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Chapter

Climate Models Accumulated Cyclone Energy Analysis

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Abstract

Looking at the connection between tropical cyclones and climate changes due to anthropogenic and natural effects, this work aims for information on understanding and how physical aspects of tropical cyclones may change, with a focus on accumulated cyclone energy (ACE), in a global warming scenario. In the present climate evaluation, reasonable results were obtained for the ACE index; the Coupled Model Intercomparison Project Phase 6 (CMIP6) models with lower horizontal and vertical resolution showed more difficulties in representing the index, while Max Planck Institute model demonstrated ability to simulate the climate with more accurate, presenting values of both ACE and maximum temperature close to NCEP Reanalysis 2. The MPI-ESM1-2-HR projections suggest that the seasons and their interannual variations in cyclonic activity will be affected by the forcing on the climate system, in this case, under the scenario of high GHG emissions and high challenges to mitigation SSP585. The results indicate to a future with more chances of facing more tropical cyclone activity, plus the mean increase of 3.1°C in maximum daily temperatures, and more heavy cyclones and stronger storms with more frequency over the North Atlantic Ocean may be experimented, as indicated by other studies.

Keywords: climate change, accumulated cyclone energy, SSP585 scenario, tropical cyclones, CMIP6

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1. Introduction

The challenge of connecting climate change to tropical cyclones (TCs) lies in determining that a change has occurred given natural variability whether by significant changes in climate forcing such as greenhouse gases (GHGs) or aerosols or by the sum of both natural and anthropogenic factors.

Tropical cyclone activity has complex characteristics that make it difficult to achieve robust future projections. The onset, duration, intensity, and phenomenology associated with these storms carry many uncertainties in numerical modeling, due to limitations of models to represent local/micro-scale physical processes and tangents to the computational aspect in simulating the climate of long periods, from decades to centuries.

Changes in natural variability, volcanic emissions, and solar activity have made a small contribution to the changes in climate over the last century [1, 2]. The natural cycles observed in climate records do not explain the increases in the heat content of the atmosphere, ocean, or cryosphere since the industrial age [3–6].

Earth's climate has been affected by changes in factors that control the amount of energy entering and leaving the atmosphere. These factors, known as radiative forcings, include changes in albedo through land use and cover, greenhouse gases, and aerosols. The increase in the concentration of greenhouse gases by emissions from human activities is the largest of these radiative forcings. By absorbing longwave radiation emitted by Earth and redirecting it equally in all directions, greenhouse gases increase the amount of heat retained in the climate system, warming the planet [2, 7–9].

A comparison of a model's simulation of internal multidecadal climate variability with the observed increase in an Atlantic hurricane rapid intensification metric (1982–2009) finds a highly unusual behavior in the metric result and is consistent with the long-term response sign expected by the model to anthropogenic forcing [10]. In the same direction, the 2018 US National Climate Change Assessment reports that decreases in air pollution and increases in GHGs have contributed to increases in Atlantic hurricane activity since 1970 [11].

There is growing evidence of a significant increase in the TC's proportion that become major hurricanes, although the frequency of TCs has remained roughly constant in recent decades [12–17]. A recent study showed that in the central and eastern tropical Atlantic basin during 1986–2015, the 95th percentile of 24 h intensity changes increased significantly [18]. The intensification rate of intensifying storms, another metric that is not dependent on TC frequency, exhibited significant growth during 1977–2013 in the West Pacific basin [19]. In both studies, the large-scale environment became more conducive to TC intensification over time. Areas with increases in potential intensities [20] and the largest increase in sea surface temperatures (SSTs) seem to be located with the largest positive changes in intensification rates.

How future anthropogenic warming can affect TC is an important issue, mainly due to the large social impacts they can cause [21], as discussed in previous reports of the Intergovernmental Panel on Climate Change (IPCC) [22] and World Meteorological Organization (WMO) [23].

The IPCC-AR5 [24] concludes for a 2°C global warming that there is more than 66% likelihood to the TC rainfall rates increase in the future and accompanying increase in atmospheric moisture content. Modeling studies on average indicate increase rainfall rates averaged within about 100 km of the storm by 10–15%. The TC intensities increase on average (1–10%), which would imply an even larger increase of percentage in the destructive potential per storm, assuming no reduction in storm size (responses to anthropogenic warming are uncertain).

The future projection for the global number of Category 4 and 5 storms is likely to increase due to anthropogenic warming over the twenty-first, but there is less confidence since most modeling studies project a decrease (or little change) in the overall frequency of all combined TC [24].

Links between climate and tropical cyclones were analyzed in [25], with a good understanding of the relationship at various time scales, with significant trends observed for cyclone intensity and frequency over the past decades over Atlantic. Most climate models simulate fewer tropical cyclones and stronger storms, with increase in precipitation rates. Further sea level rise is likely to increase storm threats, with studies of combined effects of floods and storms projecting that increases are due to global warming [26].

Given the importance of tropical cyclone study, and how changes induced by human actions in the terrestrial system may affect such phenomena, the aim of this study is to evaluate simulations of global numerical models of the Coupled Model Intercomparison Project Phase 6 (CMIP6) [27], by representing the recent past, and thus access future projections that may occur and indicate trends of changes in cyclone events.

2. Accumulated cyclone energy (ACE) approach

ACE uses the maximum wind speed over time to quantify hurricane activity by season, defined as the sum of the squares of the maximum wind speeds at 6-h intervals, considering the time while the hurricane is at tropical storm strength or greater [28]. As kinetic energy is proportional to the square of velocity, ACE is a value proportional to the energy of the system, by adding together the energy per some interval of time.

A review by [29] evaluates different hurricane indexes, indicating ACE as a valuable metric for quantifying the overall impact of tropical cyclones on the Earth's climate, classifying this index as a duration-based integral of a time series.

The ACE definition given by [28, 29] was adapted to use the monthly output from models, setting a related ACE:

$$ACE = 10^{-1} {V_{max}}^2 \tag{1}$$

where V_{max} applied to this work was the monthly mean of maximum daily wind speed in knots, with ACE units being $10^{-1} knots^2$.

The primary energy source for TC is the heat from the evaporation that comes from the warmed ocean surface; several studies showed the correlation between sea surface temperature and TC [21, 23, 30, 31]. Additionally, the increase in precipitation rates is largely based on the Clausius-Clapeyron ratio, which produces about a 7% increase in water vapor in the atmosphere by 1°C warming [32, 33]. Thus, the maximum near-surface air temperature at 2 m (TASMAX) expresses a direct physical relationship with the TC occurrence, used here to be an auxiliary proxy to help the discussion ahead.

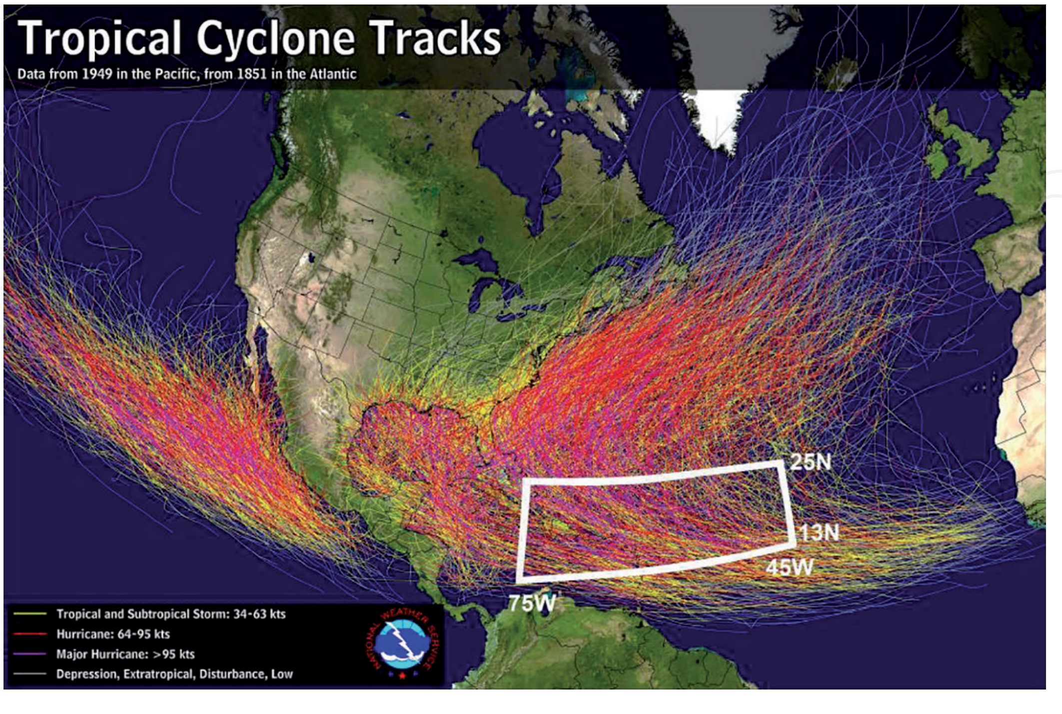

Figure 1.
Tropical cyclone tracks map (adapted from [34]) with the region delimitation for this study: 75 W to 45 W and 13 N to 25 N.

Most tropical cyclones are formed in the intertropical convergence zone (ITCZ). Tropical waves are another important source of atmospheric instability, contributing to the development of about 85% of cyclones over the Atlantic Ocean [35, 36]. TC rarely forms or moves around 5° from the equator where the Coriolis effect is more weak, with most of them appearing between 10 and 30° latitude away from the equator [37]. Thus, the delimited area in the central region in **Figure 1** was chosen as representative to develop the objective of this work.

3. Climate data overview

Climate models have been used to understand how the climate has changed in the past and may change in the future. These models simulate the physics, chemistry, and biology of the atmosphere, land, and oceans, now called Earth system models, and require supercomputers to generate their climate projections.

A set of standard experiments was designed for CMIP, allowing results to be comparable across different model simulations, to see where models agree and disagree on past and future scenarios [38].

CMIP6 historical experiment covers the period 1850–2014, forced by datasets that are largely based on observations, used as an important benchmark for assessing performance through evaluation against observations, and are well suited for quantifying and understanding important climate change response characteristics [38, 27]. The characteristics and forcings included in historical were described in [27]:

- Emissions of short-lived species and long-lived GHGs
- GHG concentrations
- Global gridded land use forcing datasets
- Solar forcing
- Stratospheric aerosol dataset (volcanoes)
- AMIP sea surface temperatures and sea ice concentrations (SICs)
- For simulations with prescribed aerosols, a new approach to prescribe aerosols in terms of optical properties and fractional change in cloud droplet effective radius to provide a more consistent representation of aerosol forcing
- For models without ozone chemistry, time-varying gridded ozone concentrations and nitrogen deposition

Shared socioeconomic pathway (SSP) scenarios are part of a framework designed to span a range of futures in terms of the socioeconomic challenges that they imply for mitigating and adapting to climate change. In short they are:

SSP1 - Low challenges to mitigation and adaptation.
SSP2 - Intermediate challenges to adaptation and mitigation.
SSP3 - High challenges to mitigation and adaptation.
SSP4 - Low challenges to mitigation and high challenges to adaptation.
SSP5 - High challenges to mitigation and low challenges to adaptation [39, 40].

SSP585 results of a complementary effort by SSP narrative and the Representative Concentration Pathways (RCPs), representing the high end of the range of future pathways. SSP5 was chosen for its forcing pathway because its emissions pathway is high enough to produce a radiative forcing of 8.5 W/m^2 by the end of the century, updating RCP8.5 [39, 40]. **Figure 2** summarizes all the current SSP scenarios for CMIP6 in terms of radiative forcing.

3.1 NCEP-DOE AMIP-II reanalysis

Climate reanalysis aims to assimilate historical observational data with numerical models to generate consistent time series of multiple climate variables. These are a comprehensive description of the observed climate as it has evolved during recent decades, providing global datasets at sub-daily intervals, turning possible more detailed approaches, and then having just observation data [41, 42].

NCEP-DOE Reanalysis 2 project performs data assimilation using past data from 1979 through the present. The data is available at PSD portal (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.html) in its original four times daily format and as daily averages. The horizontal resolution is 210 km and 28 vertical levels [42].

The zonal and meridional wind components at 2 m and 6-6 hs data were used to compute monthly maximum wind speed. The ACE index was obtained by applying this monthly maximum wind speed in Eq. 1. Similarly, the monthly maximum temperature (TASMAX) was calculated through the daily maximums obtained with 6-6hs data. These variables provided by NCEP reanalysis were used as a reference to evaluate the recent past simulations.

3.2 CMIP6 historical and SSP585 simulations

CMIP6 simulation outputs are available in the Earth System Grid Federation (ESGF), through a distributed data archive developed. The data are hosted on a collection of nodes across the world by modeling centers [43]. The main portal to access the datasets is https://esgf-node.llnl.gov/search/cmip6/.

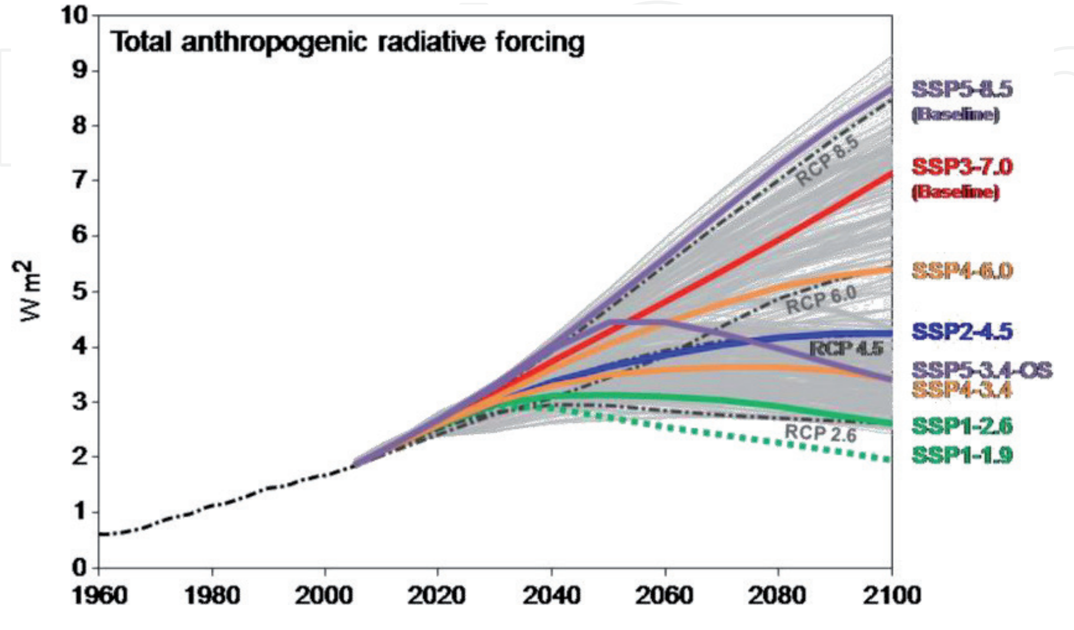

Figure 2.
Anthropogenic radiative forcing for the twenty-first-century scenarios in the ScenarioMIP design (from [39], shown in [40]).

Model	Run	Nominal resolution	Vertical levels	Components
CNRM-CM6-1	r1i1p1f2	250 km	91	AOGCM
CNRM-ESM2-1	r1i1p1f2	250 km	91	AOGCM/BGC/AER/CHEM
IPSL-CM6A-LR	r1i1p1f1	250 km	79	AOGCM/BGC
MPI-ESM1-2-HR	r1i1p1f1	100 km	95	AOGCM
	Institution/Center			Reference
CNRM-CM6-1	CNRM (Centre National de Recherches Meteorologiques, Toulouse 31,057, France), CERFACS (Centre Europeen de Recherche et de Formation Avancee en Calcul Scientifique, Toulouse 31,057, France)			[44]
CNRM-ESM2-1				[45]
IPSL-CM6A-LR	Institut Pierre Simon Laplace, Paris 75,252, France			[46]
MPI-ESM1-2-HR	Max Planck Institute for Meteorology, Hamburg 20,146, Germany			[47]

Table 1.
CMIP6 global models and their physical and numerical characteristics.

The complexity of the models, experiments, and methodologies makes it hard for modeling centers to complete the entire archive to participate in CMIP6. Thus, at this time the available datasets to use in this work, for both historical and SSP585, are listed in **Table 1**.

4. Analysis

The models simulate their own climate, with no obligation to get it right exactly when specific events have occurred in relation to observational data. On the other hand, they should be able to represent global or large-scale phenomena such as El Niño, La Niña, ITCZ, and ocean circulation. Thus, the models are expected to represent the average climate of the recent past, as well as to simulate the future in the same direction.

Thus, the regional annual cycle for variables with approximately linear behavior, such as temperature, should be easier to represent. Episodic variables such as precipitation and local wind speed are more difficult to model numerically, given the randomness of events. But it is expected that for long periods, good results will be obtained from the models on average terms, as suggested by the WMO to use at least 30 years for climate studies.

The ACE, because it depends directly on the wind, can be assumed to present results that are less well behaved concerning the reference data than the temperature. This occurs in the results obtained here through the CMIP6 models; the ACE index shows similarities for the monthly climate average through the annual cycle (**Figure 3**), although with a discrepancy between the models higher than the maximum temperature (**Figure 7**). In addition to the nonlinearity involved, the models themselves have their limitations, which may be due to the physical, numerical, or computational approach. Model scaling errors for the ACE index are in the order of −12%. Among the models, MPI-ESM1-2-HR performed better in representing the annual ACE cycle, with a good approximation of the mean monthly values compared to reanalysis, with a correlation of 0.93 and bias error − 1.28%.

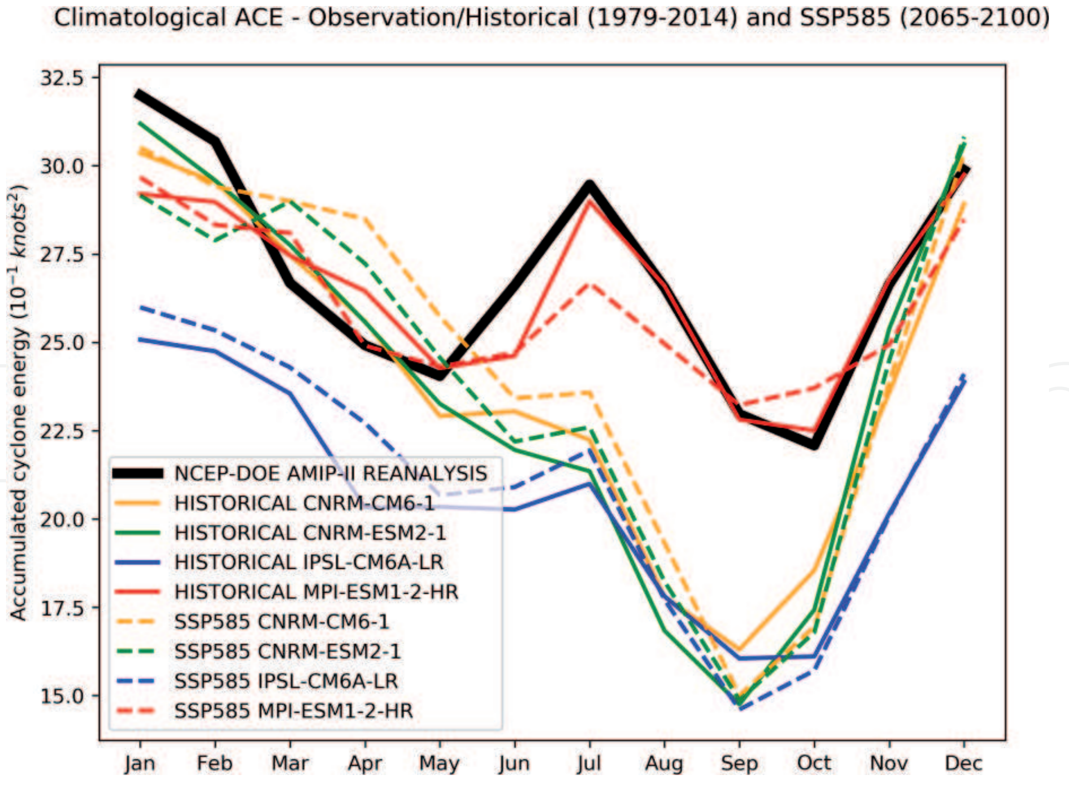

Figure 3.
Annual cycle of the study region for ACE.

The French model IPSL-CM6A-LR has the highest percentage error among the others for ACE, at 22.70% of the reanalysis (**Figure 3**). On the other hand, this same model obtained a better representation of seasonal variability (0.85 correlation) than the two CNRM models, which presented smaller errors (−11%) but with lower correlations, 0.76 (CNRM-CM6-1) and 0.74 (CNRM-ESM2-1). The critical value of the sample correlation, for 95% significance (n-2 degrees of freedom), is 0.576, with all model results performing significant correlations.

The variation coefficient (VC), defined as the ratio of standard deviation by the mean, represents the relative standard deviation, used here to assess whether the models have significant monthly interannual variability or whether they represent climate more closely than stationarity.

The months with the highest percentage variation range from December to May (**Figure 4**), where there is a relative skill of the models, VC values not exceeding 5% from NCEP-DOE Reanalysis 2. In the months from June to November, models have more difficulties to simulate the maximum wind speeds, possibly resulting from the higher activity of the ITCZ in the region selected for the study and being also the months with the high temperatures of the year (**Figure 7**). The MPI-ESM1-2-HR model best quantified the interannual ACE variations for the months with the highest CT activity, followed by the IPSL model, erring only in magnitude, hitting the temporal evolution in most months.

The polynomial curve fitting creates an approximating function that attempts to capture important patterns in the data while leaving out noise or other fine-scale structures/rapid phenomena. This method can aid in data analysis by being able to extract more information from the data as long as the assumption of smoothing is reasonable and to provide analysis that is both flexible and robust.

The first-degree coefficient represents the linear trend of the data, and, as shown in **Figure 5**, the NCEP reanalysis has a small negative trend in annual ACE over the recent past (1979–2014). With the same trend signal, IPSL-CM6A-LR follows the observation pathway, while the other three models simulate a positive

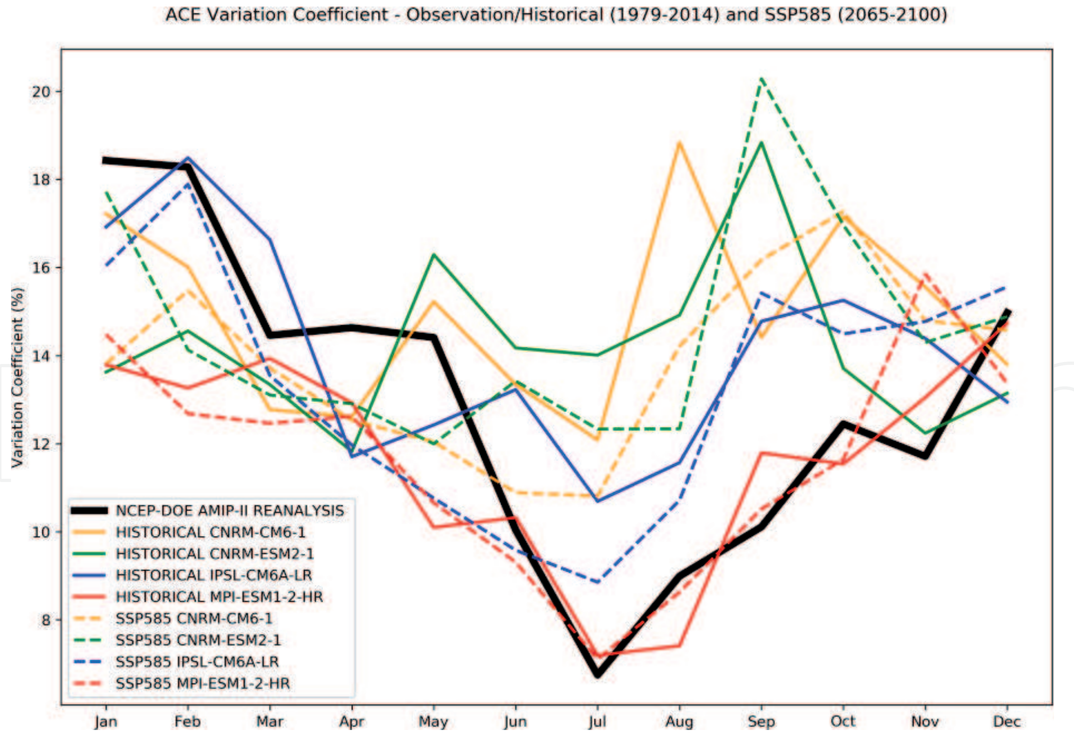

Figure 4.
Percentage variation coefficient for ACE monthly values.

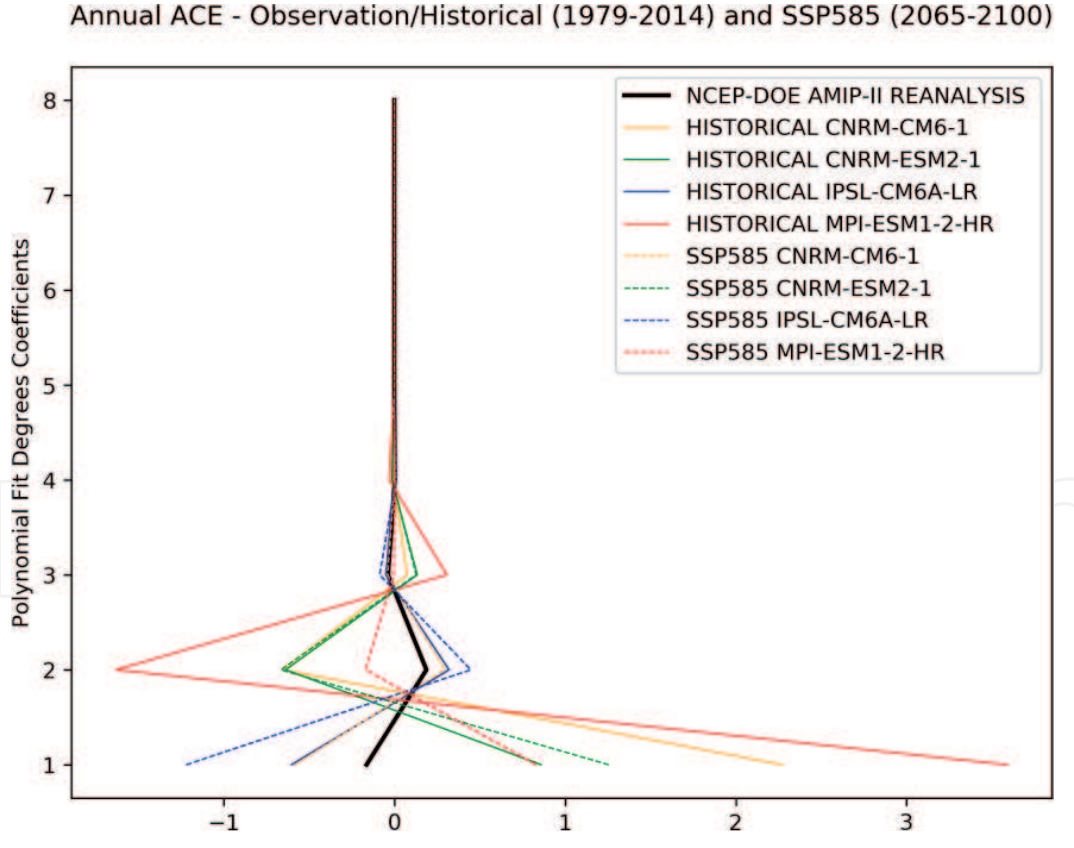

Figure 5.
Polynomial adjustment coefficients for annual ACE of the study region.

trend. From the second-degree coefficient to further ahead, the adjustments are related to patterns with more oscillatory rates, and in the present analysis, this type of signal has no significance. Thus, it can be assumed that models with coefficient values close to reanalysis, in modulus, should have a similar pattern of variability in different modes. The German model was the most difficult to obtain the adjustment, probably because it has a higher horizontal resolution, making it possible to discretize more climate phenomena, which has coefficient values more distant than the obtained for the reanalysis.

The projection of annual ACE for the twenty-first century (**Figure 6**) has a similar average behavior among models, without abrupt trend changes, presenting modes of variation not far from the simulated for the recent past. The long-term trend for the period 2065–2100 is an increase in the average annual ACE values for the CNRM-ESM2-1 and MPI-ESM1-2-HR models and a reduction for the IPSL-CM6A-LR and CNRM-CM6-1, with no majority agreement.

The TASMAX annual cycle has a good performance by the models; in terms of seasonality, all models show suitable patterns, with low errors in representing the evolution of the monthly cycle. The bias error is a problematic aspect, the three French models have sub estimate ~2°C, while MPI-ESM1-2-HR fits almost the entire NCEP reanalysis climatology (**Figure 7**).

The annual TASMAX projections for the future (**Figure 8**) are similar to that described in the IPCC Special Report on the impacts of global warming of 1.5°C above preindustrial levels and related global greenhouse gas emission pathways [48], in which there is a high confidence that the estimated anthropogenic global warming is currently increasing at 0.2°C per decade due to past and ongoing emissions.

The mid- and long-term ACE future projections for most models analyzed indicate to the increase of the index and just the MPI-ESM1-2-HR follows a different pathway (**Figure 9**). The approaches used in the results shown in **Figures 9** and **10** consist of calculating the future percentage change over the periods and applying this change to the reanalysis recent past value. This way, the projection has no bias error associated to it, bringing the right value expected in the future for the projection.

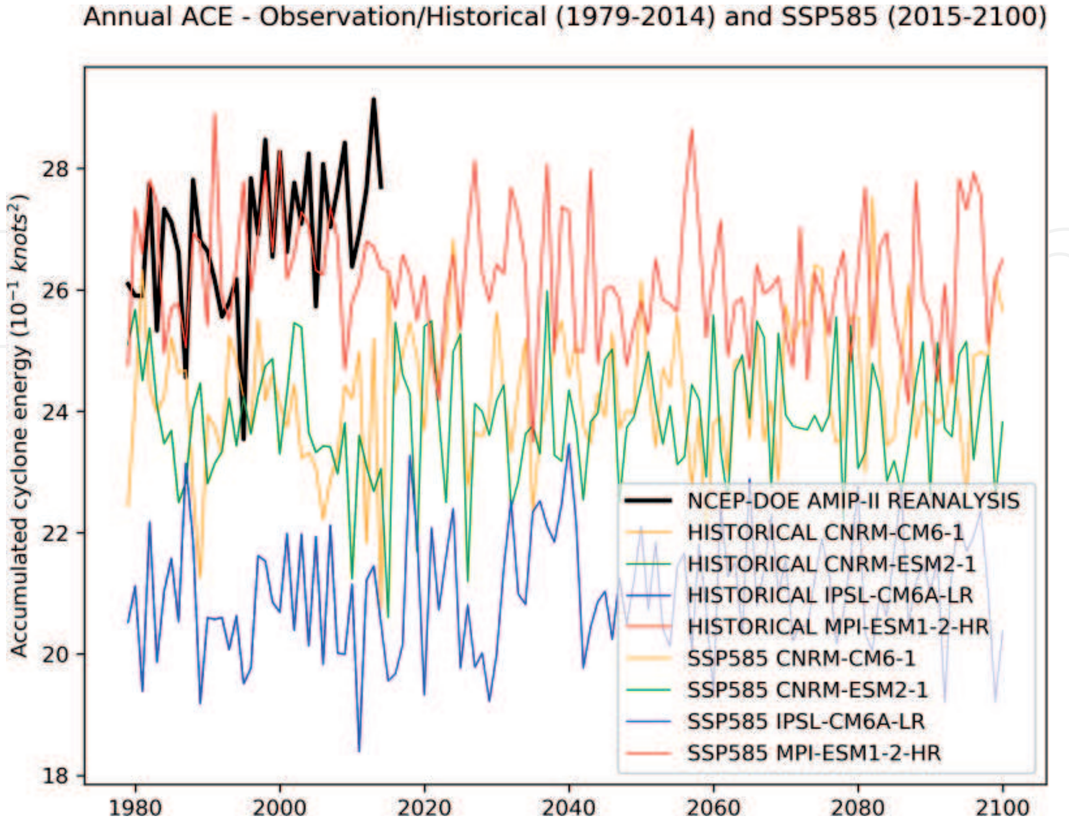

Figure 6.
Annual ACE time series for recent past and future simulation under SSP585.

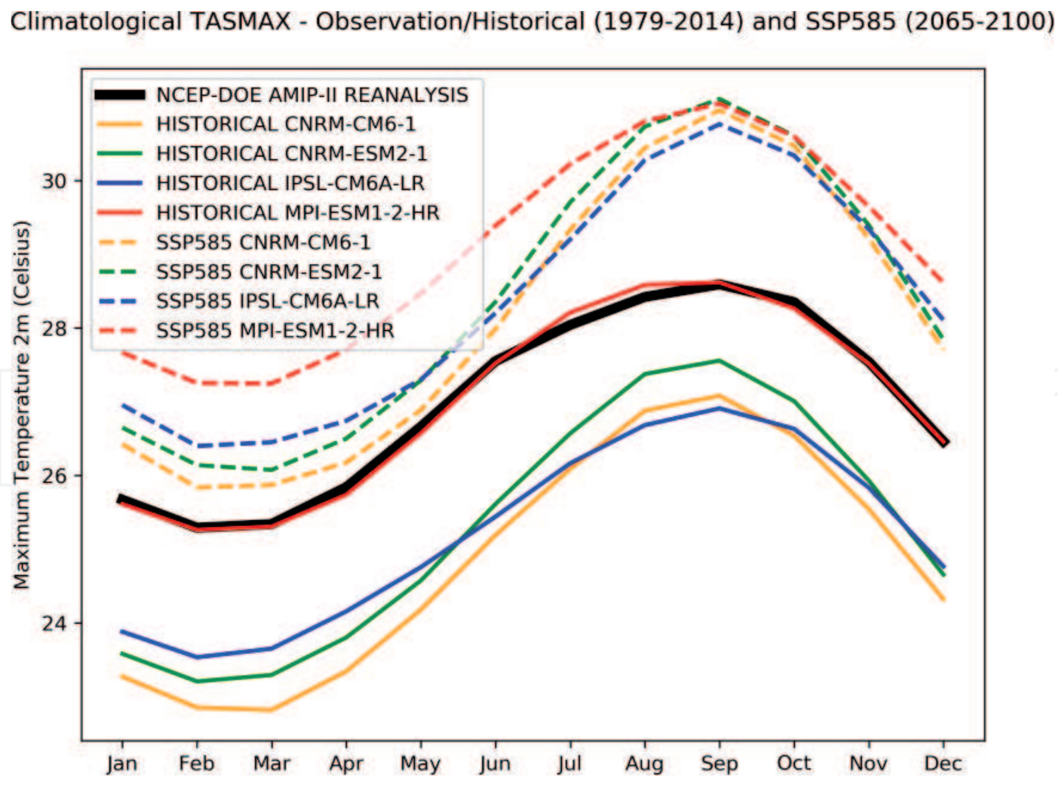

Figure 7.
Annual cycle of mean over the study region for TASMAX.

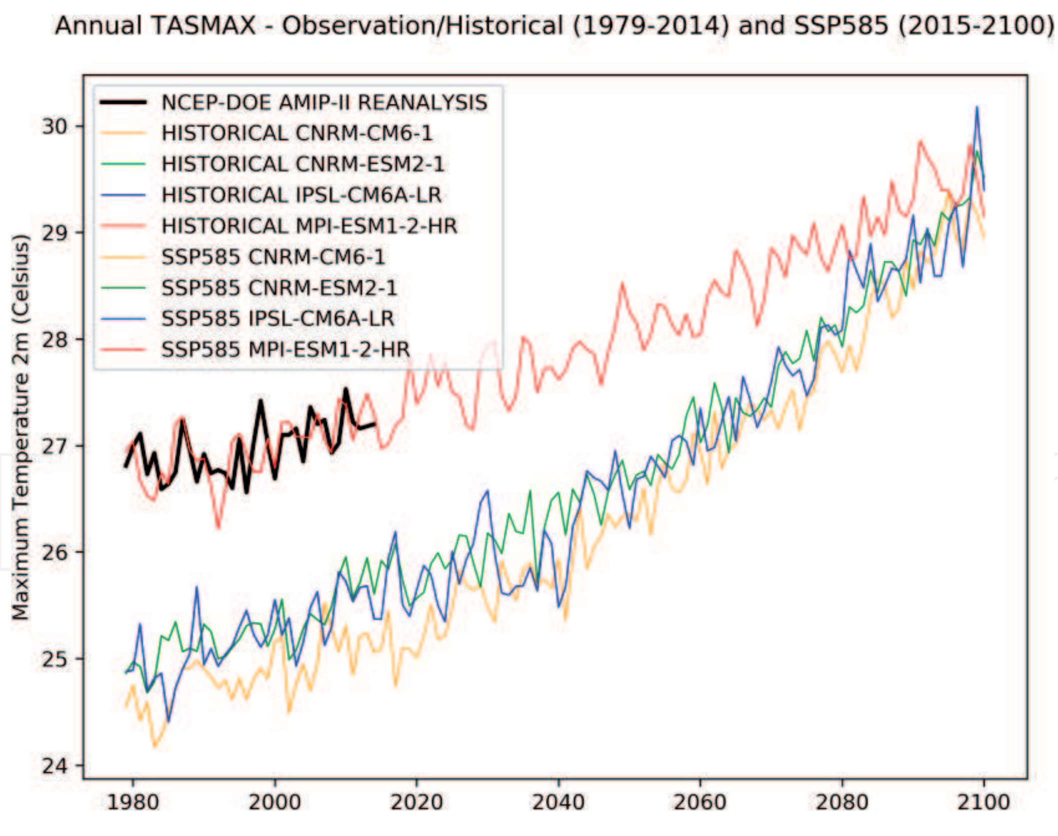

Figure 8.
Annual TASMAX time series for recent past and future simulation under SSP585.

The model with better results, MPI-ESM1-2-HR, trends to increase annual ACE under the projection period, but points the opposite to mid- and long-term mean (**Figure 9**). One of the changes in the annual cycle is an increase in the index in months where TC activity is not intense, as in the months of the beginning and end of the year, in which there is also an increase in VC. These factors suggest that the

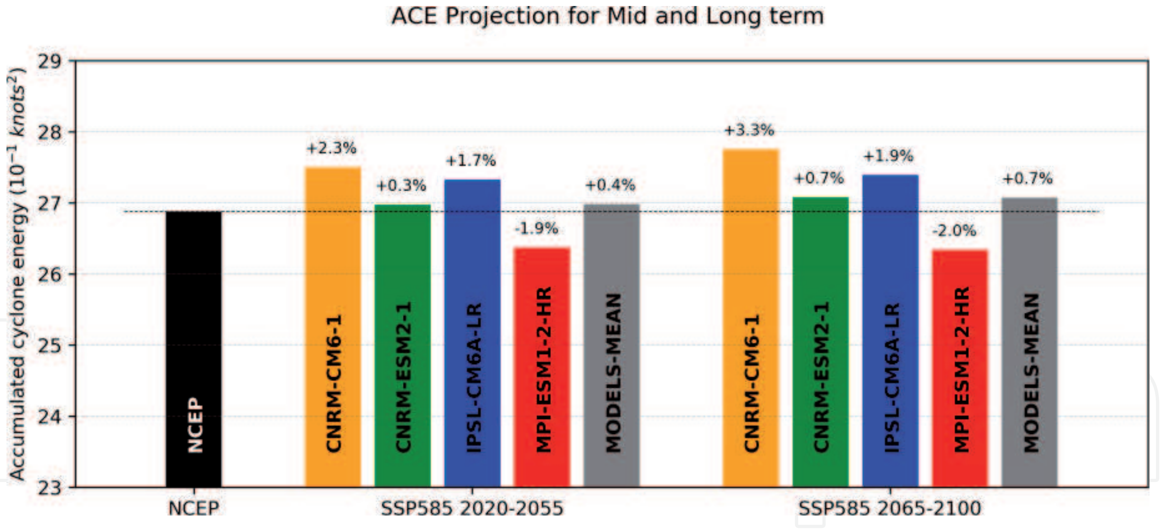

Figure 9.
Future ACE projection under SSP585 for mid (2020–2055) and long (2065–2100) terms.

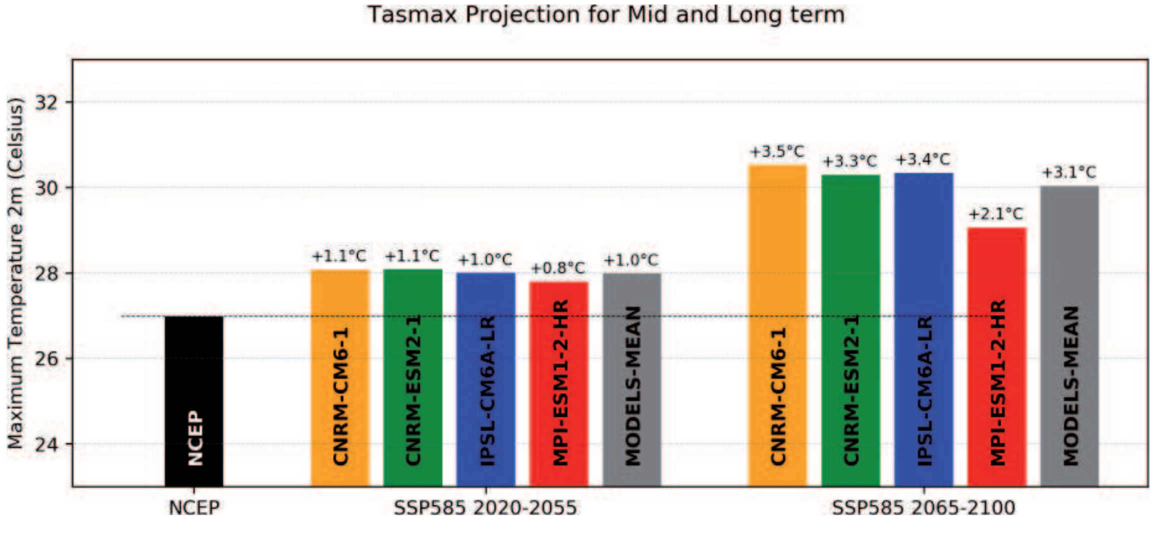

Figure 10.
Future TASMAX projection under SSP585 for mid (2020–2055) and long (2065–2100) terms.

seasons and their interannual variations in cyclonic activity will be affected by the forcing on the climate system, in this case, under the scenario of high GHG emissions and high challenges to mitigation SSP585.

The MODELS-MEAN projection (**Figures 9** and **10**) was computed by the weight mean, considering the annual cycle correlation value as the weight for each model. Thus, MODELS-MEAN performs a more confident projection. The results for that concern to a future with more chances of facing more tropical cyclone activity, plus the huge long-term TASMAX increase of 3.1°C (**Figure 10**); the twenty-first century may experiment more heavy cyclones and stronger storms with more frequency, as indicated by other studies [21, 23, 25, 26].

5. Conclusions

The accumulated cyclone energy index adapted for this work has made it simpler to assess the recent past and to obtain projections of CMIP6 models, given the use of monthly data directly.

In the present climate evaluation (1979–2014), reasonable results were obtained for the ACE index; the French models of lower horizontal and vertical resolution showed more difficulties to represent the index, while the Max Planck Institute model demonstrated ability to simulate the climate with more accuracy than the others, presenting values of both ACE and TASMAX very close to NCEP Reanalysis 2.

TASMAX was already expected to obtain good results numerically; in terms of seasonality all models show suitable patterns, with low errors in representing the evolution of the monthly annual cycle.

The annual ACE projection has a similar average behavior among models in the recent past, without abrupt trend changes, but with no major agreement to increase or reduce trend. The mid- and long-term mean for most models analyzed shows an increase in ACE.

The MPI-ESM1-2-HR projections suggest that the seasons and their interannual variations in cyclonic activity will be affected by the forcing on the climate system, in this case, under the scenario of high GHG emissions and high challenges to mitigation SSP585.

The results indicate to a future with more chances of facing more tropical cyclone activity, plus the mean increase of 3.1°C in maximum daily temperatures, and more heavy cyclones and stronger storms with more frequency may be experimented, as indicated by other studies [21, 23, 25, 26].

The study needs to be expanded, including more models, to increase the range of results and to narrow down potential trends that may occur in ensemble analysis.

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