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CLIMATE CHANGE PERSPECTIVES OF THE CYCLONES AND OCEANIC HAZARDS IN THE WESTERN SOUTH ATLANTIC OCEAN

Perspectivas das mudanças climáticas dos ciclones e riscos oceânicos no oeste do Oceano Atlântico Sul

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ABSTRACT

Cyclone-related oceanic hazards, such as extreme waves and surges, are frequently reported on the western South Atlantic. These events are associated with coastal erosion, coastal infrastructure damage, maritime navigation, and offshore industry incidents, being important for safety and maintenance management in ocean engineering. Present climate trends and future projections of this event are frequently linked with the expected general poleward shift of the storm track over the globe, but regional approaches revealed a slight increase in the cyclonic activity in South America 35ºS and 40ºS, which would be restricted to the coast. However, the signals of these changes are weak and frequently of the same magnitude of model biases, producing results with a lack of confidence, especially in the coastal zone. Extreme events related to waves and surges used to present large uncertainty and heterogeneity around the globe. Most of the problems regarding future estimation rely on methodological limitations that will not overrun without collaborative efforts to the improvement of observational-based science. Taking advantage of the UN Ocean Decade goals, national and regional initiatives need to collaborate towards a robust and continuous Brazilian observational network in order to face the climate crises in the country.

Keywords: ocean wind-waves, coastal flooding, storm surge, extratropical cyclones, ocean waves, natural hazards.

RESUMO

Riscos oceânicos relacionados a ciclones, como ondas extremas e inundações costeiras, são frequentemente relatados no oeste do Atlântico Sul. Esses eventos estão associados a erosão costeira, danos à infraestrutura costeira, navegação marítima e incidentes na indústria offshore, sendo importantes para a gestão de segurança e manutenção na engenharia oceânica. As tendências climáticas atuais e as projeções futuras desse evento estão frequentemente relacionadas com o deslocamento generalizado da trajetória preferencial de ciclones em direção aos polos no globo, mas abordagens regionais revelaram um ligeiro aumento na atividade ciclônica na América do Sul entre 35º S e 40º S, que ficaria restrita à costa. No entanto, os sinais dessas mudanças são fracos e frequentemente da mesma magnitude dos vieses do modelo, produzindo resultados com falta de confiança, especialmente na zona costeira. Eventos extremos relacionados à agitação marítima e às inundações coste iras costumam apresentar grande incerteza e heterogeneidade ao redor do globo. A maioria dos problemas relativos às estimativas futuras resultam de limitações metodológicas que não serão superadas sem esforços colaborativos para o aprimoramento da ciência baseada na observação. Aproveitando os objetivos da Década do Oceano da ONU, as iniciativas nacionais e regionais precisam colaborar para uma rede de observação brasileira robusta e contínua para enfrentar as crises climáticas no país.

Palavras-chave: *ondas de tempestade, inundações costeiras, ciclones extratropicais, ondas oceânicas, desastres naturais.*

INTRODUCTION

Most of the coastal and oceanic hazards around the world are generated by cyclones. Extreme waves and storm surges are frequently reported on the Brazilian coast (Marone & Camargo, 1994; Machado *et al.*, 2010; Campos *et al.*, 2018a; Godoi *et al.*, 2021) and are usually related to coastal erosion and infrastructure damage. Severe sea states generated by cyclones are also associated with maritime navigation and offshore industry incidents, and need to be taken into account in safety and maintenance management planning in ocean engineering (Bitner-Gregersen *et al.*, 2018; Vettor & Guedes Soares, 2016). Although for most of the population cyclones are only remembered when their cold front brings low temperature or severe rains, these atmospheric systems are always somehow present in day-to-day human activities around the world.

In this way, the understanding of the future changes regarding cyclones and their consequences on the distribution and intensity of oceanic hazards are of utmost importance to the management and mitigation of climate change. Although the last decade advances in observational data sources and modelling systems, some issues are still influencing our ability to estimate future patterns. Some of them are inherent to the limitations of the state-of-art of global climate science, but a large part relies on the lack of knowledge about specific physical processes, especially in the South Atlantic Ocean.

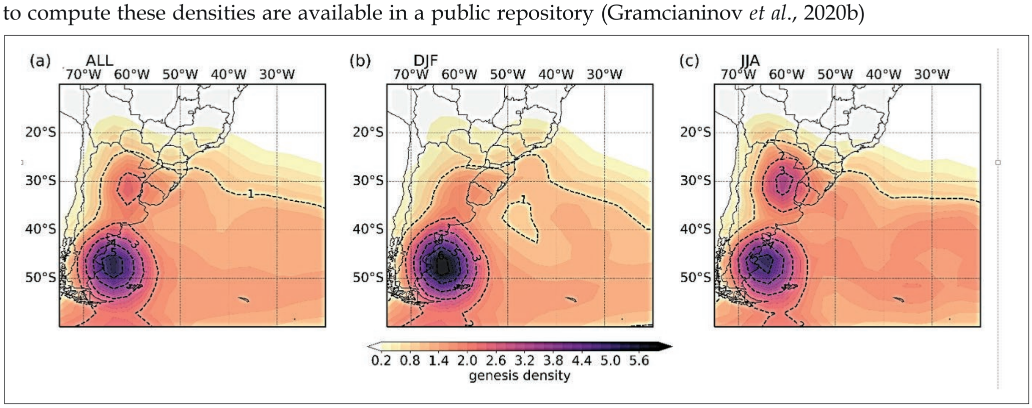
This article presents an overview of the recent findings regarding the relationship between cyclones and coastal and oceanic disasters in the western portion of the South Atlantic and their future perspectives, as well as the issues and limitations in the field. The goal is to enrich the discussion about the current challenges of ocean science in light of the United Nations Decade of Ocean Science.

South American cyclones and their future projections

The generic term “cyclone” is used in modern meteorology to designate low-level pressure systems in synoptic-scale (American Meteorological Society, 2021), which present a cyclonic circulation. These systems can be classified according to their genesis (i.e., generation) environment that usually influences their core temperature, symmetry, and vertical structure (e.g., Reboita *et al.*, 2017). In Brazil, we are most affected by cold core, asymmetric systems, the so-called extratropical cyclones. In some special and rare situations, cyclones with tropical characteristics (i.e., warm core and symmetric systems) were reported in the south/southeastern Brazilian coast (Pezza & Simmonds, 2005; Reboita *et al.*, 2021a). In addition to those two classical types, several subtropical cyclones have been reported on our coast, which are hybrid systems presenting a warm low-level core with a cold upper-level core, revealing both tropical and extratropical characteristics.

We have three preferring cyclogenesis regions over South American with a strong seasonal variability (Figure 1; e.g., Hoskins & Hodges, 2005; Crespo *et al.*, 2020). The more active region is around 45ºS on the Argentinean coast. This region is active all year round, presenting slightly more cyclones during the summer. A secondary genesis region occurs in the La Plata river basin, around 30ºS, which is more active in the winter (Gan & Rao, 1991; Gramcianinov *et al.*, 2020a). The cyclones originated in this region tend to be more intense (Gramcianinov *et al.*, 2019) and are directly related to extreme wave events in the wSA (Campos *et al.*, 2018a; Gramcianinov *et al.*, 2020c, 2021). A third genesis region in the Southeastern Brazilian coast was only reported in the 2000’s (e.g., Hoskins & Hodges, 2005; Reboita *et al.*, 2010). The reason for the late discovery is that the cyclones that developed in that region tend to be smaller and shorter, so the tracking method needs to be adjusted to such characteristics. This region is more active in the summer and brings attention by its proximity to the coast and its potentially suitable environment to subtropical genesis and transitions between cyclone types (Gozzo *et al.*, 2014; da Rocha *et al.*, 2019; Reboita *et al.*, 2021a).

Figure 1 – Preferential cyclogenesis regions in the western South Atlantic between 1979 and 2020 in (a) all seasons, (b) summer (DJF), and (c) winter (JJA). The density unit is genesis per month per 10^6 km^2. The tracks to compute these densities are available in a public repository (Gramcianinov *et al.*, 2020b)



Present climate trends and future projection shows a general poleward shift of the storm track (i.e., the main path where cyclones move eastward) over the globe (e.g., Ulbrich; Leckebusch & Pinto, 2009; Catto *et al.*, 2019), although there is still a large uncertainty in this matter. Despite the expected southward shift of cyclonic activity, most of the future cyclone changes focused on South Atlantic also reveals a slight increase in the cyclogenesis

La Plata River discharge region and southern Brazil, around 35ºS (e.g., Reboita *et al.*, 2018; Gramcianinov, 2018; Reboita *et al.*, 2020). The track derived from this genesis region increases locally without spreading throughout the entire South Atlantic, indicating short trajectories and restricted influence to the coastal and offshore zone (Gramcianinov, 2018; de Jesus *et al.*, 2020). The increase in cyclones in this location may be followed by their intensification due to the increase in the low-level temperature advection and available moisture contribution to rapid development (Reboita *et al.*, 2021b). Recently, Reboita *et al.* (2021b) showed an increase of 13% in the occurrence of bomb cyclones in the South American domain, reporting deeper, faster and shorter systems in the worst future projection scenario. The local effect of more intense cyclones acting over Uruguay and southern Brazil in the future have been related to the increase of precipitation at these locations (Reboita *et al.*, 2020) and will possibly bring consequences to coastal disasters and marine extremes. The problem in this projection is that although these changes were reported by several studies, both with global and regional climate models, the signals of the change are weak and frequently of the same magnitude of model biases, producing results with lack of confidence (e.g., Reboita *et al.*, 2021b; Gramcianinov *et al.*, submitted).

Actually, the sensibility of cyclone genesis and track change estimation goes far beyond and passes through the nature of the feature-based analysis, usually applied to study cyclonic systems. Tracking methods can provide a valuable set of information that needs to be joined in distribution and density maps where synoptic-scale cyclones are represented by a single point. The position of the cyclone centre (i.e., latitude and longitude) becomes the main source for all estimations (e.g., occurrence, intensity, lifetime, etc), even knowing that it may vary depending on the dataset (e.g., reanalysis), tracking method, smooth parameters, model, etc (Pinto *et al.*, 2005, 2016). Automatic tracking methods surely represent an important milestone in cyclone-based studies and are still one of the best approaches to do so. However, it is important to recognize their limitations to understand the estimation uncertainties. The results of future changes in the storm track related fields are usually very noisy density differences or trend maps showing positive and negative signals so close to each other that it becomes difficult to interpret considering the scale of the target phenomena. Usually, the changes are more robust in the main storm track where the number of features (i.e., cyclones centres) reinforce the statistical analysis, but in coastal zones, especially in mid-latitudes, a robust estimation is very challenging.

Extreme events over western South Atlantic

In the lower counterpart, the ocean response to its interaction with the cyclone's wind ranges on different scales and depends upon a variety of factors related to the cyclone structure and orientation. On a more energetic scale, high ocean waves demand strong winds blowing in a large area and for a long time – elements potentially supplied by a cyclone. Despite the intensity and scale of the cyclones, which guarantee two of the three elements to wave generation, their displacement speed is usually a limiting factor. A fast-moving cyclone will not generate extreme waves due to the lack of persistence of its associated winds at the same location. The time of interaction between the strong winds and the ocean surface is essential to energetic wave packages, putting slower cyclones as potentially damaging systems. To sum to that, the evaluation of cyclone-wave interaction becomes more complex with the possibility of extended fetch (also called dynamical fetch or trapped-waves), in which the speeds of the cyclone and the wave group are similar allowing the growth of waves beyond the developing curve (Kudryavtsev; Golubkin & Chapron, 2015). The extended fetch is widely documented and studied in tropical cyclones (Young & Vinoth, 2013) while the studies regarding extratropical cyclones are restricted to few case studies (e.g., Bakhtyar *et al.*, 2018). Nevertheless, there are pieces of evidence of the occurrence of these phenomena in the western South Atlantic Ocean (Gramcianinov *et al.*, 2020c, 2021), but further investigation is needed.

Cyclone-related extreme waves have been widely reported in the western South Atlantic Ocean (e.g., Innocentini & Caetano Neto, 1996; da Rocha; Sugahara & Silveira, 2004; Mello; Romeu & Hammes, 2010; Dragani *et al.*, 2013; Campos *et al.*, 2019; Gramcianinov *et al.*, 2020c, 2021; Godoi *et al.*, 2021). Most of these events occur in the winter with Hs that can reach 7.3 m along the south Brazilian coast and predominantly direction from the south (Pianca; Mazzini & Siegle, 2010). From the coastal perspective, severe cases are related to strong and persistent southeasterly winds over the continental shelf, promoting very energetic waves along with South America, from Uruguay to the central Brazilian coast (da Rocha; Sugahra & Silveira, 2004; Dragani *et al.*, 2013). This configuration is the most common, when the extreme waves are generated in the fetch westward of the cyclone centre, located in the cold sector of the cyclone, behind the cold front. An anticyclone above the continent increases the pressure gradient and, consequently, elongates and strengthens the fetch (da Rocha; Sugahara & Silveira, 2004; Gramcianinov *et al.*, 2020c, 2021).

Besides this pattern, two more patterns are revealed when offshore extremes are included in the analysis. Gramcianinov *et al.* (2020c) found three atmospheric situations driving extremes in the western South Atlantic analysing severe cases in 5 years of Climate Forecast System Reanalysis (CFSR, Saha *et al.*, 2010), which are summarized in Figure 2. The first situation is the above-mentioned case in which the extreme occurs eastward of the cyclone centre due to the southwesterly winds (label 1, Figure 2). In the other situations, the extreme can occur ahead of the cold front or along the warm front, denoted by labels 2 and 3 of Figure 2, respectively. Both of these last two situations are associated with the warm conveyor belt, an important air flux within the cyclone related to its development and intensification (e.g., Browning & Roberts, 1996). Moreover, they are more frequent in the summer and in the northern edge of the domain, covering the region offshore of Rio de Janeiro and Espírito Santo (Gramcianinov *et al.*, submitted).

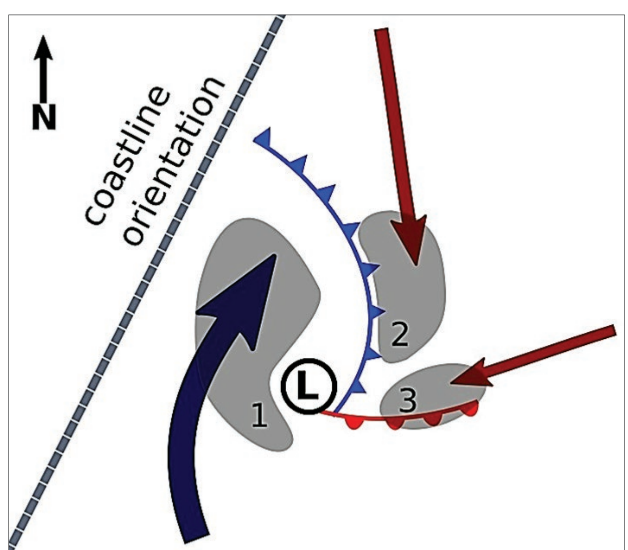


Figure 2 – Scheme of an extratropical cyclone horizontal structure related to extreme wave occurrence in the western South Atlantic Ocean. The thick arrows represent the approximate influence of the cold (dark blue) and warm (dark red) conveyor belts. Grey shaded regions indicates the location where the extreme waves occur according to Gramcianinov et al. (2020c): (1) in the cold sector of the cyclone, behind the cold front, and in the warm sector (2) ahead of the cold front and (3) along the warm front. The cold and warm fronts are represented according to meteorological convention and the approximated low-pressure center is represented by "L"

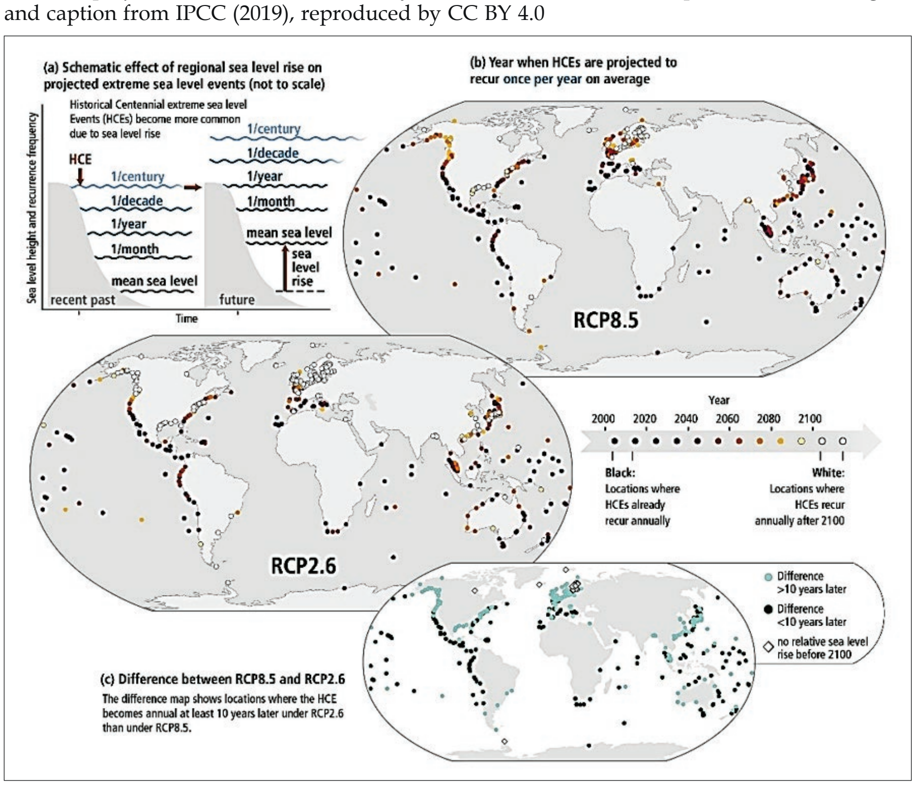
Besides the wind waves, cyclones also impact the coastal sea level with longer waves known as storm surge. Strong winds combined with a long and persistent fetch parallel to the coast generate the rise or drop of the sea level on the shore as a result of Ekman transport. This sea-level oscillation, which diverges from the predicted astronomical tide, is called meteorological tide and is independent of wind waves. In the case of the storm surge, the longer wave reaches the coast with a high amount of water, increasing the sea level above the expected tide level. The condition leading to label 1 in Figure 2 shows a similar atmospheric pattern leading to the transport of the water towards the Brazilian coast (e.g., Campos *et al.*, 2010; Harari & de Camargo, 2019). The opposite case, when the wind-resulting Ekman transport removes waters from the shore are most related to a transient anticyclone (Campos *et al.*, 2010), and causes a negative meteorological tide impacting harbours operation, fishery, and other coastal activities.

In the matter of cyclone-related coastal hazards, storm surge is surely one of the greatest, being directly related to coastal management and mitigation of climate change (Harari *et al.*, 2019). The possible combination between a high meteorological and astronomical tide causes abnormal sea-level rise, promoting severe flooding. Besides that, despite the fact that meteorological tide differs from wind-wave scale, the two elements can reach the shore at the same time increasing the damage. The coastal inundation allows the wave to break further on (e.g., Godoi *et al.*, 2021), reaching inner land structures that are not prepared or built to such strength. Coastal erosion is also directly related to storm surges with severe impact on social-economic activities along the coast. de Gouveia Souza, Souza and Harari (2019) presented a full review of the present climate trends focusing on the south-southeast Brazilian coast and added an 89-years historical analysis of extreme coastal events in the region. These authors claim attention for other parameters that may be included in the study of surges, such as wave direction, local wind, and coastal currents. Moreover, the beaches' morphodynamic state preceding an extreme event may affect its ability to receive the storm surge, facilitating the incursion of water. Further overview of the main meteo-oceanographic condition to storm surge on the Brazilian coast can be found in Campos *et al.* (2010), Harari and de Camargo (2019), and Harari *et al.* (2019).

Surely new perspectives of these cyclone-related marine extremes can be reached when they are studied considering the cyclone's characteristics and the whole atmospheric condition evolution. The traditional extreme analysis based on one or a few points are valuable but hamper some important aspects of the event development. The asymmetric nature of the extratropical cyclones brings a challenge to the analysis of wave generation and development within the cyclone structure, even more, if an extended fetch process is considered. Increasing efforts of spatio-temporal analysis regarding the cyclone-related events are crucial, as well as more interaction between atmospheric and ocean science knowledge. Regarding storm surge, the trajectory of the cyclone and wave direction plays a big role in the coastal damage and erosion, being the inclusion of these parameters indispensable for a good assessment (Parise; Calliari & Krusche, 2009; Machado *et al.*, 2010). Currently, some approaches have been contributing in the field in a global and regional perspective including the extratropical cyclone structure in wave analysis (Hanafin *et al.*, 2012; Bell; Gray & Jones, 2017; Kita; Waseda & Webb, 2018; Ponce de León & Bettencourt, 2021) and the use of the statistical downscaling framework and clustering to obtain the weather-types (Rueda *et al.*, 2016; Camus *et al.*, 2014; Leo; Solari & Besio, 2019). The last approach, also called weather-pattern (Solari & Alonso, 2017) is an interesting method but presents issues related to the non-homogeneity that affect most of the reanalysis, which use to be worse in the South Hemisphere (Stopa & Cheung, 2014; Chawla; Spindler & Tolman., 2013; Rascle & Ardhuin, 2013).

The great urgency regarding the pursuit of a better understanding of these coastal hazards is the increasing evidence of the occurrence of more and/or more intense events with the climate changes. According to the SROCC[1] (Collins *et al.*, 2019), there is medium confidence of the increase in extreme waves by around 1.0 cm yr-1 in the Southern Ocean over the period 1985-2018. Nevertheless, due to projected global mean sea level rise, centennial extreme events are expected to occur more frequently, becoming decadal or annual events. Figure 3 (IPCC, 2019) shows this tendency in some locations of the globe, also revealing that the magnitude of the changes varies regionally. Nevertheless, wave climate change is little addressed in all IPCC reports even though its strict relation with coastal hazards. Wave models are still out of the modern Earth System Models (ESM) used by Coupled Model Intercomparison Project (CMIP). Fortunately, some efforts have been made to produce a high-quality set of wave climate projections around the world (e.g., Morim *et al.*, 2020).

Figure 3 – The effect of regional sea-level rise on extreme sea-level events at coastal locations. (a) Schematic illustration of extreme sea-level events and their average recurrence in the recent past (1986-2005) and the future. As a consequence of mean sea level rise, local sea levels that historically occurred once per century (historical centennial events, HCEs) are projected to recur more frequently in the future. (b) The year in which HCEs are expected to recur once per year on average under RCP8.5 and RCP2.6, at the 439 individual coastal locations where the observational record is sufficient. The darker the circle, the earlier this transition is expected. The likely range is ±10 years for locations where this transition is expected before 2100. White circles (33% of locations under RCP2.6 and 10% under RCP8.5) indicate that HCEs are not expected to recur once per year before 2100. (c) An indication at which locations this transition of HCEs to annual events is projected to occur more than 10 years later under RCP2.6 compared to RCP8.5. Figure and caption from IPCC (2019), reproduced by CC BY 4.0



[1] Special Report on the Ocean and Cryosphere in a Changing Climate (https://www.ipcc.ch/srocc).

The Coordinated Ocean Wave Climate Project (COWCLIP, Hemer *et al.*, 2012) emerged as an international collaborative working group focused on producing wave future projections by running dynamical wave models or statistical estimators. Until now, several works derived from this task force have shown important features of wave climate changes using CMIP3 and CMIP5-based wave models, both global (e.g., Hemer *et al.*, 2013; Dobrynin *et al.*, 2015; Semedo *et al.*, 2018; Lemos *et al.*, 2019; Morim *et al.*, 2019, 2021; Meucci *et al.*, 2020) and regional scales (e.g., Bernardino; Gonçalves & Guedes Soares, 2021; Lemos *et al.*, 2021). Considering the worst future scenario (RCP8.5), 30%-40% of the global ocean will suffer from changes in wave extremes (Morim *et al.*, 2021). Despite discrepancies, Morim *et al.* (2019) made a unified review of the COWCLIP products and showed an increase in extreme parameters in the Southern Hemisphere, although most of it occurring at higher latitudes, which are in agreement with observational studies using satellite and buoy data (e.g., Young; Zieger & Babanin, 2011; Young & Ribal, 2019). The observed and future changes also include mean wave period (Morim *et al.*, 2021) and direction (Silva *et al.*, 2020; Lobeto; Menendez & Losada, 2021) and may severely affect 50% of the world's coastline. However, the non-integration of wave processes in the ESM, other modelling issues, and extreme event estimation methods lead to a large set of uncertainty sources, decreasing the robustness level of the estimations.

Numerical Modelling of extreme events and uncertainties

The numerical simulation of extreme waves is associated with a broad range of uncertainties and sources of errors. Rogers *et al.* (2012), Cavaleri *et al.* (2007), Campos *et al.* (2018a), and Campos *et al.* (2020a) cover in detail this topic. The limitations of surface wind fields have a direct impact on the wave generation, which propagates through the misrepresentation of the wave spectrum, compromising the wave fields not only in the generation zone but also further away. Subtropical and tropical cyclones are known for the challenges posed to atmospheric modelling, especially when linked to rapid development and growth of wind intensity at short fetches. This problem is pointed out as one of the main issues for the wave simulation of extreme waves. Furthermore, the input source-terms of third-generation wave models, despite the great progress during the last decades, still suffer from shortcomings under severe and turbulent wind conditions. A complete review of estimates of ocean surface drag in strong winds is presented by Curcic and Haus (2020).

Nevertheless, the mostly unknown term of numerical wave models is still the nonlinear interactions, which controls the wave energy transfer among different frequencies, being directly driving the shape of the wave spectra. A usual problem of the combined limitation of atmospheric and wave modelling under extreme cyclonic conditions is the underestimation of significant wave heights at the peak of the storms (Campos *et al.*, 2018b; Cavaleri, 2009).

When the lack of accuracy of simulated storms spreads over many years, through the hindcasts databases, the long-term effects become more complex and important to be deeply investigated. Besides the time-domain assessments and widely used error metrics, such as bias and root-mean-square-error, the hindcast errors are also found and quantified in the probabilistic domain. This effect is very critical to the offshore and marine industry due to the extreme value analysis (EVA) that rely on hindcasts as input data for the long-term probabilistic distribution function and statistical methods such as peaks over threshold (POT).

To illustrate the problem, Figure 4 shows long time-series measurements of significant wave heights (Hs) of four NDBC[2] buoy data in the Atlantic Ocean. By extracting the same information of Hs from five recent wave hindcast datasets (Table I, at the buoy's positions, it is possible to provide a valuable assessment of these simulations in the probabilistic domain. Figure 5 shows a QQ-plot where the quantiles and quantile functions (inverse of cumulative distribution function) of the hindcasts can be compared with the quantiles of the measurements. The dashed grey line (main diagonal) represents the line of perfect agreement. Figure 5 indicates two problems with hindcasts. First is the overestimation or underestimation of simulated Hs, being shown as curves above or below the main diagonal in Figure 5. The second is the misrepresentation of the shape of quantile functions, observed by the snaked-type evolution of the quantiles towards larger waves. These two limitations prove that hindcasts cannot represent the quantile function, and therefore the CDF, with great accuracy, which compromises the estimation of extrapolated quantiles and return values (e.g. the 100yrs Hs). These characteristics suggest that proper calibration and processing is necessary before the application of EVAs.

Figure 4 – (a) Locations of the four NDBC buoys with long-time record in the Atlantic Ocean used to exemplify the main problems on the analysis and estimation of extreme waves. (b-e) Time series of significant wave height (Hs), in meters, of the buoys. The buoy data is available in the NOAA's National Data Buoy Center on https://www.ndbc.noaa.gov

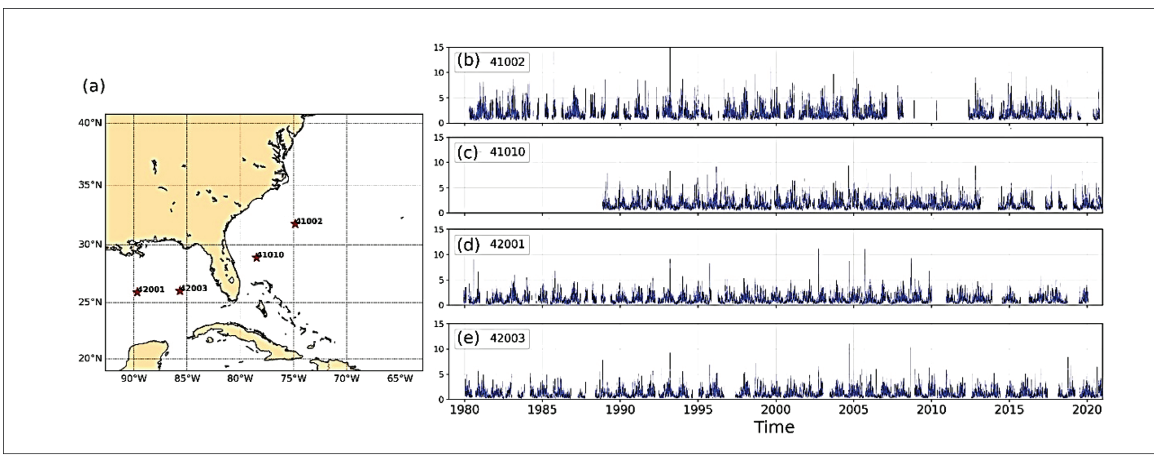


Table I – Summary of reanalysis and hindcasts used in Figures 5 and 6. For more information see the recommended reference

	Institution/source	Reference
ERA5	European Centre for Medium-Range Weather Forecasts (ECMWF)[1]	Hersbach *et al.* (2020)
IFRMRcfsr	National Institute for Ocean Science (France, IFREMER)[2]	Ardhuin *et al.* (2010)
IFRMRera		Rascle and Ardhuin (2013)
WAVERYS	Copernicus Marine Service (CMEMS)[3]	Law-Chune *et al.* (2021)
UMST6	University of Melbourne[4]	Liu and Babanin (2021)

Data available in [1] https://climate.copernicus.eu; [2] http://tinyurl.com/iowa-gaftp/HINDCAST; [3] https://marine.copernicus.eu ; [4] https://wiki-rcs. unimelb.edu.au/display/RCS/Mediaflux.

[2] NOAA's National Data Buoy Center (https://www.ndbc.noaa.gov/).

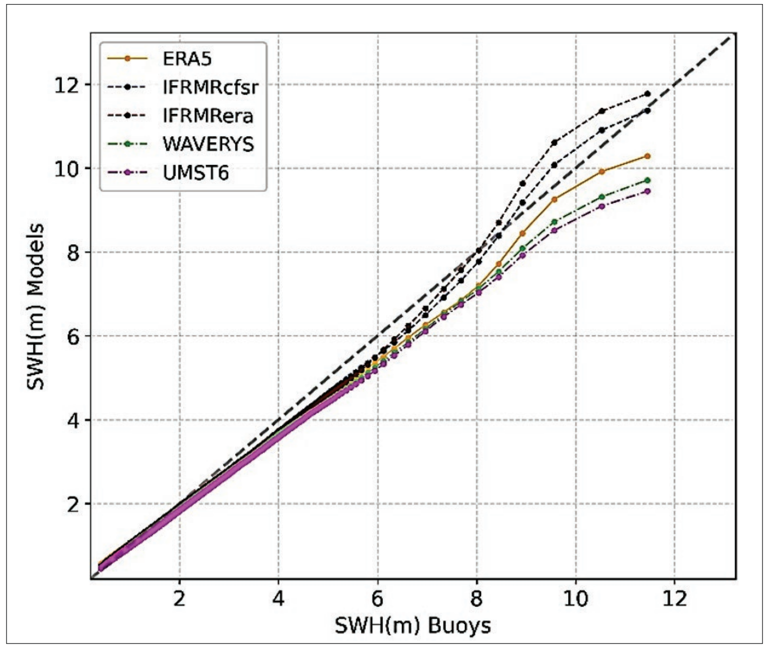
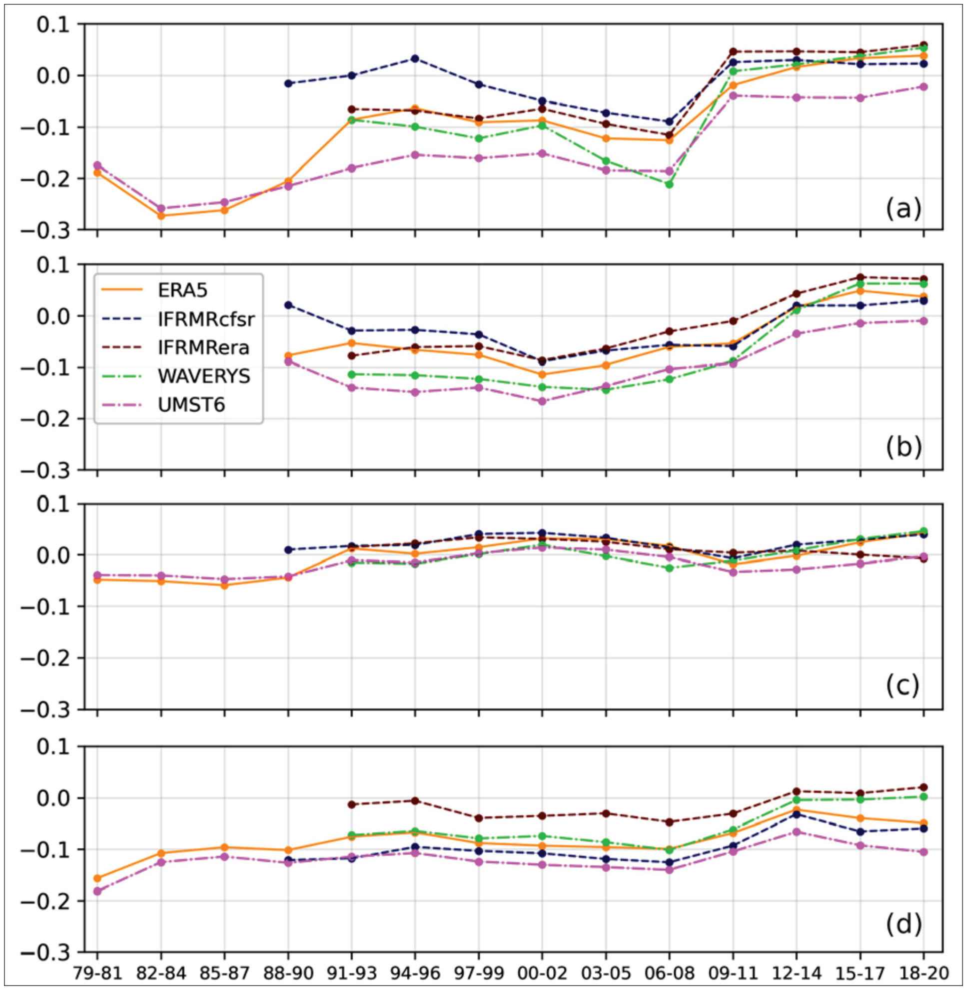


Figure 5 – QQ-plot of five recent wave reanalyses (Table I) for the sea wave height (swh), compared to NDBC buoy observations in the Atlantic Ocean

Another important threat to reliability of return values is the effect of climate changes and trends in the time-series. Vanem and Walker (2013) worked on the identification of trends in the ocean wave climate and Bitner-Gregersen *et al.* (2018) discuss the effect of climate change on safe design of ship structures. Nowadays it is a consensus that long-term climate variations must be considered in metocean design criteria and return values estimation. Leo *et al.* (2021) proposes a Nonstationary Extreme Value Analysis (NEVA) for significant wave height and peak periods that account for trends.

Lastly, the possible heterogeneity of the quality of hindcasts cannot be discarded. Wave hindcasts directly depend on the quality of wind reanalyses, which assimilate distincts amount of observations throughout the decades. Consequently, its accuracy may vary as a function of time. When such variation is small and randomly distributed over the years, it does not severely compromise the long-term analyses and it does not risk being misinterpreted as possible trends. However, as the amount of data assimilated has increased with time, leading to better simulations and partially attenuating the underestimation of the peak of the storms, the systematic errors of hindcasts progressively change throughout the years. Figure 6 presents the bias of five hindcasts computed using the four NDBC buoys (Figure 4). Figure 6 shows that the bias changes from negative to positive values, indicating a progressive modification of the pattern from underestimation to overestimation of the simulations. This feature is not associated with climate changes but instead, it is linked to the variation of the hindcast accuracy over the years, which must be carefully analyzed and amended so it is not associated with a positive trend in the real evolution of Hs.

Figure 6 – Evolution of bias (model minus observation) of significant wave height (y-axis, in meters) with time (x-axis) for the NDBC buoys shown in Fig. 4: (a) 41002, (b) 41010, (c) 42001, and (d) 42003. The error metric is computed using segments of three years, as shown in the x-axis



Perspectives and challenges in the Ocean Decade

As exposed herein, many factors limited the estimation of future changes in cyclone-related extreme events in the ocean. Such methodological limitations exist, demanding caution on analysis in the present climate and projections. Innovative methods are always being developed and adjusted for global or regional purposes, as weather-type or weather-pattern approaches. Artificial Intelligence and machine learning come also as powerful tools, being a promise to revolutionize reanalysis, hindcast, and forecast performance (Campos *et al.*, 2020b; Goulart & de Camargo, 2021; Campos *et al.*, 2021). Currently, the incorporation of machine learning approaches in physical models is a milestone for a high amount of dataset producers around the world (e.g., Pappenberger; Rabier & Venuti, 2021). However, we note that even this method presents a limitation and either short- and long-range forecasts or projection cannot be improved without a better knowledge of the physical processes.

In fact, several processes in nature remain poorly explained, compromising their representation through models (Emanuel, 2020). Good examples are the non-linear wave-wave interaction and the wave-driven turbulence, which are still not fully understood and were just recently successfully implemented in ocean circulation models (for a complete review, see Fox-Kemper *et al.*, 2019). The lack of knowledge regarding variables' behaviour in the marine boundary layer, especially in severe sea states, increases the error in extreme wave analysis (e.g., Campos *et al.*, 2019; Collins *et al.*, 2021) and makes the fully coupling between waves and other ESM components challenging (Cavaleri; Fox-Kemper & Hemer, 2012). The constant increase in model resolution demands such coupling, once the wave effects in air-sea fluxes and ocean current become dominant in smaller scales and coastal zones (Staneva *et al.*, 2016). Some efforts are being done toward the fully-coupled wave models (e.g., Kourafalou *et al.*, 2015; Staneva; Behrens & Wahle, 2015), but some gaps in the knowledge remain and they can only be addressed with the existence of high-quality observational data.

Available high-quality data is still an issue hunting Earth scientists, especially for climate purposes when long and continuous time series are required. Change in the equipment and measure methods can compromise the consistency of data series, creating artificial trends and even invalidating the dataset. The satellite era has come as an improvement for in situ data coverage, but even they present issues regarding sampling frequency and continuity since a mission endures by around 10 years per time-leg. Unfortunately, the Southern Hemisphere faces a bigger problem related to the lack of in situ data coverage, especially in coastal zones. As a clear example, we can see the smaller number of available gauge stations in Figure 4. Rodrigues (2021) brought a good perspective on the heterogeneity in science funding and achievement between the two hemispheres, which can be also interpreted as wealthier and middle- and low-incoming countries. She remarks that there is no way of facing the climate crisis without the participation of the Global South, which can be extended to observation networks covering also the southern hemisphere. The emerging problem is global, thus blind zones on the Earth become a problem for everyone, severely compromising the understanding and simulation of the climate.

The UN Ocean Decade presents several purposes with the powerful statement "the science that we need for the ocean that we want". This sheds light on a very basic concept that may not be forgotten, since sustainability, management, and mitigation to climate change pass through science. Between the established actions they have pursued a predictable ocean, considering both present and future climate, a safer ocean, regarding ocean hazards, and a transparent ocean, highlighting the need for facilitated access to data, information, and technologies. Without the last one, any of the other activities can be successful. "In Brazil, we have some projects that support free available observation data products, such as PNBoia (Pereira et al., 2017), Rede Ondas[3], SIMCosta[4], and REMO[5] which are supported by the government, industry, scientific community, and Brazilian Navy. Recently, the Brazilian Sea Observatory (BSO[6], Franz *et al.*, 2021) was released aiming to be a free access platform to present and distribute several modelling and observation products of our coast. However, the success of efforts such as the BSO depends on the collaboration among Brazilian scientists and funding source agreements for data sharing." Franz *et al.* (2021) give an overview of the existing national and regional initiatives regarding coastal observation and modelling on the Brazilian coast and suggest that the alignment among

[3] https://redeondas.furg.br.
[4] Sistema de Monitoramento da Costa Brasileira (https://simcosta.furg.br).
[5] Rede de Modelagem e Observação Oceanográfica (www.rederemo.org)
[6] https://brazilianseaobservatory.org

them could maximize the investments and socioeconomic benefits. Nevertheless, it is impossible to achieve scientific advancement in ocean hazards or any other oceanography process without thinking about coastal and ocean observation networks in a continuous way, which demand collaborative actions between the scientific community, decision-makers, and society.

FINAL REMARKS

Even though the increasing evolution of models and methods, trends and future changes on the cyclone-related ocean hazards are still difficult to access, especially in the coastal zone. The listed reasons are extensive and are mainly related to methodological limitations. Most recent studies are still kept in lack of confidence and robustness in their findings led by uncertainties related to modelling and extreme event analysis. It is undeniable that modelling plays an essential role in Earth Science, being one of the most powerful tools that we have. However, the climate crisis demands a multi-level approach that includes the return of pure science, related to findings based on observational data and the development of new theories and methods. Only with a collaborative robust observation network is possible to accomplish that. At the end of the day, observational efforts return as modelling improvement and the so-aimed uncertainty reductions.

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