The Role of Physical Parameterization Schemes in Capturing the Characteristics of Extratropical Cyclones Over the South Pacific Ocean

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Abstract  The extratropical cyclone (ETC) of August 2015 in central Chile was investigated using the WRF model to analyze the sensitivity of meteorological variables to different physical parameterization schemes. This study assesses the performance of different physical schemes in the simulation of track, core pressure, mean sea level pressure, wind direction and wind speed associated with ETC over the South Pacific. The analysis uses a total of 36 sensitivity experiments, consisting of: two microphysics schemes; three surface layer and planetary boundary layer; two cumulus schemes; two longwave and shortwave radiation; and Noah for land surface. Sensitivity experiments indicate that the cumulus, planetary boundary layer and surface layer scheme have a fundamental role in the characterization of ETC track and intensity, while the microphysics scheme plays a secondary role in determining these variables. On the other hand, long- and shortwave radiation do not have a significant impact. The sensitivity experiments indicate that exp24 provides the best results overall. The results of this work allow the selection time of the different physical schemes to be optimized according to the ETC characteristics that are to be simulated.

1. Introduction

Extratropical cyclones (ETC) are a dominant feature of the midlatitudes (Mäll et al., 2017, 2020; Ulbrich et al., 2006; Yáñez-Morroni et al., 2018). The most intense of these ETC can have huge socioeconomic repercussions on the impacted regions due to the associated strong winds, heavy rain and storm surges (Befort et al., 2018; Bitencourt et al., 2011; Catto, et al., 2010; Domingues et al., 2019; Parise et al., 2009; Pezzi et al., 2016; Piva et al., 2008). Thus, prediction of ETC characteristics and paths is important in terms of disaster planning, prevention and mitigation measures (Ulbrich et al., 2009).

Mesoscale numerical models are sophisticated tools that are essential complements to the traditional study of atmospheric dynamics (Pradhan et al., 2019). Currently, the Weather Research and Forecasting model (WRF) is widely used to simulate a wide range of weather phenomena (Feng et al., 2019; Skamarock et al., 2008; Wang et al., 2017; Zhang et al., 2017). The WRF is a mesoscale model that solves the three-dimensional Euler equations. This mesoscale model allows different physical and numerical options to be applied to a set of atmospheric/geographic scales (Gonzalez Alonso-de-Linaje et al., 2019; Skamarock et al., 2008). However, many physical processes (e.g., cloud effects, cloud detrainment, surface emission, surface fluxes, albedo, downward SW and LW, among others) cannot be solved within the dynamical core of the model and must be parameterized. The physical schemes of the WRF model take into account microphysics, cumulus, surface layer (SL), land surface model (LS), planetary boundary layer (PBL) and long- and shortwave radiation components.

Various studies have explored WRF’s hindcast abilities and subsequent sensitivity configurations by investigating different physical parameterizations and horizontal resolutions for tropical cyclones, while few have done so for ETCs. The results of tropical cyclone simulations show that cumulus and microphysical parameterizations play an important role in cyclone track prediction (Fovell & Su, 2007; Krishna, 2014; Li & Pu, 2008; Loh et al., 2010; Mallard and Lackmann, 2006; Mylonas et al., 2019; Nasrollahi et al., 2012; Parodi et al., 2017; Zhu & Zhang, 2006). Rao and Prasad (2007) suggested that PBL controls the genesis and intensification, while Parodi et al. (2017) and Pattanayak et al. (2012) indicated that cumulus parameterizations, together with PBL and microphysics parameterizations, play a more significant role in track and intensity than the other physical schemes of the model. However, Loh et al. (2010) concluded that PBL parameterization schemes do not have a significant
impact on the prediction of track and intensity. Finally, Mylonas et al. (2019) and Loh et al. (2010) indicated that a higher horizontal resolution increases the accuracy of predicted tropical cyclone trajectory and other characteristics. In contrast, Pradhan et al. (2018) examined the role of cumulus parametrization for ETC over the North Atlantic Ocean, concluding that it is important for determining the trajectory and intensification of the storm. Meanwhile, Pradhan et al. (2019) analyzed the impact of different PBL schemes (the Quasi Normal Scale Elimination [QNSE], University of Washington Moist Turbulence [UWMT] and Yonsei University schemes [YSU]) on the prediction of rapidly developing North Atlantic mid-latitude wind storms. Their sensitivity experiments indicated slight differences among the schemes in reproducing the storm tracks, with the QNSE and UWMT schemes showing greater accuracies than YSU in capturing the cyclogenesis, wind and pressure fields during the explosive stage of the storms. However, the best set of parameterization schemes in WRF may not be the same for all storms (Catto et al., 2010; Miglietta et al., 2015; Pytharoulis et al., 2018), as it depends on the purpose (Powers et al., 2017). Pezzi et al. (2016) reported that there is a lack of ETC studies over South America that allow a greater understanding of the effects of physical parameterization on the prediction of ETC genesis and intensification in this region.

The analysis of mitigation measures to reduce socioeconomic impacts of extratropical cyclones in South America requires a more comprehensive understanding of the various physical parameterization schemes in the WRF model. Therefore, this study has two main objectives: (a) to assess the performance of different physical schemes in order to evaluate the track, core pressure, mean sea level pressure, wind direction and wind speed, and (b) to assess the ability of the WRF model to represent the characteristics of the ETC in different stages over the ocean and complex topography. To this end, the August 2015 event in central Chile was analyzed. This article is organized as follows: Section 2 describes the synoptic conditions of the analyzed ETC. Section 3 describes the data sources used for ETC simulation and explains the methodology for assessing model uncertainty. Section 4 presents the results: conditions for different storm stages, comparison with the existing meteorological hindcast model, sensitivity experiments performance and the sensitivity of physical parametrization schemes. Section 5 presents the discussion of the results and Section 6 concludes this study.

2. **Synoptic Features of the ETC of August 2015**

For the analysis, the authors selected a mid-latitude South Pacific winter storm that occurred in August 2015. This storm was one of the most powerful on record in Chile, with winds reaching 110 km/hr, with waves as high as 8 meters reported (Winckler et al., 2017). The August 2015 ETC formed at 32°S in the Pacific Ocean, some 1,700 km off the Chilean coast. From cyclogenesis (06 August 18:00 UTC), the vortex moved eastward before shifting southeast on August 8th 06:00 UTC. It reached a minimum core pressure of 981 hPa on August 8th 00:00 UTC (Winckler et al., 2017). During the night of August 9th at 01:00 UTC, the storm reached the Chilean coast in the Ñuble Region. The storm caused a wide range of damage, including flooding due to 75 mm of rainfall, suspension of port operations and severe damage to the coastal infrastructure along the 500 km of coastline (from the Coquimbo Region to the Bío-Bío Region). The greatest storm impact occurred in the Valparaíso Region (see Figure 1) (Campos-Caba, 2016).

The waves caused the fissure of the Valparaíso port breakwater, the displacement of tetrapods and the loss of the fill material that supports the boardwalks of the region. In the Valparaíso Region, the frontal system left one dead and affected 4,276 people, with a total of 533 homes damaged to various extents. In the Coquimbo Region, the storm caused one death, with 54,087 people affected and a total of 2,002 homes damaged. In other regions, four deaths were reported. In addition, the economic impact was estimated to be more than $7.2 million USD (Winckler et al., 2017).

3. **Methodology**

To study the meteorological characteristics of the August 2015 ETC, the Advanced Weather Research WRF model (version 4.1.2; Skamarock et al., 2019) was used. The sensitivity experiments included four nested domains (see Figure 1) with a two-way nesting strategy. Furthermore, hybrid option and treatment of the SSTs by lateral conditions were considered. The largest domain had a resolution of 24.3 km and covered an area of 62.1° to 107.1°W and 16.6° to 43.6°S, effectively covering most of the storm's evolution during its life cycle, from its formation in the southwest until its arrival at the Chilean coast. Nested domains had a nest ratio of 3, thus D2
and D3 had a resolution of 8.1 and 2.7 km respectively. The innermost domain (D4) used a resolution of 0.9 km to resolve most of the areas affected by the ETC, which extended from the Valparaíso Region to the O’Higgins Region. Following the González-Alonso de Linaje et al. (2019) results, the sensitivity experiments considered 61 sigma layers non-manually defined and a pressure top at 1 hPa.

WRF was forced by the products of the Reanalysis of the Climate Forecast System CFSv2 (Saha et al., 2014; e.g., after; Mäll et al., 2020), which for pressure levels has a horizontal resolution of 0.5° and surface horizontal resolution of 0.204°. Lateral conditions were updated every 6 hr. Domain 1 had the largest simulation period, from 04 August 06:00 UTC to 11 August 00:00 UTC, while Domain 2 covered the period from 05 August 00:00 UTC to 11 August 00:00 UTC. Finally, Domain 3 and 4 had a simulation period from 06 August 00:00 UTC to 11 August at 00:00 UTC.

Based on the recommendations of Gonzalez Alonso-de-Linaje et al. (2019), Mattar and Borvarán (2016), Nakamura et al. (2017) and Pradhan et al. (2018), a total of 36 physical parametrization configurations were utilized. All physical configuration sets are composed of three surface layer and planetary boundary layer schemes, two microphysics schemes, three cumulus schemes, two long- and shortwave radiation schemes and one land surface scheme, which are summarized in Table 1.

Cumulus parameterization was turned off for domain 4 as the horizontal resolution in this domain is considered fine enough for adequate resolution of cumulus processes (Pennelly et al., 2014).

3.1. Data Source

The analysis considers data from 8 meteorological stations (see Figure 1) provided by the Dirección Meteorológica de Chile (http://www.meteochile.cl/PortalDMC-web/index.xhtml). From these stations, wind speed ($W_v$), wind direction ($W_d$) and mean sea level pressure ($P_0$) data were used. Meanwhile, track ($T_r$) and core pressure ($P_c$), were compiled and obtained objectively from the weather charts prepared by the Chilean Navy Weather Service (https://www.armada.cl/), the Dirección Meteorológica de Chile and the Dirección de Aeronáutica Civil (https://www.dgac.gob.cl/). Finally, the European Center for Medium-Range Weather Forecast (ECMWF) Reanalysis V5 (ERA5) dataset (Hersbach et al., 2020) was used for the wind and pressure field validation.
Wind direction, wind speed and mean sea level pressure data were obtained through nearest neighbor interpolation method from Domain 4, except for the La Punta location, for which data were taken from Domain 2. In order to determine the core location and ETC track, the 2D Vortex Core Tracking algorithm proposed by Zigunov (2020) was used and modified. This modification consisted of including the effects of wind magnitude and perturbation pressure in the Gamma_1 function (Endrikat, 2020) in order to avoid selecting vortexes in the mountainous areas.

### 3.2. Sensitivity Experiments Performance

The performance of each sensitivity experiment, following the methodology proposed by Beyá et al. (2017), for different combinations of error statistical parameters associated with storm characteristics. The statistical parameters were combined to form different sensitivity experiments performance scores (SEPS), ranging from 0 (worst) to 1 (best).

#### 3.2.1. Error Statistical Parameters

First, sensitivity experiments performance was assessed by comparing the simulated data and observed data (described in section 3.1) using the following error statistical parameters: coefficient of determination $R^2 = [0, 1]$, root mean square error $\text{RMSE} = [0\infty]$, and $\text{BIAS} = [-\infty \infty]$ (Montgomery et al., 2008). These parameters are described below:

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (S_i - O_i)^2}$$

(1)

$$\text{BIAS} = \frac{1}{N} \sum_{i=1}^{N} (S_i - O_i)$$

(2)

$$R^2 = \frac{\sigma^2_{OS}}{\sigma^2_O \sigma^2_S}$$

(3)

Observed data are denoted by $O_i$, while simulated data are denoted by $S_i$, where the subscript $i$ indicates that the value can be compared in terms of both spatial and temporal proximity. The total number of comparisons is denoted by $N$, $\sigma^2_{OS}$ is the covariance of $(O, S)$, $\sigma^2_O$ is the variance of the variable $O$ and $\sigma^2_S$ is the variance of the variable $S$.
The above statistical parameters were used to evaluate $T$, $P$, and $W_t$, $W_d$ and $P_z$ at meteorological stations (see Figure 1). In order to analyze the wind direction at meteorological stations, RMSE, BIAS and $R^2$ were used:

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i \in I} (S_i - O_i)^2 + \frac{1}{N} \sum_{i \in I^c} (360 - |S_i - O_i|)^2}$$

$$\text{BIAS} = \frac{1}{N} \sum_{i \in I} (S_i - O_i)/360 + \frac{1}{N} \sum_{i \in I^c} (360 - S_i - O_i)/360$$

where $I = \{i \in \{1, 2, 3, \ldots, N\} / |S_i - O_i| \leq 180\}$ and $I^c = \{1, 2, 3, \ldots, N\} \setminus I$

$$R^2 = \frac{4 \left( \left( \sum_{i=1}^{N} \cos(O_i) \cos(S_i) \right) \left( \sum_{i=1}^{N} \sin(O_i) \sin(S_i) \right) - \left( \sum_{i=1}^{N} \cos(O_i) \sin(S_i) \right) \left( \sum_{i=1}^{N} \sin(O_i) \cos(S_i) \right) \right)^2}{\left( \sum_{i=1}^{N} \cos(O_i) \right)^2 - \left( \sum_{i=1}^{N} \sin(O_i) \right)^2}$$

These parameters were selected because they are commonly used in model performance assessments and represent different characteristics of the error (e.g., Arduhin et al., 2011; Dee et al., 2011).

The average of the statistical parameters for $T$, $P$, $W$, $W_d$ and $W_t$ was used; thus, the five statistical meteorological parameters have the same importance. In addition, since the statistical parameters cover different ranges, the following normalization was undertook to bind their values between 0 and 1:

$$\hat{x} = \frac{x - \min(x)}{\max(x) - \min(x)}, \hat{x} = [0, 1] \ for \ x = R^2$$

$$\hat{x} = 1 - \frac{x - \min(x)}{\max(x) - \min(x)}, \hat{x} = [0, 1] \ for \ x = \text{RMSE}$$

$$\hat{x} = 1 - \frac{|x| - \min(|x|)}{\max(|x|) - \min(|x|)}, \hat{x} = [0, 1] \ for \ x = \text{BIAS}$$

where $\hat{x}$ is the normalized error parameter $x$.

The SEPS for the error statistical parameters was defined as:

$$\text{SEPS}^{EP}_{(i,k)} = \sum_{j=1}^{3} \frac{1}{N^{EP}} \cdot \hat{x}_{(i,j,k)} \ for \ j = R^2, \text{RMSE}, \text{BIAS}$$

Where $i$ represents the index of each test, $j$ is the index of the error statistical parameter, $k$ is the index of the meteorological statistical parameter and $N^{EP}$ is total error statistical parameter ($N^{EP} = 3$). All the error statistics have the same importance factor due to the best-performing test changing significantly depending on the favored error parameter (Beyá et al., 2017).

### 3.2.2. Meteorological Parameters

In the second level, the SEPS was calculated for meteorological parameters from meteorological stations ($W_t$, $W_d$, $P_z$) and weather charts ($T$, $P_z$).

The sensitivity experiments performance score for each meteorological parameters is defined as a linear combination of the performance scores for error statistical parameters:

$$\text{SEPS}^{MP}_{(i,j)} = \sum_{k=1}^{5} \frac{1}{N^{MP}} \cdot \text{SEPS}^{EP}_{(i,j,k)} \ for \ k = W_t, W_d, P_z, T, P_z$$

Where the weight factor for meteorological parameter $1/N^{MP}$ was set to 0.2, giving the same importance to all meteorological parameters for track, core pressure, wind speed, wind direction and pressure relative to mean sea level at the meteorological stations.
3.2.3. Scheme Ranking

Finally, schemes were ranked according to their performance in the different SEPS for the error statistical parameters (SEPS\(\text{SEPS}_{\text{SEPS}}\)) and general performance (SEPS\(\text{SEPS}_{\text{MP}}\)).

3.3. Uncertainty

In order to assess and quantify the reliability of the sensitivity experiments, uncertainty analysis was carried out using the Generalized Likelihood Uncertainty Estimation Framework (GLUE) (Beven & Binley, 1992). GLUE is a statistical method for simultaneously calibrating the input parameters and estimating the uncertainty of predictive models. The GLUE methodology is based upon a large number of models runs performed with different sets of input parameter, sampled randomly from prior specified parameter distributions. The simulation result corresponding to each parameter set is evaluated by means of its likelihood value, which quantifies how well the model output conforms to the observed values. The higher the likelihood value, the better the correspondence between the model simulation and observations. Simulations with a likelihood value larger than a user-defined acceptability threshold will be retained to determine the uncertainty bounds of the model outputs (Li et al., 2013).

GLUE considered the sensitivity experiments performance score SEPS\(\text{SEPS}_{\text{SEPS}}\) and SEPS\(\text{SEPS}_{\text{MP}}\) as objective functions and a confidence interval of 95%. GLUE with SEPS\(\text{SEPS}_{\text{SEPS}}\) as an objective function allows the reliability of the sensitivity experiments in terms of each single variable to be determined, while SEPS\(\text{SEPS}_{\text{MP}}\) indicates the reliability of the sensitivity experiments by considering the average of all variables. It was decided to use the SEPS as an objective function due to the fact that it considers different characteristics of the observed data \((R^2\) determines if the simulated and observed data have the same patterns, BIAS is the relative percentage difference between the average of the simulated and observed data and RMSE reflects the magnitude of the error and it is influenced by larger errors. On the other hand, to distinguish between realistic (behavioral) and unrealistic (nonbehavioral) data sets, a threshold of \(\bar{x} + \sigma\) was considered, where \(\bar{x}\) and \(\sigma\) are the median and standard deviation of the likelihood function, respectively. Finally, the threshold and objective function proposal presented in this study avoid subjectivity (Blasone et al., 2008; Mantovan & Todini, 2006; Thiemann et al., 2001).

4. Results

The results obtained from the case study simulations are presented in this section. SEPS\(\text{SEPS}_{\text{SEPS}}\) and SEPS\(\text{SEPS}_{\text{MP}}\) for each physical parameterization, simulated track, core pressure, wind speed and direction and mean sea level pressure were compared with the observed data provided by the Chilean Air Force Meteorological Directorate (see Section 3.1).

Figure 2 illustrates core pressure, track, wind speed and direction, mean sea level pressure and overall sensitivity experiments performance for microphysics, SL, PBL, long- and shortwave radiation and cumulus. The performance of each parameterization scheme was determined through the sensitivity experiments performance score median value. The upper and lower quartile represent the non-linear interaction between the different physical parameterizations. It is observed that the microphysics scheme affects track and core pressure, slightly affects wind speed and mean sea level pressure and does not present significant variations in wind direction and general performance. This could be related to the fact that microphysics scheme resolve cloud, water vapor and precipitation processes. Thus, cloud microphysical processes are important because of their direct influence on cold-pool strength and latent heating, which can affect wind fields close to the surface.

Since the SEPS mean value does not change among long- and shortwave radiation schemes, these physical schemes do not have an impact on the representation of the analyzed variables. Longwave radiation compute clear-sky and cloud, upward and downward radiation fluxes and it consider infrared emission from layers. While, shortwave radiation compute clear sky and cloudy solar fluxes, including the annual and diurnal solar cycle, also, consider downward and reflected fluxes. They consider primarily a warming effect in clear sky and it is an important component of surface energy balance. Therefore, long- and shortwave radiation schemes do not considerably affect the analyzed variables in this study.

The atmospheric SL is the lowest part of the PBL, and it determines the atmosphere-land interaction. The SL scheme handles the fluxes of heat, moisture and momentum from the model surface to the boundary layer above.
On the other hand, PBL is the lower troposphere portion directly affected by the earth’s surface. The exchanges of moisture, heat, and momentum occur within the PBL through mixing associated with turbulent eddies. These eddies influence the way in which lower-tropospheric thermodynamic and kinematic structures evolve. Thus, the necessary conditions of humidity and stability for the generation and intensification of cyclones are highly influenced by the PBL scheme. Figure 2, show that SL and PBL influence ETC intensity and track performance. Furthermore, it is observed that the MM5 Surface Layer scheme, together with the YSU PBL scheme, performs better in the characterization of track, mean sea level pressure and overall, while the MYNN surface layer scheme, together the MYNN3 PBL scheme, more accurately simulates core pressure and wind direction.

Finally, cumulus is crucial in the characterization of track, core pressure, wind direction and mean sea level pressure and slightly affects wind speed. In this respect, the GF cumulus scheme performs better in core pressure, mean sea level pressure and wind speed and provides the best trajectory and the KF cumulus scheme predicts more accurate wind direction and has the best general performance.

Figure 3 shows mean sea level pressure (contours), wind speed (shaded contours) and wind direction (vectors) for ERA5 (left), and for the experiments with best general performance SEPS(︤MP) (center) and worst general performance SEPS(︤MP) (right) at 20 hr intervals. It is observed that the WRF model manages to capture the ETC in all the configurations of physical parameterizations analyzed. In general, WRF underestimates pressure and wind speed during the early stages, although during the explosive phase and landfall WRF is able to capture these characteristics. Furthermore, it is observed that the trajectory obtained by exp24 (best SEPS(︤MP) fits the observed data, unlike exp09 (worst SEPS(︤MP), which has a deviation toward the north. Both the best and the worst scenarios, however, overestimate the wind speed in the mountainous area; there is also a discrepancy between the pressure field in the continental area during all storm stages.

Figures 4–7 show the results for the observed, and simulated ETC characteristics considered through GLUE method with a 95% confidence interval (see Section 3.2). A good fit between the observed and simulated trajectories can be seen for sensitivity experiments that show good behavior (see Figure 4a). Furthermore, the uncertainty decreases when the sensitivity experiments performance score for the general performance SEPS(︤MP) (greenish-gray shade) is considered.

The observed core pressure reached a minimum of 980 hPa on 07 August at 21:00 UTC (see Figure 4b). It is observed that the WRF model does not manage to capture the increase in core pressure before 07 August, although it is able to reproduce the core pressure of the event with a delay of three hours. Meanwhile, it is observed that
The observed and simulated mean sea level pressure values for the Viña del Mar, Santo Domingo, San Diego and Marchigue stations are shown in Figure 5. The comparison period covers 5 days, from 06 to 11 August. At all the stations two instances of pressure drops in measurements were observed, the first on 06 August (previous low-pressure system) and the second on 08 August. The pressure curve at the Viña del Mar, San Diego and Marchigue stations present a delay, while at the Santo Domingo station this delay is smaller given that it is closer to the path of the ETC. In addition, it can be seen that the sensitivity experiments performance score for general performance $\text{SEPS}^{\text{ME}}_\text{g}$ indicates less uncertainty compared to the sensitivity experiments performance score for mean sea level pressure $\text{SEPS}^{\text{ME}}_\text{P}$ and the other sensitivity experiments performance score for meteorological variables $\text{SEPS}^{\text{EP}}_{(i)}$. In general, the sensitivity experiments manages to capture the variation in mean sea level pressure; however, there are discrepancies at the stations that are further from the path of the ETC.

Simulated and observed wind direction data are illustrated in Figure 6, where high wind direction variability is observed. There is a predominant north wind (with respect to true north) prior to storm cyclogenesis, between 07 and 08 August the wind presents a south direction and after 08 August the direction changes to the north again. It is observed that the sensitivity experiments presents a lower wind direction variability at the coastal stations (Viña del Mar and Santo Domingo) compared to the stations in the central valley (San Diego and Marchigue), which generates an increase in the uncertainty of this variable (see Figure 7).
The observed and simulated wind speeds at the different meteorological stations are presented in Figure 7. Two peaks associated with the two frontal systems are observed. According to observations, there are peaks speeds of 19 m/s at the Viña del Mar station, 13 m/s at the Santo Domingo station and 9 m/s and 8 m/s at the San Diego and Marchigue stations, respectively. Wind speeds are higher at the Viña del Mar and Santo Domingo stations since they are located on the coastline, while at the Marchigue and San Diego stations wind speeds are lower since they are located in the central valley. It is observed that the sensitivity experiments manages to represent the magnitude of the wind at the different stations, capturing both the peaks and calm periods; however, an increase in uncertainty is noted during the peaks due to variability in the magnitude of the wind.

Figure 4. Extratropical Cyclone (ETC) track (a) and core pressure (b). Observed data in black; green and yellow shades are the 95% confidence interval for the sensitivity experiments performance score for track and core pressure ($\text{SEPS}_{\text{track}}$ & $\text{SEPS}_{\text{core}}$) and the gray shade is the 95% confidence interval for the sensitivity experiments performance score for general performance $\text{SEPS}^{\text{SEPS}}$; red, blue and purple lines are the 95% confidence interval for the sensitivity experiments performance score for pressure, wind speed and wind direction.
5. Discussion

The WRF sensitivity experiments manage to represent the characteristics of the storm over the ocean; however, there are discrepancies over the continental zone due to the complex Chilean topography and the fact that ERA5 are reanalysis data that have a larger resolution than the WRF results. Furthermore, Dimitrova et al. (2016) and Siuta et al. (2017) indicated that none of the PBL parameterizations accurately predict the abrupt wind speeds near the surface in complex terrain and Pontoppidan et al. (2017) argued that increasing the vertical resolution of the computation grid near the land surface could improve the modeling results in places with complex topography.
Zhang and Li (2015) argued that a simple objective function can focus on one part of the characteristics of the observed data while another function focuses on another characteristic. Some parameters cannot be identified using the GLUE method with a simple objective function; therefore, a combined function of multiple objective functions would effectively reduce the uncertainty of the sensitivity experiments. In this study the sensitivity experiments performance scores \( A_{SEPS_E} \) and \( A_{SEPS_M} \) were used to assess the WRF physical scheme performance for each meteorological variable and overall performance. The main findings are as follows:

1. The cumulus scheme has a great impact on capturing the track, wind direction, wind speed and mean sea level pressure. This coincides with what is stated by Pradhan et al. (2018) and Pytharoulis et al. (2018), who evaluated the role of the cumulus scheme in ETC development over the North Atlantic Ocean and Tropical-Like Cyclone (Medicane) respectively. Furthermore, SL and PBL are crucial in determining the track and intensity of the ETC, which agrees with what was found by Pradhan et al. (2019). Meanwhile, the microphysics scheme has a secondary role in determining the characteristics of the ETC and long- and shortwave radiation do not affect the performance of the variables analyzed in this study. Despite the different generation mechanisms of extratropical and tropical cyclones, the impact of the physical parameters on cyclogenesis and intensification is the same for both phenomena.

2. In general, there is a good agreement between observed and simulated variables. The simulated track is similar for the sets of sensitivity experiments that consider each meteorological variable independently \( A_{SEPS_E} \). Furthermore, \( A_{SEPS_M} \) significantly decreases the uncertainty of the ETC track compared to \( A_{SEPS_E} \). Regarding the core pressure, \( SEPS_{P_c} \) gives more accurate results compared to \( SEPS_{M} \). Meanwhile, the mean sea level pressure does not present great differences between the stations located on the coastal area (Viña del Mar and Santo Domingo) and in the central valley (Marchigue and Santo Domingo). Moreover, \( SEPS_{M} \) represents mean sea level pressure with less uncertainty compared to \( SEPS_{P_c} \). Despite the complex topography of the central Chilean coastline, the sensitivity experiments simulate wind direction at all stations reasonably well, although it tends to present shortcomings in the simulation of wind direction at locations with higher terrain complexity. In this respect, less wind direction variability is observed at the coastal stations, which generates less uncertainty in this variable compared to the stations located in the central valley; however, there is a tendency to simulate stronger winds in the coastal zone compared to the stations located in the central valley. This fact is not at all surprising for offshore sites, as the WRF model considers the ocean a flat and constant surface. The discrepancies between the simulated and observed wind direction and magnitude could be related to the local conditions of the study area (coastal stations are on hills and central valley stations are in fruit tree fields).

Figure 7. Wind speed at meteorological stations. Same as Figure 3, blue shade is the 95% confidence interval for SEPS* wind speed \( SEPS_{W_S} \).
and the ability of the WRF model to describe complex topographies. This fact is crucial to incorporate into the WRF simulation because the model tends to simplify the topography and does not take into account local features that might influence the climatological characteristics of an area (Mäll et al., 2017, 2020; Yáñez-Morroni et al., 2018).

Yáñez-Morroni et al. (2018) indicated that all the parameterizations are involved in the output performance due to the complexity and non-linearity of the atmospheric equations, such that the performance of a model cannot be attributed to a single set of parameterization schemes. In addition, Powers et al. (2017) argue that parameterization schemes can be used with different types of combinations depending on the requirement and can be adjusted based on the characteristics of the meteorological event. Table 2 provides the sets of parameterization schemes that most accurately represent each meteorological variable analyzed in this study.

Based on Table 3, WSM6 microphysics, BMJ cumulus and RRTM/dudhia long- and shortwave radiation give the best representation of the ETC core pressure, while surface layer does not significantly affect the result. The best simulated track is obtained by WSM6 microphysics, MM5 surface layer, YSU PBL and GF cumulus. Mean sea level pressure at meteorological stations is well simulated by WSM6 microphysics, MYNN surface layer and MYNN3 PBL. WSM6 microphysics, MYNN surface layer and MYNN3 PBL give the best wind speed. The wind direction is relatively well represented by WSM6 microphysics, MYNN surface layer, MYNN3 PBL, RRTM/dudhia long- and shortwave Radiation. Finally, WSM3 microphysics, MYNN surface layer, MYNN3 PBL, KF cumulus, RRTM/dudhia long- and shortwave radiation give the best representation of all the variables analyzed in this study.

| Performed experiment | Microphysics | Surface layer and planetary boundary layer | Cumulus | Long- and shortwave radiation | Performed experiment | Microphysics | Surface layer and planetary boundary layer | Cumulus | Long- and shortwave radiation |
|----------------------|---------------|--------------------------------------------|---------|-------------------------------|----------------------|---------------|--------------------------------------------|---------|-------------------------------|
| Exp01                | 6             | 5/6                                        | 3       | 4/4                           | Exp19                | 3             | 5/6                                        | 3       | 4/4                           |
| Exp02                | 6             | 5/6                                        | 3       | 1/1                           | Exp20                | 3             | 5/6                                        | 3       | 1/1                           |
| Exp03                | 6             | 5/6                                        | 2       | 4/4                           | Exp21                | 3             | 5/6                                        | 2       | 4/4                           |
| Exp04                | 6             | 5/6                                        | 2       | 1/1                           | Exp22                | 3             | 5/6                                        | 2       | 1/1                           |
| Exp05                | 6             | 5/6                                        | 1       | 4/4                           | Exp23                | 3             | 5/6                                        | 1       | 4/4                           |
| Exp06                | 6             | 5/6                                        | 1       | 1/1                           | Exp24                | 3             | 5/6                                        | 1       | 1/1                           |
| Exp07                | 6             | 2/2                                        | 3       | 4/4                           | Exp25                | 3             | 5/6                                        | 3       | 4/4                           |
| Exp08                | 6             | 2/2                                        | 3       | 1/1                           | Exp26                | 3             | 2/2                                        | 3       | 1/1                           |
| Exp09                | 6             | 2/2                                        | 2       | 4/4                           | Exp27                | 3             | 2/2                                        | 2       | 4/4                           |
| Exp10                | 6             | 2/2                                        | 2       | 1/1                           | Exp28                | 3             | 2/2                                        | 2       | 1/1                           |
| Exp11                | 6             | 2/2                                        | 1       | 4/4                           | Exp29                | 3             | 2/2                                        | 1       | 4/4                           |
| Exp12                | 6             | 2/2                                        | 1       | 1/1                           | Exp30                | 3             | 2/2                                        | 1       | 1/1                           |
| Exp13                | 6             | 1/1                                        | 3       | 4/4                           | Exp31                | 3             | 1/1                                        | 3       | 4/4                           |
| Exp14                | 6             | 1/1                                        | 3       | 1/1                           | Exp32                | 3             | 1/1                                        | 3       | 1/1                           |
| Exp15                | 6             | 1/1                                        | 2       | 4/4                           | Exp33                | 3             | 1/1                                        | 2       | 4/4                           |
| Exp16                | 6             | 1/1                                        | 2       | 1/1                           | Exp34                | 3             | 1/1                                        | 2       | 1/1                           |
| Exp17                | 6             | 1/1                                        | 1       | 4/4                           | Exp35                | 3             | 1/1                                        | 1       | 4/4                           |
| Exp18                | 6             | 1/1                                        | 1       | 1/1                           | Exp36                | 3             | 1/1                                        | 1       | 1/1                           |

Note. Number indicates the number scheme in WRF manual (see Table 1).
6. Conclusions

In this study the ETC of August 2015 in central Chile was investigated through WRF model to analyze the sensitivity of wind speed, wind direction, core pressure, track and mean sea level pressure related to ETC to different physical parameterization schemes. Also, the ability of the WRF model was assessed to represent the ETC characteristics in different stages over the ocean and complex topography. Based on the findings presented in this study, the choice of the set of schemes to use in meteorological simulation applications can lead to significant differences in the results. Based on the Sensitivity Experiments Performance Score (SEPS) for each parameterization scheme, cumulus, PBL and SL play a fundamental role in the characterization of the track and intensity of the ETC, while the microphysics scheme has a secondary role in determining these variables and long- and short-wave radiation do not present a significant impact. In general, the WRF model manages to represent the track and core pressure, as well as to capture the ETC in all the analyzed configurations of physical parameterizations. In addition, it was also observed that WRF underestimates wind speed and pressure during the early stages, although during the explosive phase and landfall, WRF is able to capture these characteristics. Despite the complex topography of the region, the WRF model estimates wind speed, wind direction and pressure reasonably well.

The multivariate analysis of the different physical schemes studied allowed the non-linear interaction between physical parameterization schemes to be included in the representation of ETC characteristics, providing a greater understanding of the effects of the physical parameterization on ETC genesis and intensification. The results of this work allow the selection time of the different physical schemes to be optimized according to the characteristics of the ETC over the South Pacific that are to be simulated.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The authors would like to thank NCEP for providing the CFSv2 data (DOI: 10.5065/D61C1TXF), UCAR for providing free access to the WRF model (http://dx.doi.org/10.5065/d1ff-6p97) and the Dirección Meteorológica de Chile (http://www.meteochile.cl/PortalDMC-web/index.xhtml), Dirección Aeronáutica Civil (https://www.dgac.gob.cl/) and the European Center for Medium-Range Weather Forecast (ECMWF) Reanalysis V5 (ERA5) dataset.

| Rank | Scheme | Score | Rank | Scheme | Score | Rank | Scheme | Score |
|------|--------|-------|------|--------|-------|------|--------|-------|
| 1    | Exp10  | 1.000 | 1    | Exp14  | 1.000 | 1    | Exp20  | 0.834 |
| 2    | Exp16  | 0.958 | 2    | Exp13  | 0.960 | 2    | Exp23  | 0.827 |
| 3    | Exp24  | 0.863 | 3    | Exp20  | 0.926 | 3    | Exp14  | 0.815 |
| 4    | Exp22  | 0.826 | 4    | Exp24  | 0.870 | 4    | Exp13  | 0.769 |
| 5    | Exp09  | 0.818 | 5    | Exp02  | 0.84  | 5    | Exp31  | 0.766 |

Table 3: Different Physical Schemes Used and Their Scheme Number as Indicated in WRF Manual
(https://doi.org/10.5065/BH6N-5N20) for providing the meteorological data used to validate the model. These data set and scripts are available at Mendeley Data (doi:10.17632/2tn396tm8y.1).

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