



Facultad de Ciencias

**IMPLEMENTATION AND VALIDATION OF A
CYCLONE TRACKING ALGORITHM.
PROJECTED CHANGES UNDER FUTURE
CLIMATE CONDITIONS OVER THE
IBERIAN**

**(Implementación y validación de un algoritmo de
seguimiento de ciclones. Cambios proyectados
para el clima futuro sobre la Península Ibérica)**

**Master's Thesis
to access**

**MASTER IN PHYSICS, INSTRUMENTATION AND THE
ENVIRONMENT**

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Abstract

Despite the important social impact and the human and material losses associated to extreme wind events in the last years, the number of studies analyzing projected changes in future climate conditions are still scarce. For example, the Xynthia storm occurred in 2010 produced 59 deaths and around 2.5 billion euros cost in Europe, affected also to Spain. The storm was reflected as an ephemeris by the Spanish Meteorological Agency (AEMET). In order to reduce the effects of these extreme events, there are different cyclone tracking algorithms that help identifying the centers of the windstorms and characterizing their trajectories from their creation until their dissolution. The present Master's thesis analyzes the frequency of occurrence of extreme wind events in the Iberian Peninsula and the projections for the 21st century according to the different climate change scenarios defined by the Intergovernmental Panel on Climate Change (IPCC). An algorithm has been implemented using the R programming language to characterize and analyze possible future changes in storm tracking. As a result, the R package named *cyclonTrackR* has been created. The package is already available in GitHub (<https://github.com/SantanderMetGroup/cyclonTrackR>) and will be included as part of the bundle of R packages Climate4R (<http://meteo.unican.es/en/climate4R>) developed by the Meteorology Group from the University of Cantabria where this work has been carried out.

Key words: Explosive cyclogenesis, tracking algorithm, climate projections, cyclonTrackR, climate4R, CMIP5

Resumen

Los estudios sobre proyecciones de cambio climático para eventos de viento extremo son aún escasos a pesar del gran impacto social y las grandes pérdidas humanas y materiales que estos eventos producen. A modo de ejemplo, en el año 2010 la tormenta Xynthia produjo 59 muertos y unos costes de 2.5 billones de euros en Europa, afectando, entre otros países, a España. Esta tormenta es uno de los eventos de ciclogénesis explosiva reflejados como efeméride por la Agencia Estatal de Meteorología (AEMET). Con el fin de mitigar los efectos de estos eventos, existen algoritmos de seguimiento de trayectorias que permiten identificar los centros de las tormentas y caracterizar sus trayectorias desde su formación hasta su disolución. El presente trabajo fin de Máster analiza la frecuencia de ocurrencia de eventos de viento extremo en la Península Ibérica y los cambios proyectados para el siglo XXI según los distintos escenarios de cambio climático definidos por el Panel Intergubernamental de Expertos sobre el Cambio Climático (IPCC). Con este fin se ha implementado un algoritmo de seguimiento de las trayectorias de tormentas en el entorno de programación R que permite caracterizar y analizar posibles cambios futuros en estas trayectorias. Como resultado, se ha creado un paquete de R llamado *cyclonTrackR*. El paquete esta disponible en GitHub (<https://github.com/SantanderMetGroup/cyclonTrackR>) y se incorporará al conjunto de librerías Climate4R (<http://meteo.unican.es/en/climate4R>) desarrolladas por el grupo de Meteorología de la Universidad de Cantabria en el que se ha llevado a cabo este trabajo.

Palabras clave: Ciclogénesis explosiva, algoritmo de seguimiento, proyecciones climáticas, cyclonTrackR, climate4R, CMIP5

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Acronyms

AEMET: Spanish Meteorological Agency
AOGCM: Atmosphere-Ocean General Circulation Model
CCS: Consorcio de Compensación de Seguros
CMIP: Coupled Model Intercomparison Project
CMIP5: Coupled Model Intercomparison Project Phase 5
CMIP6: Coupled Model Intercomparison Project Phase 6
ECA&D: European Climate Assessment & Dataset
ECMWF: European Center for Medium-Range Weather Forecasts
FGGE: First GARP Global Experiment
EMIC: Earth system Models of Intermediate Complexity
ESGF: Earth System Grid Federation
ESM: Earth System Models
FFSA: Fédération Française des Sociétés d'Assurances
GARP: Global Atmospheric Research Program
GCM: Global Circulation Models
IPCC: Intergovernmental Panel on Climate Change
KS: Kolmogorov-Smirnov test
MetGroup : Meteorology Group from the University of Cantabria
NAO: North Atlantic Oscillation
NDR: Normalized Daily Gradient
RCP: Radiative Concentration Pathways
RCM : Regional Circulation Models
RF: Radiation Forcing
sd: Standard Deviation
SLP: Sea Level Pressure
SNR: Signal Noise to Ratio
UDG: User Data Gateway
WGCM: Working Group on Coupled Modelling

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CHAPTER 1

Introduction

Intense extratropical cyclones are one of the main natural hazards in mid-latitudes and are often responsible for large social and economic impacts. In particular, there is a phenomenon known as explosive cyclogenesis (Sanders and Gyakum, 1980) associated with especially large economic and human costs that displays low predictability in most of the cases. Such destructive meteorological events include windstorms, heavy torrential rains and strong waves in coastal areas. A recent example was the storm Xynthia (Liberato et al., 2013) that crossed the Iberian Peninsula in February 2010 causing 59 deaths and costs of 2.5 billion euros in Europe (FFSA, 2011). Xynthia is a clear example of the devastating effects of this type of events and was classified as the 2ND insurance loss event in 2010 lead by the Chilean Earthquake (Benfield, 2010). However, it is not the only one. In the last years there have been more storms that also left damages in the European Atlantic region such as Klaus (Liberato et al., 2011) or Gong (Liberato, 2014).

As a result, there is an increasing interest in providing accurate diagnosis of the cyclone's activity to the society, including current state and possible changes projected for the future in frequency of occurrence, intensity and tracking. Researchers, media and even insurers are focusing their efforts in this field with the objective of preventing and mitigating future catastrophes. They try to reduce the investments required in the last decade due to the economic losses. These studies on climate change projections for extreme wind events focus on knowing the frequency, intensity and location of these storms. Recent studies suggest that the total number of extratropical cyclones may decrease in certain regions of the Northern Hemisphere

in which the Atlantic Ocean and some European regions are included. Furthermore, in the same area, an increase in extreme cyclones is detected. However, more studies are needed to achieve more precise conclusions since this increase varies according to the definition used for its detection. Discrepancies between different studies are shown (Ulbrich et al., 2009).

To contribute to these analysis, trajectory tracking algorithms are used to identify the storm centers and characterize their trajectories from their formation until their dissolution. The monitoring and detection of cyclones has been studied for years, in consequence there are many algorithms based on different concepts (Serreze, 1995; Sinclair, 1997; Inatsu, 2009; Benestad and Chen, 2006; Wernli and Schwierz, 2006; Kew et al., 2010; Hewson and Titley, 2010; Hanley and Caballero, 2012; Flaounas et al., 2014). For instance, Neu et al. (2013) show a comparison of different algorithms applied for mid-latitudes cyclones showing that the tracking method can significantly affect the results. For this reason it is important to carefully analyze the aims of the study, the results obtained and the uncertainties associated in order to proceed adequately. Additionally, they also comment that temporal and spatial resolution of the dataset can produce significant impacts on cyclone statistics.

The objective of this Master's Thesis is to analyze and characterize the future changes projected for events of strong wind storms affecting the Iberian Peninsula for the 21st century according to the different climate change scenarios defined by the Intergovernmental Panel of Experts on Climate Change (IPCC). To this aim, the frequency of occurrence and the trajectories followed by these extreme wind events are studied. In addition, a storm trajectory tracking algorithm that combines different approaches is defined and implemented using the programming language R. Furthermore, the criterion established by Sanders and Gyakum (1980) to identify the explosive character of the cyclones is considered.

Once the storm tracking algorithm is validated, an evaluation of the historical simulations obtained from the climate models contributing to the Coupled Model Intercomparison Project Phase 5 (CMIP5) shown in Table 3.2 is applied. To this end, the reanalysis data from ERA-Interim is used as reference, considered here as pseudo-observations. Following this analysis for the present period, climate projections for the future period of interest for the insurance community (2021-2050) are considered. Moreover, European Climate Assessment & Dataset (ECA&D) is also considered to analyze the impacts caused by these extreme events in the Iberian Peninsula.

R free software environment (R Core Team, 2018) is used in this work since there are several packages and libraries available for the analysis of climate data.

In particular, to facilitate the acquisition and previous processing of climate data the bundle of packages called *Climate4R* (Cofiño et al., 2018; Iturbide et al., 2018) is applied. This bundle has been developed by the Meteorology Group from the University of Cantabria (hereinafter MetGroup) where this study was carried out. In addition, one of the secondary objectives of the present work, as far as possible, is to create a new package with the algorithm elaborated to add it to the *climate4R* bundle.

The present work is divided into five chapters. The first one introduces the state-of-the-art of the cyclone's activity and the motivation of the study. In the second chapter, a description of the phenomenon studied, explosive cyclogenesis, is provided. In addition, the techniques and algorithms used for the detection and tracking of cyclones are explained. The third chapter describes the methodology and datasets used to carry out the present work, as well as, the R programming language packages used. The fourth chapter presents the results obtained in the study as well as the analysis and the discussion made. Finally, the main conclusions and future lines of research are mentioned in the last chapter.

CHAPTER 2

Explosive cyclogenesis

Cyclogenesis is the creation, development and maintenance of a cyclone. These phenomena is known by a wide range of names - windstorm, typhoons, depressions or cyclones, among others - depending on the location of their formation. However, all of them share the same characteristics: they have a center of low pressures and rotate in the counterclockwise direction in the Northern Hemisphere and clockwise in the Southern Hemisphere. The generation of the low pressure center depends on the atmospheric situation over the region and consequently a classification of different types of cyclones is done accordingly, highlighting extratropical, tropical and polar cyclones.

This work is focused on the extratropical cyclones formed at mid latitudes on a synoptic scale, due to the contrasts of temperature between air masses in the atmosphere. For the creation of this type of cyclones an atmospheric instability is required due to a baroclinic atmosphere, high horizontal gradients of temperature, humidity on the surface and strong winds in the upper level. Moreover, several studies have shown that the release of latent heat also plays an important role (Aubert, 1957; Kouroutzoglou et al., 2015).

At mid latitudes the deepening phase of the cyclone can become especially severe, implying a sudden and significant drop in pressure. This phenomenon is known as explosive cyclogenesis (Sanders and Gyakum, 1980). Cyclogenesis is usually mostly baroclinic driven but some studies shown that the release of latent heat plays a key role in the creation of deep windstorm (Reed et al., 1988). As an example, Fink et al. (2012) suggest that selected cases of explosive cyclogenesis, such as Xynthia and

Klaus, were influenced more by this process than by a baroclinic process. However, more studies are needed to analyze the role that latent heat plays since the process varies strongly from case to case. Additionally, different studies conclude that, apart from the latent heat, other processes can reinforce the generation of an explosive cyclogenesis. Thus, the reason why a cyclone is transformed violently in a explosive cyclogenesis in the extratropical region is an issue with multiple responses. This generates different types of cyclones arose from various mechanisms and with their particular characteristics as was suggested by Wang and Rogers (2001).

The fast formation and intensification of the low pressure center in a explosive cyclogenesis extremely increases the risk of damages and impacts on land and sea. One of the main risks of these sudden storms is associated with gusts of wind that can reach the same speed as hurricane winds and cause strong waves in coastal areas. Moreover, the torrential rains produced by the convective processes of the atmosphere also involve considerable risks (Kouroutzoglou et al., 2015).

Sanders and Gyakum (1980) developed a study from 1976 to 1979 about the climatology of this type of events in the Northern Hemisphere. They show that this explosive cyclogenesis occurs in cold periods of the Northern Hemisphere, i.e., since November to March. Furthermore they conclude that these events are usually created in maritime environments with the highest frequencies over the northwestern coasts of the Pacific and the Atlantic Oceans. This was confirmed in a later study by Roebber (1989). However, it does not imply that continental explosive cyclogenesis do not occur, there are also cases but the frequency is lower (Ruscher and Condo, 1996; Possia, 2002).

The present study is focused on cyclogenesis with oceanic origin since they are those that mostly affects the Iberian Peninsula. An example are cyclones Klaus and Xynthia that are described deeper in the following paragraphs.

The extratropical cyclone Klaus (Liberato et al., 2011) affected the southwest region of the European continent on 23 and 24 January 2009. The explosive development of the cyclone started on the 23rd over the North Atlantic Ocean between the Azores and the Iberian Peninsula, with a deepening rate of 37 hPa in 24 hours. Figure 2.1(b) (blue line) shows graphically the fast pressure decreasing that creates the heavy windstorm. The system was originated under very favorable growing conditions: barocline atmosphere, upper level strong winds, horizontal gradients of temperature and moisture and surface interaction with an upper-level low center among others. This extratropical cyclone intensified and moved eastward until it reached the Galician coast. Then parallel to the Spanish Cantabrian coast arrived at France where reached its maximum intensity and began to weaken. The trajectory

is reflected in the figure 2.1(a) (blue line). The high intensity of this extratropical cyclone caused high economic losses, around 500 millions euros in Spain, and human deaths along the affected regions, mainly due to the strong wind generated, reaching maximum gusts of up to 198 km/h in Spain. More information about the characteristic of the phenomenon in Spain is available on the Spanish Meteorological Agency (AEMET), <http://www.aemet.es>.

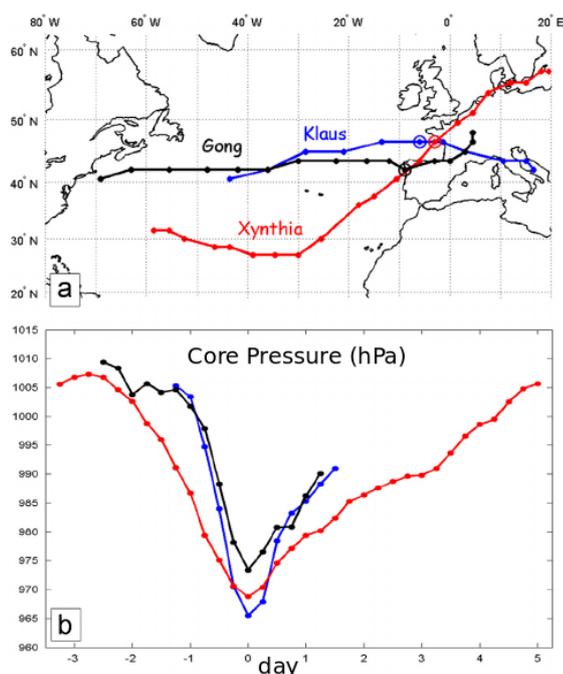


Figure 2.1: Information about three extreme storms that affected the Iberian peninsula: Gong (January 2013, in black), Xynthia (February 2010, in red) and Klaus (January 2009, in blue) (a) Cyclone tracks based on ERA-Interim reanalysis data. Dots indicate storm's location at six hour intervals. Open circle marks the location of the minimum core pressure. (b) Evolution of the pressure center over cyclone's lifetime. Dates are relative to the minimum core pressure time (zero Julian day). Source: (Liberato, 2014)

Xynthia cyclone (Liberato et al., 2013) had an uncommon genesis. Its development and path extended from 25th to 28th of February 2010. The center of the cyclone was located over the North Atlantic Ocean, near Canary Island, and experienced a pressure drop of about 20 hPa during the first 18 hours. Later, the cyclone center moved towards the Bay of Biscay driven by strong upper level winds, striking Portugal and Spain. Once past the coast, it entered France reaching its absolute minimum core pressure below 970 hPa, and continued its track towards north-east

to Belgium, the Netherlands and Germany. Figure 2.1 (red line) shows the trajectory and pressure of the storm. It can be seen the sharp deepening rate that caused the heavy effects of the storm. The meteorological and socio-economic impacts of storm Xynthia affected a wide region in western Europe, causing damages around 50 million euros in Spain (CCS, 2016). The intense wind and hurricane storms were the most significant and devastating effects of the cyclone. Moreover other phenomena were characteristic in other regions such as the high waves induced in coastal locations by the strong winds.

2.1 Cyclone center detection and tracking algorithm

Several algorithms are used for the detection and monitoring of cyclones. The most basic algorithm consists of two phases. First, points detected as cyclone centers are collected in the established time period following some predefined identification criteria. Second, the centers obtained in the first step are joined following a temporal correlation that allows to build the track of the storm. According to these two phases, two functions have been programmed in R to perform the present study: *getCyclonCenters.R* and *getCyclonTrack.R*. In addition, this strategy allows us to save computational cost when only cyclone centers are needed.

The first function created in R is focused on searching cyclone centers (*getCyclonCenters.R*). The criterion established to detect a cyclone center may vary depending on the purpose. In the present work, an algorithm has been created to combine two common criteria usually applied independently. These are the Laplacian of the sea level pressure (Δ SLP) and the vorticity of the lower troposphere (850 hPa). They consider different characteristics of cyclones, wind and mass density (Hodges et al., 2003). In particular, the vorticity and the change in the sea level pressure in a selected region and period of time must exceed established thresholds to be classified as a cyclone center. Hence, the user should establish appropriate threshold values before calling the function. In case these values are not provided, the function default values mentioned in Table 2.1 will be used.

Table 2.1: Default thresholds considered in the study

Vorticity	Δ SLP
1×10^{-4}	20

Once the center of the cyclone is detected, the criterion established by Sanders and Gyakum (1980) is applied to detect if the cyclogenesis is explosive or not. These

authors developed a criterion based on the temporal pressure gradient to locate points in which a meteorological “bomb” is generated. This criterion is established according to the value of the normalized daily gradient (NDR) defined as follows:

$$\text{NDR} = \frac{\Delta P_c}{24} \cdot \frac{\sin(60)}{\sin(\varphi)} \quad (2.1)$$

where ΔP_c is the system’s change in pressure in 24 hours at the latitude of the cyclone core at the maximum deepening point (φ). The criterion states that an explosive cyclogenesis is being created when this number, NDR, is greater than one.

Once the R function is called, it covers all the spatial and temporal items available, searching for the points where the threshold value is exceeded in the two variables mentioned above. At the same time, the type of formation, explosive or not, is also analyzed. Finally, all cyclone centers are saved in a variable with all the data that characterize them (NDR, vorticity, SLP, Δ SLP, longitude, latitude, wind maximum speed, explosive or not) for each temporal step.

The second R function developed is focused on the creation of the cyclonic track (*getCyclonTrack.R*) using the centers obtained in the previous phase and taking into account the temporal and spatial threshold established. To consider that a point is suitable for the trajectory, it has to be within a spatial radius established by the user. If more than one point is near the cyclone center, that with the maximum vorticity, NDR, Δ SLP or minimum SLP will be chosen, as specified by the user. Therefore, the results depend on the user selection according to the variable(s) considered as driver(s) of the events of interest for him.

The way this second function is programmed shows two clear advantages. On one hand, it is possible to obtain all the trajectories occurred on the whole period of time studied, which is the default behavior for the function. On the other hand, it is possible to obtain only the trajectories corresponding to the specific dates introduced by the user.

To achieve all the trajectories occurred on the period of time studied, the most intense center for the initial time step is first selected and established as the beginning of the track. Then, if a point in the next time step is within the thresholds, it is chosen as the following point in the track. This new point become the next reference point and the process is repeated for the next time step. The tracking will be completed after few time steps (e.g. days) when no point satisfied the criterion selected in the next time step. In this case, a new cyclonic center is selected to start a new tracking until all the list of centers obtained from the first phase is completed.

In case the objective is to establish the trajectories for particular dates provided

by the user, the function collects all the available data for those dates. If there is more than one time step in the input dates, that with a center which satisfied the criterion of maximum vorticity, NDR, Δ SLP or minimum SLP, is chosen, according to the user's convenience. This point is established as the initial one. Then, the function searches for a point within the thresholds in the next and previous time step. These new two points become the next reference points and the process is repeated for the next and previous time steps. The tracking will be finished once the period of time determined by the user is completed.

In this function, all the possible trajectories are saved in a list where the cyclone centers that compose each tracking and its corresponding date are shown. The cyclone centers are characterized with the information as in the previous function (NDR, vorticity, SLP, Δ SLP, longitude, latitude, wind maximum speed, explosive or not).

CHAPTER 3

Data and Methods

3.1 Data

Different datasets have been used in this study. On one hand, data from the ERA-Interim (Dee et al., 2011) reanalysis are used as reference to evaluate the tracking algorithm efficiency as well as to validate the CMIP5 models. On the other hand, data from the global climate models available in CMIP5 (Taylor et al., 2012) are used to extend the study to the future. In this case, changes of frequency or tracking of extreme wind events in the future are analyzed. Finally, data from the ECA&D project (Klein-Tank et al., 2002) are considered to illustrate the impact of these events in the north of the Iberian Peninsula for the Xynthia cyclone (Liberato et al., 2013).

The area considered extends from the North Atlantic to Europe (Figure 3.1) since this is the area of genesis and development of the cyclones affecting the Iberian Peninsula.

The period of time studied extends from 2000 until the present and from 2021 to 2050, in the case of future projections.

A detailed explanation of each dataset mentioned is presented below.

3.1.1 ERA-Interim reanalysis

Reanalysis are among the most used datasets in the study of weather and climate. They are produced by the combination of observations (ground-based stations, ships, airplanes and satellites) and models via a process called data assimilation. The set



Figure 3.1: Area of interest for this Master's Thesis. It extends from North Atlantic to Europe where the cyclones affecting the Iberian Peninsula developed.

of observations usually comprises several types of measurement, each with its own accuracy and distribution (Uppala et al., 2005). Nevertheless, reanalysis provide a multivariate, complete and coherent record of the global atmospheric circulation at regular intervals over a long time period that can extend back by decades or more. The main objective of these kind of data is to produce an homogeneous record of the past atmospheric evolution that is free of spurious non-climatic signals introduced by changes in the model formulation, the assimilation system, etc. However, changes in the global observation system and the presence of time-varying biases in the models and observations inevitably affect the representation of climate signals in reanalysis.

Despite this hybrid origin, data from reanalysis are commonly referred to as *pseudo-observations* or even observations and used for the same purposes as observations, even though this equivalence is not always justifiable. It must be taken into account that reanalysis data present biases with respect to observations, consequently, the results of different reanalysis may differ significantly in certain regions (Brands et al., 2013).

The reanalysis data used in this work, ERA-Interim (Dee et al., 2011), is a global atmospheric reanalysis produced by the European Center for Medium-Range Weather Forecasts (ECMWF). ECMWF climate reanalyses began with FGGE (First GARP (Global Atmospheric Research Program) Global Experiment) reanalyses (Bengtsson et al., 1982) and they followed with ERA-15 (Gibson et al., 1997), ERA-40 (Uppala et al., 2005) and ERA-Interim. Currently, a new reanalysis product is being produced by the ECMWF, ERA5¹, but it is only partially available and has not been considered in the present study.

¹More information about this new product is available in the following link <https://confluence.ecmwf.int/display/CKB/ERA5+data+documentation>

ERA-Interim project was carried out, in part, to prepare a new atmospheric reanalysis to replace ERA-40 by addressing problems encountered during its production. It was confirmed that most of the variables in ERA-Interim are superior to ERA-40 in quality, therefore, the use of ERA-Interim is supported and it is currently a reference among these kind of products. Furthermore, Dee et al. (2011) stated that due to these new improvements in data assimilation, more intense cyclones can be detected. Additionally, this new dataset improved several technical aspects of reanalysis such as data selection, quality control, correction of bias and performance monitoring.

ERA-Interim is produced with the atmospheric model and reanalysis system from the ECMWF, IFS, which incorporates a forecast model with three coupled components: atmosphere, land surface and ocean waves. The model is based on Cy31r2 version used for the operational forecast in the ECMWF. It also includes a 4-dimensional variational analysis (4D-Var) with a 12 hours temporal resolution. The spatial resolution of the dataset is approximately 79 km or T255 spectral resolution and it is developed in 60 vertical levels from the surface up to 0.1 hPa.

ERA-Interim covers a period from 1979, originally since 1989, until near-time. Among other things, this dataset contains 6-hourly gridded estimates of three-dimensional meteorological variables covering the troposphere and the stratosphere. It also contains 3-hourly estimates of a large number of surface parameters, which describe the climate and conditions of the surface-land and waves-ocean. For more information, the reader is referred to the detailed description in Berrisford et al. (2011).

As previously stated, these type of data are used to substitute observations and different reanalysis may differ significantly in the results. However, in the Northern Hemispheric extratropics this uncertainty is negligible and, therefore, it will not affect in this work (Brands et al., 2013).

The variables chosen from ERA-Interim dataset to carry out the study are listed in Table 3.1. These variables are standard predictors in cyclone tracking, as mentioned in previous sections. Since the vorticity is not commonly available, it has been estimated from the geopotential height by applying the Quasi-Geostrophic approximation (Chen and Bromwich, 1999):

$$\xi = \frac{1}{f_0} \Delta z g$$

where f_0 is the Coriolis parameter, $z g$ is the geopotential height and Δ is the Laplacian operator.

Table 3.1: Meteorological variables considered in the study

Code	Name	Height	Unit
zg	Geopotential	850hPa	m/s ²
SLP	Sea-level pressure	mean Sea-level	Pa

3.1.2 Global Climate Model (CMIP5)

Global Circulation Models (GCMs) are essential tools for climate studies and have been evolving since 1960s (Manabe and Wetherald, 1967). They are the most advanced and complex software tools currently available for simulating the global climate system and its possible alteration in the future due to increasing greenhouse gas concentrations. GCMs try to represent the physical processes in the different components of the climate system (atmosphere, ocean, cryosphere and land surface), their interactions and evolution via process equations that are numerically solved. GCMs divide the globe in a three dimensional grid, nowadays having a horizontal resolution around 200Km, 10 to 20 vertical atmospheric layers and around 30 layers in the oceans. Hence, GCMs provide valuable information to understand the dynamics of the climate and determine the effects and possible impacts of climate change. However, although their spatial resolution is enough to reproduce the main large scale features of the climate system, they fail in providing information about regional climates mainly due to unresolved sub-grid-scale processes and the inadequate representation of regional characteristics, especially the orography (von Storch et al., 1993).

In 1995, in order to provide a public dataset with multiple models in a standardized format that offers information about climate change projections, the Coupled Model Intercomparison Project (CMIP²) began under the auspices of the Working Group on Coupled Modelling (WGCM). For this purpose, CMIP develops and defines protocols and standard formats, allowing researchers to compare and analyze the latest outcomes of global climate models in a systematic way. It also establishes distributing mechanisms to ensure the availability of the results of the experiment to researchers.

Since its creation, several phases of the project have been carried out, with Phase 6 currently under development. Nevertheless, until the third phase these models did not follow a realistic scenario because climate forcing was held constant. Consequently, they could not be used to make projections or comparisons with

²<https://www.wcrp-climate.org/wgcm-cmip>

observations.

The aim for the last phase conceived in 2008 (CMIP5) (Taylor et al., 2012), is to address outstanding scientific questions arose from the fourth IPCC assessment process, improve understanding of climate, and to provide estimates of future climate change that will be useful to those considering its possible consequences (Taylor et al., 2012). More than 20 groups have participated in the project contributing with more than 50 different models. The models and experiments collected in this phase of the project were created to answer three main issues:

1. Evaluating the factors responsible for the differences found between the different projections of the models when simulating feedbacks associated with the carbon cycle and the clouds.
2. Examining the climate predictability and predictive capabilities of forecast systems at decadal and longer time scales.
3. Determining the reason why models with similar forcing produce different responses.

The strategy followed by CMIP5 includes two types of climate change modeling, long-term (century time scale) and near-term or decadal (10-30 years) prediction experiments. Moreover, new types of models have been included since the CMIP started as an experiment to study the results of the coupled atmosphere-ocean general circulation models. These new models of different types and complexity make possible to study carbon feedback and climate change impacts on terrestrial and ocean biosphere. The different kind of models in CMIP5 are:

1. Atmosphere-Ocean General Circulation Model (AOGCM), the standard models used to understand the dynamics of the components of the climate system and make future projections.
2. Earth System Models (ESM) which couple biogeochemical components to the standard model to account fluxes of carbon between the ocean, the atmosphere and terrestrial biosphere carbon reservoirs. In order to compare the results with the other models, they will be executed with concrete CO₂ concentrations.
3. Earth system Models of Intermediate Complexity (EMIC) that describe most of the processes implicit in comprehensive models using more parametrizations.

In addition to these new models, a new approach about the characterization of the future evolution of greenhouse gases concentration was established for the fifth IPCC

assessment report. In previous reports, socio-economic arguments have been defined to generate emission scenarios and then, prepare projections of climate change based on such scenarios. Currently, the first step is the identification of scenarios of radioactive forcing and then, at the same time, the location of possible socio-economic, emission and climatic scenarios that entail such forcing. The new experiments, Radiative Concentration Pathways (RCP), are based on the total value of radiation forcing (RF) at 2100 relative to the pre-industrial values. In particular, four scenarios have been added, RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5, each one corresponding to a path of specific radiative forcing. In these experiments the full range of scenarios is sampled, which includes emissions and concentrations of greenhouse gases, aerosols and chemically active gases, as well as land use and land cover.

RCP2.6 contains the lowest value representing a mitigation scenario, RF peaks at 3.0 W/m^2 and then declines to 2.6 W/m^2 by 2100. The RCP4.5 and RCP6.0 scenarios stabilize after 2100 at 4.2 and 6.0 W/m^2 respectively. Finally, RCP8.5 shows a scenario in which the concentration of greenhouse gases increases. It reaches a level of 8.3 W/m^2 by 2100 on a rising trajectory. These values are approximations since the climatic forcing resulting from all the factors varies, depending on the characteristics of the model and the treatment of short-lived substances. All the models developed in the CMIP5 project have generated variables of 20th Century Climate, known as historical scenario, and future climate projections for the 21st century, the previously mentioned RCPs (Collins et al., 2013).

In this study, the data belonging to the fifth phase of the CMIP project are used. The datasets are publicly available for non-commercial purposes through gateways to worldwide servers. In the case of the following work, they will be obtained from the Santander User Data Gateway (UDG), a climate data access maintained by MetGroup(Cofiño et al., 2018).

The variables chosen to carry out the present study are listed in Table 3.1, the same as for ERA-Interim. They are obtained for the CMIP5 models specified in Table 3.2. The historical experiment is used as reference period from 1979 until 2005. The RCP4.5 and RCP8.5 experiments are considered for the future analysis since they are the scenarios most commonly used in the literature.

3.1.3 *European Climate Assessment (ECA)*

ECA&D (Klein-Tank et al., 2002) is a dataset of daily resolution climatic variables that have been compiled by 68 European national meteorological services, universities and research centers. ECA&D collects several elements from around 10500

Table 3.2: CMIP5 Earth System Models considered in this work. Institutions acronyms are available in <https://pcmdi.llnl.gov/mips/cmip5/availability.html>.

ID	Model	Institution	Reference	Resolution
m1	CNRM-CM5	CNRM-CERFACS	(Voldoire et al., 2013)	1.40° x 1.41°
m2	CANESM2	CCCMA	(Chylek et al., 2011)	2.79° x 2.81°
m3	EC-EARTH	EC-EARTH	(Koenigk et al., 2013) (Hazeleger et al., 2010)	1.12° x 1.12°
m4	IPSL-CM5A-MR	IPSL	(Dufresne et al., 2013)	1.27° x 2.5°
m5	MIROC-ESM	MIROC	(Watanabe et al., 2011)	2.79° x 2.81°
m6	MPI-ESM-LR	MPI-M	(Giorgetta et al., 2013)	1.86° x 1.87°
m7	MPI-ESM-MR	MPI-M	(Giorgetta et al., 2013)	1.86° x 1.87°
m8	NORESM1-M	NCC	(Iversen et al., 2013) (Bentsen et al., 2013)	1.89° x 2.5°
m9	GFDL-ESM2M	NOAA-GFDL	(Dunne et al., 2012)	2.02° x 2.5°

stations throughout Europe and the Mediterranean area, such as minimum, maximum and mean temperature or precipitation.

The variables from ECA&D chosen to carry out this study are listed in Table 3.3. This station data were selected to study the impact of explosive cyclogenesis at particular locations.

Table 3.3: Variables from ECA&D considered

Code	Name	Unit
T	Maximum daily temperature	0.1 C
Precip	Total precipitation accumulated in 24 hours	0.1 mm
wss	Daily maximum wind speed	0.1 m/s

3.2 Climate4R

R programming language (R Core Team, 2018) is used in the present work to carry out the study of cyclones. R is an open source programming language and software environment originally designed for statistical computing and graphics. Nowadays, it has become a powerful language since it is an open source tool that has plenty of packages with many tools developed by experts with accompanying books or papers.

In particular, an infinity of packages have been developed to access climate information and perform typical transformations of these data such as spatial and temporal means, regridding, etc. Hence, the use of this language facilitates the

recompilation and postprocessing of climate information which both are very time consuming and error prone processes. In this study *climate4R* package developed by the MetGroup (<https://github.com/SantanderMetGroup>) will be used.

Climate4R is a bundle of R packages for climate data access, postprocessing and visualization. The interface is formed by four main packages (*loadR*, *transformeR*, *downscaleR* and *visualizeR*) remotely connected to the UDG (Cofiño et al., 2018). The UDG was developed to mitigate the typical problems that users of climate data usually find such as the collection of data from different data providers, temporal scales/aggregations and vocabularies that in most cases are not homogeneous across the different datasets. Then, UDG allows users to transparently access harmonized data in terms of format, temporal aggregations and vocabularies from several state-of-the-art datasets for climate analysis. At the same time, it favours science transparency, openness and reproducibility, issues of major concern in all experimental disciplines (see the special issue on reliability and reproducibility of published research go.nature.com/huhbyr). All the details about the UDG can be found in <https://meteo.unican.es/trac/wiki/udg/ecoms>.

One of the packages that form *climate4R* is *loadR* (Bedia and Iturbide, 2018). This package was built on NetCDF-Java to provide a climate data access in a user-transparent way. The package is integrated with UDG but it also allows loading local and/or remote data. It is designed to work with observations, seasonal forecast and global and regional climate change projections. Furthermore, *loadR.ECOMS* (Cofiño et al., 2018) was developed as an extension of the *loadR* package to provide a centralized access point to collections of impact-relevant variables, gathered from existing state-of-the-art datasets. All the variables collected by ECOMS-UDG and accessible by this packages are described in this catalog <http://meteo.unican.es/ecoms-udg/catalog>.

In addition to these data access facilities, *climate4R* includes other packages such as, *transformeR* (Bedia and Iturbide, 2017) for data postprocessing, *downscaleR* (Bedia et al., 2017) for bias adjustment and statistical downscaling or *visualizeR* (Frías et al., 2018) which implements a set of advanced tools for forecast and climatological visualization and verification. All these packages are built on the same data structure as *loadR*. In the following work three of them (*loadR*, *visualizeR* and *transformeR*) will be used to carry out the study.

More information about all the packages that form *climate4R* can be found at the wiki of each package in GitHub- available in <https://github.com/SantanderMetGroup>- that includes several examples of application of the different functions. Moreover, Cofiño et al. (2018) presents an illustrative example related with the North Atlantic

Oscillation (NAO) predictability.

3.3 Methodology

The steps followed to achieve the objectives of this work are detailed in this section. Cyclone detection and tracking algorithm are implemented in R language introducing a new criterion to detect cyclone centers that combines two variables usually applied independently (SLP and vorticity at 850 hPa). It has been considered as starting point a previous version developed in the programming language Fortran 77 (Stormking), that only takes into account the SLP (Serreze, 1995; Serreze et al., 1997). Apart from the new criterion, several changes and improvements are introduced in order to adapt the algorithm to the particular objectives of this Master's Thesis and to make it more flexible and compatible with the data structure used in *loadER*:

- The algorithm has been divided in two different functions as explained in Section 2.1, one for searching cyclone centers and another one for the cyclone tracking.
- The algorithm has been made compatible with the R packages of *climate4R* in order to be applicable to the data loaded with these libraries. This allows end-to-end experimental reproducibility, a major issue nowadays (Baker, 2016).
- The algorithm was designed to be applicable to different time-scales (daily, 6-hourly, etc.) and coordinate systems, regular or not. Note that the coordinate system used by the climate models are not regular in longitude-latitude and most of the reanalysis use Gaussian grids which is not regular in the latitude coordinate for numerical reasons.
- All the parameters of the original algorithm have been defined as arguments. This change make the algorithm more flexible since different criteria can be applied to identify a cyclone center and its possible track.
- New arguments have been added to the function.
 - An argument to choose a cyclone center selection criterion. The criteria available to choose are those used in the previous algorithm (maximum vorticity or minimum SLP) and the global one created in this work that combines Δ SLP and vorticity. Default value of the function is the global

criterion, but with this argument it is possible to obtain results based on different climate variables.

- The maximum length of the cyclone trajectory, expressed in time steps, can be selected. In this way, the lifetime of the cyclone can be specified. Default value is 4, i.e, if daily data are used the cyclone maximum lifetime is 4 days.
- An argument to choose a date is also available. In this argument some dates can be specified by the user activating the second option available in *getCyclonTrack.R* function for particular dates. Then the tracks developed in the dates specified are obtained. Default value for the argument is NULL, since the principal objective of this function is to obtain all the possible trajectories.

An R-package, *cyclonTrackR*, has been built with the two main functions created. Moreover, an example with data from ERA-Interim reanalysis has been included in the same package, using the *climate4R* R-packages and the UDG mentioned in Section 3.2. In this way, the use of the functions are illustrate. The package will be added to the bundle *Climate4R*.

The two R functions developed are evaluated using the reanalysis ERA-Interim to ensure its ability to detect storm centers and tracks. For illustrative purposes, a known event such as Xynthia is chosen to show how the functions are able to reproduce its trajectory correctly. Additionally, stations from the ECA&D are considered to observe the impacts that this event supposed for the Iberian Peninsula.

Once the effectiveness of the algorithm is evaluated with observations, the results provided by the 9 models from CMIP5 are reviewed. The respective GCM climatologies from 1979 to 2005 are compared to the climatology from the ERA-Interim reanalysis data. In this comparison, the Taylor diagram (Taylor, 2001) and the Kolmogorov-Smirnov test (KS) (Frank and Massey, 1951) are used since they provide enough statistical information about the possible errors from the GCMs.

Finally, the algorithm is executed with future values from the CMIP5 GCMs. This allows to evaluate the possible projected changes in frequency and intensity of explosive cyclogenesis events affecting the Iberian Peninsula.

CHAPTER 4

Results and Discussion

This chapter presents the results carried out in the study. It is divided into three sections according to the steps followed in the analysis: evaluation of the cyclone tracking algorithm for a particular windstorm, Xynthia in this case, evaluation of the CMIP5 models versus the ERA-Interim reanalysis for the historical period and finally analysis of possible changes of cyclone activity projected in future climate conditions.

4.1 Evaluation of the algorithm

Results for the cyclone Xynthia are shown here as evaluation of the algorithm defined in the previous Chapter. Data from the ERA-Interim reanalysis are used for the validation.

Figure 4.1 shows the track of the cyclone Xynthia considering the output file saved by the function *getCyclonTrack.R* implemented in this study. For a qualitative evaluation, this track can be compared with the path reflected in Figure 2.1 (Liberato et al., 2013), concluding that the algorithm is able to detect this cyclone tracking correctly. A more general validation of the algorithm has been performed considering other cyclones. The methodology performs also well in those events and the resulting tracks obtained also agree with those shown in the literature (not shown). According to these results, it can be assumed that the algorithm created is able to detect storm centers and properly performs the corresponding tracking.

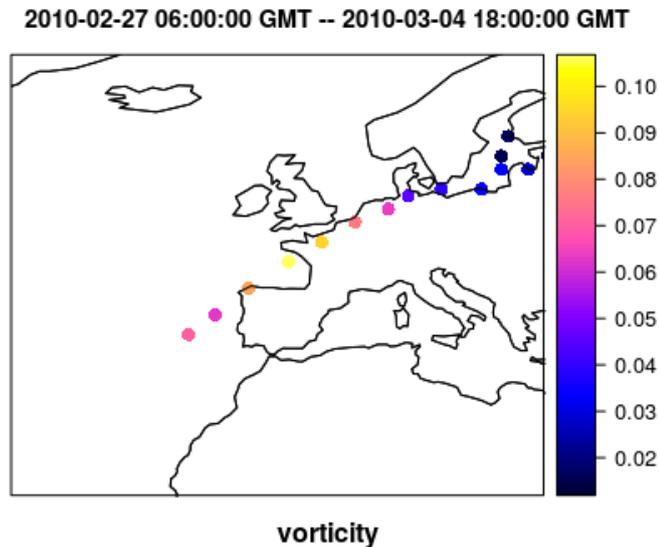


Figure 4.1: Xynthia cyclone trajectory obtained using the algorithm implemented in this work with ERA-Interim dataset. Dots indicate storm location at six hour intervals. Shading represents vorticity. The windstorm begins on 27th of February 2010 at 6am and ends on 4th of March at 6pm. The R code to obtain this plot is detailed in the Appendix A.

The climatologies for the four climate variables considered in the algorithm to detect cyclone centers (vorticity, SLP, NDR and Δ SLP) during the lifetime of the windstorm Xynthia have also been analyzed. As shown in Figure 4.2, during the cyclone, these four variables registered maximum or minimum values, depending on the variable, along the path of the storm represented with dots in the maps. It can also be concluded that the variables included in the algorithm to detect the cyclone centers are appropriate. In particular, Figure 4.2(c) shows the criterion established by Sanders and Gyakum (1980), NDR. In this figure, areas with high value of NDR move around Xynthia cyclone track. It is appreciable that the sizes of the areas decrease as the end of the storm approaches, showing the largest contour in the North of the Iberian Peninsula where Xynthia storm left considerable damages during its lifetime. Thus, it can be seen that the NDR value is suitable to make an approximation of the strength and the explosive character of the windstorm.

The impacts caused by the storm Xynthia in the Iberian Peninsula have also been studied using ECA&D. Several climate variables in the most intense days of the storm have been analyzed to study these impacts. Figure 4.3 presents the results obtained for the cumulative precipitation (first row), maximum temperature

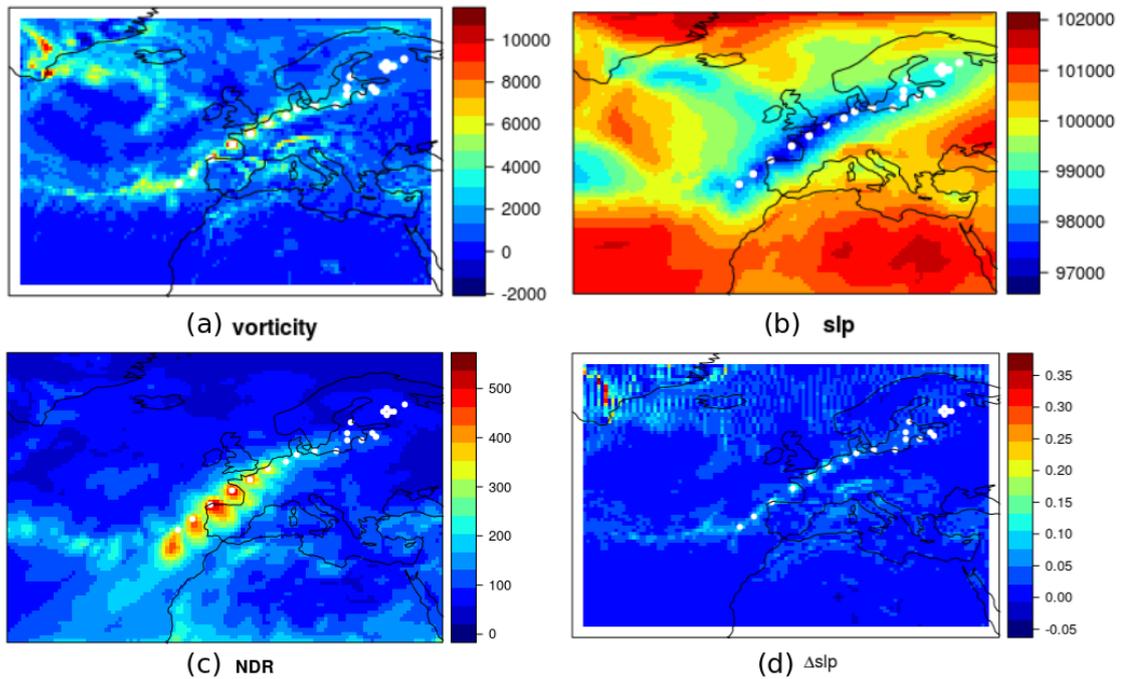


Figure 4.2: Climatology from different climate variables during the lifetime of the cyclone Xynthia. White dots indicate storm location at six hour intervals obtained from the results of the algorithm with the ERA-Interim dataset. The climate variables are the ones introduced in the R function to detect cyclone centers: (a) vorticity, (b) SLP, (c) NDR and (d) Δ SLP.

(second row) and maximum wind gust (third row) for those days. All the values increased on day 27 when the pressure deepening rate reached the highest value. These increases were considerably in North of the Iberian peninsula, the area where cyclone Xynthia passed through (Figure 4.1) and left high social and economic damages. Nevertheless, it is appreciable that the changes occurred in all the peninsula. For example the Galician coast suffered huge changes in a day, especially in the cumulative precipitation and the maximum wind gust. Conversely, inside of the region, such as Madrid, an increase in the variables was noticeable but in smaller magnitude. Hence, it can be seen that the influence of an explosive windstorm can extend beyond its trajectory. On day 28, in spite the values of the variables are higher than in day 26, they started decreasing, implying that the storm left the region and a normal situation for those variables was reaching over the area. The intense wind gusts is the most characteristic phenomenon, reaching speeds of 142.9

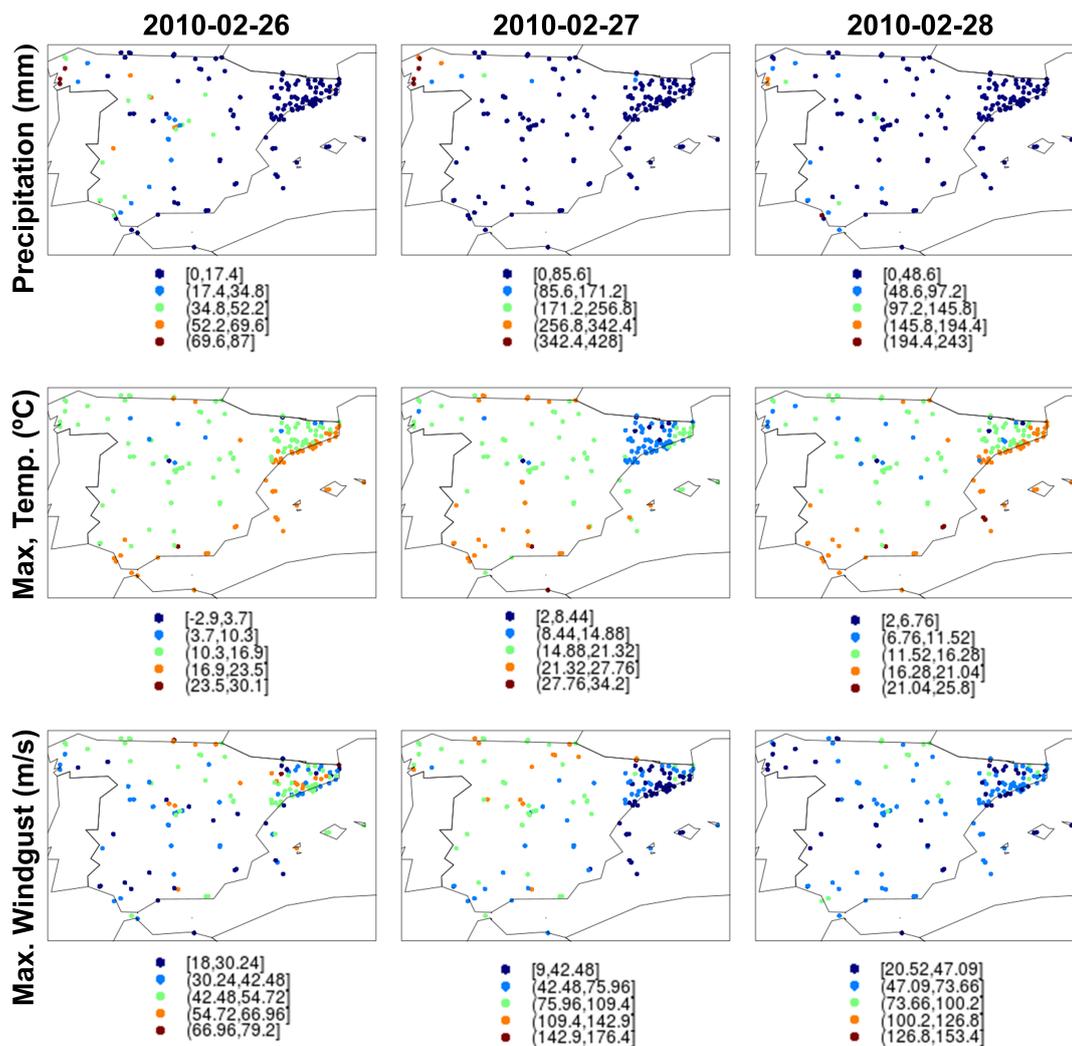


Figure 4.3: Station values of cumulative precipitation (first row), maximum temperature (second row) and maximum wind gust (third row) available in the European Climate Assessment & Dataset. Values for the most intense days of cyclone Xynthia in the area, 26, 27 and 28 of February 2010.

km/h. However, the rain in certain regions and the increase in temperature are also representative and singular elements of this event. The adverse situation reflected in the maps, as previous mentioned, was the reason for the social and economic damages of Xynthia.

4.2 Evaluation of the CMIP5 models

As a previous step to study the CMIP5 projections for cyclone activity, the evaluation of these models is carried out for the historical period. The climatology of the frequency of the cyclones provided by the algorithm for the mean of the nine models shown in Table 3.2 is compared in Figure 4.4 to that from the ERA-Interim reanalysis used as referenced. For a more detailed comparison the analysis is made for two different situations. On one hand, results for all the cyclone centers have been obtained (Figure 4.4, left column) and on the other hand, only those associated to explosive cyclogenesis ($NDR > 1$) are taking into account (Figure 4.4, right column).

In the case of ERA-Interim dataset, two climatologies are displayed over the domain considered using different temporal resolution. On one hand, the density of cyclones was obtained with daily data in order to have a result comparable with the CMIP5 model outputs (Figure 4.4 second row). On the other hand, a more accurate result is shown using 6-hourly data (Figure 4.4 first row). Despite having the maximum density points scattered, the spatial pattern of the climatological density of cyclones obtained for this reanalysis agrees, independently on the temporal resolution, with that found in previous studies (Michaelis et al., 2017; Donat et al., 2010; Neu, 2009; Semmler et al., 2008), showing the highest activity over the southern coast of Greenland. In the case of explosive cyclogenesis events (Figure 4.4 (b) and (d)), this high density area is more apparent, since, it is almost the only area affected by the event. This region is more appreciable in the climatology obtained with 6 hourly data, but its also noticeable in the result of daily data. Again these results highlight the proper functioning of the algorithm created which is able to detect cyclone centers and perform the subsequent tracking.

The value of the climatology density decreases considerably when daily data is used. See for instance the differences between values in Figure 4.4 (a) and (c) that shows a density reduction from 200 to 50. It implies that the frequency of these events is being mitigated, i.e., the number of detected centers is lower. This indicates that daily data is not capable of detecting all the cyclone centers, not even for explosive cyclogenesis. As expected, algorithm effectiveness will depend on the time resolution.

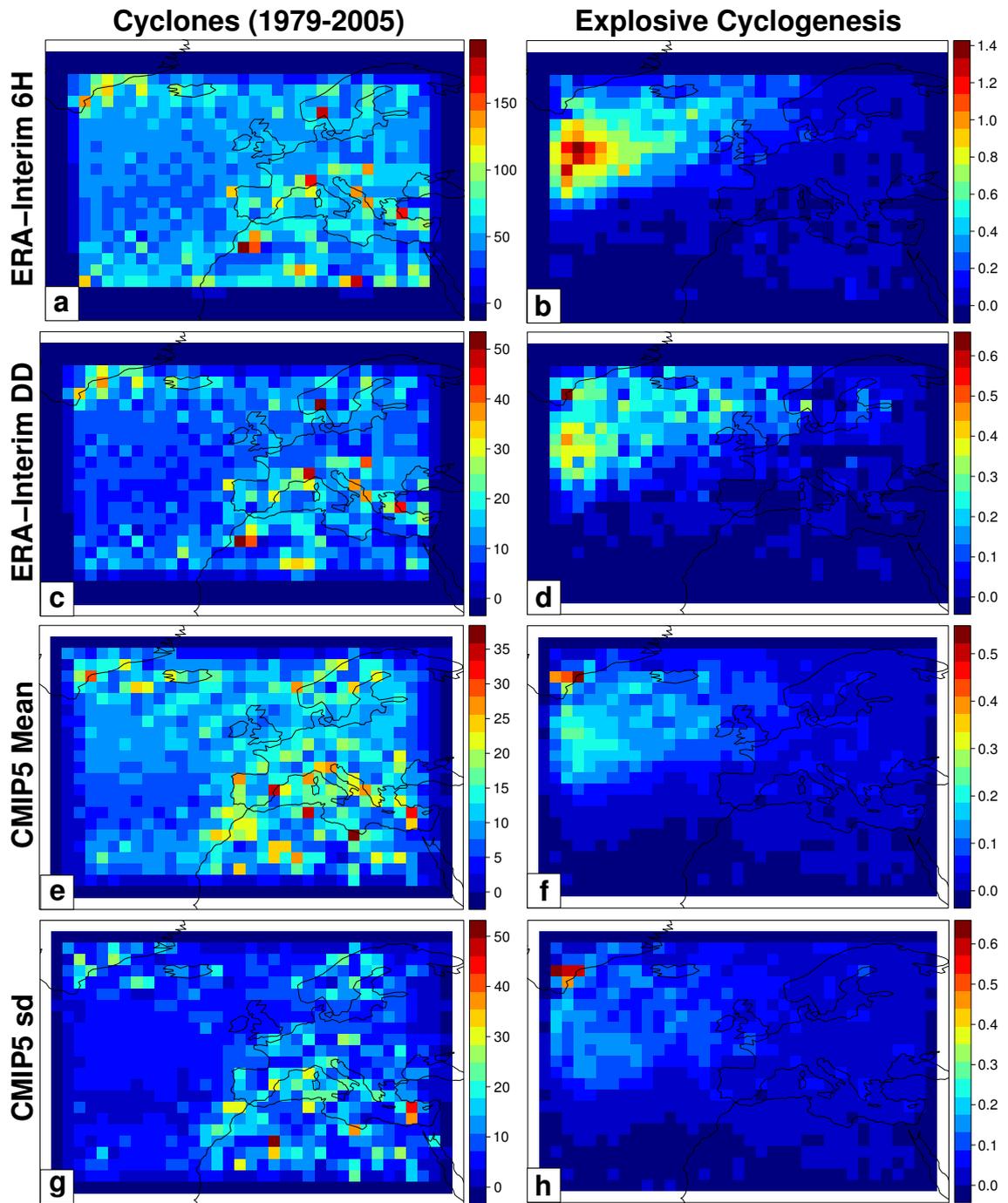


Figure 4.4: Climatology of the density of cyclones (left) and explosive cyclogenesis (right) that passed through the north of the Atlantic and Europe during the period 1979-2005 for the 6-hourly (first row) and daily (second row) ERA-Interim, and the ensemble mean (third row) and standard deviation (fourth row) of the CMIP5 models.

Despite the time resolution limitation, ERA-Interim climatologies from daily data are used as reference to validate the CMIP5 models since the temporal resolution for the models is also daily. The ensemble average climatology for the CMIP5 models and the corresponding standard deviation are shown in Figure 4.4, third and fourth rows respectively. It is observed that the model uncertainty given by the standard deviation increases with the density of the climatology. This implies that the different model outputs detect the cyclone centers in different areas. This is more remarkable for the case of explosive cyclogenesis events. Nevertheless, the area of high density highlighted in the literature is also appreciable for the CMIP5 models.

In a graphical qualitative comparison between CMIP5 climatology for cyclones and that from ERA-Interim, it can be observed that the results present some differences in distribution and density values. However, the corresponding climatologies for explosive cyclogenesis exhibit more similarities. It is shown that the models are able to record the area of high cyclones frequency between Iceland and Greenland. It seems that the generation of cyclones in this area is sufficiently continued and rugged to be detected by the model outputs.

This statement can be confirmed making a statistical comparison with a Taylor diagram and the KS test. On one hand, the Taylor diagram compares the reference and modeled spatial patterns in terms of the centered root mean square error, the spatial variability and the Pearson correlation. On the other hand, the KS test evaluates the null hypothesis that both the observed and modeled patterns come from the same statistical distribution. As a result, both approaches are complementary and give us a complete picture of where the models fail.

The resulting Taylor diagram for all the cyclone centers, Figure 4.5 left, shows that there is a poor spatial correlation between the different members of the ensemble and the ERA-Interim values used as reference. It is also observed a considerable disagreement in terms of spatial variability and errors comparable to the spatial standard deviation. For the case of explosive cyclogenesis (Figure 4.5 right), results are better in terms of spatial correlation, but similar for the other two scores. Note that for the explosive cyclogenesis the spatial pattern has lower spread than for the case that considers all the cyclones and therefore, the spatial correlation is expected to be higher. Taking this into account, it can be concluded that the results are very similar for both cases.

Besides that, KS test states that the distribution of climatologies are totally different since the value of the probability is around zero for all the cases.

Taking into account that the algorithm works properly, it can be assumed that

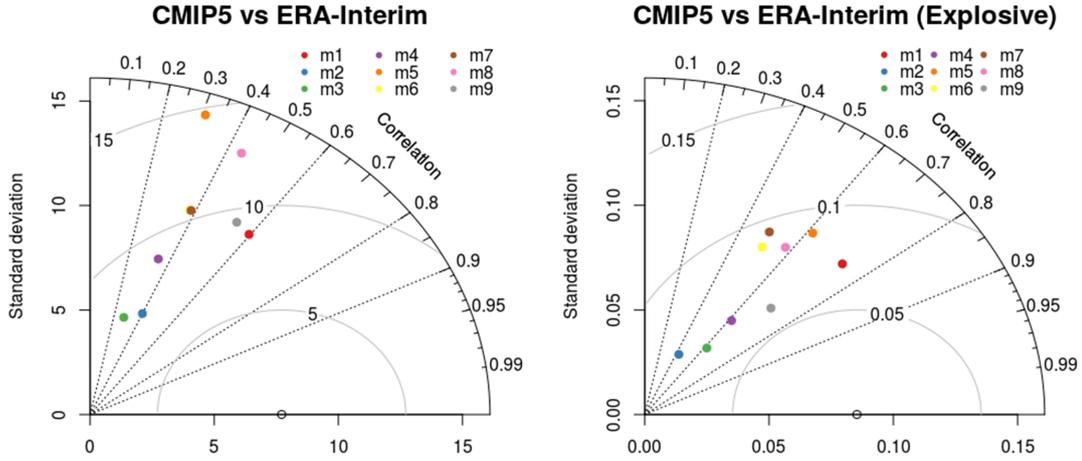


Figure 4.5: Comparison made to analyze the response of the 9 CMIP5 models for the detection and tracking of cyclones using the algorithm developed in the work. Taylor diagrams have been developed taking into account all the cyclone centers (left) and only the events of explosive cyclogenesis (right). ERA-Interim reanalysis is used as reference.

the differences are due to the model data. The CMIP5 model outputs underestimate the observed values, so they are not able to detect all the cyclone centers detected in the reference dataset. One reason of this underestimation could be due to the differences found between the results from 6 hourly and daily data (Figure 4.4 first and second row), reflecting that the cyclones in this area are mainly developed at an intra-daily scale. Another possibility can be the coarse spatial resolution of the models (~ 200 km) which does not allow to properly reproduce convective events. Deeper analysis is needed to properly understand and explain this issue.

Although the CMIP5 models present some differences respect to the observed cyclones from the ERA-Interim in the area analyzed, this tool can be considered suitable to perform an approximation to future situations and to analyze possible changes projected for the future. This analysis could be used to propose adaptation measures that mitigate human, economic or environmental losses.

4.3 Projected changes under future climate conditions

In this last section results obtained for the future projections from the CMIP5 models are shown, i.e., the projected changes in cyclogenesis events for the future period of interest for the insurance community (2021-2050). Historical simulations

for the period 1979-2005 are here considered as reference.

In the following analysis, the outputs of the nine models could not be taken into account for various reasons. On one hand, the third model, EC-EARTH, was not available in the ESGF for the RCP4.5 scenario on the date of download (August 2018). For this reason this model was excluded in the part of the study focused on the RCP4.5 scenario. On the other hand, it was observed that the fifth model, MIROC, in both RCP scenarios showed considerable differences with respect to the other models. This difference is clearly shown in figure 4.7 for the number of cyclones (first row) and explosive cyclogenesis events (second row) that pass through the Iberian Peninsula. The differences between MIROC (orange line) and the rest of models is appreciable. The fifth model exhibits a considerable decrease in 2006 when the data change from the historical period to the RCP scenario. The reason of this issue was that the data downloaded from UDG had errors in some variables for the RCP future period (more details about the issues available in <https://cmip.llnl.gov/cmip5/errata/cmip5errata.html>). Finally, as the corrected model data were not available in ESGF at the time of the realization of this study, results for the MIROC model had to be removed in this part of the analysis. Consequently, the changes projected for the future under the RCP4.5 scenario are studied with the ensemble mean of 7 CMIP5 models and those under the RCP8.5 are analyzed with the mean of 8 CMIP5 models.

Figure 4.6 shows the ensemble average of changes in climatology for the CMIP5 models and the corresponding signal-to-noise ratio (SNR) for the two future scenarios selected and for the cyclones (left column) and explosive cyclogenesis (right column). The SNR is computed as the ensemble delta mean divided by its standard deviation. This quantity is used to provide an idea about the significance of the scattering of the results but when it is applied to the climate change signal, it can be interpreted as the uncertainty of the different models, i.e., change signal model agreement. In this way, the areas where the models agree in the climate change signal will be identified, showing ensemble mean significance. Assuming a Gaussian distribution for the ensemble and taking into account that model agreement represents the percentage of models that agree on the signal's sign, the SNR can be translated as follows (Collins et al., 2013):

- $\text{SNR} < 0.5$ — Model agreement $< 70\%$
- $\text{SNR} = 1.0$ — Model agreement = 85%
- $\text{SNR} = 2.0$ — Model agreement = 97.5%

- SNR > 3.0 — Model agreement > 99.5%

The changes projected for the cyclones in the near future defined by the RCP4.5 scenario (Figure 4.6 (a)) display some points with increasing (red) and decreasing (dark blue) density values, but most of the area has the same color, showing and projecting no apparent change. In the case of explosive cyclogenesis events (Figure 4.6 (b)), it can be seen that most of the studied area is red, projecting an increase in the frequency of these events. Nevertheless, the SNR values for this scenario (Figure 4.6 second row) are lower than 1 almost everywhere, therefore the results are not reliable. The spread of the ensemble is around the same magnitude or higher than the mean, i.e the noise is higher than the signal. Therefore, there is no agreement for the sign of the change between the models. For this reason it is concluded that there is no projected change of these events for the near future according to the RCP4.5 scenario.

For the RCP8.5 experiment (Figure 4.6 third row), the areas in red are more appreciable, showing an increase in the density of cyclones and explosive cyclogenesis events, especially in the south. However, the values of SNR (Figure 4.6 fourth row) present similar results as for the RCP4.5 scenario, there is no model agreement in the sign of the change. Hence, the conclusion for both scenarios is the same.

This last statement suggests that the projections for the climatology of storms for the future will not suffer significant changes with respect to the current climatology because the results do not depend on the future scenario. This can be expected since the scenarios defined by the IPCC have a similar behavior for the near future and begin to differentiate as they approach to the last decades of the century.

Figure 4.7 shows the number of cyclones (first row) and explosive cyclogenesis (second row) events that pass through the Iberian Peninsula in a year within the whole period 1979-2050 for the two scenarios, RCP4.5 on the left and RCP8.5 on the right. These figures also reassert the previous conclusion that all the models project no clear changes in the occurrence of cyclogenesis events, explosive or not, in the Iberian Peninsula for the period 2021-2050. Moreover, it can be seen that the two scenarios, RCP4.5 and RCP8.5, project almost the same number of events per year in the Iberian Peninsula for the future. Thus, the similarities in the scenarios behavior is also appreciable in these results.

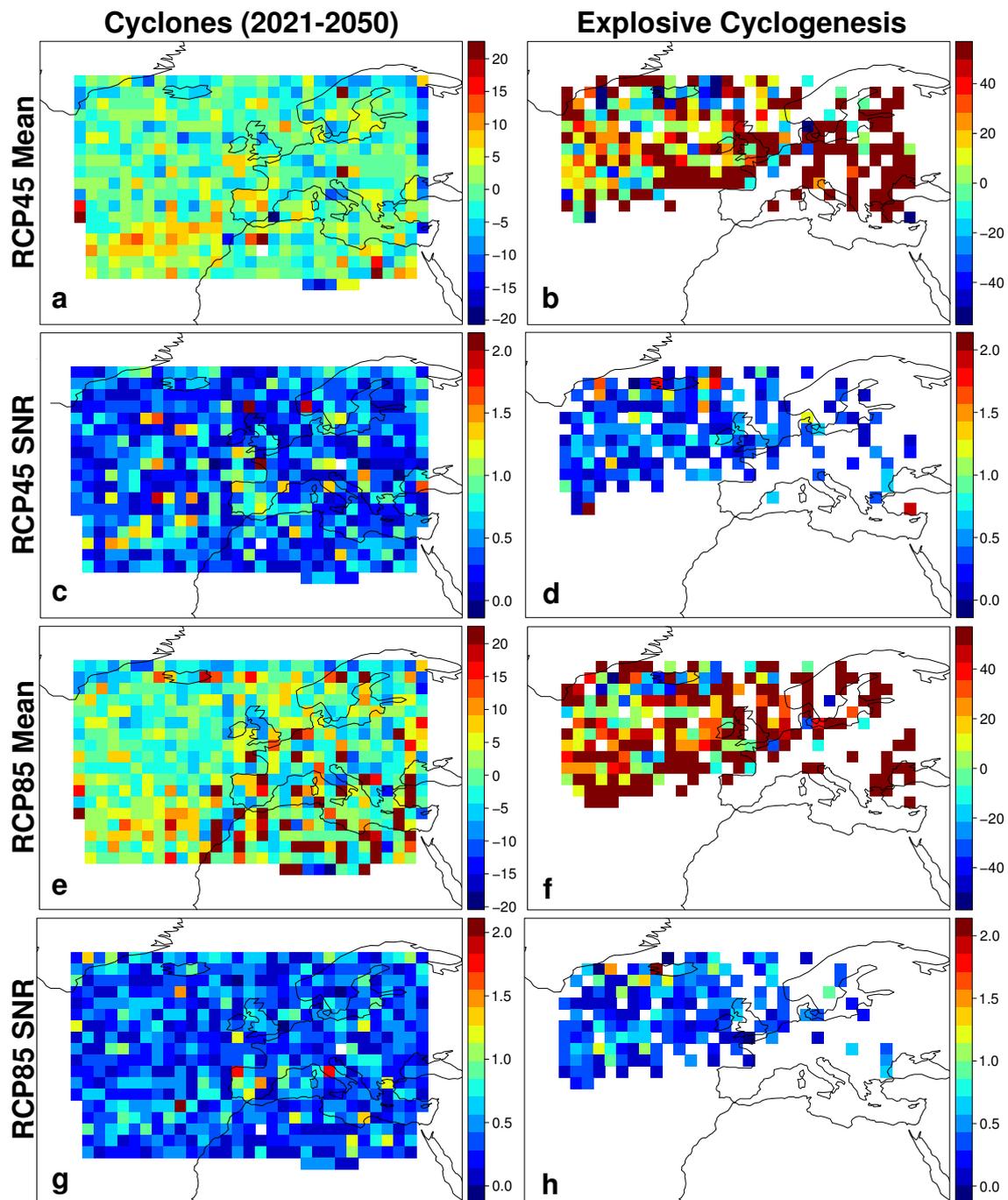


Figure 4.6: Projected changes (rows 1 and 3) and signal-to-noise ratio (SNR, rows 2 and 4) in cyclones (left column) and explosive cyclogenesis (right column) events for the future period 2021-2050 considering the RCP4.5 and RCP8.5 experiments. Historical simulations for the period 1979-2005 are considered as reference.

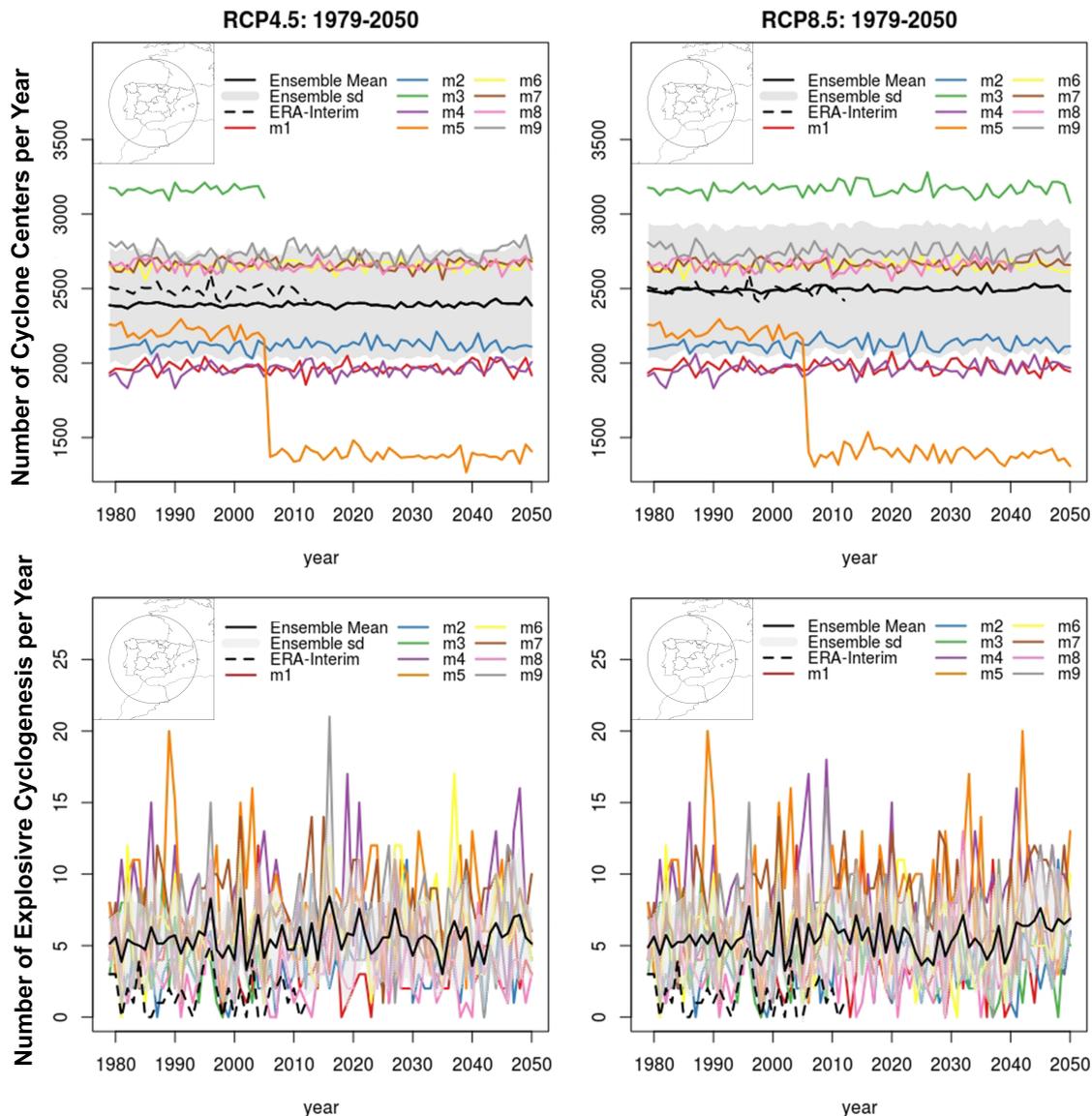


Figure 4.7: Number of cyclones (top) and explosive cyclogenesis (bottom) that pass through the Iberian Peninsula per year within the period 1979-2050. The domain considered to detect these events is also included on the top. Results are obtained from the algorithm for the CMIP5 models and the ERA-Interim reanalysis. Each panel shows the results for the 9 models as well as the ensemble mean (black line) and the error for the two different future scenarios selected, RCP4.5 (left) and RCP8.5 (right).

CHAPTER 5

Conclusions and outlook

This Master's Thesis analyzes the frequency of occurrence of extreme wind events over the Iberian Peninsula for the historical period and the CMIP5 projections for the 21st century according to two different climate change scenarios, RCP4.5 and RCP8.5. To this end, a cyclone tracking algorithm was implemented in R language to detect cyclone centers. This algorithm combines two common criteria usually applied independently, the vorticity at 850 hPa and Δ SLP. The main objectives of the study have been achieved and some conclusions can be outlined:

- A program capable of detecting cyclone centers and tracking them has been developed. Although, it has been seen that the algorithm is sensitive to the resolution of data, both spatially and temporally. Moreover, a package has been created in R programming language with these cyclone centers detecting and tracking functions and illustrative examples. This package is already available in GitHub (<https://github.com/SantanderMetGroup/cyclonTrackR>) and will be added to the *Climate4R* bundle. Thus, the scientific community benefits from free access to the software.
- Some known windstorm events, such as Xynthia, have been detected and tracked with the algorithm. Furthermore, the impacts that these events caused in climate variables have been verified, showing the risk that this type of windstorm can suppose.
- It has been seen, using ERA-Interim data, that cyclones created in the studied area are mostly formed on intra-daily scales since the frequency of cyclone

events increased when 6 hourly data is used. In this line, it has been deduced that the daily outputs available for the CMIP5 models are not able to detect all the cyclone centers because their time resolution. Nevertheless, they can detect the area of Greenland and Iceland as the one with the highest density of storms, as stated in the literature.

- It has been observed that CMIP5 models do not project changes for cyclogenesis events in the near future for the RCP4.5 and RCP8.5 scenarios in the area extended from North Atlantic until Europe. In this analysis some models were not included since they were not available in the data provider. However, it can be considered that the results including the removed models would be the same to those shown with the GCMs considered. An analysis is necessary to prove it.

Taking into account these conclusions, new future work and research lines are opened.

- The algorithm dependence with the type of dataset can be analyzed in more detail carrying out the study with different reanalysis data.
- If possible, the analysis can be extended considering 6 hourly data in the models to verify if it improves the estimation of cyclones with the CMIP5 models. Higher time resolution data are not available in the ESGF at the moment but it would be an aspect to analyze when this dataset is accessible either for the CMIP5 models or the future CMIP6 ones. In this line, the impacts of using 6-hourly projections instead of daily projections also could be analyzed.
- The analysis can be extended to higher spatial resolution data. Thus, changes projected can be analyzed in more detail. The algorithm's spatial resolution dependency could also be studied. For example, Regional Circulation Models (RCMs) with resolutions around 12km can be used to perform this analysis in Europe. Moreover, some sort of downscaling or bias correction technique to the GCMs can be done using, e.g., the reanalysis ERA-Interim as reference.
- The analysis can be extended to other future periods (e.g. 2041-2070 or 2071-2100) in order to propose mitigation and adaptation measures at different time-horizons.
- The analysis can be extended to the new generation of models included in the 6th Phase of CMIP (CMIP6).

Bibliography

- AUBERT EJ (1957) On the release of latent heat as a factor in large scale atmospheric motions. *Journal of Meteorology*, 14(6):527–542
- BAKER M (2016) 1500 scientists lift the lid on reproducibility. *Nature*, 533:452–454
- BEDIA J, GUTIÉRREZ JM, HERRERA S, ITURBIDE M and MANZANAS R (2017) *downscaleR: An R package for bias correction and statistical downscaling*. R package version 2.0.4
URL <https://github.com/SantanderMetGroup/downscaleR/wiki>
- BEDIA J and ITURBIDE M (2017) *transformeR: An R package for climate data manipulation and transformation*. R package version 1.2.0
URL <https://github.com/SantanderMetGroup/transformeR/wiki>
- BEDIA J and ITURBIDE M (2018) *loadeR: The generic data loading package of the climate4R Bundle*. R package version 1.3.0
URL <https://github.com/SantanderMetGroup/loadeR/wiki>
- BENESTAD R and CHEN D (2006) The use of a calculus-based cyclone identification method for generating storm statistics. *Tellus A: Dynamic Meteorology and Oceanography*, 58(4):473–486
- BENFIELD A (2010) Annual global climate and catastrophe report. Impact forecasting – 2010. Technical report, Aon Benfield
URL http://www.aon.com/attachments/reinsurance/201012_if_annual_global_climate_cat_report.pdf

- BENGTSSON L, KANAMITSU M, KÅLLBERG P and UPPALA S (1982) FGGE 4-dimensional data assimilation at ECMWF. *Bull Am Meteorol Soc*, 63:29–43
- BENTSEN M, BETHKE I, DEBERNARD JB, IVERSEN T, KIRKEVÅG A, SELAND Ø, DRANGE H, ROELANDT C, SEIERSTAD IA, HOOSE C and KRISTJÁNSSON JE (2013) The Norwegian Earth System Model, NorESM1-M – Part 1: Description and basic evaluation of the physical climate. *Geoscientific Model Development*, 6(3):687–720
URL <https://www.geosci-model-dev.net/6/687/2013/>
- BERRISFORD P, DEE D, POLI P, BRUGGE R, FIELDING K, FUENTES M, KÅLLBERG P, KOBAYASHI S, UPPALA S and SIMMONS A (2011) The ERA–Interim archive version 2.0. Technical Report 1, ECMWF, Shinfield Park, Reading
- BRANDS S, HERRERA S, FERNÁNDEZ J and GUTIÉRREZ JM (2013) How well do CMIP5 Earth System Models simulate present climate conditions in Europe and Africa? A performance comparison for the downscaling community. *Climate Dynamics*, 41:803–817
- CCS (2016) Estadística: Riesgos extraordinarios. Serie 1971-2017. Technical report, Consorcio de compensación de seguros (CCS)
URL https://www.conorseguros.es/web/documents/10184/44193/RREE_2016.pdf/14ca6778-2081-4060-a86d-728d9a17c522
- CHEN QS and BROMWICH DH (1999) An equivalent isobaric geopotential height and its application to synoptic analysis and a generalized ω equation in σ coordinates. *Monthly Weather Review*, 127(2):145–172
- CHYLEK P, LI J, DUBEY MK, WANG M and LESINS G (2011) Observed and model simulated 20th century Arctic temperature variability: Canadian Earth System Model CanESM2. *Atmospheric Chemistry and Physics Discussions*, 11:22893–22907
URL <https://www.atmos-chem-phys-discuss.net/11/22893/2011/>
- COFIÑO AS, BEDIA J, ITURBIDE M, VEGA M, HERRERA S, FERNÁNDEZ J, FRÍAS MD, MANZANAS R and GUTIÉRREZ JM (2018) The ECOMS User Data Gateway: Towards seasonal forecast data provision and research reproducibility in the era of climate services. *Climate Services*, 9:33 – 43

- COLLINS M, KNUTTI R, ARBLASTER J, DUFRESNE JL, FICHEFET T, FRIEDLINGSTEIN P, GAO X, GUTOWSKI W, JOHNS T, KRINNER G, SHONGWE M, TEBALDI C, WEAVER A and WEHNER M (2013) *Long-term Climate Change: Projections, Commitments and Irreversibility*, book section 12, page 1029–1136. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
- DEE D, UPPALA S, SIMMONS A, BERRISFORD P, POLI P, KOBAYASHI S, ANDRAE U, ALONSO-BALMASEDA M, BALSAMO G, BAUER P, BECHTOLD P, BELJAARS A, VAN DE BERG L, BIDLOT JR, BORMANN N, DELSOL C, DRAGANI R, FUENTES M, GEER AJ, HAIMBERGER L, HEALY S, HERSBACH H, HÓLM EV, ISAKSEN L, KÅLLBERG P, KÖHLER M, MATRICARDI M, MCNALLY A, MONGE-SANZ B, MORCRETTE JJ, PARK BK, PEUBEY C, DE ROSNAY P, TAVOLATO C, THÉPAUT JN and VITART F (2011) The ERA–Interim reanalysis: configuration and performance of the data assimilation system. *Quart J Roy Meteor Soc*, 137:553–597
- DONAT MG, LECKEBUSCH GC, PINTO JG and ULBRICH U (2010) Examination of wind storms over Central Europe with respect to circulation weather types and NAO phases. *International Journal of Climatology*, 30(9):1289–1300
- DUFRESNE JL, FOUJOLS MA, DENVIL S ET AL. (2013) Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5. *Climate Dynamics*, 40(9):2123–2165
- DUNNE JP, JOHN JG, ADCROFT AJ, GRIFFIES SM, HALLBERG RW, SHEVLIKOVA E, STOUFFER RJ, COOKE W, DUNNE KA, HARRISON MJ, KRASTING JP, MALYSHEV SL, MILLY PCD, PHILLIPPS PJ, SENTMAN LT, SAMUELS BL, SPELMAN MJ, WINTON M, WITTENBERG AT and ZADEH N (2012) GFDL’s ESM2 global coupled climate–carbon earth system models. Part I: Physical formulation and baseline simulation characteristics. *Journal of Climate*, 25(19):6646–6665
- FFSA (2011) La tempête Xynthia du 28 février 2010. Bilan chiffré au 31 décembre 2010. Technical report, Association Française de L’assurance
URL <http://www.mrn.asso.fr/wp-content/uploads/2018/01/2010-bilan-tempete-xynthia-2010-ffsa-gema.pdf>
- FINK AH, POHLE S, PINTO JG and P KNIPPERTZ (2012) Diagnosing the influ-

- ence of diabatic processes on the explosive deepening of extratropical cyclones. *Geophysical Research Letters*, 39(7)
- FLAOUNAS E, KOTRONI V, LAGOUVARDOS K and FLAOUNAS I (2014) CycloTRACK (v1.0) – tracking winter extratropical cyclones based on relative vorticity: Sensitivity to data filtering and other relevant parameters. *Geoscientific Model Development*, 7(4):1841–1853
- FRANK J and MASSEY J (1951) The Kolmogorov-Smirnov test for goodness of fit. *Journal of the American Statistical Association*, 46(253):68–78
- FRÍAS MD, ITURBIDE M, MANZANAS R, BEDIA J, FERNÁNDEZ J, HERRERA S, COFIÑO AS and GUTIÉRREZ JM (2018) An R package to visualize and communicate uncertainty in seasonal climate prediction. *Environmental Modelling and Software*, 99:101 – 110
- GIBSON J, KÅLLBERG P, UPPALA S, HERNANDEZ A, NOMURA A and SERRANO E (1997) ERA description. Technical Report 1, ECMWF, Shinfield Park, Reading
- GIORGETTA MA ET AL. (2013) Climate and carbon cycle changes from 1850 to 2100 in MPIi-ESM simulations for the Coupled Model Intercomparison Project phase 5. *Journal of Advances in Modeling Earth Systems*, 5(3):572–597
- HANLEY J and CABALLERO R (2012) Objective identification and tracking of multicentre cyclones in the ERA-Interim reanalysis dataset. *Quarterly Journal of the Royal Meteorological Society*, 138:612 – 625
- HAZELEGER W ET AL. (2010) EC-Earth: A seamless earth-system prediction approach in action. *Bulletin of the American Meteorological Society*, 91(10):1357–1364
- HEWSON TD and TITLEY HA (2010) Objective identification, typing and tracking of the complete life-cycles of cyclonic features at high spatial resolution. *Meteorological Applications*, 17(3):355–381
- HODGES KI, HOSKINS BJ, BOYLE J and THORNCROFT C (2003) A comparison of recent reanalysis datasets using objective feature tracking: Storm tracks and tropical easterly waves. *Monthly Weather Review*, 131(9):2012–2037
- INATSU M (2009) The neighbor enclosed area tracking algorithm for extratropical wintertime cyclones. *Atmospheric Science Letters*, 10:267 – 272

- ITURBIDE M, BEDIA J, HERRERA S, BAÑO-MEDINA J, FERNÁNDEZ J, FRÍAS MD, MANZANAS R, SAN-MARTÍN D, CIMADEVILLA-ALVAREZ E, COFIÑO AS and GUTIÉRREZ JM (2018) climate4R: An R-based open framework for reproducible climate data access and post-processing. *Environmental Modelling and Software*
- IVERSEN T, BENTSEN M, BETHKE I, DEBERNARD JB, KIRKEVÅG A, SELAND Ø, DRANGE H, KRISTJANSSON JE, MEDHAUG I, SAND M and SEIERSTAD IA (2013) The Norwegian Earth System Model, NorESM1-M – Part 2: Climate response and scenario projections. *Geoscientific Model Development*, 6(2):389–415
- KEW SF, SPRENGER M and DAVIES HC (2010) Potential vorticity anomalies of the lowermost stratosphere: A 10-yr winter climatology. *Monthly Weather Review*, 138(4):1234–1249
- KLEIN-TANK AMG, WIJNGAARD JB, KÖNNEN GP, BÖHM R, DEMARÉE G, GOCHEVA A, MILETA M, PASHIARDIS S, HEJKRLIK L, KERN-HANSEN C, HEINO R, BESSEMOULIN P, MÜLLER-WESTERMEIER G, TZANAKOU M, SZALAI S, PÁLSDÓTTIR T, FITZGERALD D, RUBIN S, CAPALDO M, MAUGERI M, LEITASS A, BUKANTIS A, ABERFELD R, VAN ENGELEN AFV, FORLAND E, MIETUS M, COELHO F, MARES C, RAZUVAEV V, NIEPLOVA E, CEGNAR T, LÓPEZ JA, DAHLSTRÖM B, MOBERG A, KIRCHHOFFER W, CEYLAN A, PACHALIUK O, ALEXANDER LV and PETROVIC P (2002) Daily dataset of 20th century surface air temperature and precipitation series for the european climate assessment. *International Journal of Climatology*, 22(12):1441–1453
URL <https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/joc.773>
- KOENIGK T, BRODEAU L, GRAVERSEN RG, KARLSSON J, SVENSSON G, TJERNSTRÖM M, WILLÉN U and WYSER K (2013) Arctic climate change in 21st century CMIP5 simulations with EC-Earth. *Climate Dynamics*, 40(11):2719–2743
- KOUROUTZOGLOU J, FLOCAS HA, HATZAKI M, KEAY K, SIMMONDS I and MAVROUDIS A (2015) On the dynamics of a case study of explosive cyclogenesis in the Mediterranean. *Meteorology and Atmospheric Physics*, 127:49 – 73.
Export Date: 18 September 2015
- LIBERATO M (2014) The 19 January 2013 windstorm over the North Atlantic: large-scale dynamics and impacts on Iberia. *Weather and Climate Extremes*, 5-6:16 – 28

- LIBERATO M, PINTO J, TRIGO I and TRIGO R (2011) Klaus - an exceptional winter storm over Northern Iberia and Southern France. *Weather*, 66:330 – 334
- LIBERATO MLR, PINTO JG, TRIGO RM, LUDWIG P, ORDÓÑEZ P, YUEN D and TRIGO IF (2013) Explosive development of winter storm Xynthia over the Southeastern North Atlantic Ocean. *Natural Hazards and Earth System Sciences Discussions*, 1:443–470
- MANABE S and WETHERALD R (1967) Thermal equilibrium of the atmosphere with a given distribution of relative humidity. *Journal of the Atmospheric Sciences*, 24(3):241–259
- MICHAELIS AC, WILLISON J, LACKMANN GM and ROBINSON WA (2017) Changes in winter North Atlantic extratropical cyclones in high-resolution regional pseudo-global warming simulations. *Journal of Climate*, 30(17):6905–6925
- NEU U (2009) Influence of global warming on extratropical storms. Technical report, Swiss Reinsurance Company Ltd
URL http://www.sepanso.org/gironde/IMG/pdf/influence_of_extratropical_storms_factsheet.pdf
- NEU U, AKPEROV MG, BELLENBAUM N, BENESTAD R, BLENDER R, CABALLERO R, COCOZZA A, DACRE HF, FENG Y, FRAEDRICH K, GRIEGER J, GULEV S, HANLEY J, HEWSON T, INATSU M, KEAY K, KEW SF, KINDEM I, LECKEBUSCH GC, LIBERATO MLR, LIONELLO P, MOKHOV II, PINTO JG, RAIBLE CC, REALE M, RUDEVA I, SCHUSTER M, SIMMONDS I, SINCLAIR M, SPRENGER M, TILININA ND, TRIGO IF, ULBRICH S, ULBRICH U, WANG XL and WERNLI H (2013) IMILAST: A community effort to intercompare extratropical cyclone detection and tracking algorithms. *Bulletin of the American Meteorological Society*, 94(4):529–547
- POSSIA NE (2002) An explosive cyclogenesis over land. *Atmósfera*, 15:01–18
- R CORE TEAM (2018) *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria
URL <https://www.R-project.org/>
- REED RJ, ALBRIGHT MD, SAMMONS AJ and UNDÉN P (1988) The role of latent heat release in explosive cyclogenesis: Three examples based on ECMWF operational forecasts. *Weather and Forecasting*, 3(3):217–229

- ROEBBER PJ (1989) On the statistical analysis of cyclone deepening rates. *Monthly Weather Review*, 117(10):2293–2298
- RUSCHER PH and CONDO TP (1996) Development of a rapidly deepening extra-tropical cyclone over land. Part I: Kinematic aspects. *Monthly Weather Review*, 124(8):1609–1632
- SANDERS F and GYAKUM JR (1980) Synoptic-dynamic climatology of the “bomb”. *Monthly Weather Review*, 108(10):1589–1606
- SEMMLER T, VARGHESE S, MCGRATH R, NOLAN P, WANG S, LYNCH P and O’DOWD C (2008) Regional model simulation of North Atlantic cyclones: Present climate and idealized response to increased sea surface temperature. *Journal of Geophysical Research: Atmospheres*, 113(D2)
- SERREZE MC (1995) Climatological aspects of cyclone development and decay in the Arctic. *Atmosphere-Ocean*, 33(1):1–23
- SERREZE MC, CARSE F, BARRY RG and ROGERS JC (1997) Icelandic low cyclone activity: Climatological features, linkages with the NAO and relationships with recent changes in the Northern Hemisphere circulation. *Journal of Climate*, 10(3):453–464
- SINCLAIR MR (1997) Objective identification of cyclones and their circulation intensity, and climatology. *Weather and Forecasting*, 12(3):595–612
URL [https://doi.org/10.1175/1520-0434\(1997\)012<0595:0I0CAT>2.0.CO;2](https://doi.org/10.1175/1520-0434(1997)012<0595:0I0CAT>2.0.CO;2)
- VON STORCH H, ZORITA E and CUBASCH U (1993) Downscaling of global climate change estimates to regional scales: An application to Iberian rainfall in wintertime. *Journal of Climate*, 6(6):1161–1171
- TAYLOR KE (2001) Summarizing multiple aspects of model performance in a single diagram. *Journal of Geophysical Research: Atmospheres*, 106(D7):7183–7192
- TAYLOR KE, STOUFFER RJ and MEEHL GA (2012) An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, 93(4):485–498
- ULBRICH U, LECKEBUSCH G and PINTO J (2009) Extra-tropical cyclones in the present and future climate: A review. *Theoretical and Applied Climatology*, 96:117–131

- UPPALA SM, KÅLLBERG PW, SIMMONS AJ, ANDRAE U, BECHTOLD VDC, FIORINO M, GIBSON JK, HASELER J, HERNANDEZ A, KELLY GA, LI X, ONOGI K, SAARINEN S, SOKKA N, ALLAN RP, ANDERSSON E, ARPE K, BALMASEDA MA, BELJAARS ACM, BERG LVD, BIDLOT J, BORMANN N, CAIRES S, CHEVALLIER F, DETHOF A, DRAGOSAVAC M, FISHER M, FUENTES M, HAGEMANN S, HÓLM E, HOSKINS BJ, ISAKSEN L, JANSSEN PAEM, JENNE R, MCNALLY AP, MAHFOUF JF, MORCRETTE JJ, RAYNER NA, SAUNDERS RW, SIMON P, STERL A, TRENBERTH KE, UNTCH A, VASILJEVIC D, VITERBO P and WOOLLEN J (2005) The ERA-40 re-analysis. *Quarterly Journal of the Royal Meteorological Society*, 131(612):2961–3012
URL <https://rmets.onlinelibrary.wiley.com/doi/abs/10.1256/qj.04.176>
- VOLDOIRE A, SANCHEZ-GOMEZ E, SALAS Y MÉLIA D, DECHARME B, CASSOU C, SÉNÉSI S, VALCKE S, BEAU I, ALIAS A, CHEVALLIER M, DÉQUÉ M, DESHAYES J, DOUVILLE H, FERNANDEZ E, MADEC G, MAISONNAVE E, MOINE MP, PLANTON S, SAINT-MARTIN D, SZOPA S, TYTECA S, ALKAMA R, BELAMARI S, BRAUN A, COQUART L and CHAUVIN F (2013) The CNRM-CM5.1 Global Climate Model: Description and basic evaluation. *Climate Dynamics*, 40(9):2091–2121
- WANG CC and ROGERS JC (2001) A composite study of explosive cyclogenesis in different sectors of the North Atlantic. Part I: Cyclone structure and evolution. *Monthly Weather Review*, 129(6):1481–1499
- WATANABE S, HAJIMA T, SUDO K, NAGASHIMA T, TAKEMURA T, OKAJIMA H, NOZAWA T, KAWASE H, ABE M, YOKOHATA T, ISE T, SATO H, KATO E, TAKATA K, EMORI S and KAWAMIYA M (2011) MIROC-ESM 2010: model description and basic results of CMIP5-20c3m experiments. *Geoscientific Model Development*, 4(4):845–872
- WERNLI H and SCHWIERZ C (2006) Surface cyclones in the ERA-40 dataset (1958–2001). Part I: Novel identification method and global climatology. *Journal of the Atmospheric Sciences*, 63(10):2486–2507

APPENDIX

R code for cyclone tracking application. Xynthia cyclone

In order to illustrate the use of the functions developed in this work, the R code required to display a cyclone tracking example is displayed in the present appendix. In the example, ERA-Interim reanalysis data with 6 hourly and 0.75° resolution is used to obtain Xynthia cyclone tracking. This R language script is able to reproduce the Figure 4.1 where the tracking of the cyclone Xynthia is shown. This example presents the easy use of the functions defined in the `cyclonTrackR` package to obtain cyclone centers and their respective trajectories.

First, the R packages need to carry out the example are called. `loadeR` is used to download variables, it has to be installed previously (more information about the installation of the `climate4R` packages available in <https://github.com/SantanderMetGroup>).

```
devtools::install_github(c("SantanderMetGroup/loadeR.java",  
                           "SantanderMetGroup/loadeR"))  
library(loadeR)
```

Apart from `loadeR` other packages are called. If necessary install the packages.

```
library(sp)  
library(mopa)  
library(lubridate)
```

`cyclonTrackR` is freely accessible in GitHub (<https://github.com/SantanderMetGroup/cyclonTrackR>), but is not already build as a proper package to be installed

directly from R. We are working on that and in the near future the package will be installed as other R packages in GitHub. In the mean time, the R script with the functions is called as:

```
source("cyclonTrackR.R")
```

Once the packages are installed and loaded, the variables needed to track cyclones, SLP and vorticity, are obtained. The variables are downloaded from MeteoGroup's UDG, logging in is easy using the function *loginUDG* from *loadR*. (The registration can be made in <https://meteo.unican.es/trac/wiki/udg/registration>)

```
loginUDG(username = "", password = "")
```

After that, the function *loadGridData* is used to download the variables. Before that some arguments such as dataset, year, season and the area of study have to be defined. Here the period of occurrence of Xynthia is selected.

```
# Define date
years<-2010
season <- 1:12
# Define area
lonLim <- c(-50,40)
latLim <- c(15,75)

# ERA-Interim reanalysis Dataset URL
dataset <- 'http://meteo.unican.es/tds5/dodsC/interim/interim075.ncml'

# Download SLP
slp <- loadGridData(dataset = dataset,
                    var = "psl",
                    season = season,
                    years = years,
                    lonLim = lonLim,
                    latLim = latLim,
                    time = "none",
                    aggr.d = "none")

# Download zg and obtain Vorticity with laplacian
zg <- loadGridData(dataset = dataset,
                  var = "zg850",
                  season = season,
                  years = years,
                  lonLim = lonLim,
                  latLim = latLim,
                  time = "none",
                  aggr.d = "none")
```

```
vo <- laplacian(zg)
rm("zg")
```

Then, all possible cyclone centers are obtained using the function *getCyclonCenters* defined in *cyclonTrackR* and the variables downloaded.

```
# Define arguments
seek.radius <- 6
slp.diff.threshold <- 10
vo.diff.threshold <- 1e-6
lap.diff.threshold <- 20
ndr.threshold <- 2.5
vo.threshold <- 1e-5
criteria <- "global"

# Searching cyclone centers
Centers<-getCyclonCenters(slp,
                          vo,
                          seek.radius = seek.radius,
                          slp.diff.threshold = slp.diff.threshold,
                          vo.diff.threshold = vo.diff.threshold,
                          lap.diff.threshold = lap.diff.threshold,
                          ndr.threshold = ndr.threshold,
                          vo.threshold = vo.threshold,
                          criteria = criteria,
                          wss = NULL)
```

In the same way and with the output of the previous function, all the cyclones trajectories developed in Xynthia's date are obtained, using *getCyclonTrack* function.

```
# Define arguments
max.length <- 20
cyclon.date <- "2010-02-27"# Xynthia date
list.date <- slp$Dates$start

# Defining cyclone tracking
cyclonTrack <- getCyclonTrack(Centers,
                              seek.radius = seek.radius,
                              ndr.threshold = 1.5,
                              vo.threshold = vo.threshold,
                              max.length = max.length,
                              cyclon.date = cyclon.date,
                              list.date = list.date,
                              criteria = criteria)
```

Finally, Xynthia cyclone track with points showing the value of vorticity is plotted, obtaining the result shown in Figure 4.1.

```
# (lat, long)
po <- SpatialPoints(cbind(cyclonTrack[[1]][[2]][,5],
cyclonTrack[[1]][[2]][,6]))

# Vorticity value
dat <- as.data.frame(cyclonTrack[[1]][[2]][,3])
colnames(dat) <- "y"

kl <- SpatialPointsDataFrame(po, data = dat)

spplot(kl,
       zcol = "y",
       sp.layout = list(wrld, first = F),
       colorkey = TRUE, xlim = c(-35,25), ylim = c(20,70),
       main = list(paste0(cyclonTrack[[1]][[1]][1],'_--_',
cyclonTrack[[1]][[1]][length(cyclonTrack[[1]][[1]])]),
                  cex = 0.9),
       sub='vorticity', cex = 1)
```