature of the data. Data are tracks over time in 2D or 3D space. Therefore, if clustering is applied to the points they comprise, it will lead to a loss of information. On the other hand, by using mixture models in path clustering, the clusters assignment is done probabilistically, i.e. confidence in membership assignment is expressed as probabilities. In this case, observations (or tracks) are generally regarded as random objects derived from a mixture of component probability distributions, each of which is associated with a cluster.

A mixture model is a probabilistic model for representing the presence of subpopulations within an overall population. In this framework, the probability density function (PDF) for a d-dimensional vector **x** is modelled as a function of model parameters $\varphi = \{\alpha_1,...,\alpha_K; \theta_1,...,\theta_K\}$, by using the mixture density

$$p(\boldsymbol{x}|\emptyset) = \sum_{k}^{K} \alpha_k p_k(\boldsymbol{x}|\theta_k)$$

in which α_k is the kth component weight, and p_k is the kth component density with vector parameter θ_k; for example, K Gaussian densities each with a d-dimensional mean vector and a d x d covariance matrix. A finite mixture model can be then regarded as a PDF composed of a weighted average of component density functions (McLachlan and Peel 2000). This is what allows the mixture model framework to be used for data clustering.

A set of n vectors $\{\mathbf{x_1},...,\mathbf{x_n}\}$ is observed (e.g. trajectories) and considered as random sample from the underlying mixture model. Each data vector $\mathbf{x_i}$ is then generated by one of the Kcomponents (not observed). In the clustering framework, the K clusters would then be the estimated component models, $p_k(\mathbf{x}|\theta_k)$, $1 \leq k \leq K$, where each cluster is defined by a PDF in the d-dimensional input space **x**. Therefore, clusters can be geometrically regarded as probabilistic “flexible pipes” unfolding over time in the 2D or 3D space.

Probabilistic assignment provides more information than hard partition. In a hard partition each observation is assigned to one cluster only in a deterministic way. By indicating assignment strength of individual track to each cluster, they also provide an evaluation criterion, through which a better cluster solution which has larger fraction of tracks with strong cluster assignment can be searched next.

Prior to clustering, each component of the trajectory (e.g. latitude and longitude in 2D space) must be modelled by a polynomial regression model of order p in which time is the independent variable.

Regression mixture-model clustering works as follows:

- Mixture parameters, such as polynomial coefficients, covariance matrix and membership weights, of each of the K components (models) are calculated.
- The probability of assignment of each track to each cluster, given the shape parameters performed in the previous step, is calculated.
- The previous steps (mixture parameters and posterior probabilities) are iteratively calculated using an expectation-maximizing (EM) algorithm. This algorithm converges on a likelihood maximun, thus maximizing cluster assignment strength (e.g. Don et al. 2016).
- Clustering is repeated many times (a finite number of times) because the EM algorithm usually converges on a local, rather than global likelihood maximum. These repeated times are created with random initial membership weights, which serve to calculate shape parameter values.
- Finally, the set of cluster assignments with the highest likelihood from the previous step is taken as the final cluster solution, and each track is linked to the model (cluster) with the highest probability of having generated that path.

Prior to the clustering calculations above, the mixture-model specifications must be chosen. This means that the number of clusters and polynomial orders must be indicated first. However, in order to determine the optimal specifications, clustering is performed on all combinations of polynomial order first through fifth and 2 through 7 clusters. Then, different metrics are used to determine the optimal specification, such us Bayesian information criterion (BIC), mean-squared forecast error (MSFE) and fraction of clusters with probability of assignment below 0.95 (F0.95). In this thesis, only BIC is used. The BIC takes into account both the maximum log-likelihood (MLL; the value reached through the EM iterations) and a penalty related to the number of independent parameters (k) and number of observations (n) in the model. BIC is calculated as:

$$BIC(m) = -2L_m(m) + k \ln n$$

being $L_m(m)$ the MLL value. As MLL always favours more complex models (larger number of clusters, higher polynomial order), BIC is a better option since it favours specifications that provide a balance between goodness-of-fit and simplicity. A smaller BIC value indicates greater support for a model solution (Don et al. 2016), and a more complex model will not always have a better (smaller) BIC value with respect to a less complex model.

More information on the path-clustering theory and methodology used in this thesis can be found in Gaffney et al. (2007), Camargo et al. (2007a), Don et al. (2016) and Kowaleski and Evans (2016).

2. Hypothesis testing

When statistical computations are done for obtaining conclusions, an accompanying statistical test of significance should be provided. This is done with hypothesis testing. Hypothesis testing is a powerful tool for supporting the argumentation on a specific phenomenon, which has been based on statistical properties.

First, an initial hypothesis (null hypothesis; H_0) is considered. Hypothesis testing provides a set of statistical methods, which is applied onto a sample of data, to obtain the degree of confidence for making a decision with respect to accepting or rejecting H_0. When H_0 is rejected, the alternative hypothesis (H_1) can be then accepted with a degree of certainty. This doesn’t necessarily mean that H_1 is 100% correct, but there is a level of confidence to assume it. The parameter α is commonly used as the significance (confidence) interval. A typical value used in climate research for α is 0.05, which means that there is a probability of 95 % of being correct on the assumption that H_0 is rejected.

In climate research, where huge amounts of data are commonly used, these tests are usually required to describe the robustness of the findings, and exclude the possibility of the results being obtained by pure chance. Nevertheless, in the field of this thesis, a physical mechanism reasoning must accompany the results obtained by pure statistics.

For hypothesis testing, a substantial number of tests are available. These are divided into parametric and non-parametric tests, depending on the underlying statistical distribution used to infer the confidence levels. Parametric tests assume that data follow a given statistical distribution (e.g., a normal or Gaussian distribution). Non-parametric tests do not assume any statistical distribution of data, i.e. no parametrization can be done. The tests used in the thesis are described below. For further additional information on hypothesis testing, the reader is referred to von Storch and Zwiers (1999) and Wilks (2006).

a. Student's t-test

The t-test is any statistical hypothesis test in which the test statistic (a quantity derived from the sample) can be assumed to follow a Student's t-distribution when considering the null hypothesis. It is the most common used in significance testing and only applicable to sets of values or variables which follow a normal distribution. In this thesis, the t-test has been used in different applications. For instance, to decide if the behaviour of a chosen sample is significantly representative of the unknown behaviour of the entire sample (significance analysis of anomalies), to determine if two sets of data are significantly different from each other (significance analysis of changes), to know if two datasets are significantly correlated between each other (significance analysis of correlation) or if a linear regression in a time series is significantly sloped (significance analysis of trend).

As a detailed example, if there is a correlation between two datasets, one must know if this correlation is statistically significant or not. In this case, the student's t test of correlation is applied onto two different samples of data (x, y) to obtain information about their linear dependence. The null hypothesis considers that both samples are independent, i.e. $r = 0$, and the alternative hypothesis is then the contrary. The test statistic is calculated through

$$t = \frac{r\sqrt{N-2}}{\sqrt{1-r^2}}$$

where N is the number of data in both samples and r the correlation coefficient. The null hypothesis will be rejected when $|t| > t_{\alpha/2,\, n-2}$, a fixed value which is obtained from the t-table. The typical value used for α is 0.95, which gives a p-value of 0.05. By obtaining a p-value of 0.05, it can be said that there is a probability of 5% that the null hypothesis is true, i.e, there is not a correlation. In other words, there is a probability of 95% that the two datasets are correlated.

In addition, this example can be used (modified) to obtain the significance of the obtained slope when a linear regression in a time series is performed. The sign of the slope must be tested to know the significance of the result. The null hypothesis would be transformed into $b = 0$, i.e. the value of the slope is zero ($y = a + bx$. In order to do this, the test statistic is calculated as

$$t = \frac{b}{\sigma_b}$$

$$\sigma_b = \frac{\sigma_{y \cdot x}}{\sigma_x \sqrt{N-1}}$$

$$\sigma_{y \cdot x} = \sigma_y \sqrt{(1 - r^2)\frac{N-1}{N-2}}$$

being σ_x and σ_y the respective standard deviation of the two datasets x and y.

b. Mann-Whitney U test

When the data cannot be assumed to follow a given distribution, it is more appropriate to use non-parametric tests (cf. Section V.4) The Mann-Whitney U test (also called the Mann–Whitney–Wilcoxon, Wilcoxon rank-sum test, or Wilcoxon–Mann–Whitney test) is a non-parametric test that, when applied onto two data samples, assumes as the null hypothesis (H_0) that both samples (x, y) have the same median (or mean). Thus, it can be used for the mean in the same way as Student's t-test. The alternative hypothesis (H_1) is then that both samples have different means, thus indicating that both means are part of different populations.

This test works as follows:

- The test statistics U orders the mixed members from the two datasets (x, y) and gives a rank to each one.
- For each sample obtained in the previous step, the sum of all ranks is calculated and compared against each other.
- If the null hypothesis is true, i.e. the two datasets have the same mean, then the sum of ranges of both datasets (x, y) might be equal independently on the way chosen for partitioning the data composed of the two datasets.

As the possible combinations of data partitioning could be large $(n!)/(n_1!)(n_2!)$, where n_1 is the number of elements in x, n_2 the number of elements in y, and $n = n_1 + n_2$, in order to accept or reject the null hypothesis, the test statistic is taken as the minimum of the following two quantities U_1 and U_2 :

$$U_1 = R_1 - \frac{n_1}{2}(n_1 + 1)$$

$$U_2 = R_2 - \frac{n_2}{2}(n_2 + 1)$$

where R1 and R2 are the sum of ranks in each dataset.

When datasets are moderately large, i.e. $(n_1, n_2) > 10$, the U statistic can be approximated as a Gaussian distribution with mean μ_u and σ_u calculated as:

$$\mu_u = \frac{n_1 n_2}{2}$$

$$\sigma_u = \sqrt{\frac{n_1 n_2 (n_1 + n_2 + 1)}{12}}$$

In this thesis, the Mann-Whitney U test is applied in Section V.4 to cluster's composites to infer whether changes in features appearing in the compared composites are statistically significant or not.

3. Dynamical diagnostics

a. Cyclone identification and tracking algorithm

In order to detect and track cyclones in this thesis, the method of Picornell et al. (2001) is used. This method is aimed at studying mesoscale cyclones and is suitable for objective identification of cyclones in long-term studies. An example of a tracked cyclone is provided in Figure 19.

In this algorithm, the detection procedure follows three steps:

1) All the relative pressure minima are first considered as potential cyclones in 6-hourly SLP fields analysis, after applying a Cressman filter with a radius of 200 km (Sinclair 1997). The filter is applied to smooth out noisy features appearing in the SLP field and small cyclonic structures.

2) In order to filter weak cyclones, the behaviour of the pressure field is studied along the typical eight directions surrounding the minima. Only thoses cyclone with a pressure gradient higher than 0.005 hPa km^{-1} at least along six of those eight directions are selected, which is equivalent to a mean geostrophic wind speed of 5 m s^{-1}, i.e. a significant flow.

3) A restriction is finally imposed on the size of the cyclones; if two minima are nearer than four grid points, only the one with the largest circulation is selected.

In order to characterize the selected low-pressure centres for each cyclone, some parameters are defined and calculated, like closed or open character, domain, radius, vorticity or circulation. Also, whether the low is secondary or not, is indicated.

Once cyclone's centres are obtained at each time step, the next calculation is to obtain their respective tracks. An automated method is followed to determine the tracks of the cyclones in agreement with Alpert et al. (1990). It is based on the assumption that the 700-hPa level is the steering level of the movement of a cyclone (Gill 1982). Thus, considering locations of the low-pressure centres in successive analyses and the horizontal wind at 700 hPa to determine the direction in which the cyclone will preferably move, a cyclone track can be calculated.

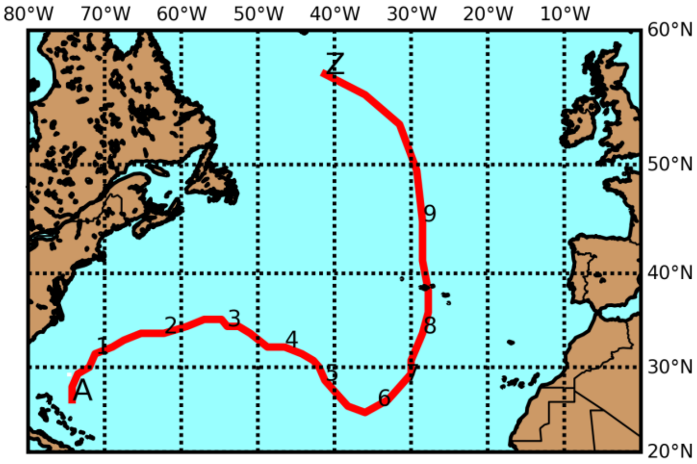

Figure 19. Example of the application of tracking algorithm of Picornel et al. (2001) to Hurricane Alex (2016). A (Z) indicates the initial (final) point. Numbers indicate days after the initial point.

The method is to perform a search in the next analysis within an elliptical area, whose major axis is proportional to the wind at the 700-hPa level. As Picornell et al. (2001) states, this hypothesis is reasonable for baroclinic cyclones with a deep vertical structure but is not always verified for weak low-pressure centres. In order to try to describe accurately the movement not only of mobile and deep cyclones but also shallow and stationary or quasi-stationary cyclones, other elliptical areas for searching are considered.

b. Cyclone phase space

The cyclone phase space (CPS) framework is applied in this thesis to select hybrid or tropical cyclones among all the detected cyclones. According to Hart (2003) and as shown in the Introduction section, the CPS serves to depict the cyclone structure three-dimensionally by thermodynamically classifying cyclones with respect to their horizontal symmetry and vertical thermal structure. The CPS arose from the idea of trying to treat cyclone types objectively based on their thermal and dynamical structure. Any cyclone with a closed circulation at surface can be evaluated within the CPS from numerical model or reanalysis outputs. Once calculated, the cyclone type (extratropical, tropical or hybrid) can be determined. Three parameters are used in to build this space:

Thermal symmetry parameter: The storm-motion-relative 900-600hPa thickness gradient across the cyclone, giving a measure of the frontal nature of the cyclone. It is denoted by B and is evaluated via:

$$B = h(\overline{\Delta Z_R} - \overline{\Delta Z_L})$$

where, Z is isobaric height, R indicates right of current storm motion, L indicates left of storm motion, and the overbar indicates the areal mean over a semicircle of the considered radius. h is 1 for Northern Hemisphere and -1 for Southern Hemisphere.

B is calculated generally within a 500-km radius of the storm centre. A smaller radius can be used for small cyclones like the medicanes (150 km in the case of the medicanes study presented here). Depending of the B value, there can be two possibilities:

- B ≈ 0 m --> $\overline{\Delta Z_R} \approx \overline{\Delta Z_L}$, i.e. the cyclone has non-frontal characteristics.

- B > 0 m --> $\overline{\Delta Z_R} > \overline{\Delta Z_L}$ in the Northern Hemisphere. In this case the cyclone has nature with temperature gradients within the cyclonic region. B > 10 m is considered a better limit above which a cyclone can be said to be frontal (Evans and Hart 2003).

Thermal winds: Thermal wind parameters are evaluated over layers in the lower (L; 900–600 hPa) and upper (U; 600–300 hPa) troposphere as follows:

$$-|V_T^L| = \left|\frac{\partial(\Delta Z)}{\partial lnp}\right|_{900hPa}^{600hPa}$$

$$-|V_T^U| = \left|\frac{\partial(\Delta Z)}{\partial lnp}\right|_{600hPa}^{300hPa}$$

where $\Delta Z = (Z_{max} - Z_{min})_p$ is the cyclone height perturbation at constant pressure and is evaluated within the same radius as in B.

These parameters measure the thermal vertical structure of the cyclone.

- If $-|V_T^{L,U}| > 0$, warm core.

- If $-\left|V_T^{L,U}\right| < 0$, cold core.

The combination of these three parameters allows to obtain two different 2D diagrams with a coordinate system in the form of $(-V_T^L, B)$ y $(-V_T^L, -V_T^U)$. Both diagrams provide the necessary information to deduce frontal nature and thermal structure of cyclones.

V. Results

The results of this thesis are divided into four different sections. Each section corresponds to an article published (V.1, V.2, V.3) or under review (V.4) in journals from the Science Citation Index. Supplementary material files are provided after each article.

1. Classification and synoptic analysis of subtropical cyclones within the northeastern Atlantic Ocean

Abstract: Since more research is needed on subtropical cyclones (STCs) formed within the North Atlantic eastern basin, this survey analyzes them from a synoptic point of view, on a climatological basis, with the main aims of studying their common features, complementing other studies of these storms in the North Atlantic, and aiding the forecasting community. Fifteen cases of STCs were identified during the period 1979–2011 by applying a set of criteria from two databases. Composite analysis reveals that an extratropical depression acts as a precursor when it is isolated from the westerlies and then suffers a deepening when becoming subtropical instead of decaying through occlusion. This process is accompanied by an atmospheric circulation, within the North Atlantic, whose main feature is characterized by notable departures from the climatological pattern with a statistically significant anomalous high pressure to the north of the STCs. Three conceptual models of synoptic pattern of subtropical cyclogenesis are derived and show that these departures appeared because the westerly circulation moves poleward and/or the flow has a great meridional component, with the possibility of a blocked flow pattern occurring. Moreover, the identified STCs predominantly formed in a highly sheared (>10 m s^{-1}) environment with low sea surface temperature values (<25°C), which differs from the dominant features of STCs in the North Atlantic, especially within its western region. Finally, a recent (2010) STC, identified by the authors, is synoptically discussed in order to achieve a better interpretation of the general results.

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Classification and Synoptic Analysis of Subtropical Cyclones within the Northeastern Atlantic Ocean*

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ABSTRACT

Since more research is needed on subtropical cyclones (STCs) formed within the North Atlantic eastern basin, this survey analyzes them from a synoptic point of view, on a climatological basis, with the main aims of studying their common features, complementing other studies of these storms in the North Atlantic, and aiding the forecasting community. Fifteen cases of STCs were identified during the period 1979–2011 by applying a set of criteria from two databases. Composite analysis reveals that an extratropical depression acts as a precursor when it is isolated from the westerlies and then suffers a deepening when becoming subtropical instead of decaying through occlusion. This process is accompanied by an atmospheric circulation, within the North Atlantic, whose main feature is characterized by notable departures from the climatological pattern with a statistically significant anomalous high pressure to the north of the STCs. Three conceptual models of synoptic pattern of subtropical cyclogenesis are derived and show that these departures appeared because the westerly circulation moves poleward and/or the flow has a great meridional component, with the possibility of a blocked flow pattern occurring. Moreover, the identified STCs predominantly formed in a highly sheared ($>10\ \mathrm{m\ s^{-1}}$) environment with low sea surface temperature values ($<25°\mathrm{C}$), which differs from the dominant features of STCs in the North Atlantic, especially within its western region. Finally, a recent (2010) STC, identified by the authors, is synoptically discussed in order to achieve a better interpretation of the general results.

1. Introduction

Subtropical cyclones (STCs) are low pressure systems showing characteristics of both tropical and extratropical cyclones, thus being between the theoretical extremes of cyclones. They have a hybrid thermal structure with cold upper-tropospheric and warm lower-tropospheric thermal anomalies as main feature. In recent years, there has been a growing interest in STCs because of their recognition as damaging weather systems, such as pre–Hurricane Karen's landfall over Bermuda in October 2001 (Steward 2001; Guishard et al. 2007) to mention just one example. They tend to develop in environments with little low-level baroclinicity in conjunction with diabatic processes.

The formation, development, maturity, and decay of cyclones have been studied for decades, and it was generally believed that tropical cyclones had a life cycle that was distinct from extratropical cyclones. For instance, midlatitude cyclones grow mainly because of baroclinic instability, which requires that there are horizontal temperature gradients and vertical wind

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shear, and then decay as this instability is removed (Bjerknes and Solberg 1922; Charney 1947; Eady 1949; Holton 2004). The thermal structure is asymmetrical, with cold advection generally to the north and to the west of the surface low, and warm advection to the south and to the east; if the cyclone is cut off from the westerlies, the thermal structure will have a deep cold core located over the surface pressure minimum. Satellite imagery of baroclinic cyclones reveals an asymmetric cloudiness pattern associated with horizontal thermal contrast.

Unlike extratropical cyclones, tropical cyclones develop in a barotropic environment with no important horizontal thermal gradients, depending strongly on latent and sensible heat fluxes from the ocean (Charney and Eliassen 1964), since their main source of potential energy is the thermodynamic imbalance between the atmosphere and the underlying ocean (Ooyama 1969; Emanuel 1988). They are governed by latent heat release through cumulus convection (Kuo 1965), and the mechanism of air–sea interaction (Emanuel 1986; Rotunno and Emanuel 1987) is a crucial requirement for their intensification. Tropical cyclones have a suitable development in environments with large-scale low-level convergence and upper-level divergence, small amounts of vertical wind shear, high values of low-level vorticity that may be associated with large horizontal shear, and conditions favorable for barotropic instability (McBride and Zehr 1981). The thermodynamic structure in the vertical has a well-defined warm deep core above the center, and satellite imagery reveals an eyelike feature and an axisymmetric shape.

However, it seems that there is no sharp dividing line between tropical and midlatitude cyclones. In this way, Davis and Bosart (2003) outlined a new mechanism for the development of a tropical cyclone, linking both classical archetypes of cyclones. They called this process tropical transition, whereby a baroclinically induced surface depression may initiate via quasigeostrophic dynamics and amplify through convective diabatic heating to build a warm thermal core from the lower troposphere upward once the development and maintenance of convection near the center is established. The hybrid nature of these cyclones, with a cold core aloft and a warm core near the surface, is characteristic of STCs, which results from the lack of sustained convection near the cyclone center, unlike tropical cyclones. Thus, the distinction between a subtropical depression that goes through its life cycle in a sheared environment and a tropical cyclone that forms via the tropical transition process is often subtle.

One of the major justifications for the study of STCs is that they are associated with both damaging winds and rainfalls and the public expect warnings on such systems. Indeed, the motivation of this study is as a result of the landfall of an STC over the Canary Islands and the Iberian Peninsula at the beginning of February 2010. Since this event was unusual in that region, knowing whether there were more STC cases in the past or it was a unique occurrence is necessary in order to provide a context for STC development of use to the forecasting community, especially in the eastern part of the North Atlantic (ENA), where they are less known and have not been studied as a whole. In addition, this study will serve as a basis for creating a future objective climatology of STCs over this basin. In contrast, STCs have been researched by Guishard et al. (2007) near Bermuda, by Evans and Guishard (2009) within the western North Atlantic (WNA), and by Guishard et al. (2009) over the entire North Atlantic basin. Apart from the North Atlantic, they have been also studied in other regions such as the South Atlantic (Evans and Braun 2012), central Pacific (Otkin and Martin 2004), and Tasman Sea (Holland et al. 1987; Browning and Goodwin 2013). Hereafter, the reader should note that any reference to characteristics of STCs over other regions will be based on these studies, although they will not be quoted to avoid excessive repetition of references.

This survey analyzes STCs formed over the ENA basin during the last three decades from a synoptic point of view, on a climatological basis, with the objectives of 1) highlighting their common features when they evolve over this basin, 2) complementing and contrasting the studies of STCs mentioned above within the North Atlantic, and 3) determining the conditions under which ENA STCs occur, thus providing support for the successful forecasting of such system. These aims are addressed by constructing a database of STCs based on specific criteria, exploring the dynamics with the aid of composite analysis, and classifying the events according to environmental parameters and synoptic patterns. Data used and our methodology are documented in section 2. The temporal and spatial characteristics of the STC cases are presented in section 3. In sections 4 and 5, respectively, the composite analysis and stratification of the STCs based upon their genesis environments are presented. A synoptic pattern classification is proposed in section 6 in order to facilitate the identification of the atmospheric patterns that may favor the subtropical formation. For illustrative purposes and to complement the general results, the STC formed in 2010 is described as a case study in section 7, detailing its synoptic evolution and some characteristics related to the other sections. In addition, the consideration of this cyclone as subtropical with the inclusion in our dataset is justified in this section, which is the main reason for selecting this cyclone for further analysis. Finally, the results are summarized in section 8.

2. Data and methodology

A set of STCs formed within the ENA is studied herein with the main objective of examining its common climatological and synoptic features. For this purpose, ERA-Interim (Dee et al. 2011) gridded data (sampled to 0.75° × 0.75° resolution) are utilized.

a. Databases used

Two databases for the identification of STCs in the ENA basin are used in this survey. They are compared in section 2b. On the one hand, the first and only objective STC climatology within the North Atlantic (hereinafter referred to as ERA-40 climatology), built by Guishard et al. (2009), is employed. Only STCs formed over the domain 20°–40°N, 30°W–0° were selected. Cyclones are included in the climatology if they do the following:

1) Attain gale-force winds ($17\,\mathrm{m\,s^{-1}}$) on the 925-hPa surface at some time during its life cycle, within the 20°–40°N latitude band.
2) Exhibit a hybrid structure for at least 36 h, as determined by the cyclone phase diagram (CPS; Hart 2003) with the criteria of $-|V_T^L| > -10$ and $-|V_T^U| < -10$. This feature is illustrated with examples in sections 2c and 7.
3) Become subtropical (i.e., attain a hybrid structure) within 24 h, if identified first as a purely cold- or warm-core system.

On the other hand, STCs identified by National Hurricane Center (NHC) were added as well. This NHC database (hereinafter referred to as the NHC-HURDAT database) was obtained by means of the IBTrACS project (revision v03r01) (Knapp et al. 2010). We used only STCs formed over the domain between 40.5°W and 0° with no limit on latitude, from 1979 to 2011, and those that attained subtropical storm intensity ($17.5\,\mathrm{m\,s^{-1}}$, using a 1-min average). This last criterion is used to be more consistent with ERA-40 climatology (first criterion).

NHC policy for classification of STCs has been the same since 1975, with the use of the first and only objective Hebert–Poteat (HP) satellite classification system (Hebert and Poteat 1975). This satellite recognition technique was implemented, as a complement to the Dvorak technique for tropical cyclone intensity classification (Dvorak 1975), for estimating STC intensity. Its goals were to use cloud features associated with STCs in order to be able to 1) distinguish them from tropical cyclones in the formative stages, 2) estimate their intensity, and 3) have criteria that would intermesh with the Dvorak technique when systems become tropical. The method outlined has elements of subjectivity intrinsic to this type of categorization, yet its application is supported by its use by forecasters experienced in using satellite classification techniques. Although satellite resolution has improved vastly since it was developed, the HP technique provides the only guidance for remote sensing of different intensities of STCs.

Apart from this technique, NHC has started to use new tools and data sources that have become available in the past few years (Landsea 2007), one of which is the above-mentioned CPS. The CPS is a three-dimensional descriptor of the cyclone structure, in which structure types are thermodynamically classified by reference to their horizontal symmetry (B: thermal symmetry parameter) and vertical thermal structure ($-V_T^L$, $-V_T^U$: thermal wind parameters) (Hart 2003). Despite its advantage of being objective, this diagnostic tool should be used in conjunction with synoptic fields, satellite imagery, and other analysis tools in order to produce an evaluation of the cyclone structure type as reliable as possible (Guishard et al. 2009).

Our database of STCs identified within the ENA was increased by adding the STC occurred in 2010, which has been identified by the authors in this study. In section 7, both the recognition of this cyclone as subtropical system and its inclusion in our study are justified in detail.

b. Comparison of the NHC-HURDAT database with ERA-40 climatology

The way a cyclone is included slightly differs depending on the database to which it belongs. In ERA-40 climatology, model reanalysis and the CPS are used to isolate cyclones that are unambiguously identified as STCs by applying an objective, consistent, and largely automated method. In contrast, the NHC-HURDAT database (Jarvinen et al. 1984) does not incorporate any objective methodology to include a cyclone since it is derived primarily from subjectively reanalyzed operational data and thus it may be inconsistent and biased.

However, ERA-40 climatology and NHC-HURDAT database consider STCs nearly the same structure. For instance, they both use the HP technique (in ERA-40 climatology, it is used to verify the nature of the storms). In addition, during the last decade NHC has focused more on the thermal structure of cyclones thanks to the advent of the mentioned new tools. This, together with the information provided in section 2c, allows justifying the use of both databases since the objective of this study is related to the phenomena that favor the successful development of hybrid structures that lead to STCs, more than to specific aspects of their definition. This latter issue, especially in the case of ENA STCs, needs more research and discussion in order to deal in greater depth with their definition. This is why part of this study is focused on the creation of a future objective climatology of this type of phenomena in the eastern part of North Atlantic, by gaining insight into such processes.

The overlap or coincidence between the two databases during the period 1957–2002 is considerable but not perfect (Guishard et al. 2009), as would be expected as a result of the different techniques and criteria used. ERA-40 climatology exclude systems with subtropical characteristics for a variety of reasons—for instance, those systems with no gales associated, those formed over land, or those having hybrid characteristics not observed for the required 36 h, among others. As to NHC-HURDAT database, this excludes systems with marked frontal character at surface. Therefore, the selection methodology used herein has the advantage of identifying as many STCs as possible in the region of study, which is the main reason for the inclusion of both datasets.

Comparing quantitatively the identification of STCs in the two databases, it can be seen that 92 (361) out of 453 cyclones were operationally deemed subtropical (tropical) in the NHC-HURDAT database. Also, 197 STCs were found in ERA-40 climatology; 65 of the 92 STCs found in NHC-HURDAT did not meet the STC criteria in ERA-40 climatology. Conversely, 53 are named cyclones (subtropical or tropical) in NHC-HURDAT database that overlap with ERA-40 climatology; 26 of these 53 did meet ERA-40 STC criteria but were not labeled as subtropical but as tropical. The remaining 27 (i.e., 92 − 65) were identified as STC in both databases, which is thus the key overlap and encompasses 29% (27/92) of the NHC-HURDAT database and 14% (27/197) of the ERA-40 climatology. It is important to note that this analysis is based on the period 1957–2002 (including the presatellite era). Nevertheless, 1979–2002 is the period common to the STC databases used in the present study, a period when satellite observations were commonly used. Therefore, it is likely that the percentage overlap shown above could be increased by an examination of cyclones only during the period 1979–2002 because of the advent of routine satellite observations during this period.

It is highly likely that more STCs than those obtained herein have formed during the period of study of both databases (1979–2002 for ERA-40 climatology and 1979–2011 for the NHC-HURDAT database). The criteria imposed to identify STCs in the ERA-40 climatology are rather restrictive, especially within the ENA region. Moreover, STCs have been inconsistently handled by NHC with a high degree of subjectivity as evidenced, for instance, in the policy for naming or issuing advisories on them, especially in the 1980s and 1990s. For instance, the abovementioned STC formed in 2010 was not studied by NHC. This is one of the reasons why this cyclone has been individually included as a case study in section 7.

c. *Analysis of the STCs from the NHC-HURDAT database in the terms of the CPS*

In this subsection, an analysis of two examples of cyclones detected in NHC-HURDAT database that are not included in ERA-40 climatology, and that have been used to carry out this study (see section 3), is provided. This analysis, based on the CPS, serves as a means of justifying the inclusion of the five cyclones from the NHC-HURDAT database, which allows one to add consistency to the use of both databases. For simplicity, the analysis of the other three cyclones is not shown herein given that they have a similar behavior.

1) STC4 (1990)

According to Fig. 1a, this STC started as a gale-force extratropical system at 0000 UTC 3 August in the CPS based on ERA-40. Then, after 30 h it acquired hybrid/subtropical structure ($-|V_T^L| > -10$ and $-|V_T^U| < -10$; shallow warm core) through the tropical transition process by 0600 UTC 4 August and became extratropical again at 0000 UTC 6 August.

This system was therefore not included in ERA-40 climatology because the third criterion listed in section 2a was not fulfilled. However, it does meet the first and second (the most important one) criteria. The third criterion was included in ERA-40 climatology for operational forecasting considerations since the intention was to filter out systems that, previously to the achievement of the hybrid structure, had gale-force winds and thus systems that would have already likely been monitored by forecasters, limiting the chances of a surprise storm. In other words, the intention in ERA-40 climatology was to study STC cases essentially formed in situ. However, we emphasize that this is not the aim of this survey, which is to study all STC cases occurred in the ENA basin instead, since there is less knowledge about ENA STCs and forecasters are less aware of them. We are more interested in the phenomenon itself, that is, the development of enough convection to transition into a subtropical system (acquisition of a hybrid structure). This is the reason why the third criterion has been omitted in this study.

2) STC14 (2007)

According to Fig. 1b, this gale-force cyclone started with a hybrid structure ($-|V_T^L| > -10$ and $-|V_T^U| < -10$; shallow warm-core) at 0000 UTC 3 October in the CPS

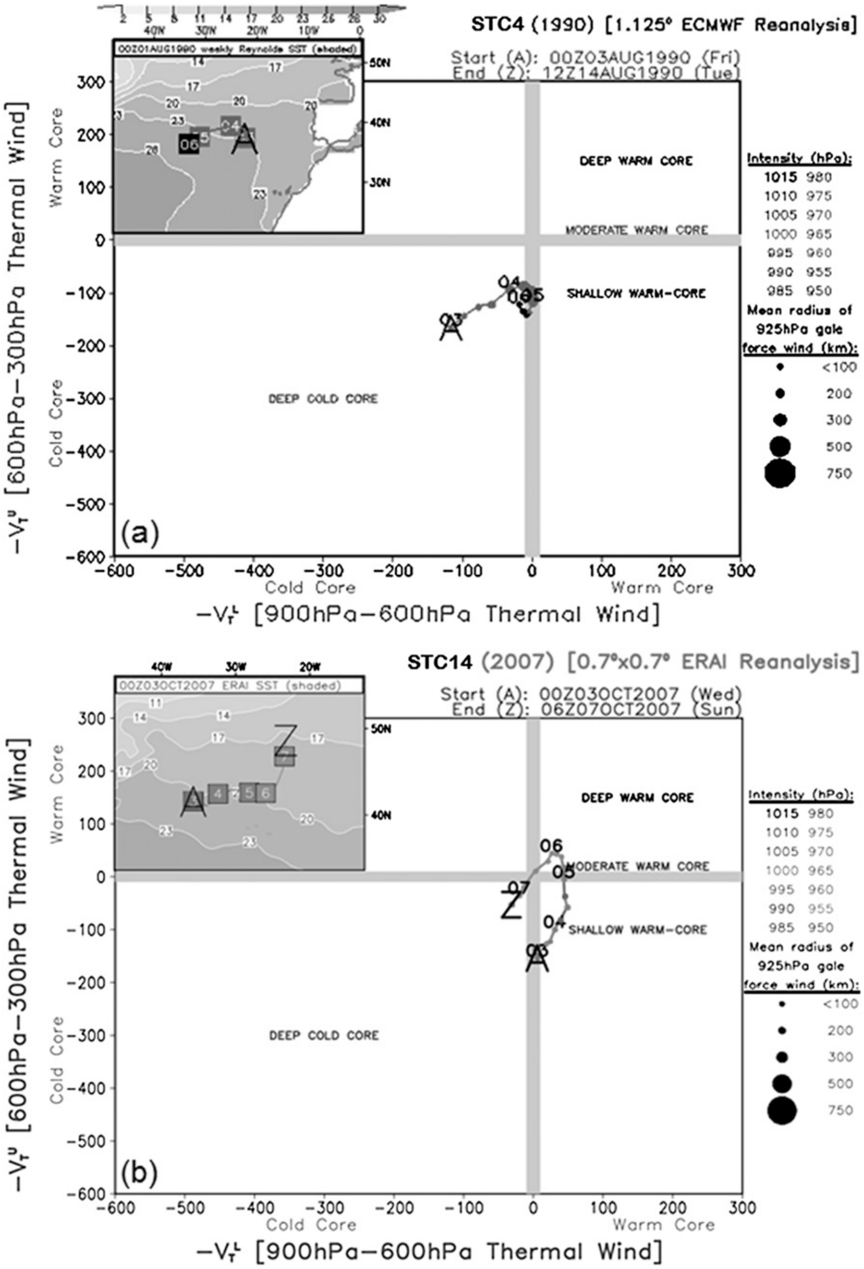


FIG. 1. (a) ERA-40 of STC4 and (b) ERA-Interim of STC14, plotted in the CPS (V_T^L vs V_T^U). The A indicates the beginning of the plotted life cycle within the reanalysis and the Z indicates the end. A marker is placed every 6 h. The shading of each marker indicates cyclone MSLP intensity and the size of the circular marker indicates the relative size (mean radius) of the 925-hPa gale-force ($>17\,\mathrm{m\,s^{-1}}$) wind field. Positions at 0000 UTC are labeled with the day. Because of visual considerations, the life cycle of STC4 has been stopped at 0000 UTC 6 Aug, before the time Z [Available online for (a) at http://moe.met.fsu.edu/cyclonephase/archive/1990s/ and for (b) at http://moe.met.fsu.edu/cyclonephase/archive/2007/gifs/aleman22007/].

based on ERA-Interim. After 48 h it clearly developed a warm core ($-|V_T^L| > -10$ and $-|V_T^U| > -10$) in upper levels, which gave it a tropical cyclone structure by 0000 UTC 5 October. Later on, it acquired a cold-core structure at 0000 UTC 7 October. This system would have been included in the ERA-40 climatology, if not for the fact that the cyclone did not attain gale-force winds within the 20°–40°N latitude band, which is

TABLE 1. STCs identified from ERA-Interim during the period of 1979–2011. The number in parentheses after the names of the cyclones indicates the database from where the cyclone comes: 1 for the climatology of Guishard et al. (2009) and 2 for the NHC-HURDAT database. STC15 was identified by the authors.

Storm	Formation time (t_0)	MSLP (hPa)	Lat (°N)	Lon (°W)
STC1 (1)	0000 UTC 12 Nov 1981	1010.7	29.25	27.75
STC2 (1)	0600 UTC 16 Mar 1984	1014.0	39.75	26.25
STC3 (1)	0000 UTC 2 Mar 1988	1004.2	30.00	9.75
STC4 (2) (pre-Edouard)	1200 UTC 3 Aug 1990	1009.4	39.75	22.50
STC5 (1)	0600 UTC 4 Dec 1991	991.2	32.25	24.00
STC6 (1)	0000 UTC 17 Feb 1996	1013.6	27.00	20.25
STC7 (1)	1800 UTC 19 Feb 1996	1012.6	27.75	26.25
STC8 (1)	1800 UTC 4 Mar 1996	999.0	31.50	23.25
STC9 (1)	0000 UTC 29 Jan 1997	1004.3	36.00	26.25
STC10 (1)	0000 UTC 6 Mar 2000	1014.0	28.50	20.25
STC11 (2)	1200 UTC 4 Oct 2005	1012.1	36.00	30.00
STC12 (2) (pre-Vince)	0600 UTC 8 Oct 2005	1002.6	32.25	21.00
STC13 (2) (pre-Delta)	1800 UTC 22 Nov 2005	980.2	30.75	40.50
STC14 (2)	0600 UTC 6 Oct 2007	998.9	42.75	25.50
STC15	1800 UTC 29 Jan 2010	996.3	30.75	31.50

a requirement added in ERA-40 climatology only to reduce the possibility of introducing pure extratropical or tropical systems and therefore is not applied herein.

d. *Methodology*

Once STCs are identified, the methodology associated with this survey has been characterized by the determination of

1) maps of geopotential height at 300 hPa and mean sea level pressure (MSLP) during the life cycle of the cyclones with the purpose of performing the synoptic classification;
2) composite maps of geopotential height at 300 hPa and MSLP fields in order to carry out the analysis;
3) monthly-mean reanalysis fields for the period of 1979–2012 to define the mean climate structure in constructing the composite anomalies; and
4) sea surface temperature (SST) and vertical wind shear (WS) within a domain centered at the low pressure minimum. This will enable the environmental classification.

The three last steps were completed following Evans and Guishard (2009), with the objective of comparing with their results. Yet the calculation of deep layer WS has differed in this study. Calculating WS by layers was considered more robust than by levels. Thus, WS is calculated as

$$\mathrm{WS} = \sqrt{(u_U - u_L)^2 + (v_U - v_L)^2}, \qquad (1)$$

where the subscript U is for the average of 200, 250, and 300 hPa (upper layer), whereas the subscript L is for the average of 700, 850, and 925 hPa (low layer). Wind speed components are denoted by u and v.

3. Identified subtropical cyclones

A set of 15 STCs formed within the ENA have been detected during the period of 1979–2011. Note that ERA-40 climatology as used here only covers the period of 1979–2002. Nine of those belong to ERA-40 climatology and five belong to the NHC-HURDAT database. The last cyclone is the STC that originated in 2010 and is identified by the authors in this study. Table 1 contains further information from ERA-Interim about the STCs identified. It is worth noting that STC4, STC12, and STC13 constituted the early stages of Tropical Storm Edouard (Case 1990), Hurricane Vince (Franklin 2006), and Tropical Storm Delta (Beven 2006), respectively.

Figure 2a depicts the tracks of the cyclones and their location at the formation time t_0, that is, the first moment when they were designated as subtropical systems in the databases (subtropical storms in NHC-HURDAT). It highlights the erratic features of the movements of the cyclones, which is in reality a manifestation of autonomy or isolation of the cyclones from the basic flow in middle latitudes. In contrast, STCs that developed within the WNA exhibit far more linear paths. This difference arises as a result of the existence of a climatological trough over this region (see Fig. 4), which is indicative of the continuous crossing of troughs steering STCs toward the east. In contrast, troughs frequently evolve into cyclones isolated from the westerly circulation (cutoff lows) over the ENA basin. Indeed, Nieto et al. (2005) noted that one of the three preferred areas of cutoff low occurrence in the Northern Hemisphere extends through southern Europe and the eastern Atlantic coast. The idea of the baroclinic origin of STCs within the ENA basin is further developed in the following sections.

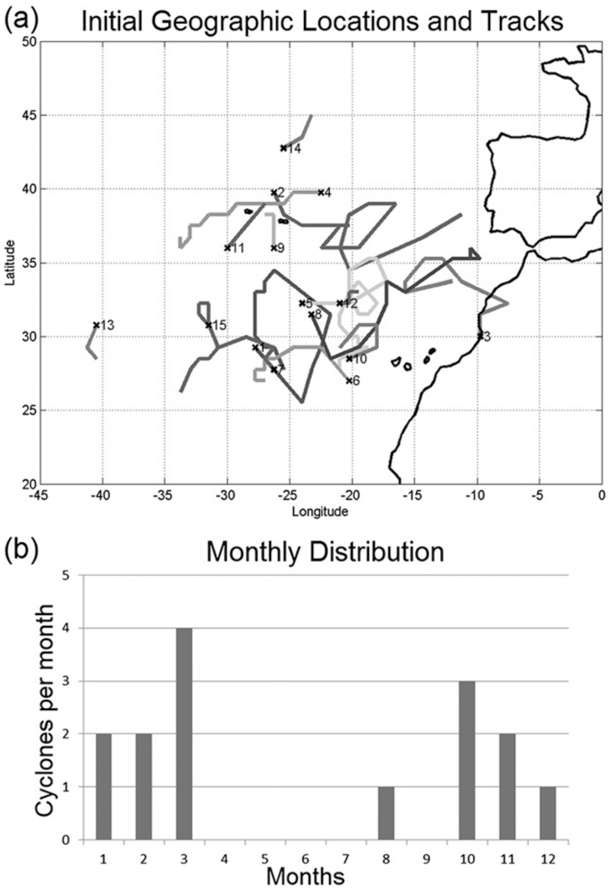


FIG. 2. (a) Initial geographic locations, tracks and (b) monthly distribution of the STCs identified within eastern basin of the North Atlantic during the period of 1979–2011. The crosses indicate the position of the cyclones at the time of their formation (t_0) and the numbers are associated with the cyclones' names as described in Table 1. The tracks have been only displayed within the time interval when the lows were considered to be subtropical cyclones in the databases.

Temporal analysis (Fig. 2b) suggests that subtropical cyclogenesis has a preferred seasonality. Note that 14 out of the 15 cyclones have in fact formed from October to March, which would be consistent with their baroclinic origin since midlatitude circulation moves southward in winter and therefore cutoff lows would be more likely to reach low mid- and subtropical latitudes. However, cutoff lows seem to be more frequent in summer over the ENA basin and Mediterranean Sea (Nieto et al. 2005). This inconsistency is likely to be as a result of the difference in temperature between SST and the cold air in the upper troposphere associated with depressions. This difference would be bigger in winter mainly because of much deeper upper-level cold lows, causing a greater destabilization of the atmosphere, and thus the associated convection would be more significant than in summer. The more convection originates within the center of the cyclone, the more likely its transition to a subtropical system (Guishard et al. 2009). Nevertheless, more research on this issue is needed to clarify the relation between cutoff lows and STCs within the ENA.

Another issue worth highlighting is the formation of STC4 in August since it was the only STC formed in summer and also because it then evolved into a tropical cyclone. By examining its synoptic history (not shown), it can be seen that it was the digging of a trough near the Azores, with the subsequent formation cutoff low, that led to the development of the STC, consistent with the genesis mechanism of the rest of the cyclones. This low then remained stationary for three days, which helped it to make a transition to its tropical stage.

A comparison with other studies in order to contrast our temporal distribution of the cyclones is needed. STCs within the entire North Atlantic predominantly formed during the midhurricane or warm season up to its end (i.e., from September to November) as a consequence of WNA STC prevalence over the North Atlantic. WNA STCs mostly form during this time of the year because relatively warm SSTs reach their northernmost extent, which contributes to the fact that the overlap between the baroclinic zone and the warm SST zone is as large as possible, particularly in October (Guishard et al. 2009). In fact, Bermuda subtropical storms, as part of the WNA STCs, show a remarkable peak in September. However, Fig. 2b does not display any leading peak in autumn, but shows the predominance of ENA STCs events in winter, which may give an idea of the differences between both types of STCs since WNA STCs tend to form in the season when SSTs are warmest whereas ENA STCs tend to form when midlatitude circulation reaches its southernmost extent. It can be therefore inferred that the major factor (SST or midlatitude circulation) that leads to the formation of an STC may differ depending on the basin, which is a result that will be also supported by the environmental classification shown in section 5. Although warm SSTs and midlatitude circulation (cutoff lows) would be considered to be necessary factors for the successful development of an STC, future work is needed to clarify the key (necessary and sufficient) factors that determine whether a low would evolve into an STC or not (Evans and Guishard 2009; Guishard et al. 2009), especially within the ENA basin.

4. Composite analysis

Geopotential height at 300 hPa and MSLP composites have been represented in this section to describe the common synoptic features arising within the North Atlantic when STCs formed at t_0 (North Atlantic basin composites; section 4a) and in the surroundings of the cyclones following their tracks (storm-centered composites; section 4b). The anomaly composites have been also constructed so as to reveal more detailed environmental features that are not evident in the non-anomaly-composited fields on their own. The anomalies represent departures from long-term ERA-Interim (Dee et al. 2011) monthly-mean values for the period of 1979–2012. To ensure that the synoptic-scale features associated with STC genesis are captured, they are computed over a cyclone-centered (at the MSLP minimum) 30° × 25° grid in 6-h intervals from 24 h prior to genesis to 24 h after—that is, from $t_0 - 24$ h to $t_0 + 24$ h. In this regard, it should be noted that the synoptic influence common to all STC cases may not be as obvious as they are in an individual case. With this in mind, it is advisable to perform case studies to complement the compositing approach. Hence, the synoptic evolution of STC15 has been analyzed in section 7.

a. North Atlantic basin composites

Figure 3a reveals the main descriptive feature of the atmospheric circulation pattern in the North Atlantic basin at the moment when the 15 STCs formed. As can be seen from this figure, a trough to the south of the ENA is located just to the southwest of the Iberian Peninsula and involves a ridge to the north, with its axis just to the west of the British Isles. This upper-level pattern influences the low-level pattern to strengthen a high pressure structure centered at the southwest of the British Isles that spreads over a large extent of the ocean. There is also an area of low pressure below the trough, associated with the STCs. Therefore, Fig. 3a shows that these STCs form in a meridional trough, with the westerly midlatitude flow blocked over Europe and North Africa by constructive reinforcement between the subtropical anticyclone and the high pressure ridge in the extratropical longwave. Such a pattern differs from the long-term climatological one (see Fig. 4). This latter is characterized by an upper subtropical ridge over the ENA basin associated with the Azores high, which provides a wide region of stable climate.

The remarkable anomalies associated with STC formation can be seen in Fig. 3b. It shows a widespread area of negative anomalies just to the west of the Canary Islands associated with the cyclone anomaly, and a broad and band-shaped area of positive anomalies encompassing from Newfoundland to the British Isles and Scandinavia. The positive anomalies are located around 60°N whereas the negative anomalies are around 30°N (Fig. 3b). This blocked flow pattern (Doblas-Reyes et al. 2002), as described in the nonanomaly composites, is the main feature of the atmospheric circulation over the North Atlantic Ocean when the STCs developed within the eastern basin. In addition, it can be noted that these upper-level anomalies are reproduced significantly at low levels, especially in the case of the anomalous high pressures. The center of this positive surface anomaly is shifted to the east with respect to the upper anomaly (as expected in an extratropical system). In the case of the negative anomaly, its center is just beneath, which is more typical of a tropical circulation. The statistical significance analysis of these anomalies as well as that of Figs. 5d–f (see section 4b) is available in the supplemental material.

To facilitate the interpretation of the composites just described here, three obtained conceptual models of atmospheric patterns when the STCs formed (section 6) and the study of the synoptic evolution of the STC15 (section 7) are included in this survey.

b. Storm-centered composites

The resulting storm-centered composites are depicted in Figs. 5a–c. They display a relevant structure of the common synoptic environment of the cyclones, which is linked to the atmospheric pattern revealed by the Atlantic composites to a great extent. The presence of an upper trough in the westerlies promotes a quasigeostrophic (QG) forcing for the development of the low pressure at the surface just to the south-southeast of the trough center. This becomes the dominant feature prior to the onset of STC genesis ($t_0 - 24$ h; Fig. 5a). In each STC case, a trough was likewise evident in proximity to the surface low although not all the troughs were in the same state of evolution at $t_0 - 24$ h. There were certain cases in which the trough was amplified, almost forming a cutoff low, whereas there were other cases in which the trough was embedded in the westerlies in a previous stage of a digging trough (i.e., just before it began to amplify). As time passes, the wave at 300 hPa evolves into a closed system and deepens as the upper ridge downstream of the trough weakens through the time (evident in the 926 dam isopleth at $t_0 + 24$ h; Fig. 5c). All these features indicate that the cyclone evolves into a closed low, isolated from the midlatitude circulation. The deepening STC tends to become vertically stacked (Figs. 5a–c), which leads to a lesser QG forcing and a greater diabatic heating forcing associated with the latent heat release provided by convection just below the upper cold air core, and therefore the cyclone adopts a more tropical structure. There is more agreement among the STC cases at $t_0 + 24$ h, when a cutoff low was evident in nearly all the cases.

This latter forcing can be explained in terms of the Lagrangian tendency of potential vorticity (PV) due to

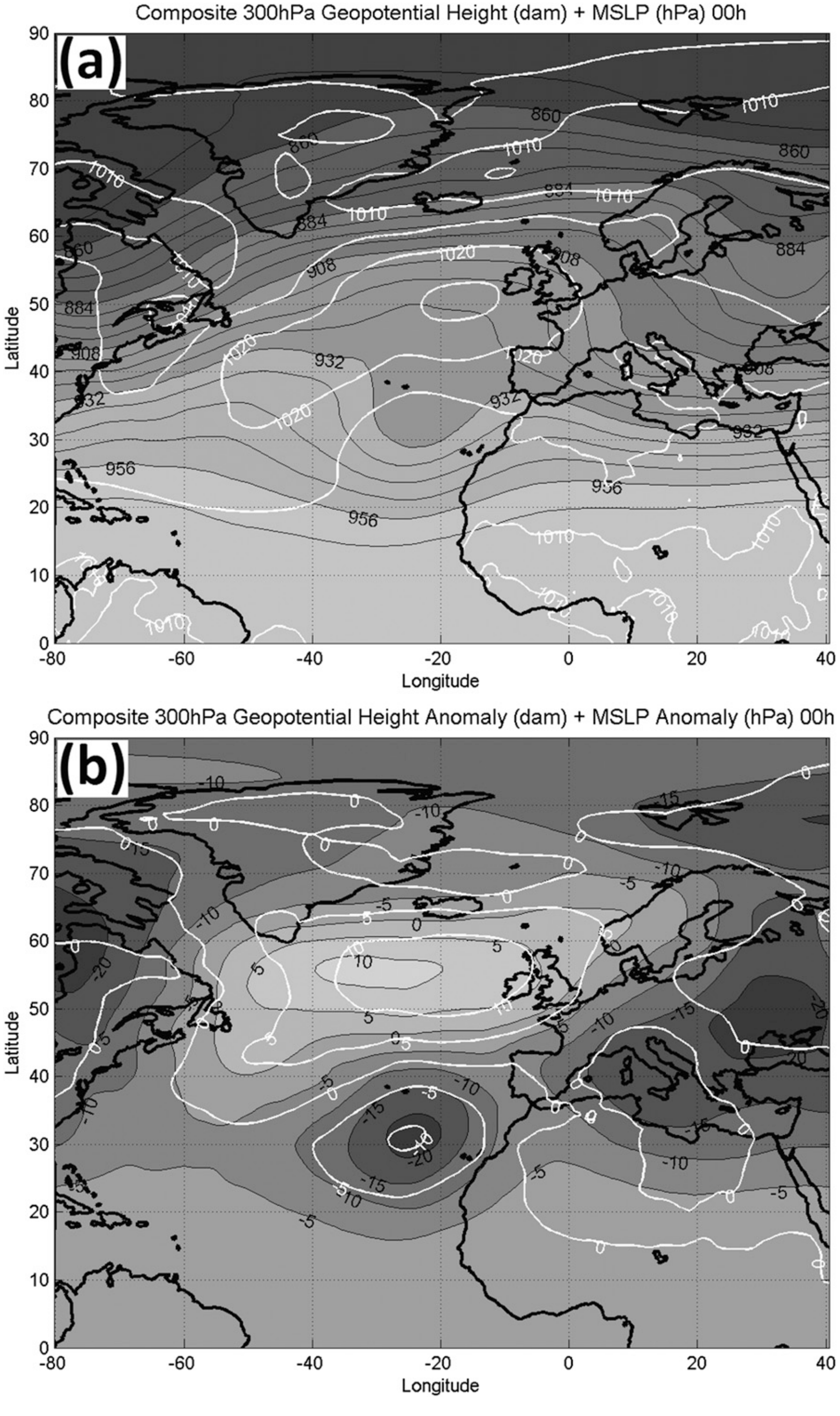


FIG. 3. (a) Composite (all 15 STCs) of 300-hPa geopotential height (shaded and gray contours; dam) and mean sea level pressure (white contours; hPa) at t_0 (0 h). (b) Also plotted is the anomaly composite. Statistical significance of (b) is available in the supplemental material.

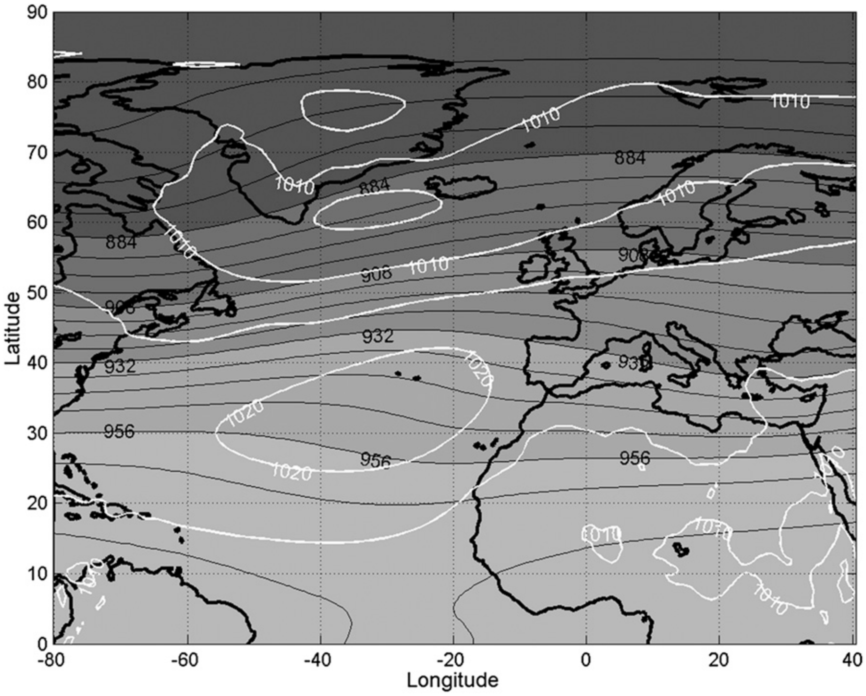


FIG. 4. Long-term (1979–2012) ERA-Interim climatology over the North Atlantic of 300-hPa geopotential height (shaded and gray contours; dam) and mean sea level pressure (white contours; hPa).

a diabatic heat source represented by (Hoskins et al. 1985)

$$\rho \frac{dPV}{dt} = \boldsymbol{\eta}_a \cdot \nabla\dot{\theta}, \tag{2}$$

where ρ is the atmospheric density, $\boldsymbol{\eta}_a$ is the three-dimensional absolute vorticity vector, and $\dot{\theta}$ is the diabatic warming rate (i.e., $d\theta/dt$). Equation (2) states that potential vorticity can be redistributed vertically by introducing a differential diabatic heat source (e.g., latent heat release) into the column. Assuming that the diabatic heating maximum is situated in the midtroposphere and the absolute vorticity vector is nearly vertical, PV will tend to increase (decrease) in the layer below (above) the heating maximum (Raymond 1992). This heating will involve an anomalously high PV in the lower troposphere with lower values near the tropopause. The deepening of the STC can be thus explained by this forcing since higher PV values in the lower troposphere lead to an increased circulation of the cyclone related to a decreased pressure at its center. This mechanism is in fact consistent with the concept of a warm core lower-tropospheric cyclone, characteristic of STCs, resulting from the large amount of released latent heat. Diabatic effects of cyclone intensification are also observed in extratropical cyclone formation (Romero 2001) and contribute to the enhancement of their warm-seclusion process as well (Gyakum 1983a,b).

When observing the temporal animation (from t_0 − 24 h to t_0 + 24 h every 6 h; not shown), the variation of the previously described features are in fact larger once the cyclone acquires subtropical characteristics (t_0), indicating the crucial difference in the structure and environment of the cyclone when this undergoes a transition to a subtropical state. Thus, these results suggest that there exist some extratropical cyclones that become subtropical and generally intensify instead of filling when they are isolated from the westerlies, along their path over the northeastern Atlantic. This process is well documented in the South Hemisphere (Holland et al. 1987; Evans and Braun 2012; Browning and Goodwin 2013). Cutoff lows commonly weaken and occlude as they move toward subtropics and baroclinicity decreases, which differs from the results obtained in this section.

Anomaly composites (Figs. 5d–f) reveal a region of negative anomalies in both fields, associated with the subtropical depressions. These anomalies are initially on the order of 10 hPa in the MSLP and 25 dam in the geopotential height. Both anomalies evolve deepening up to 15 hPa and 30 dam, respectively, which is consistent with the previously described nonanomaly composites. The strengthening and positioning of the positive anomalies just to the north of the negative anomalies, as

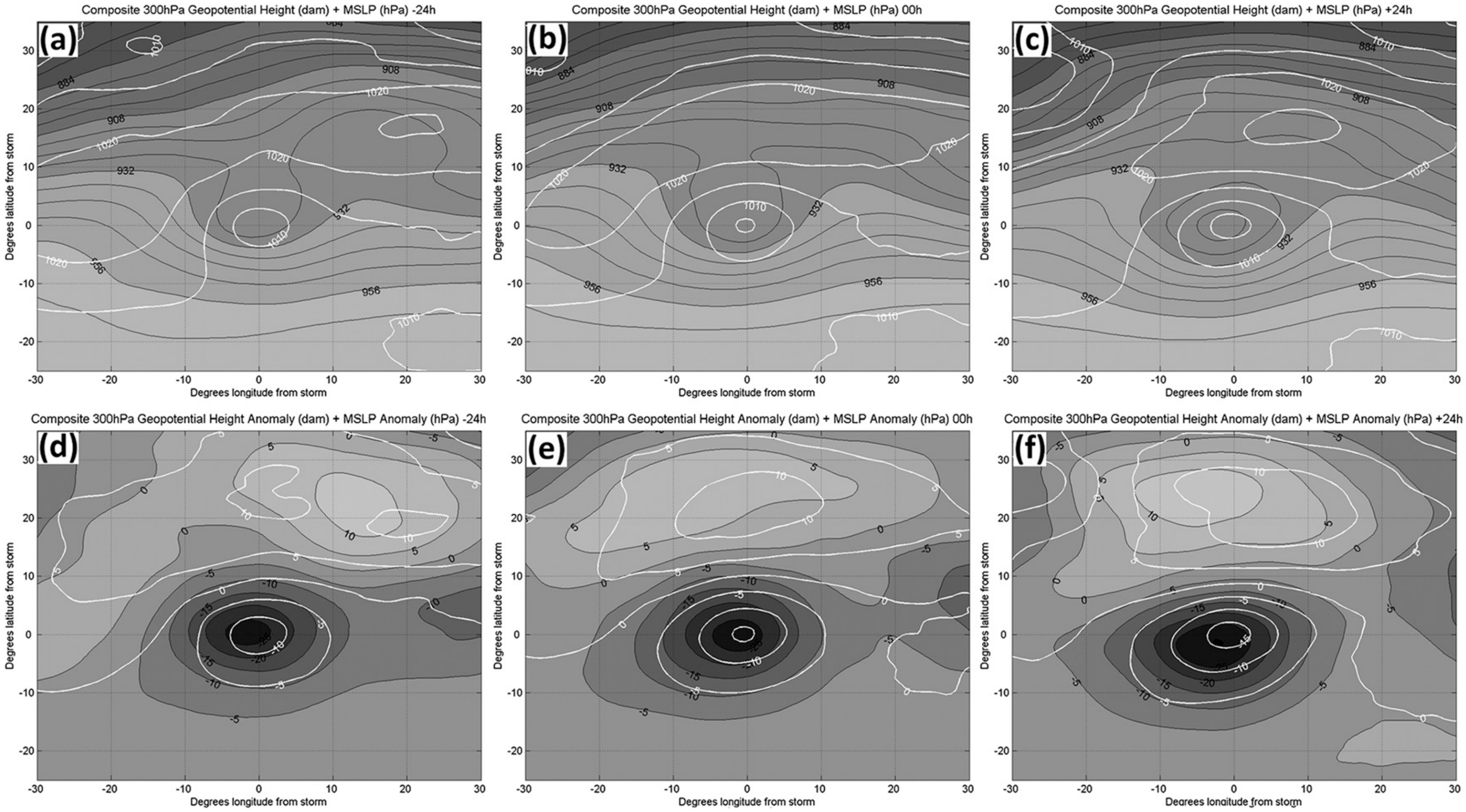


FIG. 5. Storm-centered composites (all 15 STCs) of 300-hPa geopotential heights (shaded and gray contours; dam) and mean sea level pressure (white contours; hPa) at times (a) $t_0 - 24$ h, (b) t_0, and (c) $t_0 + 24$ h. Also plotted are the anomaly fields for times (d) $t_0 - 24$ h, (e) t_0, and (f) $t_0 + 24$ h. Statistical significance of (d)–(f) is available in the supplemental material.

time passes, is the most important feature of the anomaly composites. These positive anomalies evolve covering a widespread region of +10 hPa at $t_0 + 24$ h, which would denote the reinforcing of a ridge just to the north of the cyclone and thus a greater blocked flow regime feature.

The synoptic evolution described in the storm-centered composites is consistent with the idea of the isolation from the general circulation that the cyclone undergoes when evolving into a subtropical stage, which would be a requirement for an auspicious development. Furthermore, as with WNA STCs, the greater curvature of the flow observed in the region of the upper-level cyclone, causing anticyclonic shear just to the north of the surface depression, is consistent with a Rossby wave breaking event (Thorncroft et al. 1993). This feature is verified when doing the description of the synoptic history of STC15 in section 7.

In addition, the results just described here are also consistent with the WNA STC composites in that the average cyclone deepens once it acquires a subtropical structure, and the shape of the anomalies tend to resemble each other even though the anomalies are greater here, which is reasonable since the western basin is rather different from the eastern basin in terms of climate. Note that the climatological pattern over the North Atlantic (Fig. 4) is characterized by a subtropical ridge, with its associated Azores high over the eastern basin while a trough is located over the western side. The reinforcing and strengthening of the anomalous high pressure just to the north of the cyclonic anomalies, which Evans and Guishard (2009) considered to be the manifestation of a Rex block pattern, is the main common feature of both studies. Nevertheless, it can be seen that the nonanomaly composites are differentiated from each other, in the sense that western composites do not evolve into a closed upper-level contour despite the fact that both composites have the same contour interval as Figs. 5a–c. This difference would indicate that the evolution of the trough into a cutoff low, or at least into an upper-level closed low, in the WNA is not as common as in the ENA, which reinforces the idea of the difference in the environments between the two basins when STCs form. It is also important to note that composites of Fig. 5 are consistent with results obtained, in MSLP composites, by Browning and Goodwin (2013) for southern secondary low (SSL) events, and by Otkin and Martin (2004) for cold-frontal cyclogenesis/trade winds easterlies (CT) kona lows.

5. Environmental classification of subtropical cyclogenesis

An environmental classification of the identified STCs is undertaken in this section. As in the case of Evans and Guishard (2009), the 15 STC cases have been partitioned into four classes based upon their WS and SST characteristics in the surrounding of the cyclones when they formed (i.e., t_0). These four environments are: tropical (T: SST $\geq$ 25°C, WS $\leq 10\,\mathrm{m\,s^{-1}}$), subtropical (ST: SST $\geq$ 25°C, WS $> 10\,\mathrm{m\,s^{-1}}$), the classical extratropical type 1 (E1: SST $<$ 25°C, WS $> 10\,\mathrm{m\,s^{-1}}$), and the low-shear extratropical type 2 (E2: SST $<$ 25°C, WS $\leq 10\,\mathrm{m\,s^{-1}}$). They calculated WS by taking a $5° \times 5°$ average centered on the cyclone whereas SST averages were calculated for a $2° \times 2°$ grid box. With our intention of being as consistent as possible with their methodology and because of the different grid resolution (0.75°), for this study we had two alternatives for the size of the grid boxes, which were $1.5° \times 1.5°$ for SST and $4.5° \times 4.5°$ for WS, and $3° \times 3°$ for SST and $6° \times 6°$ for WS. Table 2 shows that SST is not very sensitive to changes in the size of the calculation domain, showing insignificant differences, while WS is. For instance, STC8 and STC11 are located in different extratropical environment of formation, associated with different WS, depending on the calculation box. Therefore, an interval of uncertainty should be introduced in the partitions of the environments although the results presented here (Fig. 6) are associated with a single grid box ($3° \times 3°$ for SST and $6° \times 6°$ for WS) in order to be able to contrast them better with the other studies. The larger grid boxes have been chosen for a better representation of the structure of the cyclones.

The two parameters used above to obtain the classification of the STC environments are associated with processes that have been demonstrated to be involved in the development of cyclones. The ratio between these processes plays a decisive role in determining the final structure type (tropical, extratropical, or hybrid) attained by cyclones. Two of the large-scale conditions considered to be necessary but not sufficient for tropical cyclogenesis are weak wind shear and warm SST (Gray 1968; Evans 1993). As such, the tropical environment is the most favored of the four types for tropical cyclogenesis and thus the lack of STCs in this environment within the region of study is logical. The subtropical class also has a near-surface thermodynamic forcing resulting from heat and moisture fluxes from the warm ocean below. However, it has an environment of strong wind shear, which increases the likelihood of baroclinic development and therefore is the most adequate environment for the subtropical cyclogenesis. A baroclinic system in the upper westerlies, consistent with QG theory, tends to force mass ascent, which, in close conjunction with the warm moist near-surface layer, favors the generation of deep convection and decreasing static stability. In this neutral atmosphere, forced ascent can extend down to the surface and

TABLE 2. Selected parameters associated with the STCs' environments (ENV) at their genesis (t_0). Subscripts 1 and 2 are for the smaller and larger grid boxes, respectively.

Storm	SST_1 (°C)	SST_2 (°C)	WS_1 ($m\,s^{-1}$)	WS_2 ($m\,s^{-1}$)	ENV_1	ENV_2
STC1	22.73	22.74	17.95	18.44	E1	E1
STC2	14.81	14.83	15.33	15.82	E1	E1
STC3*	6.07*	4.57*	34.47	34.18	—	—
STC4 (pre-Edouard)	21.83	21.82	15.73	17.12	E1	E1
STC5	20.21	20.21	13.06	14.67	E1	E1
STC6	20.32	20.24	41.42	40.43	E1	E1
STC7	20.05	20.06	18.58	18.75	E1	E1
STC8	17.93	17.95	9.22	11.53	E2	E1
STC9	16.90	16.92	6.57	8.74	E2	E2
STC10	19.53	19.47	18.94	19.34	E1	E1
STC11	24.76	24.73	9.53	10.04	E2	E1
STC12 (pre-Vince)	23.67	23.63	6.50	8.96	E2	E2
STC13 (pre-Delta)	23.31	23.37	9.78	9.77	E2	E2
STC14	19.62	19.63	9.40	8.79	E2	E2
STC15	19.84	19.88	13.78	14.48	E1	E1

* The cyclone does not originate completely over ocean surface.

convective feedback can lead to STC genesis and potentially also to tropical cyclogenesis. Nevertheless, this subtropical environment does not involve the formation of STCs in our case, as noted below.

In contrast, the extratropical environments (E1 and E2) are characterized by cold SST. Thus, the proximity of an upper-level trough will lead more likely to a baroclinic development of a more purely extratropical storm structure than tropical, since lower ocean surface temperatures tend to limit enthalpy fluxes at the storm's lower levels. Nevertheless, E2 environment is characterized by low wind shear, which may aid the maintenance of convection in case of its development and thus favors the accumulation of the released latent heat. This accumulation of heating leads to the building of the warm core in low levels of the troposphere, which is characteristic of an STC structure. If this process continues, the cyclone develops a tropical structure. To sum up, the successful development of the STC will then depend on the different acting forcings and on the extent in that they act.

The identified cyclones are classified in the diagram of Fig. 6, in which the predominance (71.4%) of the classical extratropical environment (E1), characterized by high wind shear and low SST values, is noticeable. Since STC3 formed just off the African coast, its SST values are inaccurate over the calculation domain and thus this cyclone must be left out of the environmental classification. It is worth noting that STC11 is located in the diagram remarkably close to the subtropical and tropical environments boundaries, originating over the warmest waters (~25°C) with respect to the other cyclones. This happens because of the season (October) when it formed. Warm SSTs come far to the north of their usual position in late summer and early autumn. The rest of the cyclones (28.6%) originate in the low-shear extratropical environment (E2) although they are all close to the boundary with E1. In addition, it can be seen that there is no linearity between SST and wind shear at the moment of the cyclones' formation. It is worth noting that 3 out of the 15 cases (STC4, STC12, and STC13) became officially (NHC) tropical cyclones after the subtropical development, which denotes the potential for the transition to tropical cyclones of these types of cyclones despite not having been surrounded by suitable environments (E1 and E2).

Unlike ENA STCs, WNA STCs formed predominantly in the subtropical (38.9%) and tropical (38.9%) environments. Of the 18 cyclones identified in the western basin (Evans and Guishard 2009), only one and three cyclones originated under E1 and E2 situations, respectively. This relative paucity of extratropical genesis environments is due to the focus on the hurricane season, which is reasonable given the observed high incidence of North Atlantic STC events (Guishard et al. 2009) during the hurricane season. This last-mentioned climatology highlights anew the predominance of both the subtropical (33%) and tropical (24.4%) environments, which is an indication that WNA STCs influence the climatological environmental features of North Atlantic STCs more than ENA STCs, although in this case E1 and E2 environments had a greater frequency with 23.4% and 19.3%, respectively. In contrast, STCs over the South Atlantic (SA) mostly originated in the E1 environment (88%) based upon the survey of Evans and Braun (2012), which indicates that ENA STCs resemble SA STCs more than WNA STCs.

As has been noted, the cyclones studied here differ from those originating within the WNA in their formation environments, and they are also a special case of North Atlantic STC. Indeed, the predominance of the

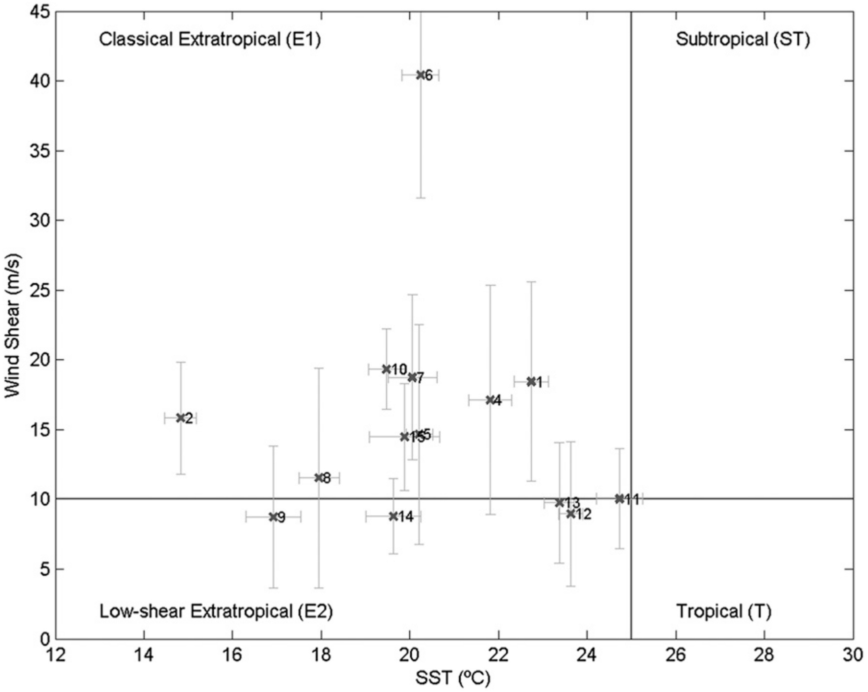


FIG. 6. Partition of the 14 STC cases based upon characteristics of their synoptic environment at genesis time (t_0). Number is associated with the name of the cyclone. Uncertainty bars indicate the standard deviation.

extratropical environment when ENA STCs form is the main reason why they are frequently confused with extratropical depressions. This disagreement is reasonable given the difference in the climatological environment between the two basins and may also suggest different environments in which an STC originates. Therefore, as was also noted in section 3, it can be deduced that ENA STCs are more similar to extratropical cyclones whereas WNA STCs are more similar to tropical cyclones. However, both types of STCs can have the same impact and even both can make a transition to a tropical cyclone in the same manner. For instance, STC4, STC12, and STC13 were ENA STCs that then evolved into tropical cyclones (Case 1990; Franklin 2006; Beven 2006), as happened in the case of Hurricanes Karen or Michael within the WNA (Evans and Guishard 2009).

The potential development of the eastern STCs in an unsuitable environment characterized by high wind shear and low SST may be explained by two fundamental reasons. On the one hand, as was noted with WNA STCs, convection might be forced either by development over warm SST or warm-air advection for ultimately inducing a hybrid STC structure. In this way, analyzing moist-air advection from the tropics when precursors of STC move southward might also provide some responses. On the other hand, genesis and maintenance of subtropical structures in a high shear environment may be due to shallow convection that accompanies these systems, as may also happen in tropical cyclones that form in environments with cool SST and high wind shear over the northeastern Atlantic Ocean. These types of tropical cyclones were studied by Mauk and Hobgood (2012). They found that the reduced depth of convection associated with tropical cyclones from nontropical precursors limits the effects of 850–200-hPa wind shear on those systems. This result would be supported by the higher sensitivity to the wind shear of tropical cyclones developing over high SSTs found by Nolan and Rappin (2008). Therefore, it is possible that the presence of low SSTs may reduce the sensitivity of tropical cyclones to wind shear by inducing shallower convection.

6. Synoptic classification of subtropical cyclogenesis

As already mentioned, one of the goals of this survey is to bring some operational assistance to forecasters. With this in mind, this section focuses on the aid consisting of identification and monitoring of atmospheric situations that are conducive to the development of STCs that can represent a threat for the countries of the eastern Atlantic coast. This objective is addressed by examining subjectively the 300-hPa geopotential height field at t_0 for the 15 cases so as to capture the main features of atmospheric patterns over the Atlantic Ocean basin when the identified STCs were forming. Based upon this analysis, one might argue that STCs formed within the ENA region tend to be developed according to one of the three idealized models shown in Fig. 7.

The cutoff/isolation model (Fig. 7a) idealizes the typical situation in which a depression embedded in the zonal flow cuts off from this. The circulation just to the north continues to be zonal and slightly undulated without great deformations although it tends to move to the north. Occasionally, the surface low is not originated by an upper cutoff depression but it may be formed by a trough that is not associated with the midlatitude circulation [a tropical upper tropospheric trough (TUTT)]. STC1, STC4, STC10, STC11, STC12, and STC14 are the cyclones fitting this first model.

The bifurcation model (Fig. 7b) whose main feature is a blocked pattern flow with the center of the ridge/high located in the vicinity of the British Isles. It resembles a Rex block, as was noted in WNA STCs. This pattern fosters the appearance of an extratropical jet becoming undulated. STCs form just to the southeast of the ridge. STC2, STC5, STC9, STC13, and STC15 are associated with this model.

The prolongation conceptual model (Fig. 7c) is associated with a highly meridional circulation as well, although in this case it is stimulated by a marked elongation northward of the subtropical ridge with its axis in a southwest–northeast orientation within the mid-Atlantic Ocean. There exists a depression (STC) just to the southeast of the subtropical ridge, which is a prolongation of a primary trough associated with the westerlies and located over central Europe. Occasionally, the subtropical ridge may be related to an omega blocked flow pattern. STC3, STC6, STC7, and STC8 fit this last model. This model is different from the cutoff/isolation model in that the midlatitude circulation seems to be highly disturbed with a great meridional movement mainly due to the displacement of the subtropical ridge toward the north.

The main common feature of the three described conceptual models is the notable departure from the climatological atmospheric circulation, as was remarked in section 4. This deviation is related to the fact that the westerly circulation is shifted poleward and/or is characterized by a large meridional component of the flow with even the possibility of the appearance of a blocked flow pattern. Therefore, the synoptic classification just described could also usefully complement the information on the composite anomalies, which can be explained by the deviations mentioned.

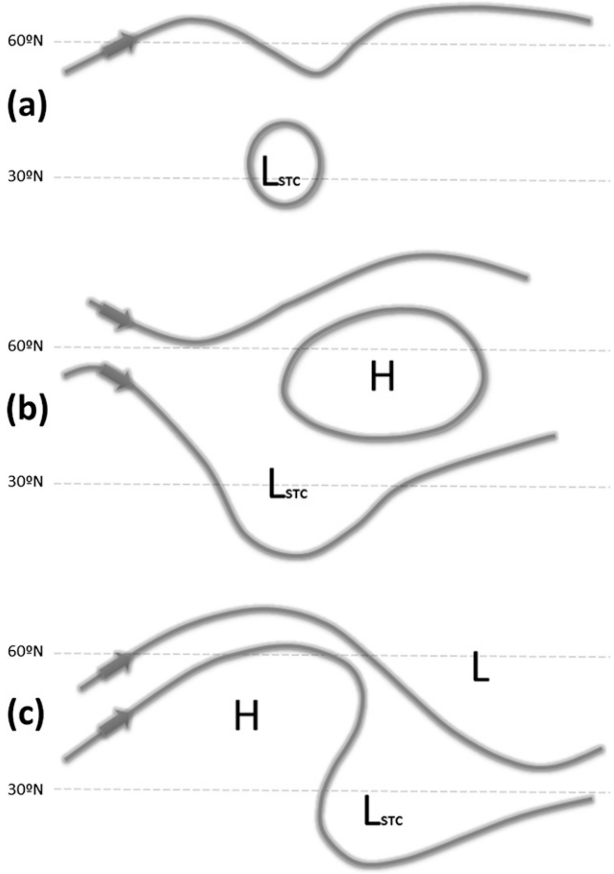
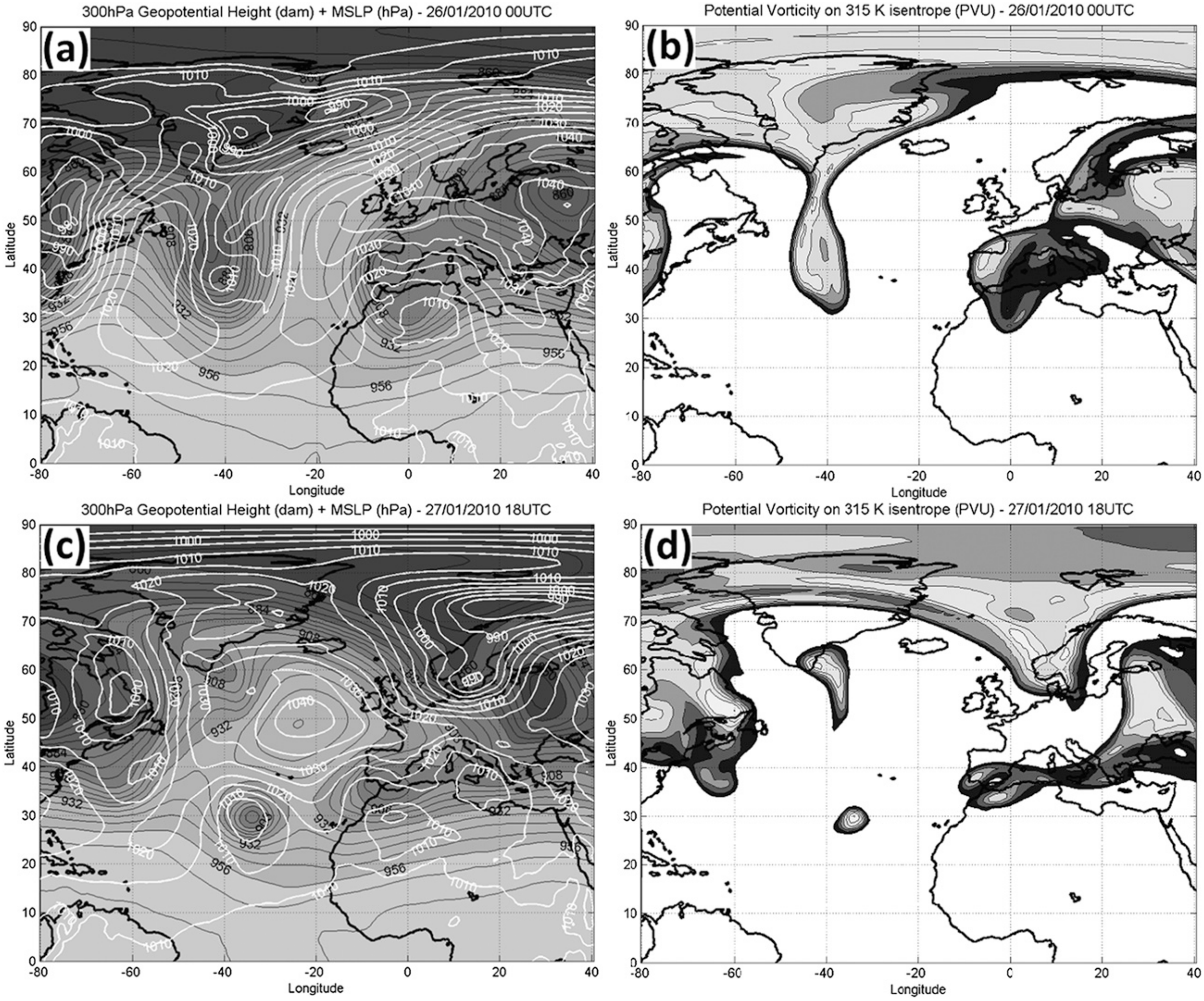


FIG. 7. Conceptual models of geopotential height at 300-hPa patterns at the formation of the cyclones (t_0): (a) cutoff/isolation, (b) bifurcation, and (c) prolongation. The arrows indicate the approximately sense of the flow at 300 hPa; H denotes a region of high pressure and L denotes a region of low pressure, where the subscript STC denotes the subtropical cyclone.

Results obtained in this section need to be complemented with more research in order to be of further help to forecasting community. For instance, one aspect of interest would be to perform some kind of evaluation of the frequency of these patterns. Another useful issue could be to analyze the probability of occurrence of formation of an STC when one of the model patterns is identified. This topic is hoped to be addressed by the authors in a future paper, in conjunction with the search of teleconnection patterns that might favor the appearance of STCs within the ENA.

7. Case study: Synoptic evolution of STC15

The synoptic history of the STC formed in 2010 (see Table 1) is described here in a way that can help to achieve a more detailed view of the results obtained in the previous sections. In addition, other characteristics



300hPa Geopotential Height (dam) + MSLP (hPa) - 26/01/2010 00UTC

Potential Vorticity on 315 K isentrope (PVU) - 26/01/2010 00UTC

300hPa Geopotential Height (dam) + MSLP (hPa) - 27/01/2010 18UTC

Potential Vorticity on 315 K isentrope (PVU) - 27/01/2010 18UTC

FIG. 8. Geopotential height (shaded and gray contours; dam) at 300 hPa and MSLP (white contours; hPa) at (a) 0000 UTC 26 Jan and (c) 1800 UTC 27 Jan 2010. Also shown is potential vorticity on the 315-K potential temperature surface (shaded) at (b) 0000 UTC 26 Jan and (d) 1800 UTC 27 Jan 2010. The grayscale color interval for (b) and (d) is 1 PVU starting at 2 PVU [1 potential vorticity unit (PVU) = 10^{-6} K kg^{-1} m^2 s^{-1}].

are detailed in order to justify the recognition of this system as subtropical and its inclusion in our database.

During 24 and 25 January 2010, the atmospheric circulation over the North Atlantic is characterized by a notable undulation in the geopotential field, associated with a Rossby wave that has both significant amplitude and wavelength. This wave favors the formation of a ridge over the eastern North Atlantic with its axis located just to the west of the Iberian Peninsula, and also favors the existence of a trough over the western North Atlantic, located to the north of Bermuda. The persistence of this trough over a baroclinic zone brings about the repeated formation of depressions downstream by QG forcing. By 26 January, the elongation of the ridge northward and the trough southward produce an omega blocked pattern flow as can be seen in Fig. 8a. By the next day, the resulting digging trough has formed a cutoff cyclone (Fig. 8c). Therefore, the surface low is now sustained by the upper positive PV anomaly inducing a cyclonic circulation that weakens toward the ground, aided by the weakly stable environment underneath (Hoskins et al. 1985). This described atmospheric pattern is consistent with the results obtained in section 4, with an upper-level ridge and its associated surface anticyclone to the west of the British Isles, and a region of low pressure just to the south of the ridge, which developed into STC15.

From a PV perspective, by the 26 January a cyclonic Rossby wave breaking (RWB) event [life cycle 2 (LC2); Thorncroft et al. 1993] can be identified to the northwest of Azores (Fig. 8b). There also exists an anticyclonic RWB [life cycle 1 (LC1)] just to the west of the cyclonic RWB. Both RWBs promote the break of the serpentine-shaped pattern and the isolation of relatively high potential vorticity values associated with the cutoff low mentioned above (Fig. 8d). At the same time, a RWB-type LC1 is occurring just to the north of Iberian Peninsula. All these wave-breaking events are associated with the omega blocked flow pattern referred to above. RWBs were found to have accompanied the formation of WNA STCs and events that suffered tropical transitions (Davis and Bosart 2003) as well. In fact, Evans and Guishard (2004) took this phenomenon into consideration when they proposed a potential vorticity mechanism for subtropical cyclogenesis and tropical transition.

Once the depression is cut off from the westerlies and diminishes its horizontal scale, the atmospheric pattern remains nearly stationary because of the blocked flow pattern, making the low pressure region persist isolated from the general circulation (i.e., detached from the main baroclinic zone). The surrounding environment then becomes more barotropic and the cyclone begins to occlude. This barotropic environment, in conjunction with the stationarity of the cyclone, provokes a decreasing in vertical wind shear from 28 $\mathrm{m\,s^{-1}}$ at 24 h prior to the formation of the STC to 4 $\mathrm{m\,s^{-1}}$ at 24 h afterward. However, the system formed in an environment type E1 with high wind shear (~14.5 $\mathrm{m\,s^{-1}}$), as seen in section 5, which is provided by a negatively tilted secondary upper-level trough located to the west of the cyclone. This seems to imply that the subtropical cyclogenesis was not caused by the decrease in vertical wind shear. In contrast, this cyclogenesis is likely to have caused the sharp wind shear weakening due to vertical distribution of PV as mentioned in section 4b, and the above described synoptic environment could have been involved in the subsequent STC maintenance.

Two days after the isolation of the precursor cyclone from the midlatitude circulation, a remarkable deepening of about 10 hPa takes place (not shown) once it experiences the transition to a subtropical stage. This deepening differs from the classical decay of extratropical cyclones at the end of their life cycles as the baroclinicity is removed and the cyclone fills. This feature also supports the results of storm-centered composites described in section 4b and implies that the cyclone is mostly governed by the PV positive anomaly created in the lower troposphere, which is caused by latent heat released by the significant convection originated around the center of the cyclone, as is shown below. In addition, a weakening of the ridge located to the east of the cyclone is evident from the temporal animation of the synoptic pattern (not shown), which, added to the positioning of this ridge just to the north of the cyclone as time approaches the moment t_0, is also in agreement with storm-center composites. Yet there is no strengthening of its associated surface high pressure after the subtropical cyclogenesis.

A fundamental feature of the atmospheric circulation over the North Atlantic during this episode is the persistence of the blocked flow, whose pattern is associated with the bifurcation conceptual model described in section 6. Furthermore, as Fig. 9 shows, as time approaches the moment of the subtropical cyclogenesis (t_0), the anomaly pattern over the North Atlantic tends to resemble the anomaly composite map (Fig. 3b) of section 4a, with positive anomalies around 60°N and negative anomalies around 30°N associated with the cyclone. This pattern shows the potential for a subtropical development 60 h prior to the formation of the STC. However, after the time t_0 there is not any strengthening of the upper and surface positive anomalies to the north of the cyclone anomaly (not shown), which is related to the abovementioned lack of reinforcement of the ridge and surface high pressure, thus being not supported by Figs. 5d–f described in section 4b either.

The series of satellite images (Fig. 10) reveals perfectly the transformation of the cloudiness pattern associated with the cyclone during its life cycle. Once the cyclone cuts off from the westerlies, it experiences the transition from a baroclinic environment to an increasingly barotropic state. This barotropic environment is related to the disappearance of the frontal structures. The depression has initially an asymmetric pattern (Fig. 10a) whose fronts then tend to disappear (Figs. 10b,c), with scattered convective cloudiness mostly created as a result of the thermal forcing of the upper troposphere cold core. The most eastern convective clouds are hypothesized to be generated by residual QG forcing. The decreasing of the wind shear, as noted above, down to 4 $\mathrm{m\,s^{-1}}$ about 24 h after starting the subtropical cyclogenesis, might have helped the formation of a formidable convective cell (Fig. 10c), resembling the typical convective cloudiness pattern of tropical cyclones. Nevertheless, this cyclone exhibits a relatively convection-free circulation center in comparison with the tropical cyclones, which often have deep and persistent convection at their centers. It is worth noting the similarity of the cloudiness pattern of this cyclone to that of the Tropical Storm Grace, which also originated in a nearly stationary occluding low near the Azores in early October 2009 (Mauk and Hobgood 2012).

The CPS (Hart 2003) is used here to complement the synoptic history and satellite images of the cyclone. ERA-Interim data were used to derive the CPS path through the life cycle of STC15 (Fig. 11). As can be deduced from Fig. 11a, the system began on 27 January with a cold anomaly at both low levels (900–600 hPa)

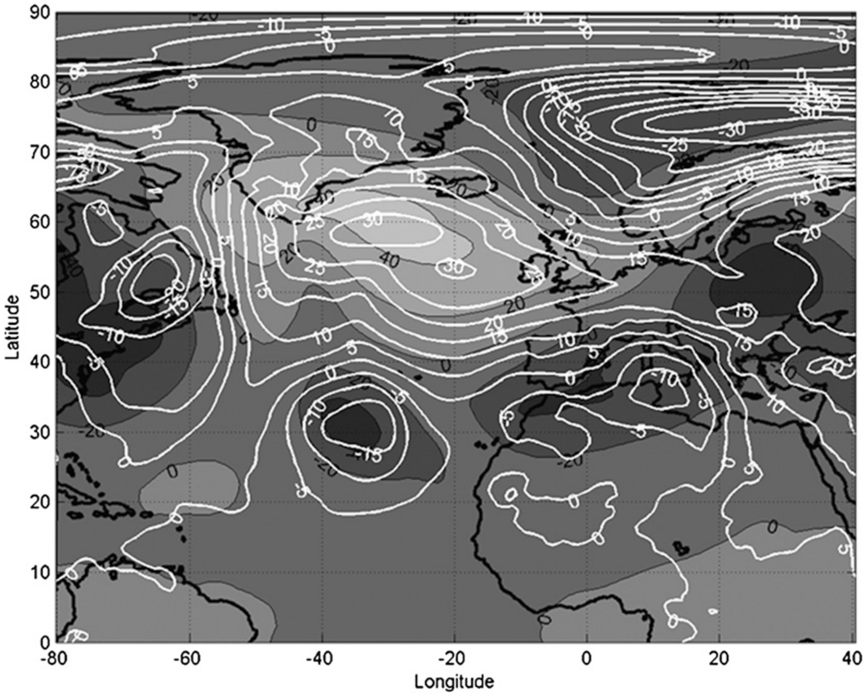


FIG. 9. Anomaly of geopotential height (shaded; dam) at 300 hPa and anomaly of MSLP (white contours; hPa) at 0600 UTC 27 Jan 2010.

and upper levels (600–300 hPa)—that is, with a deep cold core—and therefore it was a purely extratropical depression. By 1800 UTC 29 January, the storm had become a shallow warm-core system, consistent with a STC structure, and even by 30 January the system contained a moderate warm core when it started to have a warm thermal anomaly aloft for several hours, which is more consistent with the structure of a tropical cyclone. Thus, it is worth noting that despite the low SST values (~20°C), consistent with the season when it developed (winter), the storm almost suffered a complete tropical transition, which might have been favored by the stationarity and the decreased wind shear mentioned above. Later on, the system became extratropical again by 1200 UTC 31 January (after 36 h) and remained with a mix of hybrid and extratropical structure during the next four days. It is likely that real thermal anomalies were deeper than those shown here since the CPS based on GFS analysis (0.5°) and Climate Forecast System Reanalysis (CFSR; 0.5°) show a significant shallow warm core on 3 and 4 of February (see link in Fig. 11), which would suggest the need for a mesoscale study of these types of cyclones.

Based upon Fig. 11b, the system appears to have formed in a baroclinic environment ($B \sim 50$), consistent with an

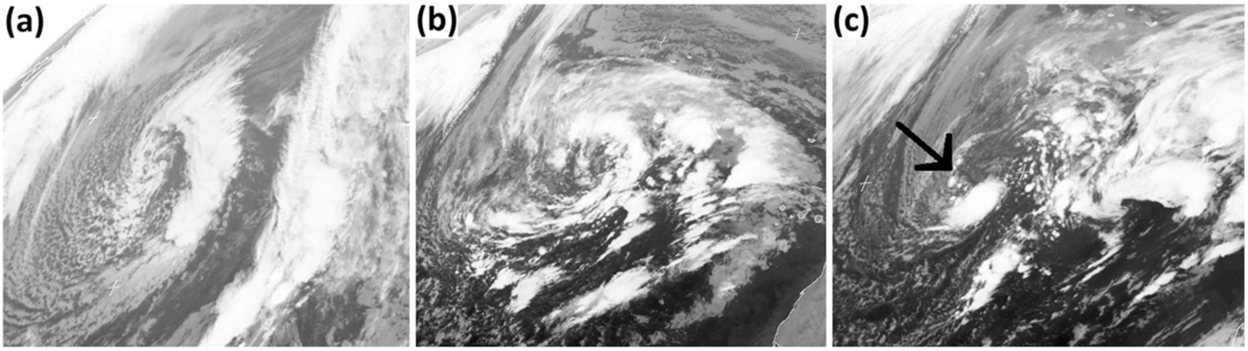


FIG. 10. Sequence of satellite imagery [channel 9 from *Meteosat Second Generation 2* (*MSG2* or *Meteosat-9*)] during the development of STC15 at (a) 1200 UTC 26 Jan, (b) 0600 UTC 30 Jan, and (c) 0000 UTC 31 Jan 2010. Source: EUMETSAT–Dundee Satellite Receiving Station (University of Dundee).

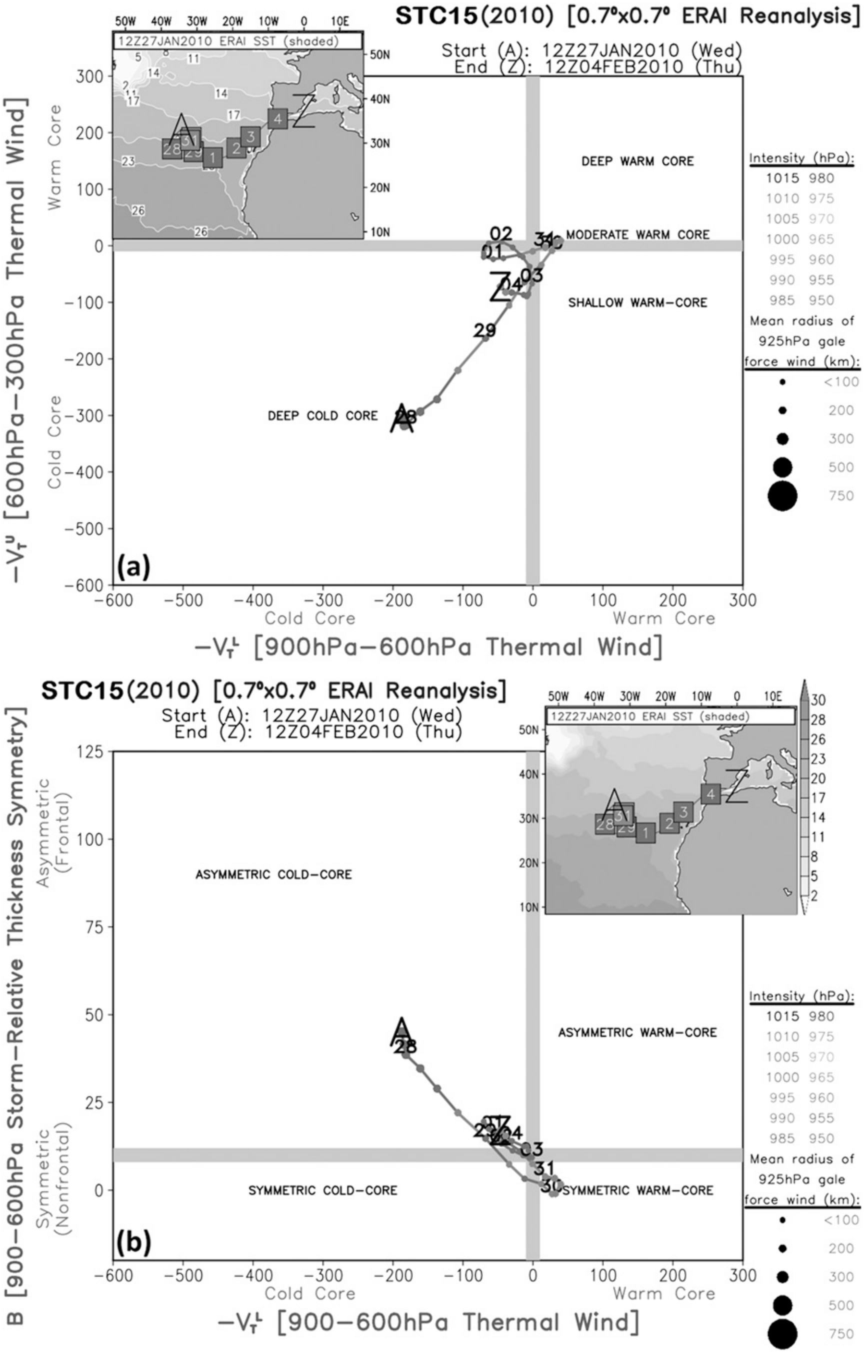


FIG. 11. ERA-Interim of STC15 plotted in the CPS: (a) V_T^L vs V_T^U and (b) V_T^L vs B. The A indicates the beginning of the plotted life cycle within the reanalysis and the Z indicates the end. A marker is placed every 6 h. The shading of each marker indicates cyclone MSLP intensity and the size of the circular marker indicates the relative size (mean radius) of the 925-hPa gale-force ($>17\,\mathrm{m\,s^{-1}}$) wind field. Positions at 0000 UTC are labeled with the day. (Available online at http://moe.met.fsu.edu/cyclonephase/archive/2010/gifs/juanje32010/).

extratropical structure, tending to occlude when moving toward a weak baroclinic environment ($B \sim 0$), which is in agreement with the satellite images shown in Fig. 10 and the isolation of the cyclone from the westerlies. By 30 January, the system already contained a symmetric (nonfrontal) warm-core cyclone and remained nearly symmetric up to the end of its life cycle based on the CPS. The mean radius of 925-hPa gale-force winds is also shown in Fig. 11, decreasing from <300 to <200 km by the end of the day 28, when the cyclone started to go directly toward a subtropical structure. This weakening was also perceived on day 31, involving a cyclonic structure with a radius around 100 km.

The CPS reinforces thus the idea of the subtropical behavior of the depression from a thermal point of view, which, added to the gale-force winds, matches the main features for a cyclone to be considered an STC based on the criteria (see section 2a) employed in ERA-40 climatology, as discussed in section 2c. Therefore, STC15 is a suitable candidate for being included in our study. It should be noted that despite the fact that the cyclone was in the tropical cyclone region in the CPS for several hours (i.e., $-|V_T^L| > -10$ and $-|V_T^U| > -10$), we decided that this is not a fundamental reason to exclude this system from the set of ENA STCs, given its transitional nature and observed genesis environment (González-Alemán et al. 2014). All the characteristics mentioned above together with the evolution toward a symmetric depression in the CPS are in agreement with the STC definition of NHC, which made it a suitable candidate for being monitored by the NHC.

8. Conclusions

By applying a set of criteria from two databases, a total of 15 STCs were identified to form during the period of 1979–2011 within the ENA and have been examined from a synoptic point of view, on a climatological basis, in this study.

October–March is their preferred season with 14 of these cases. Storm-centered composites (section 4b) depicted an extratropical cyclone as a precursor embedded in the westerly circulation that was undergoing a process of detachment and isolation from the midlatitude flow and gradually acquired the characteristics of an STC with an associated deepening, rather than a weakening as would be expected for a typical midlatitude depression after its evolution into a cutoff low. Another issue worth highlighting in these composites is the presence of a ridge intensifying just to the north of the cyclonic anomaly, which gives added strength to the idea that the cyclone becomes increasingly isolated.

The North Atlantic basin composite maps (section 4a) revealed a synoptic pattern different from the climatological counterpart, corresponding to a large region of positives anomalies to the north of the North Atlantic (~60°N) and a region of negative anomalies to the south (~30°N). The causes of this deviation were demonstrated, in section 6, to be due to a northward displacement of the westerly circulation and/or a large meridional component of the flow with even the possibility of appearance of a blocked flow pattern. These features were identified in the synoptic classification of subtropical cyclogenesis, in which the genesis-related synoptic patterns were separated into three conceptual models based on the geopotential height at 300 hPa (i.e., cutoff/isolation, bifurcation, and prolongation). In our opinion, this might be of special interest to forecasters of eastern Atlantic to anticipate the formation of an STC by only examining the atmospheric synoptic pattern.

The analysis of the environmental features that affected the cyclone at its formation phase was evaluated through SST and vertical wind shear, leading to the environmental classification in section 5. This analysis noted that ENA STCs seem to occur in a high wind shear ($>10\,\mathrm{m\,s^{-1}}$) and cold SST (<25°C) environment (E1), with 71.4% of the cyclones being developed in this state. The other 28.6% of the cyclones formed in the E2, characterized by lower wind shear ($\leq 10\,\mathrm{m\,s^{-1}}$). This causes ENA STCs to differ from their western counterparts (Evans and Guishard 2009) as regards their initial environments, making them a special case of North Atlantic STC (Guishard et al. 2009). ENA STCs have more similarities to extratropical cyclones while WNA STCs are more similar to tropical cyclones. However, ENA STCs tend to resemble SA STCs (Evans and Braun 2012) since substantial subsets of both types of STC form in the open ocean, in regions of much stronger shear and cooler SSTs than WNA STCs.

Finally, the above analysis was complemented with the study of the evolution of the cyclone originated in 2010 (STC15), which allowed us to interpret the general results more specifically. Consistent with results of section 4, STC15 was a typical extratropical cyclone in its early stage that detached from the midlatitude circulation and became a stationary cutoff low. It then underwent a transition from extratropical into subtropical cyclone in an atmospheric blocked pattern different from the climatology, leading to its inclusion in the bifurcation conceptual model of the synoptic classification undertaken in section 6. When becoming subtropical the system underwent a deepening, which matches reasonably well the storm-centered composites. The cyclone's path in the CPS was also described, showing a shallow warm core, and it even almost attained a completely tropical thermal structure, which represents the potential for a tropical cyclone genesis mechanism from a subtropical stage.

Certain questions have arisen, which motivates more research on ENA STCs. Apart from the basis for a future objective climatology of STCs within the ENA, which takes into consideration their special characteristics, the authors consider that this work opens up new lines of study in this subject in the selected spatial domain with the objective of answering the following main questions: Why are convection and warm core sustained in high wind shear and low SST environments? Is there any atmospheric pattern that most favors the subtropical cyclogenesis? Are STCs related to any teleconnection pattern? Is there any relation between them and global warming? And the crucial question: Which factors induce a subtropical structure in an extratropical depression that is isolated from the westerlies? Or in other words, what differences exist in the environment, when cyclones become isolated from the westerlies, between an extratropical cyclone that occludes and an extratropical one that becomes subtropical?

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Classification and Synoptic Analysis of Subtropical Cyclones within the Northeastern Atlantic Ocean

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Supplemental Material: Statistical significance analysis of Fig. 3b and 5 (d-f) in the manuscript.

As it can be deduced from Fig. 1 and 2 in this supplemental material, geopotential height and MSLP fields are distributed following a normal distribution approximately well during the period 1979-2012. Thus, the analysis of the statistical significance can be done by using the standard error.

Fig. 1 represents the correlation coefficients (r) at each point based on the correlation between the two vectors of the normal probability plot. In a normal probability plot, the data obtained (in this case, monthly means of geopotencial hegith and MSLP during 1979-2012) are plotted against a theoretical normal distribution in such a way that the points should form an approximate straight line. Departures from this straight line indicate departures from normality. Fig. 2 represents the differences in absolute value between the mean and the median of both fields.

It has been inferred that both geopotential height and MSLP field are distributed (in good approximation) following a normal distribution because all values of "r" are higher than 0.95. In addition, it can be seen that there is a notable overlap between the areas of relatively high difference of the mean and median values in Fig. 2, and the areas of relatively low values of "r" in Fig. 1, which indicates that these parameters are well related.

The confidence levels obtained by performing this statistical significance analysis are represented in Fig. 3, 4 and 5. The confidence levels indicate that, for instance, in the case of the 95% significance level, there is 95% of confidence that the "real" anomaly will have the same sign of the anomaly obtained with the sample of the 15 STCs studied herein.

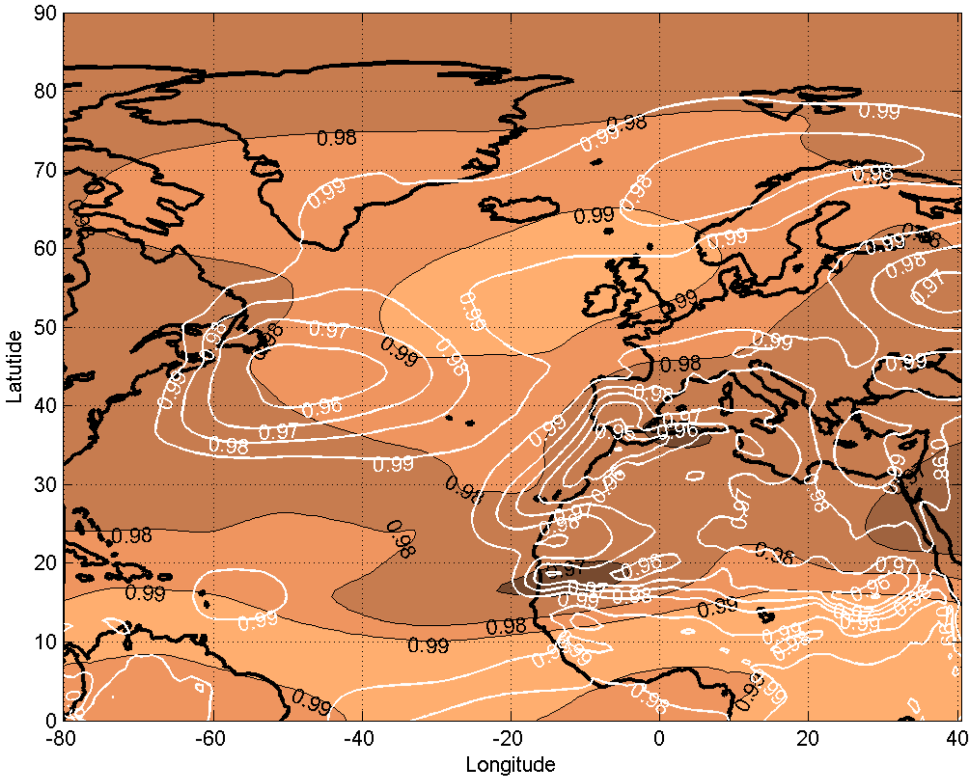

Fig. 1. Correlation coefficient "r" between the two vectors of a normal probability plot. Shaded for geopotential height and white contours for MSLP. Based on the period 1979-2012.

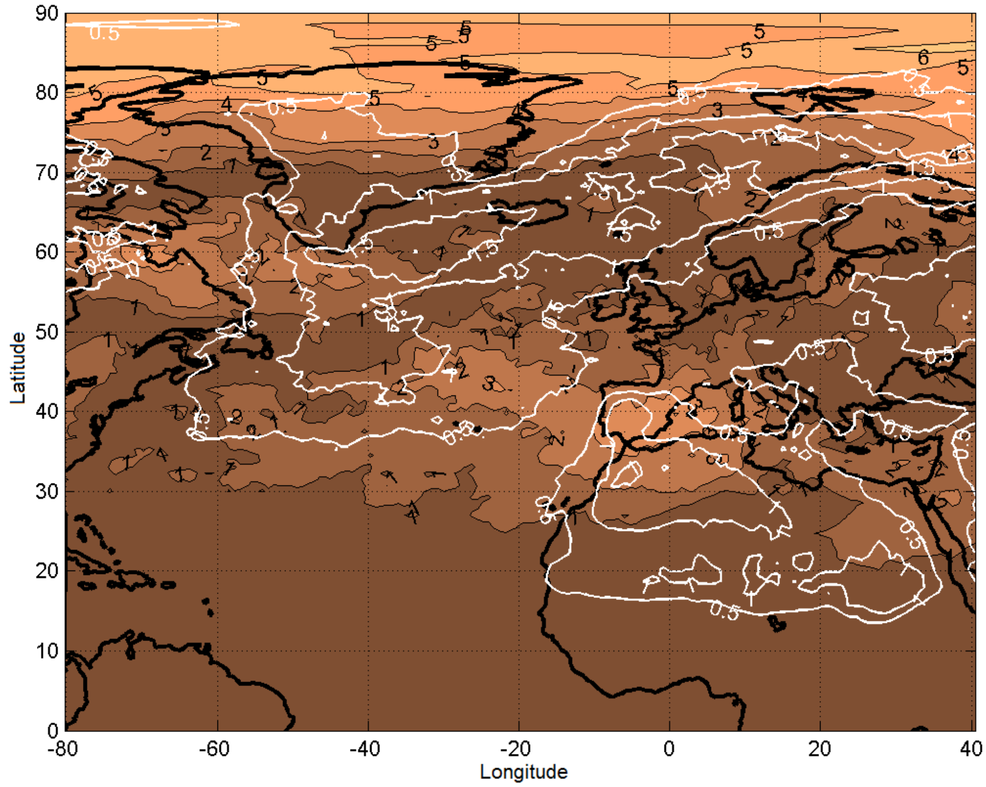

Fig. 2. Difference in absolute value between the median and the mean of the geopotential height (shaded; dam) and MSLP (white contours; hPa) based on the period 1979-2012.

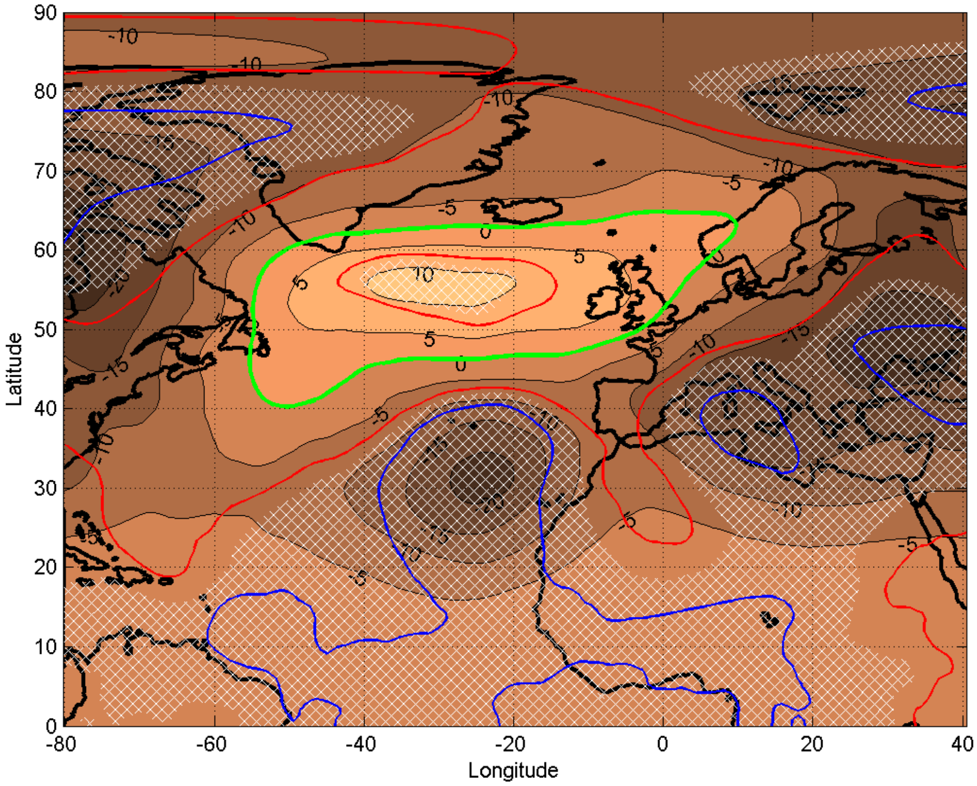

Fig. 3. Anomaly composite (all 15 STC) of 300 hPa geopotential height (shaded; dam) at t0 (00h). Also plotted are the confidence levels 90% (red contour), at 95% (cross shaded) and 99% (blue contour). The green contour is the zero anomaly isoline.

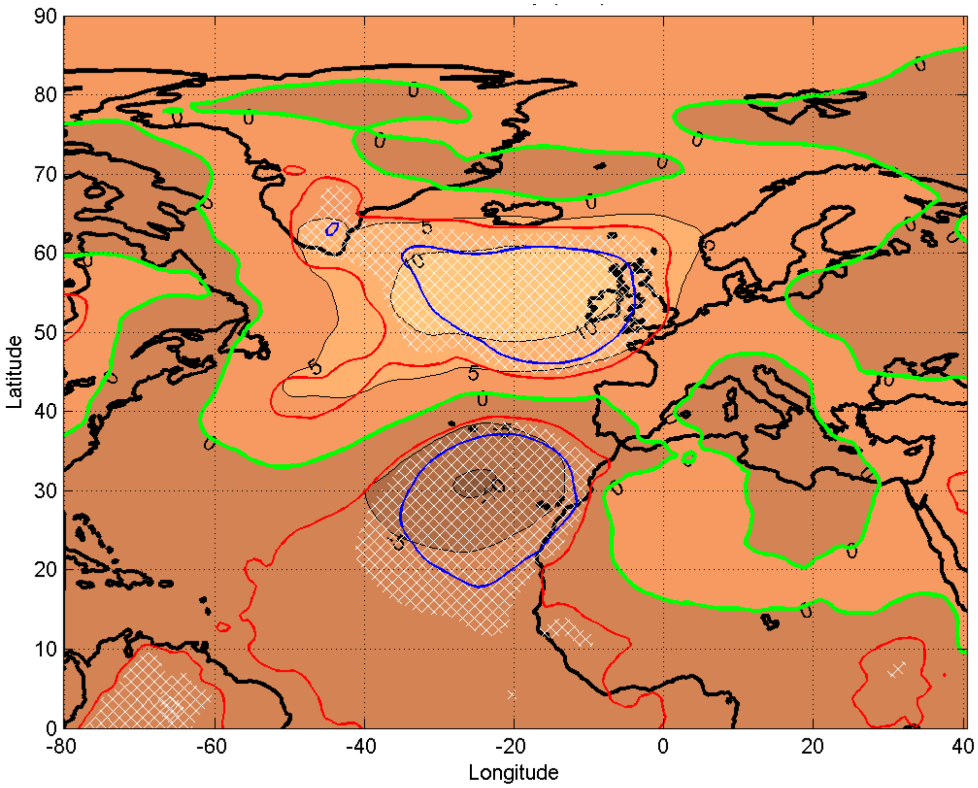

Fig. 4. Anomaly composite (all 15 STC) of MSLP (shaded; hPa) at t0(00h). Also plotted are the confidence levels at 90% (red contour), 95% (cross shaded) and 99% (blue contour). The green contour is the zero anomaly isoline.

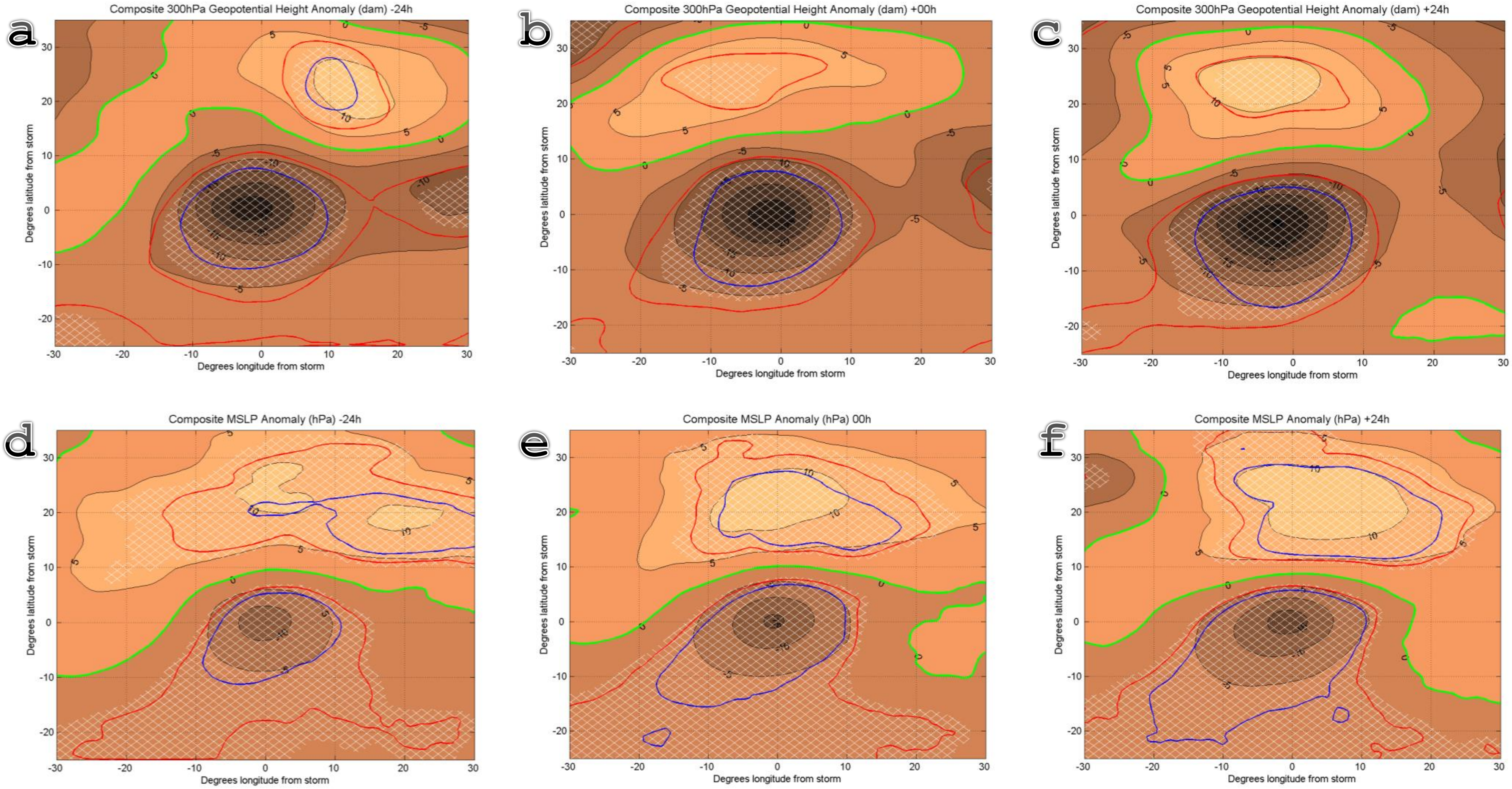

Fig. 5. Anomaly storm-centered composites (all 15 STC) of 300-hPa geopotential heights (shaded; dam) at times (a) t0 - 24 h, (b) t0, and (c) t0 + 24 h. Anomaly storm-centered composites (all 15 STC) of MSLP (shaded; hPa) at times (d) t0 - 24 h, (e) t0, and (f) t0 + 24 h. Also plotted are the confidence levels at 90% (red contour), 95% (cross shaded) and 99% (blue contour). The green contour is the zero anomaly isoline.

2. Simulation of medicanes over the Mediterranean Sea in a regional climate model ensemble: impact of ocean–atmosphere coupling and increased resolution

Abstract: Medicanes are cyclones over the Mediterranean Sea having a tropical-like structure but a rather small size, that can produce significant damage due to the combination of intense winds and heavy precipitation. Future climate projections, performed generally with individual atmospheric climate models, indicate that the intensity of the medicanes could increase under climate change conditions. The availability of large ensembles of high resolution and ocean–atmosphere coupled regional climate model (RCM) simulations, performed in MedCORDEX and EURO-CORDEX projects, represents an opportunity to improve the assessment of the impact of climate change on medicanes. As a first step towards such an improved assessment, we analyze the ability of the RCMs used in these projects to reproduce the observed characteristics of medicanes, and the impact of increased resolution and air-sea coupling on their simulation. In these storms, air-sea interaction plays a fundamental role in their formation and intensification, a different mechanism from that of extra-tropical cyclones, where the baroclinic instability mechanism prevails. An observational database, based on satellite images combined with high resolution simulations (Miglietta et al. in Geophys Res Lett 40:2400–2405, 2013), is used as a reference for evaluating the simulations. In general, the simulated medicanes do not coincide on a case-by-case basis with the observed medicanes. However, observed medicanes with a high intensity and relatively long duration of tropical characteristics are better replicated in simulations. The observed spatial distribution of medicanes is generally well simulated, while the monthly distribution reveals the difficulty of simulating the medicanes that first appear in September after the summer minimum in occurrence. Increasing the horizontal resolution has a systematic and generally positive impact on the frequency of simulated medicanes, while the general underestimation of their intensity is not corrected in most cases. The capacity of a few models to better simulate the medicane intensity suggests that the model formulation is more important than reducing the grid spacing alone. A negative intensity feedback is frequently the result of air-sea interaction for tropical cyclones in other basins. The introduction of air-sea coupling in the present simulations has an overall limited impact on medicane frequency and intensity, but it produces an interesting seasonal shift of the simulated medicanes from autumn to winter. This fact, together with the analysis of two contrasting particular cases, indicates that the negative feedback could be limited or even absent in certain situations. We suggest that the effects of air-sea interaction on medicanes may depend on the oceanic mixed layer depth, thus increasing the applicability of ocean–atmosphere coupled RCMs for climate change analysis of this kind of cyclones.

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Simulation of medicanes over the Mediterranean Sea in a regional climate model ensemble: impact of ocean–atmosphere coupling and increased resolution

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Abstract Medicanes are cyclones over the Mediterranean Sea having a tropical-like structure but a rather small size, that can produce significant damage due to the combination of intense winds and heavy precipitation. Future climate projections, performed generally with individual atmospheric climate models, indicate that the intensity of the medicanes could increase under climate change conditions. The availability of large ensembles of high resolution and ocean–atmosphere coupled regional climate model (RCM) simulations, performed in MedCORDEX and EURO-CORDEX projects, represents an opportunity to improve the assessment of the impact of climate change on medicanes. As a first step towards such an improved assessment, we analyze the ability of the RCMs used in these projects to reproduce the observed characteristics of medicanes, and the impact of increased resolution and air-sea coupling on their simulation. In these storms, air-sea interaction plays a fundamental role in their formation and intensification, a different mechanism from that of extra-tropical cyclones, where the baroclinic instability mechanism prevails. An observational database, based on satellite images combined with high resolution simulations (Miglietta et al. in Geophys Res Lett 40:2400–2405, 2013), is used as a reference for evaluating the simulations. In general, the simulated medicanes do not coincide on a case-by-case basis with the observed medicanes. However, observed medicanes with a high intensity and relatively long duration of tropical characteristics are better replicated in simulations. The observed spatial distribution of medicanes is generally well simulated, while the monthly distribution reveals the difficulty of simulating the medicanes that first appear in September after the summer minimum in occurrence. Increasing the horizontal resolution has a systematic and generally positive impact on the frequency of simulated medicanes, while the general underestimation of their intensity is not corrected in most cases. The capacity of a few models to better simulate the medicane intensity suggests

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This paper is a contribution to the special issue on Med-CORDEX, an international coordinated initiative dedicated to the multi-component regional climate modelling (atmosphere, ocean, land surface, river) of the Mediterranean under the umbrella of HyMeX, CORDEX, and Med-CLIVAR and coordinated by Samuel Somot, Paolo Ruti, Erika Coppola, Gianmaria Sannino, Bodo Ahrens, and Gabriel Jordà.

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3. Subtropical cyclones near-term projections from an ensemble of regional climate models over the northeastern Atlantic basin

Abstract: Since nearly a decade ago, hybrid cyclones called subtropical cyclones (STCs) have attracted the attention of scientific and forecasting community due to their identification as damaging weather systems. Research about them has been so far focused on present climate data. A study of STCs under future climate scenarios has not been performed yet. For the first time, in this work we analyse the capability of regional climate models (RCMs) to simulate STCs in addition to searching for possible alterations in their frequency and intensity due to anthropogenic climate change over the subtropical northeastern Atlantic basin. By using an ensemble of three RCMs nested in four different global climate models (GCMs), we find that RCMs acceptably reproduce STCs (except for certain model combinations) for the historical climate period (1951–2000), giving support for the analysis of future climate results. In pure GCM simulations, no STCs are identified. For future climate conditions under A1B, A2 and B1 scenarios (2001–2050), more simulations indicate a decrease in the frequency of STCs than those which find an increase. This decrease is showed to be partially due to a reduced presence of extratropical cyclones, from which they tend to form, within that region. However, no strong agreement between simulations has been obtained, and other factors like the changes in the conversion rate could affect STCs in the future. With respect to intensity, no clear tendency is found.

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Subtropical cyclones near-term projections from an ensemble of regional climate models over the northeastern Atlantic basin

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ABSTRACT: Since nearly a decade ago, hybrid cyclones called subtropical cyclones (STCs) have attracted the attention of scientific and forecasting community due to their identification as damaging weather systems. Research about them has been so far focused on present climate data. A study of STCs under future climate scenarios has not been performed yet. For the first time, in this work we analyse the capability of regional climate models (RCMs) to simulate STCs in addition to searching for possible alterations in their frequency and intensity due to anthropogenic climate change over the subtropical northeastern Atlantic basin. By using an ensemble of three RCMs nested in four different global climate models (GCMs), we find that RCMs acceptably reproduce STCs (except for certain model combinations) for the historical climate period (1951–2000), giving support for the analysis of future climate results. In pure GCM simulations, no STCs are identified. For future climate conditions under A1B, A2 and B1 scenarios (2001–2050), more simulations indicate a decrease in the frequency of STCs than those which find an increase. This decrease is showed to be partially due to a reduced presence of extratropical cyclones, from which they tend to form, within that region. However, no strong agreement between simulations has been obtained, and other factors like the changes in the conversion rate could affect STCs in the future. With respect to intensity, no clear tendency is found.

KEY WORDS regional climate modelling; subtropical cyclones; extratropical cyclones; convection; climate change

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1. Introduction

Subtropical cyclones (STCs) show characteristics of both tropical and extratropical cyclones. They are mainly characterized by having a hybrid thermal structure with cold upper-tropospheric and warm lower-tropospheric thermal anomalies with the absence of significant frontal systems. In recent years, scientific and forecasting community have begun to focus on STCs due to their recognition as damaging weather systems (Evans and Guishard, 2009) or their potential to transition into tropical cyclones (Davis and Bosart, 2003, 2004; Bentley *et al.,* 2016). In this sense, several studies on STCs have analysed present climate conditions, creating climatologies over the Atlantic (Guishard *et al.,* 2009; Evans and Braun, 2012; Gozzo *et al.,* 2014; González-Alemán *et al.,* 2015; Bentley *et al.,* 2016) or performing case studies (Evans and Guishard, 2009; Quitián-Hernández *et al.,* 2016). Apart from the Atlantic, they have also been studied in other regions such as the central Pacific (Otkin and Martin, 2004) or the Tasman Sea (Holland *et al.,* 1987; Browning and Goodwin, 2013).

As STCs have strong connections to the atmospheric dynamics in the extratropics and subtropics (they form from extratropical precursors; Evans and Guishard, 2009; González-Alemán *et al.,* 2015; Bentley *et al.,* 2017) and to the ocean in their lower boundary (through sea surface temperatures (SSTs) or warm-air advections) (Evans and Guishard, 2009; González-Alemán *et al.,* 2015), it is worth researching if anthropogenic climate change (ACC) could cause changes in their formation. Alterations in the atmospheric patterns over the extratropics and subtropics projected for future climate conditions (Thorne *et al.,* 2011; Francis and Vavrus, 2012, 2015) as well as alterations in SSTs distribution (Collins *et al.,* 2013) may lead to changes in their frequency of occurrence, location and/or intensity.

The present study aims at projecting the future evolution of STCs in ACC context over the northeastern Atlantic Ocean, partly as a continuation of the work done by González-Alemán *et al.* (2015), where STCs formed over this basin between 1979 and 2011 were classified and synoptically analysed. STCs strongly depend on mesoscale processes mainly due to the fundamental role played by convection in the formation and maintenance of their structure (Evans and Guishard, 2009; Bentley *et al.,* 2016). It is therefore important to use relatively high-resolution model simulations for their study.

For the first time, future projections of STCs are obtained herein. This is performed using an ensemble of regional climate models (RCMs) nested in various global climate models (GCMs). Given the typical size

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Table 1. Frequency (number per year) of STCs as simulated by RCMs nested in GCMs or ERA-Interim reanalysis in both evaluation periods, i.e., ERA-Interim (ERAIN) and GCM historical (20C3M) simulations, and also in future GCM emissions scenarios (A1B, B1, A2).

Simulation	ERAIN	20C3M	20C3M-Mean	OBS	A1B	A1B-Mean	B1	A2
PROMES	0.45		0.16	0.20		0.11↓		
ARPEG		0.00		“	0.04↑		0.02↑	
EC5R2		0.28		“	0.10↓		0.16↓	0.14↓
HDQ03		0.26		“	0.26–			
HDQ16		0.10		“	0.04↓			
MM5	0.10		0.09	0.20		0.07↓		
ARPEG		0.00		“	0.00–		0.00–	
EC5R2		0.06		“	0.12↑		0.04↓	0.06–
HDQ03		0.22		“	0.14↓			
HDQ16		0.06		“	0.02↓			
WRF	0.25		0.14	0.20		0.10↓		
EC5R2		0.14		“	0.10↓			0.06↓
Mean	0.27	0.12			0.09↓		–	–

Also presented is the frequency of observed STCs (OBS) from Guishard *et al.* (2009). Arrows indicate the tendency of the change of scenarios runs with respect to 20C3M run. Quotation marks indicate that the same value as in the previous line is applied.

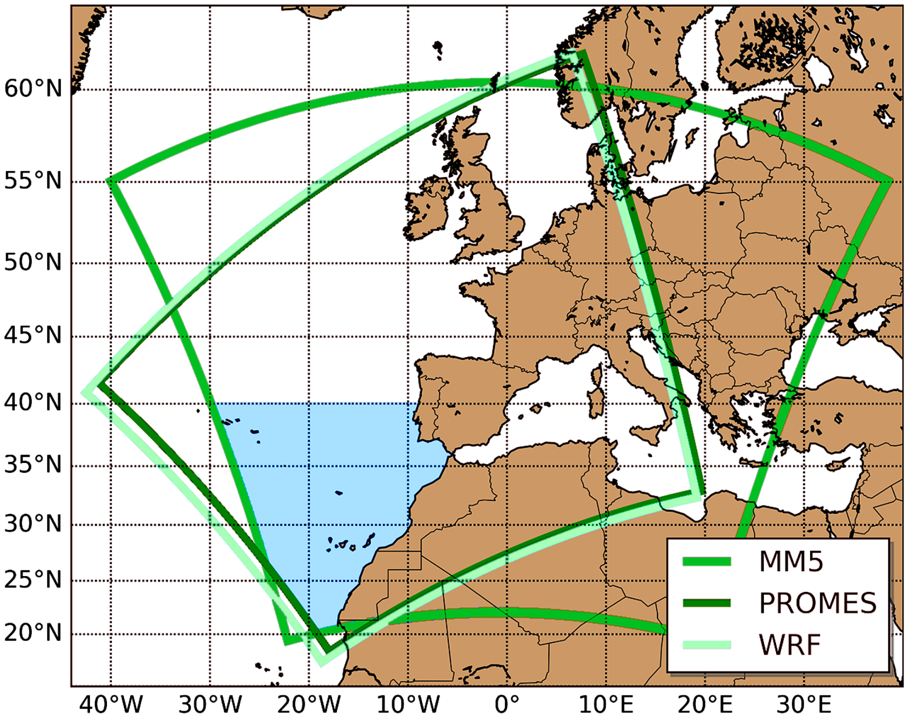
of STCs (≈300 km), RCMs (with a typical grid size of ≈25 km) are better suited than GCMs (with a typical grid size of ≈150 km). As RCMs have not been used to study STCs, another objective of this work is to evaluate their capability of simulating STCs. The climate simulated by a RCM is affected by uncertainties associated with a variety of sources such as internal variability, model formulations and imperfections in the boundary conditions. Those uncertainties can be explored by using multiple model simulations. For instance, the uncertainty related to imperfect model formulation can be addressed by running a multi-model ensemble. Simulated climate characteristics common to all the models in the ensemble are frequently considered more reliable. However, this reasoning is based on the independence of the errors between models, which may not be fully justified in some cases since differing models can have common building blocks (Knutti *et al.,* 2010).

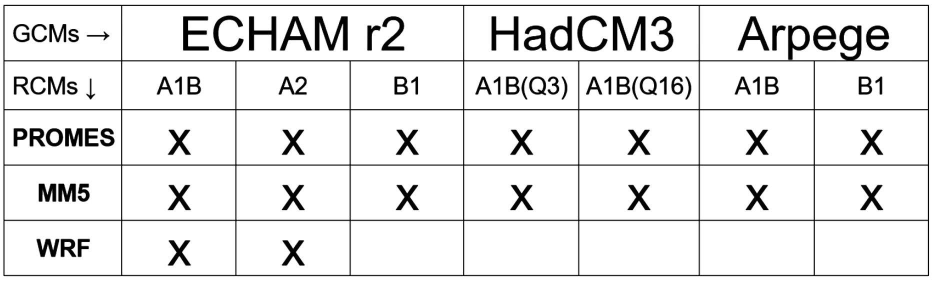
To assess RCMs' capability of simulating STCs, and give support and reliability to the STCs projection results, first an evaluation of the present climate simulations is needed. To this end, results from RCMs nested in ERA-Interim reanalysis (Dee *et al.*, 2011) (Section 3) as well as in GCMs in the historical period (Section 4) are examined. The first step will give us an idea of the ability of RCMs to simulate STCs with perfect lateral boundary forcing, whereas the second step will give us information about the influence of GCMs. In addition, the GCM simulations itself are analysed (Section 4) in order to examine the suitability of the method chosen (dynamical downscaling with RCMs) for studying STCs. Section 5 is dedicated to describing and analysing the projections of STCs and results are then discussed in Section 6. Conclusions are provided in Section 7.

2. Data and methodology

The data used in this work consist of model simulations taken from the ESCENA project (ESCENA is a Spanish acronym for 'scenarios'). The ESCENA project has been a Spanish initiative (2008–2012) which applied the dynamical downscaling technique to generate ACC projections based on an ensemble of RCMs. This ensemble is composed of the models PROMES (from the Spanish 'PROnóstico a MESoscala', Mesoscale Forecast), WRF (Weather Research and Forecasting) and MM5 (PSU/NCAR Mesoscale Model 5) over a domain covering the Iberian Peninsula, the Balearic and Canary Islands and northwestern Africa, at 25 km resolution (see Table 1 in Jiménez-Guerrero *et al.,* 2013 for more details on the RCMs). This project is somewhat comparable to the ENSEMBLES project (Van der Linden and Mitchell, 2009) or CORDEX (Giorgi and Gutowski, 2015), although ESCENA RCMs domains cover a significant part of the subtropical Atlantic Ocean, which is essential to study STCs. They reach southwest enough to capture some of the STCs which form over the northeastern Atlantic, mainly those which are more likely to threaten populated regions and represent higher societal impacts. Figure 1(a) shows the differing model domains, where the area in common is highlighted. The analysis of this study is done over this common region. Further information on the ESCENA project is available in Jiménez-Guerrero *et al.* (2013) and Domínguez *et al.* (2013). Figure 1(b) also contains information upon the different RCM/GCM combinations.

The GCMs used in ESCENA are ECHAM5-r2 (European Center HAMburg version 5), HadCM3 [Hadley Centre Coupled Model version 3; in two versions with different climate sensitivity: low sensitivity (HadCM3Q3) and high sensitivity (HadCM3Q16)] and ARPEGE-Climate version 3 (Action de Recherche Petite Echelle Grande Echelle, which means research project on small and large scales). The GCM-driven simulations cover both the present climate (historical simulations; 1951–2000) and future climate (scenario simulations; 2001–2050) period with different future greenhouse emission scenarios (A1B, B1, A2; IPCC, 2001). ERA-Interim driven simulations





GCMs →	ECHAM r2			HadCM3		Arpege	
RCMs ↓	A1B	A2	B1	A1B(Q3)	A1B(Q16)	A1B	B1
PROMES	X	X	X	X	X	X	X
MM5	X	X	X	X	X	X	X
WRF	X	X					

Figure 1. RCM's domain of the simulations (a) and model combinations from the ESCENA project (b). X in the table indicates the model combinations available in ESCENA. For HadCM3 GCM, two realizations were included; 'low' climate sensitivity (Q3) and 'high' climate sensitivity (Q16) to the external forcing. [Colour figure can be viewed at wileyonlinelibrary.com].

(evaluation period; 1989–2008) and historical simulations are compared in a statistical way to climatology of STCs (Guishard *et al.,* 2009), as in this case the specific time evolution of the GCM simulations differ from the actual one.

STCs are detected following two steps. First, the cyclone detection and tracking method described by Picornell *et al.* (2001) is applied. This method was created to study mesoscale cyclones in the Mediterranean Sea and has also been used to study medicanes (MEDIterranean hurriCANES; Gaertner *et al.,* 2007, Romera *et al.,* 2016, Gaertner *et al.,* 2016). Medicanes are cyclones which occasionally form over the Mediterranean Sea and bear tropical characteristics during part of their lifetime. They have a similar environment of formation as STCs, i.e. they both mostly form from cut-off lows in the upper troposphere or from quasi-stationary extratropical cyclones (Tous and Romero, 2013; González-Alemán *et al.,* 2015). Therefore, this algorithm is also suitable for STCs. In this algorithm, 6-hourly mean sea level pressure (MSLP) fields are analysed to identify the pressure minima after applying a Cressman filter with a radius of 200 km (Sinclair, 1997) to smooth out noisy features appearing in the MSLP field and small cyclonic structures. Due to the proximity of the RCM lateral boundaries to the area of interest, a 400-km distance threshold from the MSLP minima to the boundaries is used. Furthermore, weak cyclones are filtered out through a pressure gradient threshold (0.5 hPa/100 km). The cyclone tracks are then obtained using the horizontal wind at 700 hPa as steering wind to calculate the movement of cyclones.

Second, the cyclone phase space (CPS) from Hart (2003) is applied to select hybrid cyclones (STCs) among all the detected cyclones, following Guishard *et al.* (2009). The CPS serves to depict cyclone structure three-dimensionally by thermodynamically classifying cyclones with respect to their horizontal symmetry (B: thermal symmetry parameter) and vertical thermal structure (−VTL, −VTU: thermal wind parameters) (Hart, 2003). The CPS thermal symmetry parameter is denoted by B and is evaluated via:

$$B = \left[\left(Z_{600hPa} - Z_{900hPa}\right)_R - \left(Z_{600hPa} - Z_{900hPa}\right)_L\right]$$

where, Z is isobaric height, R indicates right of current storm motion, L indicates left of storm motion, and the overbar indicates the areal mean over a semicircle of the considered radius. Thermal wind parameters are evaluated over layers in the lower (L; 900–600 hPa) and upper (U; 600–300 hPa) troposphere as follows:

$$-\left|V_T^L\right| = \left.\frac{\partial (Z)}{\partial lnp}\right|_{900hPa}^{600hPa}$$

$$-\left|V_T^U\right| = \left.\frac{\partial (Z)}{\partial lnp}\right|_{600hPa}^{300hPa}$$

where, Z is the cyclone height perturbation and it is evaluated within the same radius as in B.

A cyclone is first identified as STCs if attains gale-force winds (17.0 $\mathrm{m\,s^{-1}}$) at a certain point and exhibits hybrid structure in the CPS ($-\mathrm{VTL} > -10$ and $-\mathrm{VTU} < -10$) for at least 36 consecutive hours. No adjustment of the wind-speed threshold due to the model resolution has been made, as for a gridpoint distance of 25 km the maximum wind near the MSLP centre should be captured with almost no reduction due to sampling, following the results of Walsh *et al.* (2007). In addition, Guishard *et al.* (2009) discarded cyclones that are of ambiguous nature or that may also have similar hybrid characteristics but extratropical [e.g. warm seclusions (Shapiro and Keyser, 1990)], by applying a regional restriction; only storms attaining gale-force winds within the 20°–40°N latitude band and over the sea are considered. Finally, to continue being consistent with Guishard *et al.* (2009), a last criterion is imposed to filter cyclones achieving hybrid structure in the CPS within the first 24 h.

Due to the limited domain of the simulations over the ocean, a decrease in the radius used in the CPS is needed to include as many STCs as possible. Hart (2003) applied a radius of 500 km, which is not adequate for this study. Therefore, an evaluation of the radius has been performed to reduce radius without losing relevant information. We have found that a 300 km radius does not alter the CPS parameters once the cyclones attain a subtropical structure. This has been therefore the radius used herein. This could occur because STCs have a vertically stacked structure (Evans and Guishard, 2009; González-Alemán *et al.,* 2015), unlike extratropical cyclones, and it is thus almost the same to evaluate their structure with a radius of 300 km than with a radius of 500 km.

3. RCMs nested in ERA-interim reanalysis (1989–2008)

To first inspect the capability of the RCMs to properly represent complex atmospheric phenomena like STCs, their frequency (number of cyclones per year) in the RCM simulations nested in ERA-Interim reanalysis have been calculated in the common domain. As STCs mostly form in winter (see Section 4), the analysis has been done only considering those STCs formed between October and April. This is also suitable for comparing STCs to their extratropical precursors, as they are less likely to trigger the formation of STCs during summer (González-Alemán *et al.,* 2015).

Results show (second column of Table 1) a certain disparity among the models. PROMES simulates a high frequency (0.45 per year) of STCs, which double the observed frequency (0.20 per year; fifth column of Table 1; see Section 4). On the other hand, MM5 simulates half (0.10 per year) of the observed frequency. WRF is the model closest (0.25 per year) to the observed values. Furthermore, certain observed STCs from González-Alemán *et al.* (2015) have been selected to determine if RCMs are effectively able to capture their hybrid structure. In 1989–2008, four STCs identified in that work have part of their tracks over the region common to all simulations used herein. For simplicity, only one cyclone is showed since the rest of the cyclones have a similar behaviour and the same conclusions can be derived from them. The cyclone named STC5 in that work has been chosen because this cyclone spends most of its lifecycle having subtropical structure within the model's domain.

According to Figure 2, this storm was regarded as STC at certain stages of its lifecycle, depending on the model, when the above-mentioned thermal structure criterion of Guishard *et al.* (2009) is met. Among the models, MM5 is the one with the less intense subtropical structure representation (maximun of $-\mathrm{VTL} \approx 20$), and PROMES the one with the deepest ($-\mathrm{VTL} \approx 50$). In any case, it can be inferred that all RCMs are able to capture the hybrid structure of this cyclone. The rest of the observed STCs are simulated by the RCMs as hybrid cyclones but with some discrepancies in the intensity of the lower tropospheric warm core (not shown). The discrepancy between models is likely not only due to their distinct dynamical core and parametrizations, but also because of the domain differences (Figure 1). This spread of RCMs in the simulation of STCs make the use of model ensembles preferable over single model studies and allows to describe uncertainties due to model differences.

The CPS evolution directly obtained from ERA-Interim reanalysis is also included in Figure 2 as an approximation to the observed structure, but the low horizontal resolution of this reanalysis (about 80 km) will likely cause an underestimation of the intensity of the lower-tropospheric warm core. For instance, STC5 is represented only with a very shallow hybrid structure ($-\mathrm{VTL} \approx 0$) in the reanalysis (Figure 2(d)), while STCs simulated by RCMs have a deeper hybrid structure (higher values of $-\mathrm{VTL}$).

4. RCMs nested in GCMs in the historical period (1951–2000)

Results for the historical period of RCMs nested in the GCMs are compared herein with the 45-years climatology of STCs over the North Atlantic (Guishard *et al.,* 2009). They conducted a study using ERA-40 reanalysis (Uppala *et al.,* 2005) with 1.125° resolution for the period of September 1957 to August 2002, where they obtained

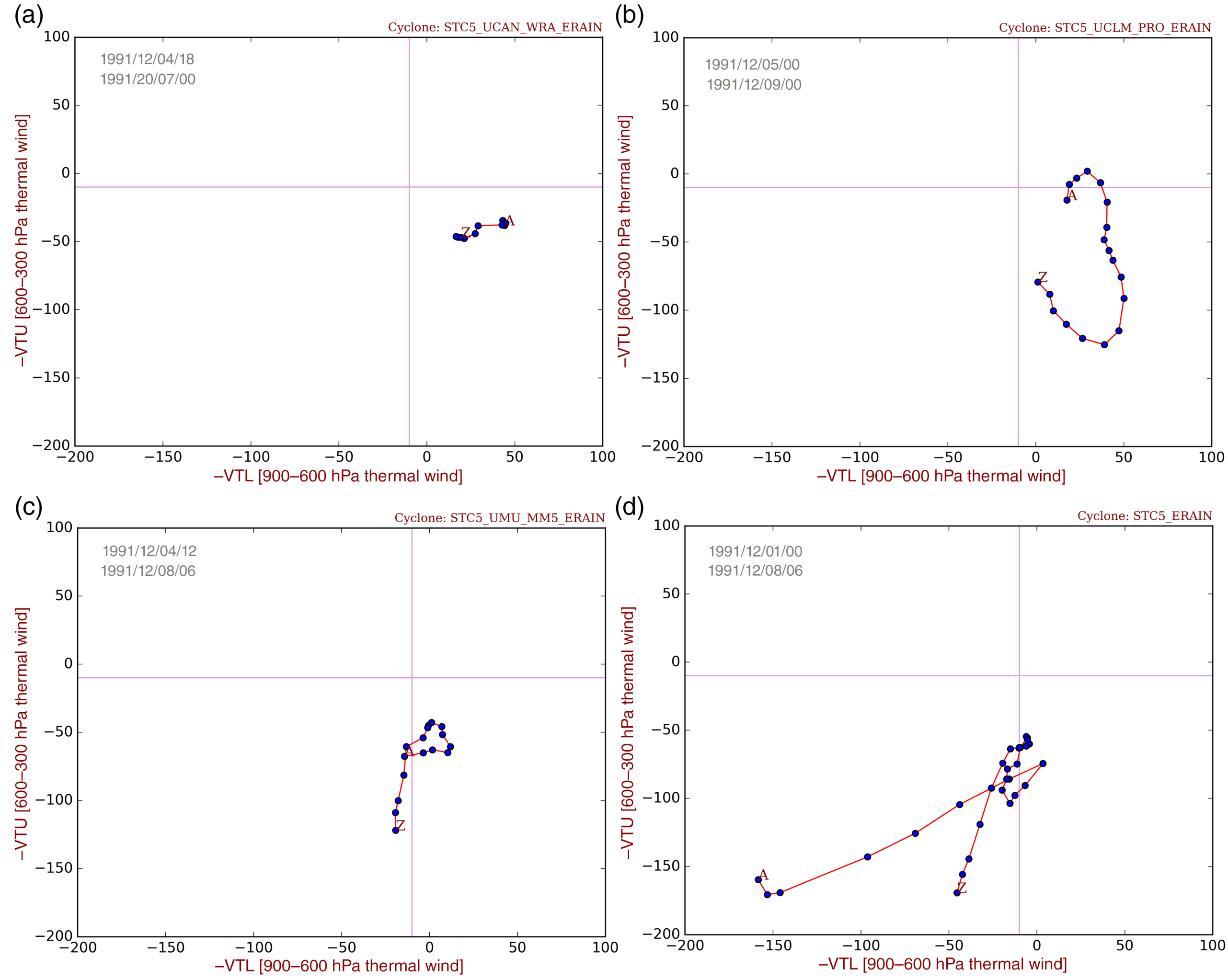


Figure 2. Cyclone phase space representation, as simulated by the RCMs (a: WRF, b: PROMES, c: MM5) nested in ERA-Interim reanalysis and (d) pure ERA-Interim reanalysis, of STC5 from González-Alemán *et al.* (2015). The A indicates the beginning of the plotted life cycle and the Z indicates the end, where each date (yyyy/mm/dd/hh) is indicated at the upper left quadrant (A and Z correspond to different dates in each simulation). A marker is placed every 6 h. The lower right quadrant is where the cyclones have hybrid structure like STCs. [Colour figure can be viewed at wileyonlinelibrary.com].

a total of 197 STCs in the entire North Atlantic. In the domain analysed in this study (i.e. the region common to all RCMs), a total of nine STCs were obtained from that climatology, which means a frequency of 0.20 STCs per year (fifth column of Table 1).

Results obtained are shown in the third column of Table 1. A disparity in the number of modelled STCs is anew observed. There are differences both related to GCMs and RCMs. Both ARPEGE-GCM forced RCM simulations do not capture any STC, while PROMES-EC5R2 is the model combination with the highest frequency of STCs (0.28 per year). In comparison to the observed number of STCs (0.20 per year; Guishard *et al.,* 2009), MM5-HDQ03 (0.22 per year), WRA-EC5R2 (0.14 per year), and PROMES-HDQ03 (0.26 per year) are the model combinations closest to it, which makes them the most reliable ones. As this study has the advantage of using an ensemble of models, it is worth considering the ensemble mean. 0.12 cyclones per year is the mean frequency of simulated STCs based on all simulations, which is a relatively low compared to 0.20 (the observed frequency). Nevertheless, due to the relatively high discrepancy between models, this mean should be taken with caution. Indeed, this low value of the mean is partly caused by the absence of STCs in ARPEGE-GCM-forced simulations; without these simulations, the mean is 0.16, closer to the observed value.

The noteworthy fact that ARPEGE-GCM differs substantially (0 STCs per year in both RCMs) from the other GCMs can be explained by analysing the number of overall cyclones which pass through the study region. This is consistent with the idea of STCs forming from extratropical precursors (González-Alemán *et al.,* 2015). For a cyclone to be considered in this count of overall cyclones, it must be tracked (without considering the CPS parameters) acquiring gale force (17 m s^{-1}) wind and spending at least 36 h over the same domain used in the analysis of STCs. In this case, CPS is not applied, i.e. also extratropical cyclones are included, but there is possibility of STCs not being included in the overall cyclones, such as those STCs being

Table 2. As Table 1, but for overall cyclones (without considering the CPS parameters).

Simulation	ERAIN	20C3M	20C3M-Mean	A1B	A1B-Mean	B1	A2
PROMES	1.65		1.06		0.98↓		
ARPEG		0.30		0.34↑		0.18↓	
EC5R2		1.30		0.98↓		1.16↓	0.48↓
HDQ03		1.58		1.76↑			
HDQ16		1.04		0.82↓			
MM5	0.85		0.64		0.53↓		
ARPEG		0.10		0.00↓		0.14↑	
EC5R2		1.10		0.72↓		0.94↓	0.50↓
HDQ03		0.94		0.90↓			
HDQ16		0.42		0.50↑			
WRF	0.55		0.70		0.58↓		
EC5R2		0.70		0.58↓			0.26↓
Mean	1.01	0.83		0.73↓		–	–

less than 36 h over the domain. Only those cyclones forming from October to April are considered, for consistency with the analysis of STCs.

As can be seen in Table 2, a strong reduction in the number of overall (mainly extratropical) cyclones is obtained for ARPEGE GCM (0.10 for MM5-ARPEGE and 0.30 for PROMES-ARPEGE) compared to the rest of the GCMs. Therefore, the lack of STCs identified in ARPEGE-GCM-forced RCM simulations is associated with the lower frequency of overall cyclones over the analysed domain in ARPEGE-GCM simulations. Similarly, those simulations which identify more STCs in the historical period are associated with those with a higher number of overall cyclones. For instance, the PROMES-RCM simulations with the highest number of identified STCs (0.28 for PROMES-EC5R2 and 0.26 for PROMES-HDQ03) also show the highest frequency of overall cyclones (1.30 and 1.58, respectively). The same reasoning can be applied to ERA-Interim forced simulations (Section 3) in PROMES RCM, where the highest frequency of STCs (0.45 per year) identified is accompanied by the highest frequency of overall cyclones (1.65). The general relationship between STCs and overall cyclones may be better established by computing their correlation coefficient based on all the 28 simulations presented in Figure 3(a). Recall that Figure 3(a) comprises of the same information as in Tables 1 and 2. A high correlation ($r = 0.78$) is obtained, statistically significant above the 99.9% confidence level (Student's t-test), which indicates that STCs are linked to overall cyclones over the region of study.

However, there are other factors influencing the differences in identified STCs. As Figure 3(a) shows, the conversion rate (red; STCs per overall cyclones) is not equal in all the simulations in the present period (ERAIN and 20C3M). Large differences are found for this conversion rate, with values ranging from 0 (for simulations nested in ARPEGE) to 0.45 (WRF nested in ERA-Interim). But, if we do not take into account runs driven by ARPEGE (as they simulate very few overall cyclones) and by ERA-Interim (as the simulation period is rather short and may increase the differences just due to small-sample effects), the range is much smaller, from 0.05 to 0.23. The reasons for these differences in the conversion rate seem to be related both to the RCMs and to the GCMs characteristics; the range of values is similarly high for a single RCM nested in different GCMs (e.g. MM5 shows values between 0 and 0.23) than for different RCMs nested in the same GCM (e.g. the three simulations nested in EC5R2 show values between 0.05 and 0.21). A fact worth mentioning is the important differences obtained in PROMES and MM5 nested in EC5R2 GCM, which indicates that the RCMs' characteristics could be more important than GCMs characteristics. This justifies the use of an ensemble of RCMs nested in different GCMs when simulating STCs. In summary, when a simulation detects a relatively very high (low) number of STCs, a higher (lower) presence of overall cyclones is found to be associated, and thus both being related. When this value is not too high or low, the conversion rate then becomes more important and the model characteristics themselves (mainly the convection schemes; Romera *et al.,* 2015) as a result to affect the frequency of STCs.

To examine the suitability of using the dynamical downscaling to study STCs and put in context the previous results, pure GCM simulations were also analysed. The GCM EC5R2 was selected because it has been used in more RCM simulations. In this case, the wind threshold has been lowered to 13 m s^{-1} (following Walsh *et al.,* 2007) in order to take into account the effects of the lower horizontal resolution (2.5° in this case). No STC was identified during 1951–2000, which clearly differs from the results obtained when downscaling is applied (PROMES: 0.28; MM5: 0.06 and WRF: 0.14 cyclones per year). Therefore, the added value from dynamical downscaling when studying STCs is clear. Among other factors like poor CPS representation (Hart, 2003), a likely reason is the poorer representation of convection in coarser resolution models, as STCs are highly dependent on moist and convective processes (Evans and Guishard, 2009).

To complement the analysis in the historical period, the monthly distribution of the simulated STCs is also compared to observations (Figure 3(b)). Observed STCs from Guishard *et al.* (2009) mostly formed during winter, which

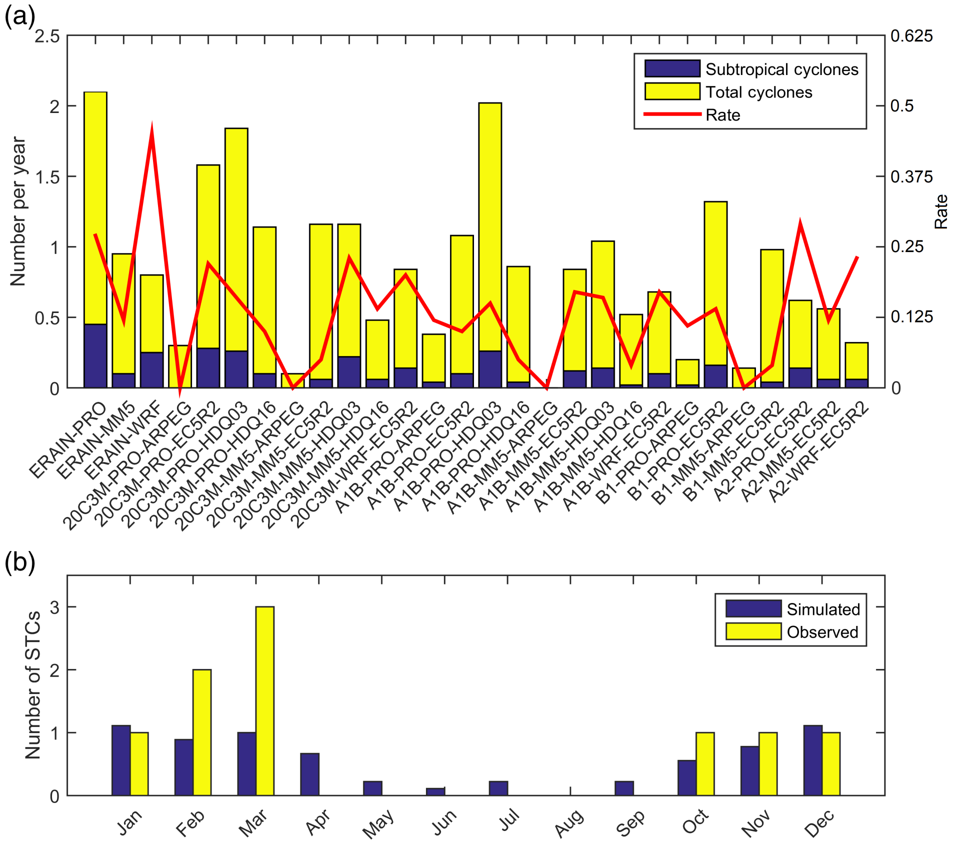


Figure 3. (a) Number of STCs and overall cyclones per year obtained in ESCENA simulations. Also depicted is the rate (red; STCs with respect to total cyclones). (b) Monthly distribution of the STCs obtained (RCM mean) and those obtained by Guishard *et al.* (2009). [Colour figure can be viewed at wileyonlinelibrary.com].

is also consistent with González-Alemán *et al.* (2015). In case of the RCM-modelled STCs, the distribution is similar to the observed values, as there is a distinct prevalence of STCs over winter months, although the observed March peak is not reproduced in the simulations. The higher prevalence in winter months gives support to the fact that the simulated STCs mainly develop from extratropical precursors, a relationship shown in observational studies (González-Alemán *et al.,* 2015, Evans and Guishard, 2009, Guishard *et al.,* 2009, Bentley *et al.,* 2016, 2017). Extratropical precursors such as upper-level troughs and cut-off lows are more likely to reach the subtropical domain in winter as the southern edge of the upper-level midlatitude circulation is located at its southernmost position. Another factor is that upper-level lows tend to be too weak during summer season to provoke a reduction in the static stability that can trigger deep convection to ultimately facilitate the formation of a STC (González-Alemán *et al.,* 2015).

5. Future climate RCMs projections (2001–2050)

With reference to future climate projections, the results obtained show a reduction (not statistically significant at the 95% confidence level with the two-sample *t*-test) in the ensemble mean frequency of STCs for scenario A1B (Table 1; sixth column, bottom row). The other scenarios are not compared in terms of their ensemble mean as the number of runs is much lower. There exist anew discrepancies among simulations, with a majority (9 of 16) of simulations showing a decrease, 4 simulations showing no change and 3 showing an increase. It is worth noting that a considerable amount (four of seven) of the simulations showing no decrease are those driven by ARPEGE GCM, which were found to be unreliable in the historic period as no STC was identified. Both WRA-EC5R2 and MM5-HDQ03, which performed rather well in the historical period, show a decrease in the number of STCs in the future, being more important in the latter (~26% and 36% of the present climate, respectively).

As for the future evolution of STCs, Figure 4(a) shows the number of STCs every two decades. A slight decreasing mean trend can be seen. Note the different behaviour of PROMES-HDQ03, showing a large decadal variability and no clear decreasing tendency, consistent with results shown in Table 1. The lower number of STCs in future climate projections with respect to the historical period is associated with generally less spread in the latter period (without considering PROMES-HDQ03). If a linear regression is applied, differences among models are also obtained. Among the simulations (four) where the linear trend is statistically significant (at the 95% level from the *p*-value of a least-squares regression), there is a predominance (three) of negative slopes, which correspond

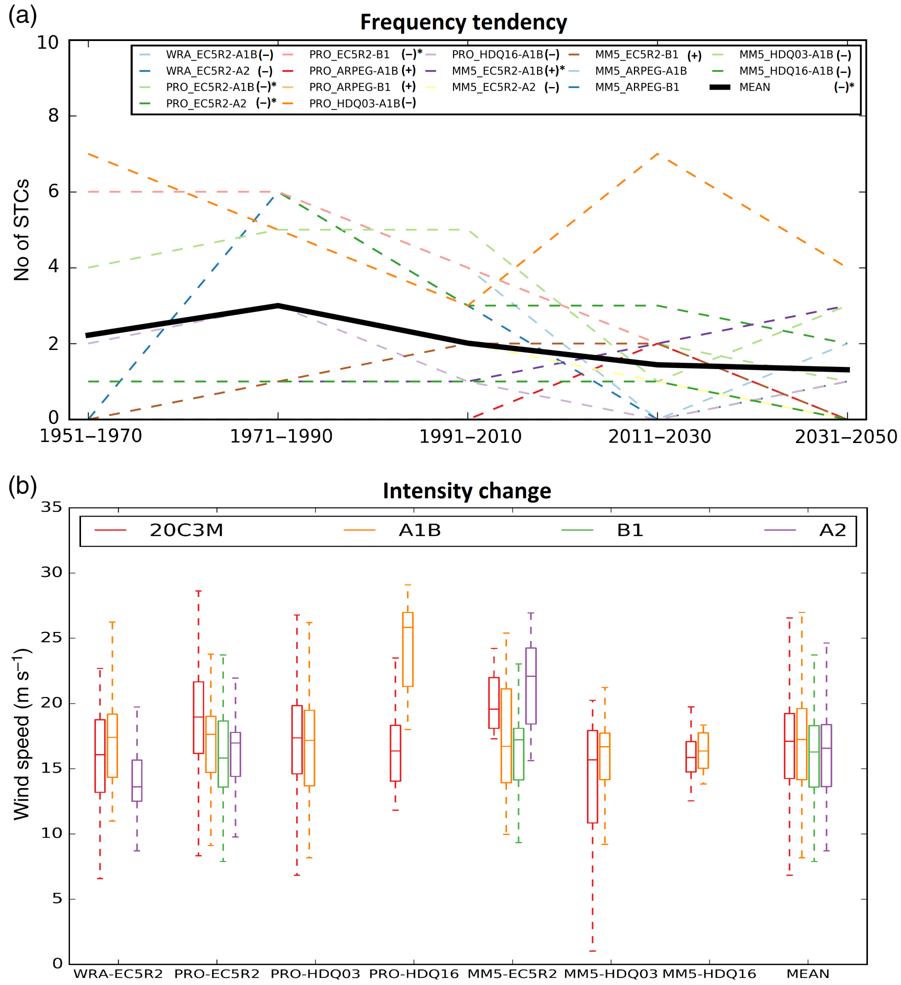


Figure 4. (a) Number of STCs per two decades, as simulated by RCMs nested in GCMs during the entire simulation period. (b) Boxplot (upper extreme, upper quartile, median, lower quartile and lower extreme) of 10-m wind speed (m s^{-1}) of the STCs obtained as a measure of their intensity. Also indicated is the sign of the slope in (a) in each simulation, accompanied by asterisk if the linear trend is statistically significant. In (b), bloxplot in the first columns are for 20C3M, second for A1B, third for B1, and fourth for A2. [Colour figure can be viewed at wileyonlinelibrary.com].

to PROMES-EC5R2 simulations (A1B, B1 and A2). The ensemble average also shows a statistically significant decrease (at the 95% confidence level). This agrees with the prevalence of simulations showing a decrease in Table 1. Nevertheless, this decreasing trend seems to be largely dominated by the PROMES simulations forced by EC5R2. Therefore, based on these results showing no strong agreement between simulations, a robust conclusion about the frequency tendency of future STCs cannot be reached.

Figure 5(b) depicts the intensity variations. Here, intensity is measured as the maximum 10-m wind speed calculated over the cyclone's lifetime. As can be seen, there is not a clear trend. Indeed, the ensemble mean indicates that the intensity of STCs in the future would be similar to that of the historical period, with no noticeable changes. Moreover, the most reliable model combinations in the historical period (PROMES-HDQ03, MM5-HDQ03 and WFR-EC5R2) not only show no clear difference in this magnitude, but they also are inconsistent in sign among them. No clear differences are found between emissions scenarios in the simulated period. Therefore, there is large uncertainty with respect to future changes in STC's intensity.

As shown in Section 4, an important factor linked to the differences in the frequency of STCs in simulations in the historical is the differences in the number of total cyclones reaching or forming over the common domain. Therefore, it is worth investigating if this factor is also acting in the case of STCs changes in the future with respect to the present climate. The future projections predominantly show a decrease in the number of overall cyclones (12 of 16 simulations; columns six to nine in Table 2). Of the nine future projections showing a decrease in the frequency of STCs, eight are associated with a decrease of overall cyclones. Table 3 summarizes all the findings. As can been deduced from it, those simulations consistent in showing a link between changes in STCs and changes in overall cyclones prevails over the rest (9 of 16). Other groups of simulations, projecting other combinations of the signs of change of STCs and overall cyclones, are clearly less populated.

There are anyway discrepancies in a substantial number of simulations (7 of 16), which do not show a connection

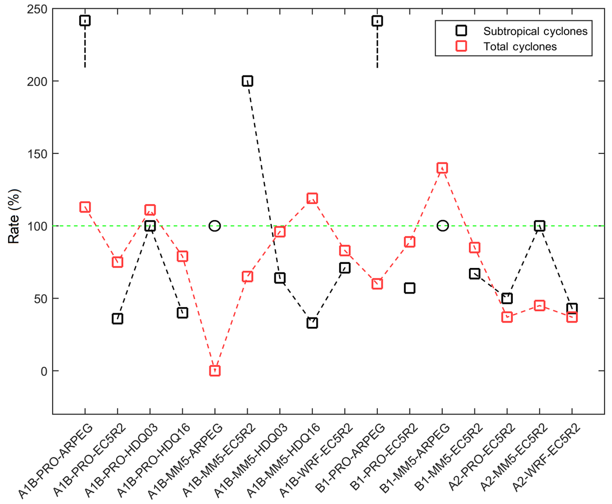


Figure 5. Rate of future cyclones over present cyclones (in %) for STCs and overall cyclones, in future climate simulations with respect to present climate simulations. The values are obtained dividing the number obtained in future climate by that of present climate (values above 100% indicate a future increase in the number of cyclones). The squares at the top of the plotting domain indicate that the value is infinite (as the denominator is zero) and the circles at 100% indicate that there is no change but the value is mathematically undefined. [Colour figure can be viewed at wileyonlinelibrary.com].

Table 3. Summary of the results showing the different combinations of changes in STCs and in total cyclones in ACC simulations with respect to present climate simulations.

Change in STCs	↓	↑	↓	↑	–	–
Change in total cyclones	↓	↑	↑	↓	↑	↓
Number of simulations	8	1	1	2	2	2

The arrow pointing up (down) indicates a positive (negative) change. No changes are indicated by the endash.

between the signs of change of STCs and of overall cyclones. This can be better seen in Figure 5, which shows the rate of future cyclones over present cyclones (values about 100% indicate a future increase in the number of cyclones). Not only the signs of change are sometimes different, but also the quantitative changes can be rather different. This indicates that ACC could also affect the conversion rate. Large variations of this magnitude are obtained indeed in some future scenarios with respect to the present climate simulations, as can be inferred from Figure 5, but no consistent sign of change is found for the conversion rate: it decreases in 8 projections, increases in 6 and does not change in 2 of the 16 projections. The important variability of the conversion rate among simulations can be also seen in Figure 3(a). A correlation analysis shows that in this case there is no lineal relationship ($r = -0.10$) between changes in overall cyclones and STCs, based on those simulations from which can be calculated. If we only take those simulations from the group where the change is of the same sign, a correlation is obtained ($r = 0.48$) but lower than that of Figure 3(a) and not statistically significant at the 95% confidence level. Therefore, this drop in correlation indicates that ACC is affecting the relationship between STCs and overall cyclones, which is consistent with the changes in the conversion rate seen above.

Another fact worth highlighting is the absence of a clear relationship between the future STCs changes and the level of radiative forcing, represented by the different emissions scenarios (B1, A1B and A2). Considering that B1 is the scenario with the weakest forcing and that the forcing is slightly stronger in A2 than in A1B up to 2050, changes in future STCs in A2 should be slightly more notable than in A1B and smallest in B1, if the amount of radiative forcing were a fundamental contributor to those changes. This cannot be inferred from Table 1, where for instance, PROMES-EC5R2 shows a less pronounced change in A2 than in A1B. MM5-EC5R2 is another model which does not match the above-mentioned relationship. WRF-EC5R2 is the only model where there is a more pronounced decrease (in STCs) in A2 with respect to A1B. In contrast, future changes in overall cyclones show some relationship to the level of radiative forcing, as the two model combinations (PROMES-EC5R2 and MM5-ECR2) covering the three emissions scenarios simulate a decreasing number of overall cyclones for an increasing level of radiative forcing (B1 projects a less perceptible reduction in overall cyclones, while it is more evident in A2; Table 2). But these two combinations are nested in the same GCM, and the simulations nested in ARPEGE do not show the same relationship. However, it is worth noting that important differences are difficult to obtain as the simulations only cover until 2050. Future climate simulations up to 2100 could add more insight to this relationship.

6. Discussion

As seen in Section 5, certain simulations show an association between a future decrease of STCs and a decrease in overall gale-force cyclones (this is the case in 50% of the simulations). It is worth mentioning that the most reliable models in the historic period and those with a statistically significant trend are in this group. Nevertheless, since this link was not systematic and the rate of change in those showing this link is rather variable (Figure 5), ACC could affect environmental conditions in such a way that the conversion rate (STCs per total cyclones) is altered. Therefore, a lower occurrence of total cyclones over the region is not the only factor explaining a reduction in STCs, but could be an important contributor by decreasing the likelihood of STCs formation. An important number of simulations from the ensemble show an increase in the rate of STCs per overall cyclones, which evidences that environmental conditions in the future could favour a higher likelihood of formation of STCs.

In addition, certain model combinations show that future changes in overall cyclones had no relationship to the level of radiative forcing, which indicate that natural multi-decadal variability could play a more important role (with respect to ACC) in STCs than in overall cyclones. This result is consistent with the uncertainty found in the link between changes in overall cyclones and STCs.

The fact that certain simulations show that a lower occurrence of STCs is partly associated with a reduction in the presence of total cyclones is consistent with conclusions obtained by Ulbrich and Christoph (1999), Lionello *et al.* (2008) and Giorgi and Coppola (2007), where a poleward movement of the midlatitude storm track is projected. Over the subtropical northeastern Atlantic, Zappa *et al.* (2013) found a slight reduction in extratropical cyclones (more important in the most forced scenario), and also in their associated intensity. This poleward shift of the southern edge of the midlatitude storm tracks has been associated with an expansion of the Hadley cell under global warming (Lu *et al.,* 2007; Mbengue and Schneider, 2017). Similar considerations can be applied for future medicanes. They are expected to decrease in frequency (Gaertner *et al.,* 2007; Romero and Emanuel, 2013; Cavicchia *et al.,* 2014; Walsh *et al.,* 2014; Romera *et al.,* 2016; Tous *et al.,* 2016), though in this case an increase in the maximum intensities is obtained.

The outcome in the case of intensity, where no future tendency is found, can be explained by the fact that STCs' intensity is not only influenced by SST (Evans and Guishard, 2009). Contrary to deep warm-core cyclones (Emanuel, 1986) or, e.g. medicanes (where an increase in intensity is expected in the future), STC structure is not solely affected by surface enthalpy fluxes. These fluxes strongly depend upon surface temperature and therefore mature medicanes' intensity is controlled by SST. The intensity of STCs depends on factors affecting the generation and maintenance of associated convection. Convection within STCs is governed by an additional source apart from the surface fluxes: the large-scale ascent via quasi-geostrophic forcing in a weakly stable large-scale environment, related to the existence of an upper-level trough or a cut-off low. This deep vertical ascent can alter convection even with only weak thermodynamic support from the sea surface fluxes. Indeed, without the presence of this cold upper feature, the STC would likely not form. Other factors like the strength of the pressure gradient created between the cyclone and the anticyclone to the north may play a role (González-Alemán *et al.,* 2015).

Given the uncertainty obtained here, the methodology of using a multi-model ensemble of simulations is justified as it reveals the whole range of possible future changes in STCs. Similar conclusions have been obtained in Romera *et al.* (2016) and Zappa *et al.* (2013), which advise the use of a multi-model approach.

Most part of the accumulated rain in this subtropical region is provided by cyclones (especially those most intense) associated with the midlatitude circulation, reaching or forming within the domain, and by their accompanying fronts (Herrera *et al.,* 2001). Consequently, the reduction in overall cyclone activity over the region projected by an important amount of simulations, would provoke a decrease in the accumulated precipitation in the wet season, assuming that the mean accumulated precipitation per cyclone is not increased in an ACC environment in this region. For example, Zappa *et al.* (2013) found a slight reduction in the mean precipitation (intensity) associated with cyclones over this region, contrary to the eastern coast of the United States.

Apart from projected changes in overall cyclones, alterations in dynamical and thermodynamical factors that could also contribute to future STCs changes are planned to be addressed in a future work. Those changes in environmental conditions would probably be related to changes in the availability for moist convection processes and/or changes in the atmospheric patterns. On the other hand, since tracks of extratropical cyclones are expected to shift towards the north, a future study of STCs' projections should consider no latitudinal limit, so that the formation of STCs north of 40°N can be analysed. Another possible issue worth researching is whether there will be an increase in tropical transitions (Davis and Bosart, 2003) from STCs in the future. Nonetheless, to pursue this, a reconsideration of the way STCs are detected is first needed, since STCs studied herein have been selected based on rather specific criteria following Guishard *et al.* (2009) (the only climatology of STCs available within the North Atlantic), like the achievement of hybrid structure before the first 24 h, which could be inconsistent with STCs that undergo tropical transition.

7. Conclusions

Using a large ensemble of RCMs simulations, this study analyses possible changes in frequency of formation and intensity of STCs over the eastern subtropical North Atlantic basin for future climate in ACC conditions within the first half of the 21st century. The analysed months are from October to April, when most of the STCs occur. RCMs are first evaluated nested in ERA-Interim reanalysis for specific observed cases of STCs, and they show relatively good ability in capturing their hybrid structure, despite some discrepancies in the details. This supports their suitability for the proposed study. The analysis of the whole 20 years period (1989–2008) of these RCM-ERA-Interim simulations shows discrepancies between RCMs, with PROMES doubling the observed frequency of STCs and MM5 identifying half of it.

The assessment of the RCM-GCM combinations in the historical climate period generally shows an acceptable reproduction of the frequency of these cyclones in general, although with certain differences. For instance, there is an underestimation in RCMs simulations nested in ARPEGE GCM. On the other hand, PROMES-RCM simulations show a higher number of identified STCs (as in the ERA-Interim driven runs). These differences are mainly associated with the frequency of overall (mainly extratropical) cyclones acquiring gale-force winds over the region but also partially to the model's characteristics themselves. If direct GCM simulations are examined, a lack of STCs is obtained, which reveals the added value of dynamical downscaling in this case.

For future ACC conditions, results are not clear and therefore it cannot be totally asserted that STCs frequency is expected to decrease, although there is a slight predominance (56.25%) of simulations showing a decrease. The ensemble mean shows a statistically significant negative tendency, but the number of simulations differing from this trend is considerable. The decrease in the frequency of STCs obtained in certain simulations is associated with a reduction in the presence of overall cyclones in the same simulations. It is worth mentioning that most of the simulations which do not show an association between changes in STCs and overall cyclones did not perform well in the present climate period. The association between STCs and overall cyclones is consistent with previous studies and resembles conclusions obtained for medicanes over the Mediterranean Sea. With respect to intensity, no apparent future tendency is projected.

The decrease of overall cyclones appears in more simulations than the decrease of STCs, which points to the influence of other factors on the projected changes in STCs frequency. There are important changes in the rate of conversion of extratropical to STCs and the association between overall cyclones and STCs was less strong if ACC was considered. This indicates that environmental conditions associated with ACC could change the likelihood of STCs formation from extratropical precursors. The future evolution of the conversion rate is very uncertain, as the number of simulations showing an increase of it is similar to the number of simulations showing a decrease. Another important result itself is the prevalence of simulations indicating a decrease of overall cyclones over the subtropics, which could alter climate conditions over the region analysed.

Certain questions remain to be solved. Apart from changes in the presence of overall cyclones over the domain studied herein, which other environmental factors could affect this result? Is it possible that the decrease in STCs over the subtropical northeastern Atlantic basin showed by certain simulations is a consequence of their shift to the north? These issues are expected to be addressed in future research, together with the study of tropical transitions. The reasons for the absence of a clear link between the level of greenhouse gas emissions and the level of STC changes are also an open issue, that could be addressed in the future by analysing possible new simulations covering this area and extending until the end of 21st century.

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4. Synoptic factors affecting the structural evolution and predictability in ensemble forecast of Hurricane Alex (2016) in the midlatitudes

Abstract: Hurricane Alex was an extremely rare hurricane event, the first North Atlantic hurricane to form in January since 1938. Alex developed from an extratropical low- pressure system that formed over the western North Atlantic basin, then underwent tropical transition after moving to the eastern basin. It subsequently underwent anomalous extratropical transition (ET) just north of the Azores Islands. We examine herein the factors affecting Alex's structural evolution and the predictability of that evolution. Potential scenarios of structural development are identified from a 51-member forecast ensemble from the European Centre for Medium-Range Weather Forecasts Ensemble Prediction System (ECMWF-EPS), initialized at 0000 UTC 10 January 2016. The EPS forecasts are clustered using a regression mixture model based on the storm’s path through the cyclone phase space. Composite maps constructed from these clusters are used to investigate the role of synoptic scale features on the evolving structure of Hurricane Alex as it interacted with the midlatitude flow. Results suggest that the crucial factor affecting this interplay was the behaviour of a large extratropical cyclone and its associated cold front and likely warm conveyor belt upstream of Alex; the intensity of these structures determined whether Alex underwent a typical cold-core ET (as observed) or a warm-seclusion ET. The clustering and compositing methodology proposed not only provides a nuanced analysis of the ensemble forecast variability, helping forecasters to analyse the predictability of future complex tropical-midlatitude interactions, but also present a method to investigate probable causes of different processes occurring in cyclones.

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Synoptic factors affecting the structural evolution and predictability in ensemble forecast of Hurricane Alex (2016) in the midlatitudes

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VI. Discussion

The studies presented in this thesis analyse cyclones with tropical characteristics in the northeastern Atlantic Ocean and the Mediterranean Sea in present climate, their potential changes in an anthropogenic climate change context, and the suitability for studying them in this future context with RCMs. This is mainly done not only to improve their forecast in actual climate, but also to provide a context with respect to future climate projections and give support to their study. Cyclones with tropical characteristics like subtropical cyclones, Mediterranean tropical-like cyclones (or medicanes), tropical and extratropical transitions are associated with high impact weather (cf. Preface and Section I) but they have been poorly studied, especially in the northeastern Atlantic. It is therefore important to increase the research on them, which is the main motivation of this thesis. Each work making up this thesis tries to answer new questions that have been unanswered so far, regarding these kinds of cyclones.

With respect to present climate, the work of González-Alemán et al. (2015) has added new insights into STCs. So far it is the first survey on STCs centred on the eastern North Atlantic (ENA). Given the context provided by Evans and Guishard (2009) and Guishard et al (2009) in their synoptic analysis and climatology of STCs in the North Atlantic, González-Alemán et al. (2015) aimed at focusing on the northeastern Atlantic subset from that climatology, added to STCs obtained from the HURDAT dataset. One of the main difficulties was the potential inconsistency between the two datasets, but it was shown that both datasets share common characteristics, which was enough for the study of both subsets of STCs as a whole. This is because the CPS is a description of the thermal structure of the cyclone, and STCs are classified as hybrids in the CPS, which is similar to the method applied by the NHC.

Fifteen cases of STCs were identified between 1979 and 2011 in the ENA basin. González-Alemán et al. (2015) applied a synoptic composite analysis on those cyclones, with the objective of highlighting their common characteristics and complementing/contrasting them with the results from Evans and Guishard (2009) and Guishard et al. (2009). The composite analysis revealed that STCs in the ENA basin were formed from the isolation of extratropical cyclones from the westerlies, reaching the region. These cut-off lows would act as precursors and were characterized by a deepening of the central pressure instead of decaying through occlusion. What this study did not address is the degree of isolation of those cut-off lows. Similar results were obtained by Evans and Guishard (2009) whose composite analysis of STCs in the western basin revealed that STC genesis is associated with the intrusion of an upper trough in the westerlies. Although they do not mention the fact that the trough must be isolated, both results point out the necessity of an upper-level disturbance in order for a STC to form, thus having connections with baroclinic processes, at least at their initial stages. These conditions correspond well with conditions required by the TT process. Indeed, Evans and Guishard (2009) found that nearly 80% of those systems eventually became named tropical systems in HURDAT database.

Despite those similarities, González-Alemán et al. (2015) found certain differences between western and eastern STC. Both types of STCs tend to form in environments with high wind shear (> 10 m s^{-1}), but SST values are different. Eastern STCs tend to form over SSTs below 25°C, whereas western STCs tend to form over SSTs above 25°C. This is an important fact, since high SSTs values would favour convection (weaker static stability), which would make western STCs be accompanied by substantially more convection. Consequently, González-Alemán et al. (2015) argue that western STCs would be more similar to tropical cyclones, whereas eastern STCs would be more similar to extratropical cyclones, which would be the reason why they are often confused with typical winter storms by forecasters in southwestern countries of Europe.

Another interesting result obtained by González-Alemán et al. (2015) is the anomalous atmospheric circulation within the North Atlantic that shows up when STCs are forming. It is characterized by notable departures from the climatological pattern with a statistically significant anomalous anticyclone to the north of the mean STC, similar to composites obtained for western STCs. This strong anticyclone to the north would be a manifestation of a blocked flow, which seems to be a requirement for a STC to form.

To add more insight into these anomalous atmospheric circulations, and add context to the operational forecasting, González-Alemán et al. (2015) also searched for conceptual models that could summarize those atmospheric patterns favouring the formation of STCs. Conceptual models are commonly used by operational forecasters, thus having a good value for them when studying a certain phenomenon. The three derived conceptual models of synoptic pattern showed that those departures from the climatological atmospheric pattern were due to a poleward movement of the westerly circulation and/or a great meridional component of the flow, with a possible blocked flow occurring.

Lastly, a case study of a recent (2010) STC was addressed for contrasting purposes. In that way, the general climatological results could be better interpreted by analysing the evolution of the cyclone. The evolution was consistent with the general results; in its early stage, a typical extratropical cyclone that detached from the midlatitude circulation and became a stationary cutoff low was found. Within an environment characterized by a blocked synoptic pattern, the cyclone then underwent subtropical transition while deepening instead of occluding. This cyclone was indeed one of the motivations of this thesis.

During the course of this thesis, a subtropical cyclone which then completed an uncommon TT, followed by an anomalous ET, in the northeastern Atlantic basin was Hurricane Alex in January 2016. It formed from an extratropical cyclone which became isolated in the subtropics (similar to the process described in González-Alemán et al. (2015) and gradually acquired a deep warm core with an eye feature. Exploiting this occurrence, the work of González-Alemán et al. (2018) analysed this phenomenon to understand the predictability of the evolution of such a complex event by using a novel methodology, which uses path-clustering in ensemble forecasts. This work analysed the suitability of that methodology for these complex cases with the purpose of both improving forecasts and its use as a research tool.

The methodology proposed consisted of applying regression mixture models clustering to the ensemble forecasts of Hurricane Alex, specifically to the CPS evolution obtained from the ECMWF-EPS. This resulted in 6 clusters or different potential evolutions of Hurricane Alex in the CPS, from which 4 clusters were objectively-determined to be suitable for composite analysis, based on statistical significance analysis. Those 4 clusters represented different ways in which Hurricane Alex could have interacted with the midlatitudes, undergoing different types of ET. The additional use of composite analysis gave further insight into those different interactions.

The main results of González-Alemán et al. (2018) suggested that the evolution of Hurricane Alex in the midlatitude in the form of an ET depended on the evolution of a large extratropical cyclone, and its attendant cold front and warm conveyor belt upstream of Alex. The composite analysis showed that the two most different scenarios (cluster 1 and 4) differed in the intensity of the convection associated with those structures, thus affecting the downstream ridge through differences in the dilution of PV and upper-level divergence associated to variations in latent heat release (Hoskins et al. 1985). In cluster 4, the scenario with the most intense cold front and warm conveyor belt, the downstream ridge is strongest, delaying and modifying the interaction between Alex and the baroclinic environment. In this scenario, Alex is steered ahead of the upper-level trough while undergoing a typical cold-core ET. A less typical warm seclusion ET (clusters 1 and 2) occurs in association with a less intense cold front and warm conveyor belt. A weaker downstream ridge in these clusters favours the presence of an upper-level trough northwest of Alex, which facilitates higher interaction of Alex with the baroclinic environment. This process is suggested to cause Alex to rapidly develop an intense low-level warm front north of Alex. Warm front-associated intense winds rapidly encircle Alex, secluding warm air in its centre.

This result is consistent with previous studies, where a connection between upstream conditions and post-ET outcome or re-intensification was found. For instance, McTaggart-Cowan et al. (2001) found that the impact of the upstream trough was more important than the low-level circulation associated with the decaying tropical cyclone in the final intensity reached by the extratropical cyclone resulted from the ET. Ritchie and Elsberry (2003) argued that it is the structure of the basic midlatitude environment what really matters, more than the strength of the upper-level trough, Ritchie and Elsberry (2007) pointed out the importance of the phasing between the tropical cyclone and the midlatitude features. However, the interaction between a tropical cyclone undergoing ET and an upstream trough has been less addressed. Munsell and Zhang (2014) and Kowaleski and Evans (2016) showed the importance of the upstream trough in altering the structure of Hurricane Sandy before landfall in an ensemble forecast. By also using ensemble forecasts, González-Alemán et al. (2018) add more insight into this latter issue of the importance of upstream conditions while the ET process is occurring.

The identification of different scenarios and their representation of different ET pathways demonstrate the potential utility of the methodology proposed in González-Alemán et al. (2018) in operational weather forecasting, through a better representation of the uncertainty of ensemble forecasts and their associated impacts. Another potential use is as a tool for elucidating the probable causes of different processes occurring in cyclones, i.e. as a research tool.

With respect to future climate, the work of González-Alemán et al. (2017) provides a first insight into future projections of STCs. This is the first survey on this issue as research on STCs has been only focused on present climate. This work was mainly motivated by one of the questions arisen in González-Alemán et al. (2015), i.e. whether STCs frequency and intensity over the subtropical northeastern Atlantic basin could be altered by anthropogenic climate change (ACC) or not.

González-Aleman et al. (2017) used an ensemble of regional climate models in order to address this question and found that there were more simulations indicating a decrease in STC frequency in the 2001-2050 period (compared to 1951-2000) than those showing an increase. A1B, A2 and B1 scenarios were all taken into account. However, this predominance of simulations showing a decrease is not high enough (56.25%) to be considered robust, and further studies are needed.

Gonzalez-Aleman et al. (2017) attributed this possible decrease of STCs to a reduced presence of extratropical cyclones over the analysed area. An association was found between both type of cyclones in the simulations, and it had been shown that extratropical cyclones act as precursor for STCs (González-Alemán et al. 2015). However, an additional possibility for the frequency variations could be changes in the rate of conversion of extratropical to STCs, as changes in environmental conditions due to ACC could modify the likelihood of STCs formation from extratropical precursors in future climate. Additional uncertainty arises from this last issue, as the number of simulations showing an increase of the conversion rate is similar to the number of simulations showing a decrease.

Another important result obtained by Gonzalez-Aleman et al. (2017) was the prevalence of simulations indicating a decrease of overall cyclones over the subtropics. Extratropical cyclones are great contributors to yearly accumulated rainfall in the Canary Islands (Herrera et al. 2001). Therefore, a reduced presence of them over this region could mean more droughts in the Canary Islands. The projected decrease of extratropical cyclones is consistent with previous studies (cf. Section I.3.a). For example, Ulbrich and Christoph (1999), Lionello et al. (2008) and Giorgi and Coppola (2007) have pointed out a poleward displacement of the midlatitude storm track. More specifically, Zappa et al. (2013) found a slight reduction in extratropical cyclones over the subtropical northeastern Atlantic. The poleward shift of storm tracks, leading to decreases in extratropical cyclone over this region, has been attributed to an expansion of the Hadley cell under global warming (Lu et al. 2007; Mbengue and Schneider 2017).

This association between STCs and overall cyclones and their reduction in an ACC context resemble conclusions obtained for medicanes over the Mediterranean Sea, which indeed can be considered a similar phenomenon as STCs (cf. Section I.1.d). As has been found by numerous studies (e.g. Cavicchia et al. 2014; Romera et al. 2017), medicanes are expected to decrease in frequency, which has also been attributed to a reduced arrival of extratropical precursors at the Mediterranean Sea in an ACC context (e. g. Walsh et al. 2014). However, an increase in medicane intensity (e.g. Gaertner et al. 2007) is expected, whereas Gonzalez-Aleman et al. (2017) did not found any consistent variation of intensity of STCs across the RCM ensemble.

Given that, to the author’s knowledge, no studies on STCs in climate models had been done before. González-Alemán et al. (2017) also analysed their when studying STCs. An initial interesting result was obtained: RCMs show added value with respect to pure GCM simulations, as no STC was identified in the GCM simulations. This result is consistent with the fact that GCM simulations in ESCENA project have a relatively low spatial resolution (~2.5°) and convection is not well represented, while STCs depend much on convection phenomena. When RCMs were nested in those GCMs, STCs were simulated and identified.

González-Alemán et al. (2017) found that RCMs acceptably reproduce hybrid characteristics in the CPS for certain observed cases of STC, with some differences related to model characteristics (in the simulations nested in ERA-Interim reanalysis). In the simulations nested in GCMs, RCMs generally reproduced well the observed frequency of STCs in the historical climate period (1951–2000), from a climatological perspective, except for some model combinations (GCM-RCM). Overall, these results thus give support to use of RCMs for studying STCs and obtaining projections.

It must be noted that some model-dependant differences were obtained in the results reached, as for example, some RCM-GCM combinations showed an increase in STCs in the future. In addition, the reproducibility of present STC climatology also depended on the combinations. Indeed, the intensity of the hybrid structure in the CPS for some cases of STCs was sensitive to the model used. All these facts demonstrate that it is important to use model ensembles when studying projections of STCs. Therefore, the use of only one model is not advisable because its associated uncertainty cannot be assessed.

This advice is also applicable when studying medicane projections, as was demonstrated by Gaertner et al. (2016). With the aim of analysing the suitability of RCMs for obtaining medicane projections in the Mediterranean Sea, the work of Gaertner et al. (2016) investigated the role of model characteristics (air-sea coupling and resolution) in the simulation of medicanes. Contrary to STCs, medicane simulations in RCMs have been analysed in several studies since the work of Gaertner et al. (2007), but a comprehensive testing study like in Gaertner et al. (2016) had not been performed yet. Medicane projections in an ACC context have pointed out that their frequency could decrease, while their intensity could increase (e.g. Gaertner et al. 2007; Walsh et al. 2014; Cavicchia et al. 2014; Romera et al. 2017). However, these projections have been generally performed through the use of individual atmospheric-only RCMs.

In this case, since a large ensemble of high resolution and ocean–atmosphere coupled RCM simulations have become available, thanks to MedCORDEX and EuroCORDEX projects (cf. Section III), the assessment of the impact of ACC on medicanes can be improved. In this context, the objective of Gaertner et al. (2016) was to analyse the ability of the RCMs used in these projects to reproduce the observed characteristics of medicanes and the impact of increased resolution and air-sea coupling on their simulation. As with STCs, the resolution of the models used is critical when simulating them due to the dependence of their structure on convective processes. Nonetheless, in contrast to STCs, medicanes (as defined in this work) are in a subsequent stage, where the cyclone has finally undergone tropical transition, thus having a fully tropical cyclone structure during part of their lifetime. Therefore, air-sea interaction could play a more important role in the intensification of these storms despite having a baroclinic origin (Emanuel 2005).

The observational reference for evaluating those simulations is that of Miglietta et al. (2013). This database was constructed by using both satellite images and high-resolution simulations, and was obtained using objective criteria, based on the CPS, for detecting medicanes. This represented an advantage with respect to other of the relatively few databases of observed medicanes available in the literature. Results from Gaertner et al. (2016) showed that the simulated medicanes in RCMs generally are not coincident with observed medicanes on a case-by-case basis. However, the most intense and lasting observed medicanes are better reproduced in the simulations.

The first task was to analyse if RCMs were able to reproduce the observed spatial and annual distribution. It was found that they do a better job in the first aspect than in the second one. RCMs struggle in reproducing September medicanes, that are the first to appear after the summer minimum. A second task was to analyse the impact of model’s horizontal resolution in simulating medicanes. The result was that increasing the horizontal resolution has a generally positive impact on the frequency of simulated medicanes, while, in most cases, the general underestimation of their intensity in lower resolution simulations is not corrected when resolution is increased in the same model. This result is consistent with González-Alemán et al. (2017), who did not identify any STCs in low-resolution GCM simulations, and can be expected given the strong reliance of both kind of cyclones on the behaviour of convection within the cyclonic region. However, Gaertner et al. (2016) also suggested that the model formulation is more important than reducing the grid spacing alone, due to the ability shown by a few models to better simulate medicane intensity.

An interesting result was obtained with respect to the impact of air-sea coupling. In other basins like in the tropics, when air-sea interaction is included in numerical simulations, a negative intensity feedback often arises because of the upwelling of cold waters produced by the intense cyclonic circulation. In contrast to that, the use of air-sea coupled models has a limited effect on medicane frequency and intensity, but it interestingly leads to a seasonal shift of the simulated medicanes from autumn to winter. By analysing two contrasting cases of medicanes, the idea of a limited (or even absent) influence of this negative feedback mechanism is supported. This limited impact might be due to the dependence of the upwelling on the oceanic mixed layer depth, which varies throughout the year. Therefore, the negative feedback should be clearer for medicanes forming in September, when the mixed layer is substantially shallower. However, only a small number of September medicanes have been simulated by the RCMs. In this way, the possible role played by the oceanic mixed layer depth in the interaction between medicanes and sea must be analysed in detail in future studies. Given that projections of the Mediterranean mixed layer depth show important future changes (Adloff et al. 2015), the potential relationship between medicanes and mixed layer depth could have important consequences for the future evolution of medicanes, which has not been considered so far, as studies has only used only-atmospheric component RCMs.

Therefore, the study of Gaertner et al. (2016) points out the importance of applying ocean–atmosphere coupled RCMs to future climate change projections of medicanes.

VII. Conclusions, Implications, and Outlook

In this thesis, an analysis of cyclones with tropical characteristics over the northeastern Atlantic and Mediterranean Sea is undertaken. The work is done for both present and future climate conditions. On the one hand, the environmental conditions leading to subtropical cyclone formation in the eastern North Atlantic are analysed and compared with subtropical cyclones in the western North Atlantic. Further investigation is done in the context of the relationship between subtropical cyclones and anthropogenic climate change, and the ability of the used tools for modelling these kinds of cyclones. On the other hand, and within the latter context, medicanes are also studied by using an ensemble of regional climate models with different characteristics in terms of air-sea coupling and resolution, in order to elucidate their simulation depending on those characteristics. This is done as a basis for better projections of medicanes. Finally, a study of a subtropical cyclone that underwent a tropical transition is addressed, and its interaction with the midlatitude flow, resulting in an extratropical transition, is analysed by using a clustering methodology.

The conclusions of this thesis are shown below. These are divided into four different blocks, each one corresponding to the outcomes of each scientific publication attached in the Results chapter. For an easier reading, the objectives are replicated here as target questions, together with the main implications of each study. For the sake of conciseness, conclusions are given as answers to those questions. The potential future research arisen from this thesis is later described at the end of this chapter.

1. Classification and Synoptic Analysis of Subtropical Cyclones within the Northeastern Atlantic Ocean (González-Alemán et al. 2015)

Target questions:

- Which common synoptic features are present when STCs evolve over the northeastern Atlantic basin (ENA)?
- What are the differences and similarities of those STCs with respect to STCs developing in the western North Atlantic?
- Under which conditions do ENA STCs occur? Could their forecasts be improved?

Conclusions:

- STCs over the ENA basin are associated with an anomalous synoptic pattern with respect to climatology characterised by a high pressure to their north, which is a manifestation of cut-off low situation.
- Eastern STCs share similar synoptic patterns with western STCs, but the latter develop in a more tropical environment (higher SSTs), which makes them more similar to tropical cyclones. Eastern STCs are more similar to extratropical cyclones.
- ENA STCs tend to form when an extratropical cyclone becomes isolated from the westerlies. Operational forecasters must be cautious when these situations are present in order to improve the forecast.

Main implications: These findings contribute to a better understanding of STCs, establishing a first approach to the knowledge of ENA STCs. This could improve weather forecasting of STCs, especially in this area. Another consequence is that this serves as a reference for STC projections over the region.

2. Simulation of medicanes over the Mediterranean Sea in a regional climate model ensemble: impact of ocean–atmosphere coupling and increased resolution (Gaertner et al. 2016).

Target questions:

- Can observed medicanes be reproduced in climate-mode simulations on a case-by-case basis?
- Are RCMs able to reproduce the observed characteristics of medicanes?
- Are RCMs therefore useful for studying projections of medicanes?
- What is the impact of increased resolution on the simulation of medicanes in RCMs?
- What is the impact air-sea coupling?

Conclusions:

- RCMs generally do not reproduce observed medicanes on a case-by-case basis, but those medicanes with highest intensity and duration are better represented.
- RCMs can be used to study medicanes, but the evaluation of medicanes in long regional climate model simulations should be done statistically.
- Medicane's warm core structure can be reproduced in RCMs. The observed spatial distribution of medicanes is generally well simulated, while the monthly distribution reveals the difficulty of simulating the medicanes that first appear after the summer minimum in occurrence.
- Higher horizontal resolution has a systematic positive impact on the frequency of simulated medicanes, but their underestimated intensity in lower resolution runs is not corrected in most cases. Indeed, model formulation is more important given that a few models better simulated medicane intensity.
- Air-sea coupling has an overall limited impact on medicane frequency and intensity, but it results in an interesting seasonal shift of the simulated medicanes from autumn to winter. The effects of air-sea interaction on medicanes may thus depend on the oceanic mixed layer depth.

Main implications: These results help to evaluate uncertainties derived from the use of RCMs when projecting medicanes in an ACC context, and can contribute to improve future studies on medicane projections. In addition, they point out the possible added value of using coupled RCMs to obtain more accurate projections.

3. Subtropical cyclones near-term projections from an ensemble of regional climate models over the northeastern Atlantic basin (González-Alemán et al. 2017).

Target questions:

- Are GCMs/RCMs able to simulate STCs? Can they be used to study ACC projections of STCs?
- Can they reproduce observed climatology of STCs?
- Will ACC affect the frequency and/or intensity of STCs in the ENA basin?

Conclusions:

- Low resolution (~2.5°) GCMs are not able to resolve STCS, while high resolution (~25 km) RCMs are. RCMs are effectively able to capture the hybrid structure of STCs and thus can be used to obtain ACC projections of STCs, but with some caution.

- When RCMs are nested in GCMs, the frequency of STCs is generally well reproduced although with some degree of uncertainty, depending on model characteristics.
- First results indicate that ACC could reduce the presence of STCs over the ENA basin, mainly due to a reduced presence of extratropical cyclones. However, uncertainty arises since conversion rate (from extratropical cyclones to STCs) seems to be also affected, especially in some simulations.

Main implications: This study serves as a first confirmation of the applicability of RCMs for studying STCs. Obtained STC projections (and uncertainty) and associated results over ENA basin will help to understand what associated risks could exist in the future in order for society and policymakers to base their decisions.

4. Synoptic factors affecting the structural evolution and predictability in ensemble forecast of Hurricane Alex (2016) in the midlatitudes (González-Alemán et al. 2018).

Target questions:

- Is a recently developed path-clustering methodology suitable for improving ensemble forecasts of complex phenomena such as a hurricane in the midlatitude?
- Is the proposed methodology suitable for researching environmental causes behind different cyclone developments?
- If the last question is true, what was the role played by synoptic-scale processes in altering the (forecasted) evolution of Hurricane Alex (2016) in the midlatitudes?

Conclusions:

- The identification of different scenarios of development for Hurricane Alex improve the information given by standard measures of uncertainty in ensemble forecasts such as ensemble mean and standard deviation. Those scenarios have their associated probability and their associated societal impact.
- The composite analysis associated with those different scenarios or clusters adds insight into the role played by synoptic scale features in the varying structural evolutions of Alex. However, it must be noted that the association obtained can only be statistical.
- The cold front and warm conveyor belt associated to a large extratropical cyclone upstream of Hurricane Alex, are statistically suggested to determine the structural evolution of Alex, by modifying its interaction with the baroclinic zone. Depending on this interaction, Alex could have evolved as a cold-core ET or as a warm seclusion ET.

Main implications: Results from this study support the use of the path-clustering methodology proposed for improving the information given by ensemble forecasts. In addition, it serves as a demonstration of the suitability of the method for research purposes. In this way, the importance of upstream conditions for different types of ET in Hurricane Alex has been determined.

Future Research Outlook

Thanks to the development of this thesis, numerous questions have been answered for the first time. As often occurs in a scientific work, certain questions have not been fully answered or more questions have arisen, thus leaving space for future research. Indeed, as the topic addressed in this thesis is relatively new, substantial work remains to be done. Potential future research associated with each work making up this thesis is given in each publication of the Results chapter. A summary is provided in this section.

The results obtained for STCs over the northeastern Atlantic basin (González-Alemán et al. 2015) need more analysis by considering more cases. To do this, a new objective climatology of STCs over the northeastern Atlantic is needed, also considering their distinct features with respect to western STCs. Once more cases of STCs are identified, it would be interesting to search for a cyclogenesis parameter that could accurately predict STC formation, and later search for possible teleconnection patterns that could favour their formation from a climatological perspective (e.g. interannual variability). This task could be done by differentiating the environment under which extratropical cyclones become isolated from the westerlies and subsequently occlude, from the environment under which subtropical transition develops.

A new objective climatology of STCs is also needed for STC projection studies as the one available so far has limitations, e.g. no STC could be identified north of 40ºN. This fact makes impossible answer one of the questions posed by González-Alemán et al. (2017): if a lower presence of STCs over the subtropical eastern North Atlantic is due to a northward shift of their area of occurrence, following extratropical cyclones, i.e. if more STCs could be expected north of 40ºN in the future. Another future potential task is the search for changes in the environmental factors that could cause the conversion rate to change, as the relationship found with a lower presence of extratropical cyclones was not robust. This will be done by using new improved climate simulations.

The most interesting result obtained in Gaertner et al. (2016), i.e. the possibility of the oceanic mixed layer depth influencing the interplay between medicanes and the sea leads to substantial work to be done. This possibility needs to be further explored because in case it is confirmed it could have important consequences either for published results on future medicane projections or future studies on the same issue. If mixed layer depth affects medicane development, then projections on medicanes must be undoubtedly analysed using ocean-atmosphere coupled RCMs and more accurately projections will be obtained. In any case, a natural continuation the work of Gaertner et al. (2016) is to analyse medicanes in a future ACC context in the Med-CORDEX and Euro-CORDEX databases.

With respect to the work of Gonzalez-Aleman et al. (2018), as the proposed methodology has produced promising results, its application to other cyclones with tropical characteristics undergoing complex structural evolution over the northeastern Atlantic is planned. Another natural continuation of this work is to employ the same methodology to investigate the early stages of Alex. By also using higher-resolution numerical simulations initialized with representative members of each cluster, the intention is to provide insight into the role played by mesoscale features in the TT process.

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List of Acronyms

3D-Var: Three-Dimensional Variational Analysis

4D-Var: Four-Dimensional Variational Analysis

ACC: Anthropogenic Climate Change

AEMET: Agencia Estatal de Meteorología

BIC: Bayesian Information Criterion

CCB: Cold Conveyor Belt

CISK: Convective Instability of Second Kind

CMIP5: Coupled Model Intercomparison Project Phase 5

CORDEX: Coordinated Regional Climate Downscaling Experiment

CPS: Cyclone Phase Space

DCB: Dry Conveyor Belt

EC: Extratropical Cyclone

ECMWF: European Center for Medium Range Forecasts

EM: Expectation-Maximizing

ENA: Eastern North Atlantic

EPS: Ensemble Prediction System

EPS: Ensemble Prediction System

ERA-40: European Centre for Medium-Range Weather Forecasts Re-Analysis 40

ESCENA: Spanish acronym for ‘scenarios’

ET: Extratropical Transition

EUMETSAT: European Organisation for the Exploitation of Meteorological Satellites

FLOR: Forecast-Oriented Low Ocean Resolution (FLOR)

GCM: Global Climate Model

GFDL: Geophysical Fluid Dynamics Laboratory

GISS: Goddard Institute for Space Studies

GPI: Genesis Potential Index

HiFLOR: High-Resolution Forecast-Oriented Low Ocean Resolution

HURDAT: Hurricane Dataset

HWG: Hurricane Working Group

IBTraCS: International Best Track Archive for Climate Stewardship

IPCC: Intergovernmental Panel on Climate Change

MARS: Meteorological Archival and Retrieval System

MLL: Maximum Log-Likelihood

MRI-AGCM: Meteorological Research Institute Atmospheric General Circulation Model

NASA: National Aeronautics and Space Administration National Aeronautics and Space Administration

NHC: National Hurricane Center

NRC: United States National Research Council

PI: Potential Intensity

PV: Potential Vorticity

QG: Quasi-Geostrophic

RCD: Regional Climate Downscaling

RCM: Regional Climate Model

SEC: Strong Extratropical Cyclogenesis

SLP: Sea Level Pressure

SST: Sea Surface Temperature

STC: Subtropical Cyclone

SVD: Singular Value Decomposition

TC: Tropical Cyclone

TC: Tropical Cyclone

TT: Tropical Transition

TUTT: Tropical Upper Tropospheric Trough

UCAR: University Corporation for Atmospheric Research

US CLIVAR: United States Climate and Ocean: Variability, Predictability and Change

VHT: Vortical Hot Tower

WCB: Warm Conveyor Belt

WEC: Weak Extratropical Cyclogenesis

WISHE: Wind-Induced Surface Heat Exchange

WMO: World Meteorological Organization

List of Publications

Within the context of this thesis:

González-Alemán JJ, Valero F, Martín-León F, and Evans JL (2015) Classification and Synoptic Analysis of Subtropical Cyclones within the Northeastern Atlantic Ocean, J. Climate, 28, 3331–3352, https://doi.org/10.1175/JCLI-D-14-00276.1

Gaertner MA, **González-Alemán JJ**, and co-authors (2016) Simulation of medicanes over the Mediterranean Sea in a regional climate model ensemble: impact of ocean–atmosphere coupling and increased resolution, Climate Dynamics, 1-17, https://doi.org/10.1007/s00382-016-3456-1

González-Alemán JJ, Gaertner MA, Sánchez E, and Romera R (2017), Subtropical cyclones near-term projections from an ensemble of regional climate models over the northeastern Atlantic basin, Int. J. Clim., doi:10.1002/joc.5383

González-Alemán JJ, Evans JL, and Kowaleski AM (2018) Synoptic factors affecting the structural evolution and predictability in ensemble forecast of Hurricane Alex (2016) in the midlatitudes, Mon. Wea. Rev., Under Review.

Other publications during the PhD period:

Quitián-Hernández L, Martín ML, **González-Alemán JJ,** Santos-Muñoz D, and Valero F (2016) Identification of a subtropical cyclone in the proximity of the Canary Islands and its analysis by numerical modelling, Atmos. Res., 178–179, 125–137.

Romera R, Gaertner MA, Sánchez E, Domínguez M, **González-Alemán JJ**, and Miglietta MM (2017) Climate change projections of medicanes with a large multi-model ensemble of regional climate models, Global and Planetary Change, 151, 134-143.