Regional modelling of extreme sea levels induced by hurricanes

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Abstract. Coastal zones are increasingly threatened by extreme sea ~~-~~level events~~. Storm~~, with storm surges ~~are one of~~being among the most hazardous components ~~of these extremes~~, especially in regions prone to tropical cyclones. This study aims to explore the factors ~~affecting~~influencing the performance of numerical ~~modelling~~models in simulating storm surges in the tropical Atlantic region. The maxima, ~~duration~~durations and time ~~evolution~~evolutions of ~~the~~ extreme storm surge events are evaluated for four historical hurricanes ~~by comparison~~ against tide gauge records. The ADCIRC and NEMO ocean models are ~~intercompared~~compared using ~~a~~ similar ~~configuration~~configurations in terms of domain, bathymetry, and spatial resolution. These models are then used to perform sensitivity experiments on oceanic and atmospheric forcings, physical parameterizations ~~for~~of wind stress, and baroclinic/barotropic modes. NEMO and ADCIRC ~~show a~~demonstrate similar ~~skill to simulate~~abilities in simulating storm surges induced by hurricanes. Storm surges simulated with ERA5 atmospheric reanalysis forcing are generally more accurate than those ~~using~~simulated with parametric wind models for the simulated hurricanes. The inclusion of ~~the~~ baroclinic processes improves storm surge amplitudes ~~in~~at some coastal locations, such as along the southeastern Florida peninsula (USA). ~~Experiments~~However, experiments exploring different ~~wind stress~~ implementations of wind stress and ~~the~~ interactions ~~between~~among storm surges, tides and mean sea level ~~however~~ have shown ~~a~~ minimal ~~impact~~impacts on hurricane-induced storm surges ~~induced by hurricanes~~.

~~1. Introduction~~

~~Coastal zones are among the most densely populated and urbanized areas in the world. 10% of the world population lives in low-lying coastal regions with 35 million people in North America, Central America and the Caribbean region (McMichael et al., 2020; Neumann et al., 2015). These regions are increasingly threatened by extreme sea levels, during which major damage to the waterfront and infrastructure is likely to occur (Hicke et al., 2022; Castellanos et al., 2022).~~

1. Introduction

Coastal zones are among the most densely populated and urbanized areas in the world. Ten percent of the global population lives in low-lying coastal regions, with 35 million people living in North America, Central America and the Caribbean region (Neumann et al., 2015; McMichael et al., 2020). These regions are increasingly threatened by extreme sea levels, during which major damage to the waterfront and infrastructure is likely to occur (Hicke et al., 2022; Castellanos et al., 2022).

Tropical cyclones are major drivers of these extreme sea levels due to large storm surges, which are rises in the sea level due to the combined ~~effect~~effects of low atmospheric pressure and strong winds (Woodworth et al., 2019). This phenomenon can drive coastal hazards such as flooding and erosion (Dullaart et al., 2021; Jamous et al., 2023). The present study focuses on four historical severe tropical cyclones (hurricanes) that have occurred in the northwestern Atlantic region in the last 20 years and have severely impacted ~~the~~ coasts: Wilma (2005), Matthew (2016), Irma (2017), and Maria (2017). ~~Wilma is the most intense Atlantic hurricane by lowest pressure on record, formed on October 15, 2005, reaching sustained winds of 295 km/h before making landfall in southwestern Florida on October 24, 2005. Matthew, has formed on September 28, 2016, causing~~

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~~generalized devastation across the Caribbean and southeastern United States, particularly in Haiti, Cuba, and the Bahamas, before weakening and dissipating over the Atlantic Ocean. Irma is also one of the strongest Atlantic hurricanes, formed on August 30, 2017, devastating several Caribbean islands and hitting Florida on September 10, 2017. Maria has formed on September 16, 2017, causing widespread destruction in Dominica and Puerto Rico before dissipating on September 30, 2017.~~ As Category 5 hurricanes, all of them are major hurricanes for the region, both in terms of the storm surge amplitudes reached and the total damage estimated ~~(Tab.~~, as presented in Table 1)~~.~~.

Hurricane	**Time period considered**	**Number of hours in category 5 (i.e., > 70 m/s or 252 km/h)**	**Maximum sustained winds (km/h)**	**Minimum atmospheric pressure (mbar)**	**Maximum storm surge level reported (m)**	**Affected zones**	**Total damage reported**
Wilma	2005/10/17 ~~–~~– 2005/11/08	3	296	882 (most intense Atlantic hurricane on record)	3.7	northeastern Yucatan Peninsula, western Cuba, southern Florida (USA), western Bahamas	33 direct deaths $21 billion ~~USD~~, US
Matthew	2016/09/28 ~~–~~– 2016/10/11	2	296	934	3.9	Haiti, southwestern Dominican Republic, ~~Eastern~~eastern Cuba, Bahamas, eastern Florida (USA)	585 direct deaths 18 indirect deaths (USA), 128 persons missing (Haiti) $15 billion ~~USD~~, US
Irma	2017/08/30 ~~–~~– 2017/09/12	17	287	914	3.5	All the northern Caribbean Islands, all Florida (USA)	47 direct deaths 82 indirect deaths (USA) $53 billion ~~USD~~, US
Maria	2017/09/16 ~~–~~– 2017/09/29	7	278	908	2.9	Puerto Rico, ~~Virgen~~Virgin Islands, western Dominican Republic, Dominica, Guadeloupe	3,000 direct and indirect deaths $92 billion ~~USD~~, US

Table 1: Information about the selected hurricanes from the tropical cyclone reports of the National Hurricane Center (Pasch et al., 2006 for Wilma, Stewart, 2017 for Matthew, Cangialosi et al., 2021 for Irma and Pasch et al., 2023 for Maria).

~~It is therefore important to monitor the spatio-temporal evolution of storm surges, especially in the context of climate change where tropical cyclone frequency and intensity might be altered (Roberts et al., 2020; Cattiaux et al., 2020; Knutson et al., 2020; Bloemendaal et al., 2022; van Westen et al., 2023). For this purpose, historical records such as tide gauge data are valuable, but they are often scarce and sometimes unavailable during the most severe events (Haigh et al., 2021). Hydrodynamic models (e.g., ADCIRC, SCHISM, GTSM, Mike21) can be used to overcome this limitation. These models are often run in a 2-D barotropic mode enabling fine resolution along coastlines, thus limiting computational costs. In recent years, they have been widely used in operational systems to forecast storm surge hazards~~ Therefore, monitoring the spatiotemporal evolution of storm surges, particularly in the context of climate change, where the frequency and intensity of tropical cyclones may change, is important (Roberts et al., 2020; Cattiaux et al., 2020; Knutson et al., 2020; Bloemendaal et al., 2022; van

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Westen et al., 2023). Historical records, such as tide gauge data, are valuable for this purpose. However, these records are often scarce and sometimes unavailable during the most severe events. (Haigh et al., 2021). Hydrodynamic models (e.g., ADCIRC, SCHISM, GTSM, and Mike21) can be used to overcome the limitation of scarce historical records. These models are often run in two-dimensional barotropic mode, enabling fine resolution along coastlines while minimizing computational costs. In recent years, they have been widely used in operational systems to forecast storm surge hazards (Dietrich et al., 2018; Fernández-Montblanc et al., 2019) or to generate regional (Haigh et al., 2014; Marsooli and Lin, 2018; Muis et al., 2019; Toomey et al., 2022; Gori et al., 2023; Martín et al., 2023; Parker et al., 2023) and global hindcasts (Muis et al., 2016; Dullaart et al., 2021). More recently, hydrodynamic models have also been employed to derive projections of storm surges at both regional (Camelo et al., 2020; Makris et al., 2023; Wood et al., 2023) and global (Vousdoukas et al., 2018; Muis et al., 2020, 2023) scales, driven by climate model data.

Primary drivers for hydrodynamic models are atmospheric forcings such as winds and atmospheric surface pressure. The use of a global or regional atmospheric reanalysis (e.g., ERA5, CFSR, JRA-55) provides a consistent hourly 2-D forcing field over the whole domain. However, in addition to unresolved processes and insufficient spatial resolution (Roberts et al., 2020), these datasets are limited in their temporal coverage, posing a challenge for hindcast production given the rarity of tropical cyclones (Dullaart et al., 2021; Wood et al., 2023). Parametric wind models, derived from observations or statistical approaches, enable to compute a large number of simulations, thereby enhancing the robustness in storm surges evaluation (Haigh et al., 2014; Toomey et al., 2022; Martín et al., 2023). However, these parametric models often rely on simplifying cyclone behavior, frequently adopting an axisymmetric cyclone model, such as in the widely used Dynamic Holland Model (Holland, 1980; Fleming et al., 2008) potentially resulting in biases (Dietrich et al., 2018).

In addition to the atmospheric forcing, oceanic drivers are also important for storm surge modelling. The consideration of other factors influencing sea level and their interactions, such as tides and regional mean sea level, can significantly modify storm surges (Marsooli and Lin, 2018; Idier et al., 2019) and generate regional (Haigh et al., 2014; Marsooli and Lin, 2018; Muis et al., 2019; Toomey et al., 2022; Gori et al., 2023; Parker et al., 2023; Martín et al., 2023) and global hindcasts (Muis et al., 2016; Dullaart et al., 2021). More recently, hydrodynamic models have also been employed to derive projections of storm surges at both regional (Camelo et al., 2020; Makris et al., 2023; Wood et al., 2023) and global (Vousdoukas et al., 2018; Muis et al., 2020, 2023) scales, driven by climate model data.

The primary drivers for hydrodynamic models are atmospheric forcings such as winds and atmospheric surface pressure. The use of a global or regional atmospheric reanalysis (e.g., ERA5, CFSR, and JRA-55) provides a consistent hourly 2D forcing field across the entire domain. However, these datasets face limitations due to unresolved processes and insufficient spatial resolution (Roberts et al., 2020). Additionally, their limited temporal coverage poses a challenge for hindcast production, given the rarity of tropical cyclones (Dullaart et al., 2021; Wood et al., 2023). Parametric wind models represent the wind field distributions of tropical cyclones using a limited number of observations or statistical methods. The simplicity and computational efficiency of these models make them powerful tools for performing many simulations, thereby enhancing the robustness of storm surge evaluations (Haigh et al., 2014; Toomey et al., 2022; Martín et al., 2023). The origin of the parametric wind models started with C.E. Deppermann (1947), who adopted the mathematical equations of the Rankine vortex model (Rankine, 1882) to depict the tropical cyclone atmospheric structure. Since then, numerous parametric models have been developed, becoming more sophisticated and complex with advancements in observational technologies. Despite these advancements, parametric models often simplify cyclone behaviour, such as by adopting an axisymmetric cyclone model, which can potentially introduce biases (Dietrich et al., 2018), as for example with the widely used dynamic Holland model (Holland, 1980; Fleming et al., 2008).

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In addition to atmospheric forcing, oceanic drivers are also important for storm surge modelling. Factors such as tides and the regional mean sea level can significantly interact with and modify storm surges (Marsooli and Lin, 2018; Idier et al., 2019). For ~~instance~~example, neglecting tide~~-~~ surge interactions can significantly reduce the accuracy ~~in~~of the storm surge prediction (Fernández-Montblanc et al., 2019), potentially overestimating extreme sea levels by up to 30% (Arns et al., 2020). ~~Other studies emphasize the importance of considering the baroclinic response in sea level due to tropical cyclones (Ezer, 2018; Zhai et al., 2019; Ye et al., 2020). 3-D baroclinic ocean general circulation models such as NEMO and ROMS can be used for this purpose. These models explicitly resolve storm surges (Chaigneau et al., 2022; Irazoqui Apecechea et al., 2023) although at higher computational expenses. Their application in modelling storm surges due to tropical cyclones therefore remains limited (Kodaira et al., 2016; Hsu et al., 2023).~~Other studies emphasize the importance of considering the baroclinic response on sea level due to tropical cyclones (Ezer, 2018; Zhai et al., 2019; Pringle et al., 2019; Ye et al., 2020). Three-dimensional baroclinic ocean general circulation models, such as NEMO and ROMS, can be used for this purpose, as they explicitly resolve storm surges (Chaigneau et al., 2022; Irazoqui Apecechea et al., 2023). However, these models have relatively high computational costs, limiting their application for tropical cyclone-induced storm surge modelling (Kodaira et al., 2016; Hsu et al., 2023). Additionally, recent research ~~highlights the significant impact of wind stress consideration on storm surge modelling, including the choice of the parameterization, the parameter tuning, and the impact of the processes considered such as waves (O'Neill et al., 2016; Pineau-Guillou et al., 2020)~~underscores the significant impact of wind stress parameterization on storm surge modelling, including the choice of parameterization, parameter tuning, and the consideration of processes such as waves (O'Neill et al., 2016; Pineau-Guillou et al., 2020).

This study aims to investigate different factors influencing the performance of numerical ~~modelling~~models in simulating storm surges caused by hurricanes. The focus is on the tropical Atlantic region, ~~covering~~including the Caribbean Sea, the Gulf of Mexico and the eastern ~~coasts~~coast of Florida (USA). Four historical hurricanes ~~that have caused~~ known for their severe coastal impacts are simulated (Tab. 1). The ~~skill~~ability of the simulations to reproduce the storm surge contribution to extreme sea levels is evaluated against ~~recorded values from~~ tide~~-~~ gauge ~~stations~~records. The ~~modelled~~ validation involves analysing both the peak surge maxima and the hourly time series ~~are analyzed~~ during these extreme events. Two ocean models (ADCIRC and NEMO) are ~~intercompared~~compared using a similar configuration: domain, a spatial resolution of 9 km, bathymetry and ~~2-D~~2D barotropic mode. ~~These models are then used to perform~~Then, sensitivity experiments~~. The~~ are conducted with these models to assess the impacts of various factors. This study evaluates the sensitivity of ~~the~~ storm surge to different atmospheric ~~forcing is assessed~~forcings by comparing ~~storm surges induced~~simulations driven by ERA5 reanalysis data ~~and~~ with those using parametric wind models ~~usually applied~~typically used for hurricanes. ~~The effect on storm surge due to non-linear~~It also examines the effects of nonlinear interactions with ~~the~~ astronomical ~~tide~~tides and variations in the mean sea level ~~is also investigated~~, as well as the sensitivity to different wind stress schemes. ~~In addition,~~Additionally, this study explores the baroclinic ~~contribution~~contributions to storm surges ~~is studied~~ using a ~~3-D~~3D configuration that ~~also~~ simulates the effects of temperature and salinity ~~and their impact~~ on ocean circulation.

The ~~remaining~~remainder of the paper is organized as ~~follows.~~described below. The ~~met-ocean~~metocean data are presented in Sect. 2. The methods are described in Sect. 3, with details of the numerical models, configurations developed and sensitivity experiments performed, as well as the statistical metrics used to ~~analyze~~analyse the simulations. The results are presented in Sect. 4, first with a comparison of the models with equivalent settings, and then with an analysis of the sensitivity experiments. ~~We notably~~Notably, we examine the influence of atmospheric forcing using ADCIRC and the ~~effect~~effects of oceanic drivers using NEMO. The results are discussed in Sect. 5, and general conclusions of the study are drawn in Sect. 6.

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2. Met-ocean data

2.1. Tide gauge data

The modelled storm surges are validated against tide gauge records extracted from the GESLA (Global Extreme Sea Level Analysis) dataset ~~version3~~version 3 (Haigh et al., 2023). The selected tide gauge stations provide high-frequency tide gauge records with ~~at least an~~a minimum hourly ~~frequency. In~~resolution. For this study, tide gauges within a 300 km radius of the hurricanes are selected ~~to analyze~~ for analysing the modelled storm surges~~. Their~~, and their locations are listed in Table 2. ~~Given the horizontal resolution of the regional models used, tide gauges~~ Tide gauges located in onshore ~~locations~~areas, such as estuaries, channels, bays, and lagoons, are excluded because of the horizontal resolution of the regional models used. Additionally, tide gauges recording storm surges of less than 15 cm are not ~~considered~~included in ~~this study. The tidal~~the analysis. Tidal harmonic constituents are extracted from the time series with the Python "utide" package (Codiga, 2011). ~~The term "~~In this context, "storm ~~surge" will be used~~surges" refer hereinafter to ~~denote the non-tidal~~nontidal residuals. ~~Tide gauges registering storm surges of less than 15 cm are also excluded from the analysis.~~

Tide gauge name	Country	Longitude ~~(°W~~(°W)	Latitude ~~(°N)~~ (°N)	Wilma	Matthew	Irma	Maria
Cedar_Key	USA	83.0317	29.135			x	
Crystal_Rv_At_Mouth_Nr Shell_Isl_Nr_Crystal_Rv_Fl	USA	82.6906	28.9253			x	
Gulf_Of_Mexico_Near_Bay port_Fl	USA	82.6501	28.5336		x	x	
Clearwater_Bch_FL	USA	82.832	27.977			x	
Naples_FL	USA	81.807	26.13	x	x	x	
Key_West_FL	USA	81.808	24.553	x		x	
Virginia_Key_FL	USA	80.162	25.732	x		x	
Lake_Worth_Pier	USA	80.0342	26.6128		x	x	
Trident_Pier	USA	80.5931	28.4158	x	x	x	
Punta_Cana	Dominican Republic	68.375	18.505			x	x
Mona_Island	Puerto Rico (USA)	67.9385	18.0899			x	x
Mayaguez_PR	Puerto Rico (USA)	67.16	18.22			x	
Yabucoa_Harbor_PR	Puerto Rico (USA)	65.832	18.055				x
Fajardo_PR	Puerto Rico (USA)	65.63	18.335			x	
San_Juan_PR	Puerto Rico (USA)	66.117	18.46			x	x
Esperanza	Puerto Rico (USA)	65.4714	18.0939			x	
Isabel_Segunda	Puerto Rico (USA)	65.4439	18.1525			x	x
Lameshur_Bay_VI	Virgin Islands (USA)	64.723	18.317			x	
PointeAPitre_60minute	Guadeloupe (France)	61.5300	16.23				x

Table 2: Selected tide gauge stations used for ~~the~~ storm surge validation.

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2.2. Atmospheric pressure and wind fields

Storm surges induced by hurricanes are simulated using ~~winds~~surface wind and atmospheric pressure fields as forcings. In this study, data from ~~the ERA5~~a reanalysis product and parametric wind models are used. The selected reanalysis product is ERA5 (Fig. 1b~~)~~), provided by the European Centre for Medium-range Weather Forecasts (ECMWF) (Hersbach et al., 2020). ~~The atmospheric variables have~~ERA5 has a horizontal resolution of 0.25 ~~º~~degrees (~31 km) and an hourly temporal resolution, ~~covering the period~~spanning from 1950 to the present. The ~~assimilation of~~reanalysis benefits from satellite data ~~since~~ assimilation starting in 1980~~ enables~~, which enhances the representation of tropical cyclones ~~in the reanalyses.~~. Compared ~~to~~with its predecessor ERA-Interim (~79 km, 6-hourly), ~~ERA5~~the higher spatial and temporal resolution ~~allows~~of ERA5 allow for an improved resolution of tropical cyclones, ~~for instance~~ including a lower central pressure (Hersbach et al., 2020). Additionally, ERA5 benefits from an improved data assimilation procedure, notably incorporating satellite observations from the Advanced Scatterometer (ASCAT) for wind speed (Dullaart et al., 2020). ~~As a result~~Consequently, when used for atmospheric forcing, ERA5 ~~has demonstrated~~offers improved ~~representation of~~accuracy in representing storm surges induced by tropical cyclones (Dullaart et al., 2020)~~, leading to a recent extensive use in large-scale studies simulating storm surges (Muis et al., 2020, 2023; Dullaart et al., 2021; Gori et al., 2023; Parker et al., 2023)~~ and has been used in large-scale studies simulating storm surges (Muis et al., 2020, 2023; Dullaart et al., 2021; Gori et al., 2023; Parker et al., 2023).

Storm surges induced by hurricanes are also simulated using parametric wind models. ~~These models represent the wind field distributions of tropical cyclones based on a limited number of observations, making them powerful tools due to their simplicity and computational efficiency. In our study, the tropical cyclone observations~~The observations used as inputs for these models are taken from the International Best Track Archive for Climate Stewardship (IBTrACS) database ~~(Knapp et al., 2010, 2018)~~(Knapp et al., 2010, 2018). ~~It provides at least six-hourly information on the cyclone position and intensity from 1851 to present, although additional variables (such as radius of maximum wind, environmental pressure, and various wind radii) are also available for the last decades. The origin of parametric wind models started with CE. Deppermann (1947), which adopted the mathematical equations of the Rankine vortex model (Rankine, 1882) to depict the tropical cyclone atmospheric structure. Since then, numerous parametric models have been developed, becoming more sophisticated and complex as increasing the observational technologies. This study evaluates four different parametric wind models. The first one, the Dynamic Holland Model (DHM), derives from the commonly used Holland profile~~The database provides at least six-hour information on the cyclone position and intensity from 1851 to the present, as well as additional variables such as the radius of maximum wind, environmental pressure, and various wind radii for recent decades. This study evaluates four recognized parametric wind models: the dynamic Holland model (DHM), the parameterization proposed by Willoughby et al. (2006), the physics-based model proposed by Chavas et al. (2015) and the generalized asymmetrical Holland model (GAHM). The DHM is an extension of the commonly used Holland model (Holland, 1980), with ~~the~~ modifications~~,~~ applied by Fleming et al. (2008), to better capture dynamic processes within and around ~~storms. Another evaluated Holland-derived model is that proposed by Willoughby et al. (2006). This is a more complex model based on a piecewise continuous wind profile developed using an extensive aircraft data for validation purposes. On the other hand, we consider the physics-based model developed by Chavas et al. (2015)~~tropical cyclones. The Willoughby et al. (2006) model, also derived from the Holland model, is based on a piecewise continuous wind profile. This model is composed of analytical segments based on a power law inside the eye and two exponential decay functions outside. These segments are patched smoothly together across the radius of maximum wind using a radially varying polynomial ramp function. The required model parameters (i.e., *R1*, *R2*, *X1*, *X2*, n and *A*) are statistically estimated by these authors based on aircraft observations for nearly 500 tropical cyclones. Done et al., 2020 provide examples of successful applications of the model to be used as the forcing of marine dynamics. The Chavas et al. (2015) model is a physics-based model that mathematically merges the ~~Emanuel (2004~~Emanuel (2004) and ~~the Emanuel and Rotunno (2011~~Emanuel and Rotunno (2011) solutions ~~for the outer- and inner-core wind changes, respectively. However, these three~~

Formatted: Font color: Text 1 (×41 margin annotations) models assume a perfect azimuthal symmetry structure of the wind fields (Fig. 1d,e,f), which can lead to largeto integrate the outer- and inner-core wind structures of tropical cyclones, respectively. In the Chavas et al. (2015) model, several parameters need to be prescribed: the drag coefficient in the outer region (set to 0.0015), the radiative-subsidence rate (set to 2 mm/s), and the ratio of surface exchange coefficients for enthalpy and momentum (set to 1). No eye adjustment was applied to reduce the wind speed within the inner core. Wang et al., 2022 demonstrated the successful application of this model to simulate extreme sea levels. These three models assume a perfectly azimuthal symmetric structure of the wind fields (Fig. 1d, e, f), which may lead to errors in storm surge forecasting (Xie et al., 2011). A more recent model, the Generalized Asymmetrical Holland Model (GAHM), is also tested incorporating asymmetries (Fig. 1c) by considering information from all available isotachs in the quadrants (Gao et al.,The GAHM is a more recent model that also derives from the commonly used Holland model (Holland, 1980) but incorporates asymmetries in the wind field (Fig. 1c) by considering information from all available isotachs (lines of constant wind speed) in the quadrants (Gao et al., 2017; Dietrich et al., 2018; Bilskie et al., 2022). All the models provide wind velocities averaged over 1 minute at the top of the boundary layer. These velocities are first reduced by a factor of 0.9 and then adjusted by multiplication by 0.8928 to convert from 1-minute to 10-minute averages to obtain surface wind speeds. No adjustment for wind speed reduction over land has been applied. The surface pressure field is estimated based on the rectangular hyperbola approximation proposed by Schloemer (1954), including the original/generalized Holland scaling parameter *b* as an exponent (Holland, 1980; Gao et al., 2017). The pressure drop is calculated by assuming a background pressure of 1013 mbar.

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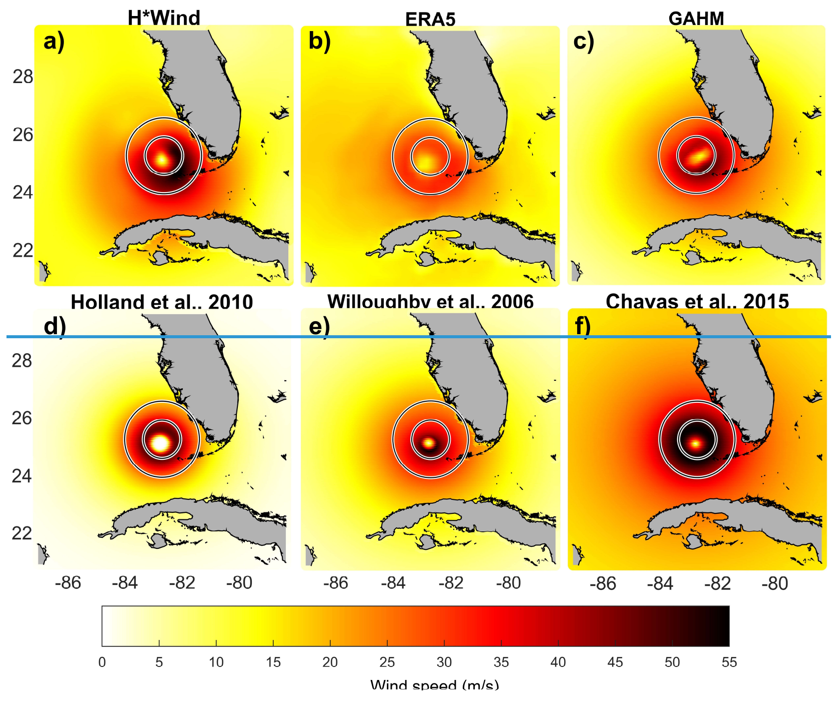

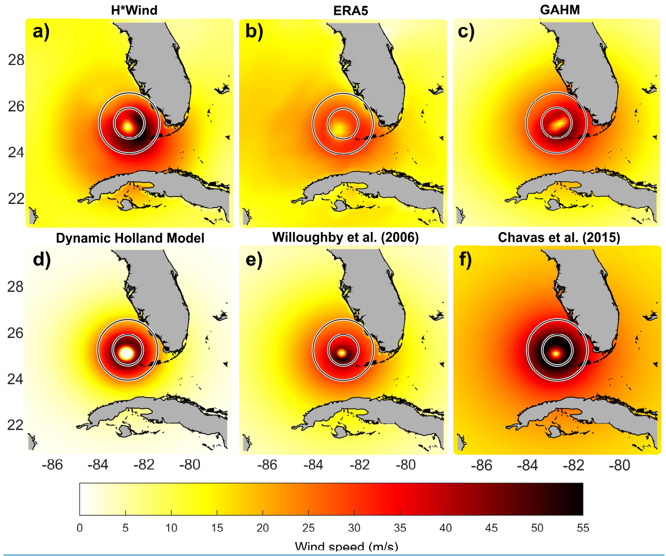

Figure 1: ~~Wind~~Example of the synoptic wind field ~~in~~for the different atmospheric forcings used in the study during ~~hurricane~~Hurricane Wilma before landfall in Florida (USA). a) H*Wind real-time hurricane wind analysis system developed as part of the National Oceanic and Atmospheric Administration (NOAA) Hurricane Research Division (Powell et al., 1998), which is considered here as the reference. b) ERA5 reanalysis data. c, d, e, f) The four different parametric wind models tested ~~in the study~~.

3. Methods

Storm surges induced by four hurricanes are simulated in the northwestern Atlantic region using two different models (ADCIRC and NEMO) ~~sharing~~with similar configurations~~. These models are then used to conduct sensitivity~~ (Sect. 3.1). Sensitivity experiments ~~on~~ are then conducted to assess the impacts of atmospheric and ~~ocean~~oceanic forcings~~.~~ on storm surge modelling (Sect. 3.2). The simulated extreme storm surge events are evaluated in terms of the maximum amplitude, duration, and correlation against tide gauge records~~.~~ (Sect. 3.3).

3.1. Numerical models and regional configurations

The Advanced Circulation (ADCIRC) ~~Model,~~ model, which is used here ~~used in~~with the v53 version, is a numerical model ~~designed~~ for simulating coastal hydrodynamics ~~(Luettich et al., 1992; Westerink et al., 1994).~~(Luettich et al., 1992; Westerink et al., 1994). It solves a formulation based on the Navier~~–~~-Stokes equations for shallow water conditions, called the shallow-water equations. ~~The equations are solved by discretizing spatial~~Spatial derivatives are discretized using a finite element method~~.~~, allowing unstructured meshes. This approach enables ~~the use of unstructured meshes, which offers the advantage of~~ high-resolution ~~discretization~~ modelling in specific areas ~~of interest —~~, such as coastal regions or inland~~—~~ zones, without the computational cost of ~~an increased~~ increasing the resolution ~~over~~across the ~~whole spatial~~entire domain. The model relies on the input of meteorological data ~~on the ocean surface, specifically~~ , such as wind and pressure fields~~. The meteorological data,~~ which can be sourced in different formats, including parametric wind models or gridded ~~wind fields from reanalyses~~reanalysis and climate ~~models.~~model outputs. Tidal levels or mean sea level ~~forcing~~forcings can be added as ~~an~~ optional ~~input~~inputs through ~~the~~ boundaries. ~~The model has been mostly~~Typically used in ~~the 2DDI~~2D barotropic mode~~,~~ for resolving storm surges and tides, ~~although it does offer the option to~~ ADCIRC can also operate in ~~a 3-D~~3D mode, which requires

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supplementaryadditional inputs such as temperature and salinity. AdditionalSeveral advanced options can also includebe included: the modelling of the wetting and drying of inundated areas (Dietrich et al., 2004), the inclusion of river flows, the representation of obstructions to flow, ((Luettich and Westerink, 1999), and the integration of the wave setup by coupling with a wave model (Dietrich et al., 2012). ADCIRC has beenis widely used in research for modelling storm surge modelling induced by tropical cyclones at various scales—global (Pringle et al., 2021), regional (Marsooli and Lin, 2018; Camelo et al., 2020; Gori et al., 2023)(Marsooli and Lin, 2018; Camelo et al., 2020; Gori et al., 2023), and more local (Yin et al., 2016; Dietrich et al., 2018)(Yin et al., 2016; Dietrich et al., 2018). In addition, ADCIRC model is usually applied in emergencyIt is also employed in operational forecasting systems, such as the NOAA Operational Model (Riverside Technology, 2015). It, and is also utilized as the standard coastal storm surge model used by the U.S. Army Corps of Engineers (USACE),) and the U.S. Federal Emergency Management Agency (FEMA).

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The ocean general circulation model NEMO (Nucleus for European Modelling of the Ocean) (Madec et al., 2023), is a numerical model designed for simulating the 3-D3D baroclinic ocean general circulation model developed by a European consortium (https://www.nemo-ocean.eu/). It solves the primitive equations, i.e., the Navier—Stokes equations and a nonlinear equation of state that couples the temperature and salinity to the fluid velocity, with assumptions based on scale considerations. The equations are solved using a finite difference method. The ocean is discretized horizontally using a curvilinear ORCA grid, almost regular in our study area, and vertically using a chosen coordinate system, resulting in a high computational cost. The model relies on the input of atmospheric fields (air temperature, specific humidity, winds, atmospheric pressure, short- and longwave radiation, precipitation and snow cover) and tidal potential at the surface., It also requires oceanic fields (3-D3D ocean temperature, salinity, currents and 2-D2D sea level) at lateral boundaries in the case of a for regional configuration, and configurations, as well as river runoff fluxes. In addition to the storm surges and tides, NEMO can also resolve the mean sea level i.e. changes related to ocean general circulation associated, i.e., due to baroclinic processes and the addition of mass to the ocean. In this study, we only used the ocean circulation module of NEMO in its version 4.0.4 (Madec et al., 2019), which we refer to as NEMO(Madec et al., 2019), but additional components can be included, such as sea ice modellingmodels and biogeochemical processes., can be included. NEMO has been recently usedapplied for sea level research at the global (Royston et al., 2022) and regional scale (Adloff et al., 2018; Chaigneau et al., 2022)scales (Adloff et al., 2018; Chaigneau et al., 2022). It is also usedutilized in the framework of the Copernicus Marine Service (CMEMS), providing free-of-charge ocean data and information derived from real-time systems and reanalyses at global and regional scales. For instanceexample, it is utilizedused to forecast extreme coastal water levels and support coastal flood awareness applications at European scaleacross Europe (Irazoqui Apecechea et al., 2023).

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ADCIRC and NEMO are intercomparedcompared for storm surge modelling in the northwestern Atlantic region. The, covering a domain extends from 98 to 55 ºW° W and from 6 to 31.5 ºN° N (Fig. 2). The region includes the wholeentire Caribbean Sea, Gulf of Mexico and a part of the northwestern Atlantic Ocean. This region is particularly prone to tropical cyclone development due to thebecause of its warm water temperatures, high moisture levels, and specific wind patterns. AThe region encompasses a variety of oceanographic processes are found in this domain that are important to considercrucial for accurate storm surge modelling. The region contains strongIt has significant bathymetric variations of bathymetry, with a wide, including a broad continental shelf in the Gulf of Mexico and around the complex islands of Bahamas and, as well as a tightnarrow continental shelf aroundnear the Caribbean islands. In terms of ocean circulation, the dominant feature is the Gulf Stream that, which originates in the Gulf of Mexico and flows through the Straits of Florida (USA) and up the eastern coastline of the United States. Tidal amplitudes are relatively moderated in the The region is microtidal, with the largest tidal amplitudes reaching approximately 2 meters in the northern Surinam and Guyana, as well as in the northeastern Florida (USA). To ensure a fair comparison between both models, two

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Two similar configurations ~~have been developed,~~ operating in a ~~2-D~~2D barotropic mode~~. While it allows only storm surges and external tides~~ have been developed to ~~be resolved, a barotropic setup is expected to represent the main ocean response to tropical cyclones.~~ensure a fair comparison between the two models. As NEMO is used mainly ~~used~~ in ~~a 3-D~~3D baroclinic mode, the code has been modified to enable running the model in ~~a~~2D barotropic mode ~~for the region of interest. Modifications were implemented~~ based on the Met Office configuration for the UK (O'Neill et al., 2016). The model operates using two vertical sigma levels with only one active layer and with typical baroclinic processes disabled. Tracers (temperature and salinity) ~~remains~~are kept constant in space and time ~~so that changes in pressure gradient generating ocean circulations~~, and ~~transport are not considered. Vertical~~ vertical physics such as vertical mixing, internal waves, and convection are entirely deactivated. Atmospheric inputs are ~~restricted~~limited to winds (wind stress) and pressure (barotropic effects due to pressure forcing), with the total turbulent heat flux set to zero ~~during the whole simulation.~~. The resolution of ~~the two~~both configurations is limited by the computational cost of the NEMO model, which has a ~~quasi-regular~~quasiregular resolution of 9 km in the region~~, here of 9 km. A~~. ADCIRC is configured to have a similar resolution ~~has been chosen for the ADCIRC, spanning,~~ ranging from 3 km near the coast or in shallow water areas to 70 km in the deeper open ocean (Fig. ~~2b). Both the~~2b), resulting in three times fewer elements than for NEMO (Tab. A1). The bathymetry and ~~the~~ coastline ~~taken~~data are derived from the NOAA Operational Model with ADCIRC (Riverside Technology, 2015) ~~have been interpolated on the ADCIRC and NEMO grids (Fig. 2a). In the NEMO configuration, dry areas are not allowed. Consequently, a minimum bathymetry value is set to 3 meters to allow lower sea levels, such as during low tides. The identical value is implemented for the ADCIRC configuration as well even if dry areas are allowed. Both configurations are driven by hourly winds and pressure from the ERA5 atmospheric reanalysis. In NEMO, the wind stress formulation has been updated to follow the same S&B scheme as in ADCIRC (Smith and Banke, 1975, eq. (1)). Additionally, they are forced by eight tidal constituents (M2, K2, S2, N2, Q1, O1, P1, K1) derived from TPXO9 (Egbert and Erofeeva, 2002). For each simulated hurricane, the model is also run with only the astronomical tidal forcing at the open boundaries, excluding meteorological forcing. This approach enables to isolate the storm surge component of the wind-driven simulations and compare to the non-tidal residuals from tide gauges. The description of the different settings and forcings used for ADCIRC and NEMO configurations are provided in the Appendix (Tab.~~and interpolated on the ADCIRC and NEMO grids (Fig. 2a). In this NEMO configuration, dry areas are not allowed; thus, a minimum bathymetry value of 3 m is set to allow lower sea levels, such as during low tides. This value is also applied to the ADCIRC configuration, despite dry areas being allowed. Both models are driven by hourly wind and pressure data from the ERA5 atmospheric reanalysis (Sect. 2.2) using the S&B scheme (Smith and Banke, 1975) for wind stress (Eq. (1)). Additionally, they are forced by eight tidal constituents (M2, K2, S2, N2, Q1, O1, P1, and K1) derived from TPXO9 (Egbert and Erofeeva, 2002) at the open boundaries. For each simulated hurricane, the models are also run with only astronomical tidal forcing, excluding meteorological forcing. This approach enables the isolation of the storm surge component, making it comparable to the nontidal residuals from tide gauges (Sect. 2.1). The detailed settings and forcings for the ADCIRC and NEMO configurations are provided in Appendix A (Tab. A1).

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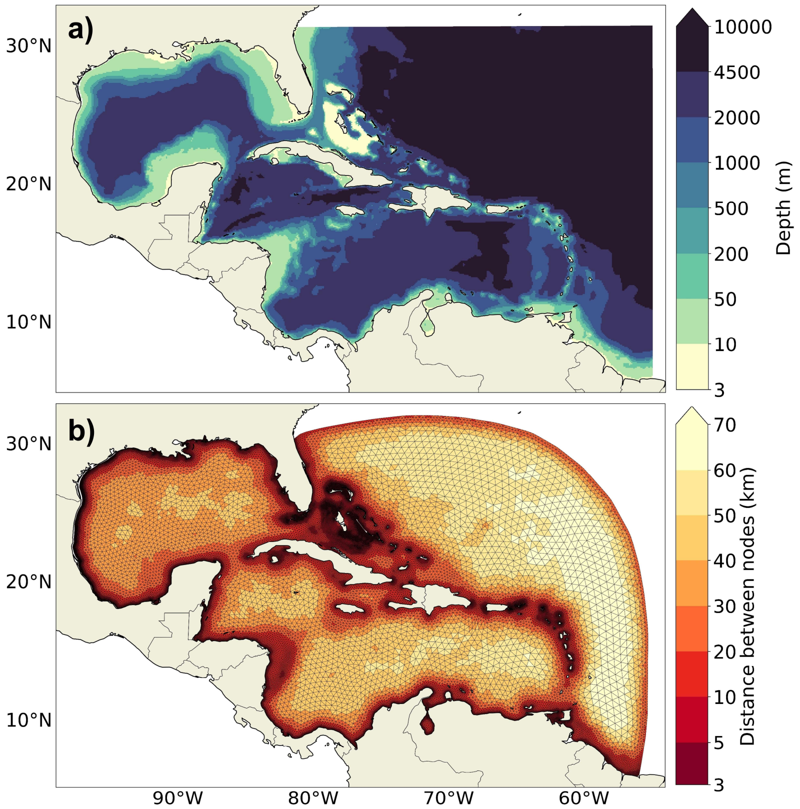

Figure 2: a) Bathymetry ~~used in the study~~ and NEMO domain. b) ADCIRC domain and grid spacing with the ADCIRC unstructured mesh.

3.2. Sensitivity experiments

Sensitivity experiments are conducted based on the developed configurations~~. Their~~ described in Sect. 3.1. The aim is to assess the ~~effect~~effects of atmospheric and oceanic forcings, physical parameterizations ~~on~~for wind stress and baroclinic/barotropic modes on the performance of the models ~~in simulating storm surges.~~. All the simulated experiments are listed in Table 3. The sensitivity of ~~the~~ storm surge modelling to atmospheric forcing ~~on storm surge modelling~~ is ~~assessed~~evaluated by comparing the ERA5 atmospheric reanalysis and parametric wind models ~~that are usually applied~~ typically used for simulating tropical cyclones~~.~~ (Sect. 2.2). This ~~experience~~experiment is conducted with the ADCIRC model ~~as it~~, which is extensively used and developed for this application, ~~notably~~particularly for operational systems (Fleming et al., 2008; Riverside Technology, 2015). ~~Then, the~~

The sensitivity of ~~the~~storm surge modelling to ocean forcing ~~on storm surge modelling~~ is assessed in terms of ~~non-linear~~nonlinear interactions of ~~surge~~surges with ~~the~~ astronomical ~~tide~~tides and variations in the mean sea level. These experiments ~~have been tested with~~are performed using the barotropic NEMO configuration ~~by introducing~~, either by excluding tidal forcing at the boundaries or by including the daily mean sea level forcing from the GLORYS ocean reanalysis at the boundaries (Garric and Parent, 2017~~) or by excluding tidal forcing at the boundaries. We have also~~). Similar tests were

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conducted these tests using the ADCIRC model; however we chose to present, only the experiment for NEMO experiments are presented, as the results were consistent between both models.

The barotropic configuration of NEMO is also used to investigate the impact of wind stress parameterization on storm surges, thanks to the flexibility of NEMO in modifying the code. Recent papers have highlighted a non-negligible impact of the selected parameterization or of the tuning of the parameters utilized within it (O'Neill et al., 2016; Pineau-Guillou et al., 2020). The S&B (Smith and Banke, 1975) scheme utilized in ADCIRC and applied in this study in NEMO (eq. (1)), is compared totaking advantage of the flexibility of NEMO in modifying the code. This study compares the S&B (Smith and Banke, 1975) scheme (Eq. (1)) with the Charnock formulation (Charnock, 1955) which is the reference formulation in NEMO (eq. (2)) (Eq. (2)). In the S&B scheme, the wind stress τ is calculated using a simple formulation for the drag coefficient C_D, which represents the drag force exerted by the wind on the water surface, as follows:

$$\text{(1)}\quad \text{S\&B: } C_D\,\tau = \rho_a C_D U^2 \text{ with } C_D = (0.75 + 0.067|U|)e^{-3} \quad \text{(1)}$$

where ρ_a is the air density and U is the 10 m wind speed.

The Charnock: relationship is a semiempirical formula that involves a more complex calculation accounting for changes in surface roughness with wind speed as follows:

$$\text{(2)}\quad \tau = \rho_a u_*^2 \text{ with } z_0 = \frac{\alpha u_*^2}{g} \quad \text{(2)}$$

with U the 10m wind speed, z_0 the bottom roughness, α the Charnock parameter, u_*^2 the friction velocity and g the gravity. In the reference NEMO code, the parameter α remains constant in space and time, equal to 0.018. We also performed another simulation with a variable Charnock parameter coming from ERA5 reanalysis outputs, thus depending on the waves (Riverside Technology, 2015).

where z_0 is the roughness length, α is the dimensionless Charnock parameter, u_* is the friction velocity and g is gravity. In general, the Charnock parameter α is generally assumed to be constant in the formulation of sea surface roughness (Eq. (2)). For example, in the standard NEMO code, it is kept constant in space and time, equal to 0.018. In reality, this parameter varies with sea surface roughness and is influenced by various wave parameters, such as wave age, wave steepness and the presence of sea foam, especially under high wind conditions, as suggested by numerous studies published in recent decades (Janssen, 1989; Moon et al., 2004; Pineau-Guillou et al., 2020; Wu et al., 2024). An additional simulation has therefore been performed using a variable Charnock parameter derived from ERA5 reanalysis outputs, which depend on wave conditions (Riverside Technology, 2015).

Finally, a sensitivity experiment onis conducted to evaluate the importance of baroclinic motions on modelled storm surges is conducted, requiring the utilization of , which require a distinct configuration. This experiment is conductedperformed with NEMO due to itsin standard operation in a baroclinic mode. A (Sect. 3.1). For this purpose, a baroclinic configuration has thus beenwith 75 vertical z-levels was set up based on Wilson et al., 2019. This configuration has 75 verticals levels and is driven by the GLORYS ocean reanalysis (Garric and Parent, 2017) at the lateral oceanic boundaries and for the initial state with the variables described in and by the NEMO description part. In addition, it is forced by more ERA5 atmospheric variables from ERA5 reanalysis (Sect. 2.2) at the air– sea interface as explained in the NEMO description part.(see the variables in Tab. 3). This configuration therefore allows for the resolution of changes in pressure gradients (due to changesvariations in temperature and salinity) generating, which generate ocean circulations and transport, as well as vertical physics. The short duration of the simulations (Tab. 1) does not allow the modelling of deep ocean circulation, but surface circulation, which occurs more rapidly.

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can be simulated. The differences between the barotropic and baroclinic NEMO configurations are summarized in ~~the~~ Appendix A (Tab. A1).

Name of the experiment	Model	Type	Atmospheric forcing: winds and pressure	Tides	Other ocean ~~forcing~~forcings at the boundaries	Wind stress formulation
ref: ADCIRC_ERA5	ADCIRC	2D barotropic	ERA5	Yes	No	S&B
ref: NEMO_ERA5	NEMO	2D barotropic	ERA5	Yes	No	S&B
ADCIRC_DHM, ADCIRC_Chavas, ADCIRC_Willoughby, ADCIRC_GAHM	ADCIRC	2D barotropic	Parametric wind models: DHM, Chavas, Willoughby, GAHM	Yes	No	S&B
NEMO_msl	NEMO	2D barotropic	ERA5	Yes	Mean sea level (GLORYS, daily)	S&B
NEMO_without_tides	NEMO	2D barotropic	ERA5	No	No	S&B
NEMO_charnock	NEMO	2D barotropic	ERA5	Yes	No	Charnock: α=0.018
NEMO_charnock_variable	NEMO	2D barotropic	ERA5	Yes	No	Charnock: α=variable
NEMO_baroclinic	NEMO	3D baroclinic (75 levels)	ERA5 (+temperature, humidity, radiative fluxes, precipitations, and snow cover)	Yes	GLORYS ~~reanalysis:~~, daily temperature, salinity, currents, and sea level	Charnock: α=0.018

Table 3: Sensitivity experiments performed with the ADCIRC and NEMO models.

3.3. Statistical evaluation of ~~the~~ extreme events

~~Hourly~~The hourly outputs from all the simulations ~~performed~~ (Tab. 3) are statistically compared ~~to~~with tide gauge records (Sect. 2.1) during the four hurricane events. We ~~have developed an automated method to identify the time window of each storm surge extreme event in order to~~ evaluate not ~~just~~only the maximum storm surge ~~reached during each hurricane~~ but also its temporal ~~behavior. The~~behaviour with an automated method we developed to identify the time window ~~is identified at each tide gauge station~~ for each ~~hurricane. The storm surges from~~ extreme event. This method is based on the ~~various simulations are extracted at the closest point to each tide gauge station, and the same time window is applied to each. To select the appropriate time window for each extreme event in the tide gauge records, we~~ analysis of wind time series, as we have found ~~that the wind time series closest to each tide gauge location was a~~them to be good ~~indicator~~indicators of ~~the~~ storm conditions. ~~The~~For each hurricane simulated and data available from each tide gauge station (Tab. 2), the following steps are applied to extract the time window~~: for each~~ of the extreme event:

1. The ERA5 wind time series ~~under~~closest to the tide gauge location is extracted for the hurricane ~~simulation~~ dates (Tab. 1~~), the~~).
2. The maximum and local maxima of the wind time series are identified, as ~~well as~~are the inflection points on either side of the maximum wind speed.
3. The ~~selected~~ time window to identify the extreme event is defined by the two inflexion points that include the maximum wind speed and all local maxima exceeding the 95th percentile threshold, as illustrated in Figure 3.
4. Storm surges from the various simulations are extracted at the closest point to each tide gauge station, and the same time window is applied to each station to identify the extreme events.

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Once the time window ~~has been~~is defined, ~~different~~various statistical metrics are ~~applied~~computed to validate the modelled storm surge against tide gauge data~~. First, the~~ as follows:

- Evaluation of the maximum surge values—The maximum values reached within the specified time window are compared between the simulations and tide gauge data~~.~~ using the bias (Fig. 3). The mean absolute error (MAE) is also used to derive a general skill value for all the selected tide gauges. ~~The second step is to evaluate~~
- Evaluation of the ~~storm~~ surge time series. ~~This is done by computing the~~ The Pearson correlation coefficient ~~and~~is computed over the time window to evaluate the correlation between the modelled and observed storm surge time series. Additionally, the difference in duration~~,~~ (in hours~~, within the extreme event,~~) exceeding the 90th percentile of the storm surge time series~~. In addition to the maximum value reached, these~~ between the simulations and tide gauges is calculated over the time window (Fig. 3). These metrics ~~depending,~~ which depend on the temporal ~~behavior can be also~~behaviour of the surge, are important for impact assessments (e.g.~~.~~, accelerated coastal erosion and increased likelihood of coastal flooding).

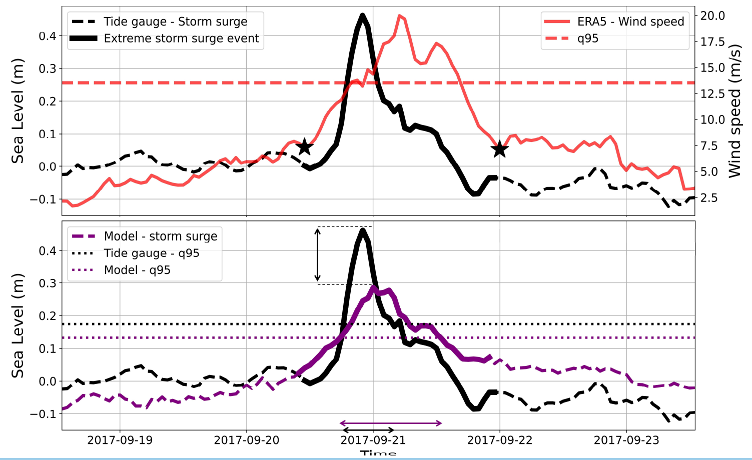
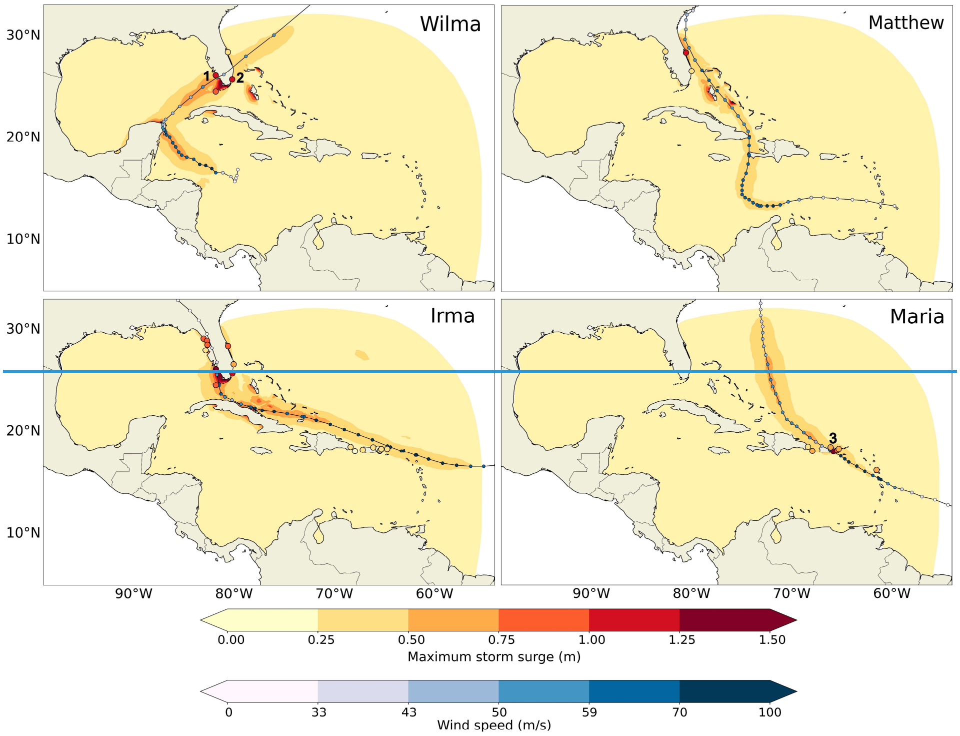


Figure 3: ~~Sketch~~Graphs of the selection of ~~the~~ storm surge extreme ~~event~~events for tide gauge records (top panel) and comparison with simulations (bottom panel). The storm surge data extracted from the ~~GESLA3~~tide gauge dataset at one station ~~is represented~~are presented in black. The wind speed ~~obtained~~extracted from ERA5 is shown in red, with the dashed line denoting the 95th percentile threshold. The simulated storm surge data ~~is represented~~are presented in purple. The two stars and wider black and purple lines indicate the beginning and the end of the time window defining the storm surge extreme event. The vertical black arrow denotes the ~~difference in~~bias between the observed and modelled maximum storm ~~surges~~surges reached within the time window. The horizontal black and purple arrows denote the ~~duration~~durations above the 90th percentile for both the observed and modelled data.

4. Results

4.1. ~~Inter-model~~Intermodel comparison

The ADCIRC and NEMO simulations are ~~intercompared~~ compared for storm surge modelling using the two similar configurations ~~and the~~ described in Sect. 3.1, both of which are forced by the same ~~storm surge~~ drivers~~. The~~ from ERA5. First, a comparison between ~~storm surge~~the maximum storm surges generated by ADCIRC ~~forced by ERA5~~ and the tide gauge data is presented for the four hurricanes simulated (Fig. 4). The validation is restricted to a few points (Tab. 2) ~~due to~~because of the scarcity of tide gauge data along the coasts of Cuba, Haiti, and northern Mexico~~, i.e. areas~~ regions significantly impacted by three of the four hurricanes (Tab. 1). The overall spatial pattern of the modelled storm surges ~~appears~~is consistent with that of the hurricane tracks ~~of the hurricanes.~~. Both~~,~~ the observed and modelled highest storm surges~~,~~ exceed one meter for each hurricane~~, however~~. However, ADCIRC simulations ~~tends~~tend to underestimate ~~the~~ maximum storm surges compared ~~to~~with tide gauge data, ~~especially~~particularly along the eastern coast of Florida (USA) and in the Caribbean Islands, resulting in a mean underestimation of at least 20% (Fig. 4).



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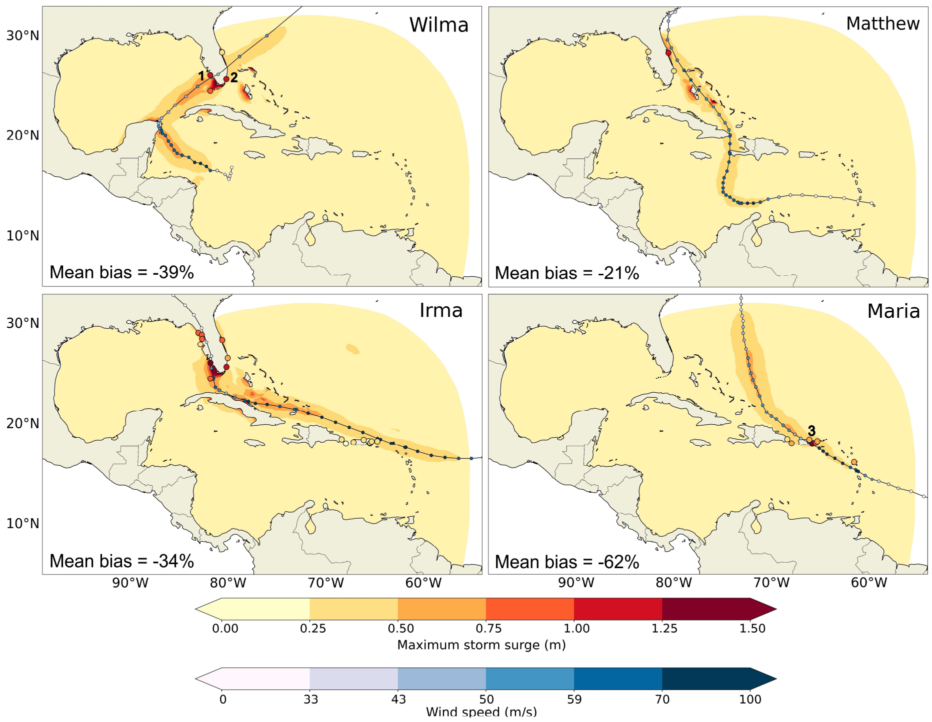

Figure 4: Modelled (ADCIRC with ERA5 forcing, map) and observed (tide gauges, circles) maximum storm ~~surge~~surges for the four simulated hurricanes. The tracks of the hurricanes and the wind speed are shown in blue. The blue ~~colorbar~~colour bar represents the different hurricane categories, from category 1 between 33 and ~~43m~~43 m/s to category 5 for winds higher than ~~70m~~70 m/s. The locations used to ~~analyze~~analyse the time series are marked with numbers 1 (Naples_FL), 2 (Virginia_Key_FL) and 3 (San_Juan_PR). The mean bias between simulated and observed maximum storm surges is shown in the bottom left corner of each panel.

~~Time~~The time series of different target locations are shown in Figure 5 to ~~analyze~~analyse the ~~response~~responses of both the ADCIRC and NEMO models. The models exhibit very similar ~~responses~~behaviours, with occasional instances where one model outperforms the other. For ~~instance~~example, NEMO displays a slightly better correlation for Wilma at the Naples station during the ~~post-peak~~postpeak period, ~~while~~whereas ADCIRC performs better in capturing the surge amplitude for Irma at the Virginia Key station. ~~In general~~Overall, the correlation between the models and observed data is well reproduced. Along the western coast of Florida (Naples), both models also satisfactorily simulate the surge amplitude, including the double-peak ~~behavior~~behaviour during ~~hurricane~~Hurricane Wilma. However, for all the simulated hurricanes, the storm surge is notably underestimated by both NEMO and ADCIRC along the eastern coast of Florida (Virginia Key) and in the Caribbean Islands (San Juan) (Fig. 5~~)~~)), as also illustrated in Figure 4.

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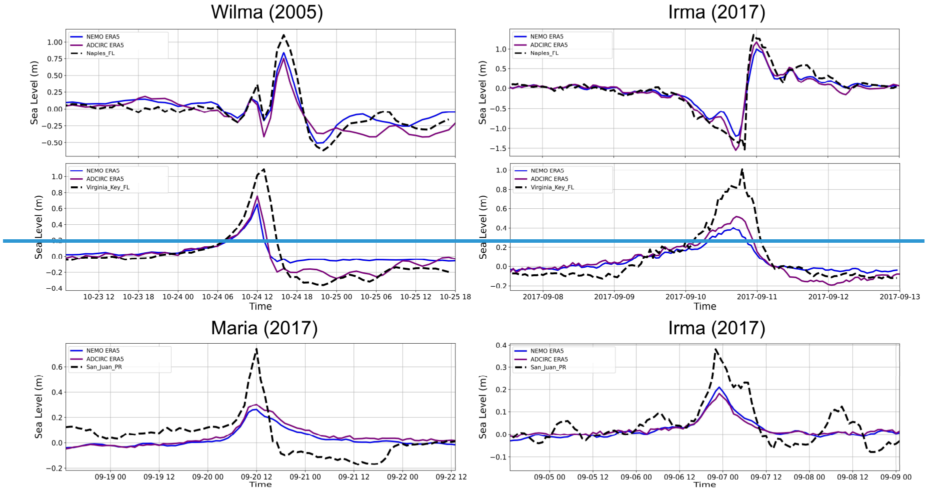

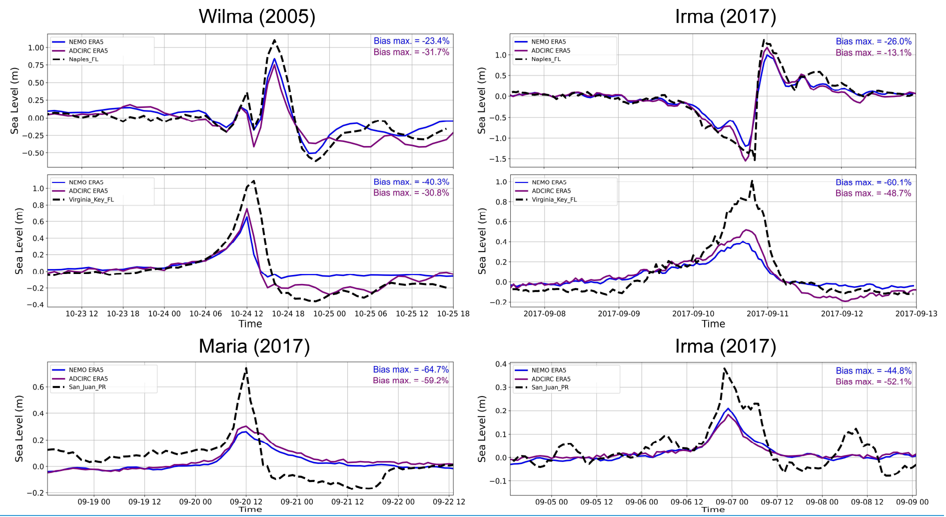

Figure 5: Modelled (blue ~~and~~line for NEMO, purple ~~lines~~line for ADCIRC) and observed (black dashed line) storm surge time series at three tide gauge locations, in the Florida region (top~~, center~~ and middle panels) and in the Caribbean region (bottom panels). The locations are marked in Figure 4. ~~Results~~The results are shown for hurricanes Wilma, Irma and Maria (Tab. 1). The bias between simulated and observed maximum storm surges is shown in the top right corner of each panel, with the colour indicating the model.

~~The similarity of the results between ADCIRC and NEMO is noticeable when considering all tide gauges available as well (Fig. 6), revealing a general underestimation, with NEMO showing slight improvements for hurricane Matthew. In comparison to others studies at this scale and resolution, both models demonstrate satisfactory performance for three of the four hurricanes with a mean absolute error of less than 0.3 m (Muis et al., 2019; Dullaart et al., 2020; Muis et al., 2020; Wood et al., 2023). However, both ADCIRC and NEMO notably underestimate storm surges associated with hurricane Maria, located north of the Caribbean Sea (Fig. 6). The time series in the Caribbean (San Juan) consistently show significant underestimations for both hurricanes Irma and Maria (Fig. 5). It suggests a region-dependent underestimation rather than one dependent on the hurricane characteristics. For hurricane Irma, in contrast to Maria, other tide gauges are utilized for statistical analysis, particularly along the western coast of Florida where models perform well (Fig. 5), resulting in an overall good performance (Fig. 6).~~

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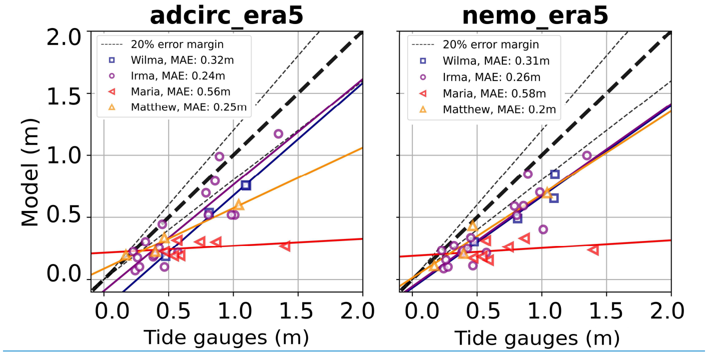

Figure 6: Scatter plot of the modelled vs. observed maximum storm ~~surge~~surges for the four hurricanes for the ADCIRC (left panel) and NEMO (right panel) simulations. The MAE value represents the mean absolute error ~~on~~of the surge maximum.

~~The general correlation is also consistent between ADCIRC and NEMO, with a satisfactory mean value of over 0.8 for both models (Fig. 7), aligning with recent literature (Muis et al., 2019; Dullaart et al., 2020; Muis et al., 2020). The extreme event duration above a high percentile is also presented as it combines both the biases on the surge amplitude and correlation. Hurricanes Wilma and Irma show a slight underestimation of the extreme event duration around 25% for both models compared to tide gauge data (Fig. 7). This doubles to 50% for hurricanes Maria and Matthew. In the case of hurricane Maria, although the correlation is high, the surge levels are significantly underestimated. Analysis of ERA5 meteorological inputs (not shown) indicates accurate hurricane track representation but notable biases in meteorological conditions, particularly around the Caribbean islands. In particular, we observed weaker extreme winds and higher atmospheric pressure in the eye of the hurricane. These biases might be attributed to factors such as reduced data assimilation in this region or the impact of the resolution of the reanalysis (i.e. difference in the land mask of ERA5 over the Caribbean islands, with about 0.25° of spatial resolution). For hurricane Matthew, the underestimation of the event duration is due to a lack of correlation with observations attributed to the hurricane track being farther from the coast and tide gauges compared to other hurricanes.~~

The general correlation between ADCIRC and NEMO is also consistent, with a satisfactory mean value of over 0.8 for both models (Fig. 7), which aligns with recent literature (Muis et al., 2019, 2020; Dullaart et al., 2020). The extreme event duration above a high percentile is also presented, combining biases in surge amplitude and correlation. Compared with tide gauge data, the duration of extreme events is slightly underestimated by both models by approximately 25% for Hurricanes Wilma and Irma (Fig. 7). This underestimation doubles to 50% for Hurricanes Maria and Matthew. For Hurricane Maria, although the correlation is high, the surge levels are significantly underestimated. An analysis of ERA5 meteorological inputs (not shown) indicates an accurate hurricane track representation but notable biases in meteorological conditions, particularly around the

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Caribbean islands. In particular, we observed weaker extreme winds and higher atmospheric pressure in the eye of the hurricane. These biases might be attributed to factors such as reduced data assimilation in this region or the impact of the resolution of the reanalysis (i.e., differences in the land mask of ERA5 over the Caribbean islands, with a spatial resolution of approximately 31 km). For Hurricane Matthew, the underestimation of the event duration is due to a lack of correlation with observations, which is attributed to its hurricane track being farther from the coast and tide gauges than that of other hurricanes.

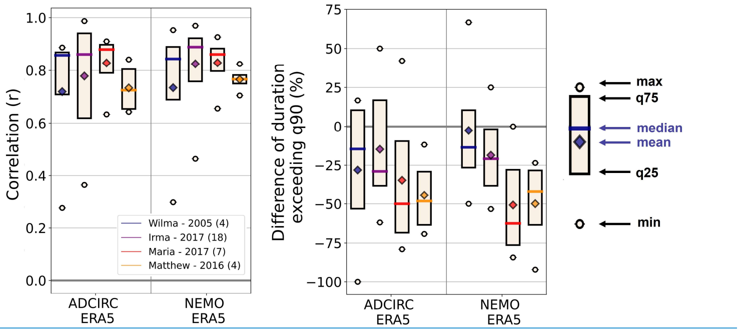

Figure 7: Boxplot of the correlation (left panel) and ~~the~~ difference in the storm surge duration above the 90^{th} percentile (right panel) for the ADCIRC and NEMO simulations. The number of tide gauges considered for each box is listed in brackets after the four hurricane names.

4.2. Analysis of the sensitivity experiments ~~on~~for storm surge modelling

Given the similar performance of the ADCIRC and NEMO models, we ~~are employing~~employ the strengths of each model ~~strength~~ to conduct sensitivity experiments (Tab. 3). These experiments aim to assess the ~~effect~~effects of atmospheric and oceanic forcings, physical parameterizations ~~on~~for wind stress and baroclinic/barotropic modes on the performance of numerical models in simulating storm surges.

First, we assess the impact of the atmospheric forcing by comparing storm surges ~~using the~~simulated with four parametric wind models ~~to~~(Sect. 2.2) against those simulated using ERA5~~.~~ (Tab. 3). The comparisons, shown in Figure 8, are performed at the same three tide gauge locations as those in Figure 5. The results ~~with~~from the parametric wind models are highly variable, displaying a range of performance between good and significant under- or ~~over-estimates, which is very dependent~~overestimates, depending on the location relative to the ~~track of the~~ cyclone track. In general, the maximum surge values obtained ~~through~~from the parametric wind models ~~appear~~are less satisfactory than those derived from the ERA5 wind fields ~~of ERA5 reanalysis.~~. The parametric wind models ~~rather accurately~~ capture the surge peaks at the Naples station~~, due to~~ relatively well because of the close proximity of ~~both hurricanes~~Hurricanes Wilma and Irma to the tide gauge (within 25 km). However, these peaks ~~exhibit~~show a time lag ~~with the parametric models~~ compared ~~to both~~with those of ERA5 and the tide gauges during ~~hurricane~~Hurricane Wilma~~. This~~, which is ~~due~~attributed to ~~differences in the location of~~discrepancies between the hurricane ~~track between~~tracks in the best track data and those in ERA5. According to the best track data, Wilma ~~passes~~passed slightly earlier and closer to the Naples station (not shown). The ~~behavior~~behaviour of ~~the~~ axisymmetric wind models also depends on the relative distance to the track. During ~~hurricane~~Hurricane Wilma, a significant ~~fall~~drop in the storm surge is detected at the Virginia Key station because the wind direction pushes ~~the~~ water away from the shore. ~~At the same station~~Conversely, during ~~hurricane~~Hurricane Irma, the peak surge is ~~significantly~~notably underestimated at the same station because the ~~center of the~~ hurricane centre is ~~further away (~~more than 100 km~~). The use of~~ away. Compared with the other models, the GAHM model shows ~~significant~~substantial differences ~~compared to the other three models, occasionally~~, sometimes improving the maximum surge~~, as~~ (e.g., at Virginia Key ~~station,~~) and sometimes worsening it~~, as~~ (e.g., at Naples ~~station, probably~~), likely due to the ~~consideration~~inclusion of asymmetries (Fig. 1c). Nevertheless, a notable improvement in

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the performance of the parametric wind models is observed for ~~hurricane~~Hurricane Maria (~~Fig~~Figs. 8 and 9a), where the maximum surge ~~was~~is highly underestimated ~~using~~with the ERA5 forcing~~, highlighting~~. This result highlights the relevance of ~~the use of~~using parametric winds in such cases.

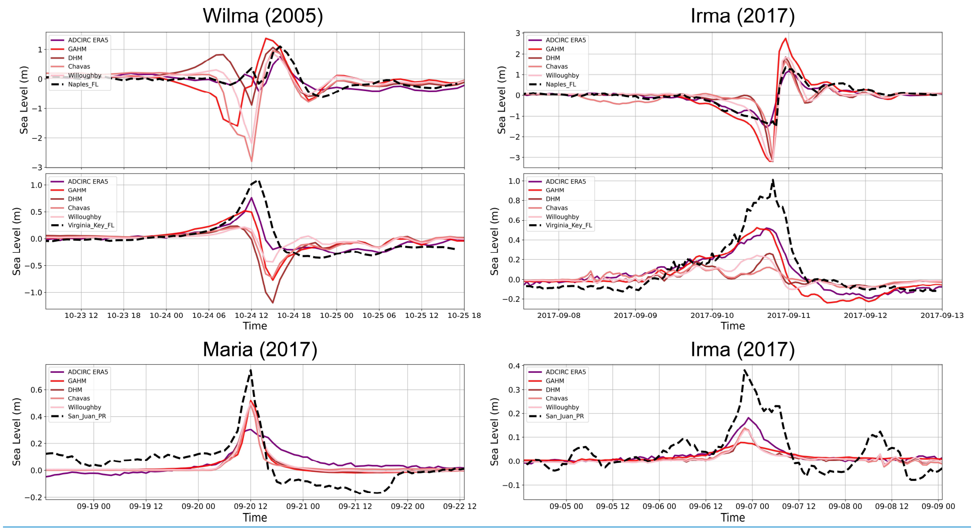

Figure 8: Modelled (~~color~~coloured lines) and observed (black dashed line) storm surge time series at three tide gauge locations, in the Florida region (top~~, center~~ and middle panels) and in the Caribbean region (bottom panel). Each ~~color~~colour represents ~~a~~an ADCIRC simulation with a different atmospheric forcing (ERA5 or a parametric wind model). The locations are marked in Figure 4. ~~Results~~The results are shown for Hurricanes Wilma, Irma and Maria ~~hurricanes~~ (Tab. 1).

The correlation between the parametric models and the observations ~~falls below~~averages less than 0.6 ~~in average, varying~~and varies significantly among hurricanes (Fig. 9). For ~~instance~~example, the DHM, Willoughby and Chavas models perform rather poorly for ~~hurricane~~Hurricane Wilma, ~~while~~whereas the GAHM model ~~does so~~underperforms for ~~hurricane~~Hurricane Matthew. These differences in the correlation compared ~~to~~with ERA5 atmospheric ~~forcings~~forcing are ~~most~~ likely due to the simplifications ~~used to generate~~in atmospheric surface conditions ~~in~~used by the parametric models (Fig. 1), in contrast to the complete ~~wind~~ spatial wind fields ~~considered when using~~provided by ERA5. ~~As explained above, it is also due to~~Additionally, variations in the location of the hurricane track in the parametric models and its relative distance ~~to~~from the tide gauges~~. For all~~ contribute to these discrepancies. A specific selection of the parameters used in the wind models for each hurricane could also increase the accuracy of storm surge simulations (Chavas et al., 2015). Across all the simulated hurricanes, the duration of extreme events is consistently underestimated ~~across~~by all the simulations (Fig. 9). While ERA5 systematically underestimates less than 50% of the time, parametric wind models tend to exhibit more substantial underestimations and ~~even~~occasionally miss some extreme events. This result is particularly clear when the distance between the hurricane and the tide gauge is greater than 50 km because far-afield winds are not captured in the parametric models (not shown).

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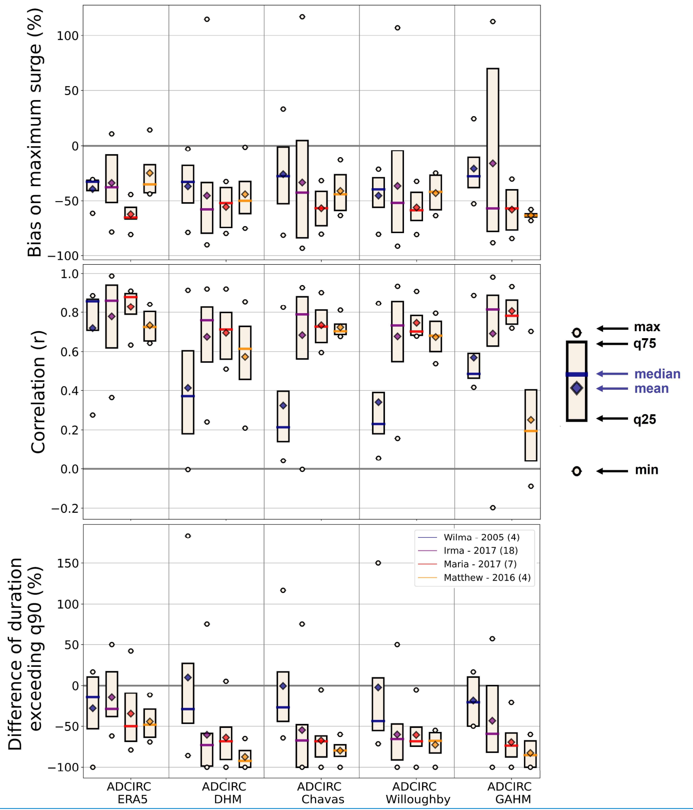

Figure 9: Boxplot of the maximum surge bias (top panel), correlation (middle panel) and ~~the~~ difference in the duration of the surge above the 90th percentile (bottom panel) for the simulations using different atmospheric forcings with ADCIRC. The number of tide gauges considered for each box is in brackets after the four hurricane names and dates. A difference of 100% corresponds to a missed extreme event.

~~Then~~Next, we assess the ~~effect~~effects on storm surge due to ~~non-linear~~nonlinear interactions with ~~the~~ astronomical ~~tide~~tides and variations in the mean sea level, as well as the sensitivity to different wind stress schemes. ~~In addition,~~We also investigate the baroclinic contribution to storm surges ~~is also studied~~ using a ~~3-D~~3D configuration with 75 vertical levels~~. Storm~~ (Sect. 3.2). Figure 10 compares the storm surges simulated by NEMO for ~~the different aforementioned~~these various experiments ~~are compared to~~ (Tab. 3) with tide gauge data obtained at the same three locations ~~in Figure 10. Non-linear~~. The results show that with our model, nonlinear interactions ~~of~~ between storm surges and tides ~~and~~or the mean sea level ~~with storm surges~~ have minimal ~~contribution~~contributions to ~~the~~ extreme sea levels, as ~~well as~~do the different ~~experiments on the~~ wind stress ~~formulation. The~~ formulations. However, incorporating the baroclinic response ~~however~~ significantly improves ~~by up to 40 cm~~ the maximum storm surge estimates ~~at~~by up to 40 cm at the Virginia Key station in the southeastern Florida peninsula, and ~~also~~ slightly in the Caribbean~~.~~ islands.

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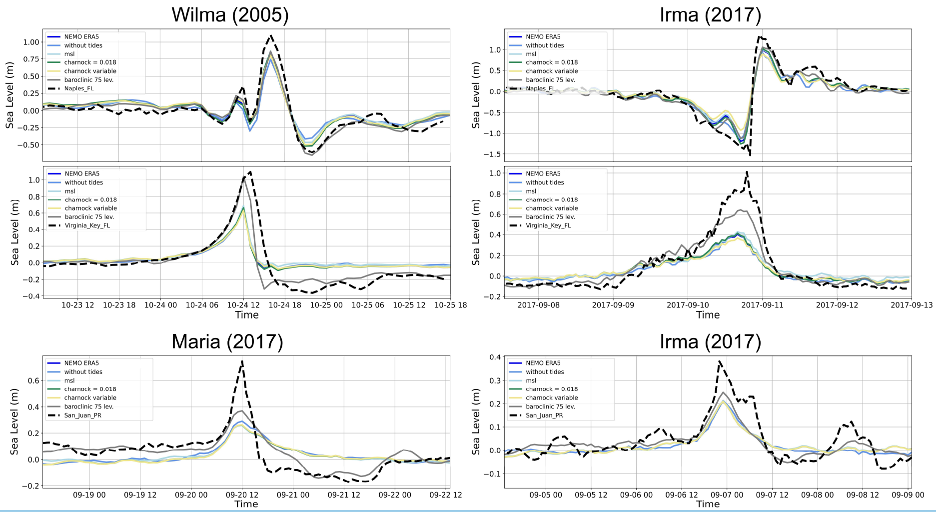

Figure 10: Modelled (~~color~~coloured lines) and observed (black dashed line) storm surge time series at three tide gauge locations~~,~~ in the Florida region (top~~, center~~ and middle panels) and in the Caribbean region (bottom panel). Each ~~color~~colour represents a different NEMO experiment (accounting for different sea level processes or wind stress ~~implementation~~implementations). The locations are marked in Figure 4. ~~Results~~The results are shown for Hurricanes Wilma, Irma and Maria ~~hurricanes~~ (Tab. 1).

In general, for all the simulated hurricanes, the inclusion of baroclinicity significantly influences the maximum surge amplitudes, reducing the bias by approximately 10 to 20% ~~in~~on average, depending on the hurricane (Fig. 11). Nevertheless, the average correlation of the surge peak events remains virtually ~~no impacted~~unaffected by the baroclinic experiment. This outcome is due to ~~compensations~~compensation between minor improvements, such as those during the ~~post-storm~~poststorm periods for ~~hurricanes~~Hurricanes Wilma and Maria at the Naples and San Juan stations, and degradations observed at the Virginia Key during the decreasing surge for Hurricane Wilma. The statistics for the other experiments are not presented, as their ~~impact~~impacts on ~~the~~storm surges ~~is very small.~~are minimal with our model setup. The baroclinic impact on the event duration is also substantial ~~for event duration~~, with a less than 20% ~~of~~ underestimation for all the simulated hurricanes.

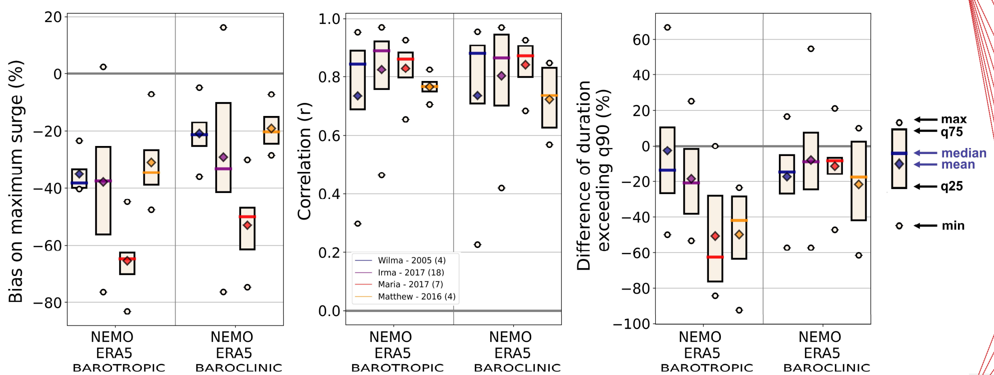

Figure 11: ~~Boxplot~~Boxplots of the maximum surge bias (left panel), correlation (middle panel) and ~~the~~ difference in the duration of the surge above the 90th percentile (right panel) for the NEMO barotropic and baroclinic simulations. The number of tide gauges considered for each box is in brackets after the four hurricane names and dates.

~~Comparing~~A comparison of the maximum storm surges in the baroclinic and barotropic simulations provides insights into the regional significance and locations of the baroclinic impact (Fig. 12). Substantial differences of more than 20 cm are identified

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along the eastern coast of Florida when the hurricane ~~is coming~~approaches from the ~~eastern domain, and~~ east, as also indicated by the various tide gauges ~~were utilized~~used in that ~~zone~~region (Fig. 4, Fig. 10). In other areas, such as the Caribbean for ~~hurricane~~Hurricane Maria ~~or~~and the Yucatan Peninsula (Mexico) for ~~hurricane~~Hurricane Wilma, differences of more than ten centimeters are observed along the hurricane track in coastal areas.

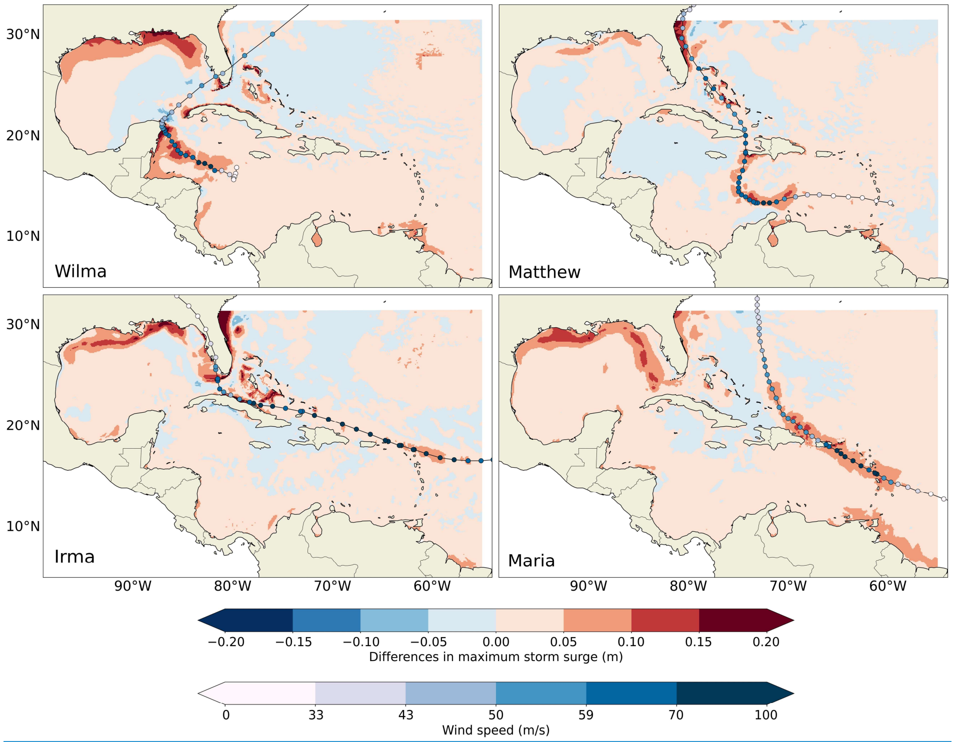

Figure 12: Differences in the maximum storm surge ~~maximum~~ between the NEMO baroclinic and barotropic simulations. ~~Results~~The results are shown for the four simulated hurricanes~~:~~ Wilma, Matthew, Irma and Maria (Tab. 1). The tracks of the hurricanes and the wind speed are shown in blue. The blue ~~colorbar~~colour bar indicates the different hurricane categories, from category 1 between 33 and ~~43m~~43 m/s to category 5 for winds higher than ~~70m~~70 m/s.

The passage of ~~the~~a hurricane affects the general surface circulation, for ~~instance~~example, through winds inducing mixing in the water column, leading to a decrease in sea surface temperature. ~~In addition~~Additionally, the baroclinic simulation considers other atmospheric variables associated with hurricanes, such as ~~precipitations. It does~~precipitation. These variables not only impact the local sea level budget but also ~~modify the~~modifies circulation due to the effect on salinity, ~~interacting~~which interacts with the existing circulation. ~~As a result~~Consequently, each cyclone generates a distinct baroclinic response, influenced by its specific characteristics and ~~by~~ interactions with ~~the~~ local oceanographic features. Other studies have investigated the impact of baroclinic motions on storm surges. For example, Ye et al., 2020 ~~,~~implemented a regional ~~3-D~~3D baroclinic model~~,~~ ~~comparing~~ and compared it to a ~~2-D~~2D barotropic model in simulating storm surges induced by hurricanes along the US east coast. The results revealed a ~~non-negligible~~nonnegligible influence of baroclinicity during the ~~post-storm~~poststorm period, with differences of up to 14% in sea level amplitude. However, this study focused on a single hurricane, and comparisons ~~to observational data were conducted in an estuarine area outside our domain.~~with observational data were conducted in an estuarine area outside our domain. Pringle et al. (2019) investigated the baroclinic contribution to storm surges using a 2DDI (depth-integrated) configuration that incorporated baroclinic effects on the free surface and depth-integrated currents without

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simulating them directly. They reported that for Puerto Rico (San Juan station) during Hurricanes Maria and Irma, the predicted maximum surge increased by approximately 20 cm because of baroclinic effects, which is greater than the increase observed in our study. Another study by Ezer, 2018 examined interactions between ~~hurricane~~Hurricane Matthew, the Gulf Stream, and coastal water levels using a ~~more basic~~simpler model. The study highlights an increase in storm surge along the eastern coast of Florida ~~with a~~that is similar ~~order of~~in magnitude to our findings. ~~It~~This increase is attributed to the passage of the hurricane reducing the sea surface height slope between the coast and the other side of the Gulf Stream, consequently reducing the geostrophic Gulf Stream flux and increasing the sea level ~~on~~along the coast.

5. Discussion

~~Results~~The results obtained ~~for~~from the ~~inter-model~~intermodel comparison between ADCIRC and NEMO and ~~for~~from the different sensitivity experiments are summarized and discussed in this section. ~~To that aim, two~~Two synthesis figures are provided: one illustrating the variance decomposition of the different sources of uncertainty (Fig. 13) and the other showing the mean absolute error (MAE) ~~on~~of the maximum storm surge (Fig. 14). ~~For the variance~~Variance decomposition~~, we have decomposed~~ uses an n-factor ANOVA-based variance partitioning method to decompose the total ensemble uncertainty ~~from the~~into different sources ~~of uncertainty~~ and ~~the~~their interactions ~~among them using a n-factor ANOVA-based variance partition method~~ (Storch and Zwiers, 1999). The sources of uncertainty ~~considered~~analysed include~~:~~ the ~~selection~~choice of simulated hurricanes, numerical models, atmospheric forcings, ocean forcings, physical parameterizations for wind stress, and barotropic/baroclinic modes.

When ~~used with a~~ similar ~~configuration~~configurations (domain, resolution, bathymetry, barotropic~~),~~) are used, ADCIRC and NEMO simulate storm surges due to tropical cyclones in a similar ~~way compared~~manner to tide gauges, regardless of the simulated cyclone. This positive outcome highlights the potential of NEMO, which is currently rather poorly employed for this application. This result is illustrated by the variance decomposition (ANOVA) depicted in Figure 13a, where the variability of the three different metrics (maximum value, bias on maximum value, and correlation) is ~~only~~ dependent only on the simulated hurricanes and not on the chosen numerical model. After testing both models, we found that NEMO and ADCIRC have comparable computation times (Tab. A1) when using similar numerical domains and resolutions. However, ADCIRC demonstrates better computational performance than NEMO because of its use of an unstructured mesh, as indicated in Table A2.

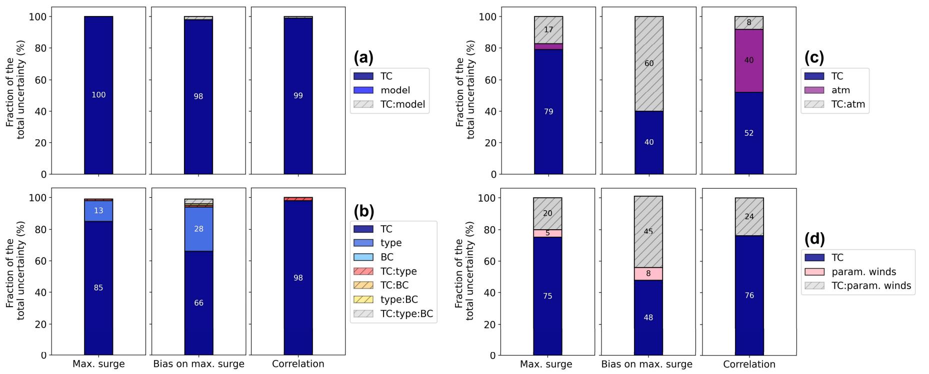

Figure 13: Relative ~~contribution~~contributions (between 0 and 100%) of different sources of uncertainty in the ~~skill~~ability to model storm ~~surges~~surge (maximum surge, bias on the maximum surge and correlation~~),~~) based on two~~-~~ (a, c, d) and three-factor (b) ANOVA ~~decomposition. To ensure a consistent number of values between the different sources of uncertainty, the~~decompositions. The four tide gauge locations where the highest surges occur are selected for each hurricane. ~~Fraction~~ to ensure a consistent number

of values between the different sources of uncertainty. The fraction of variance due to the four tropical cyclones (TC, dark blue) and (a) the two models, ADCIRC and NEMO (model, blue)), for a total of n= 16 values,; (b) the model type, i.e.., baroclinic or barotropic (type, blue)), and the boundary conditions, i.e.., with or without tides (BC, light blue)), for a total of n= 64 values,; (c) the atmosphere, i.e.., ERA5 or Dynamicthe dynamic Holland Modelmodel (atm, purple)), for a total of n= 16 values,; and (d) the parametric wind models, i.e. Dynamic., the dynamic Holland Model, model (GAHM,), Willoughby, Chavas (param. winds, pink)), for a total of n= =64 values, are shown. Interactions between the different sources of uncertainties are noted with dashed lines. Experiments (c) and (d) are performed with ADCIRC and experiment (b) is performed with NEMO. The ANOVA decomposition has beenwas performed using the "statsmodels" Python package.

The performance of these models is however significantly impacted by those of the atmospheric reanalysis forcing hence varying across regions. In general, both models underestimate the storm surge amplitudes, which is a common feature in modelling studies at large scale (Kirezci et al., 2020; Irazoqui Apecechea et al., 2023). It is often associated with meteorological forcing issues, such as too weak extreme winds in the models and biases in capturing the tracks of the tropical cyclones (Hodges et al., 2017; Dullaart et al., 2020; Gori et al., 2023). In our case, the use of the global ERA5 atmospheric reanalysis with a 1/4° resolution contributes to an inadequate resolution of the atmospheric processes particularly in complex land features, such as for hurricane Maria in the Caribbean islands. Additionally, the storm surge performance skill in the models is influenced by the quantityThe performances of these models are significantly influenced by those of the atmospheric reanalysis forcings, which vary across regions. Both models generally underestimate storm surge amplitudes, a common issue in large-scale modelling studies (Kirezci et al., 2020; Irazoqui Apecechea et al., 2023), often because of inadequate meteorological forcing, such as underestimating extreme winds and biases in tropical cyclone tracks (Dullaart et al., 2020; Hodges et al., 2017; Gori et al., 2023). In our case, the use of the global ERA5 atmospheric reanalysis with a 31 km resolution may inadequately capture atmospheric processes, particularly complex land features, such as for Hurricane Maria in the Caribbean islands. Additionally, the performance of the models is influenced by the amount of assimilated data in the atmospheric reanalysis, which varies depending on the location (Hersbach et al., 2020). In ERA5 generally provides better storm surge estimates than parametric wind models do in our tropical Atlantic region, using ERA5 to simulate the storm surge amplitudes generally outperforms various parametric wind models, except for hurricanealthough exceptions such as Hurricane Maria are noted, as shown withdepicted by the mean absolute error onof the maximum surge in Figure 14c. In addition, as illustrated with theThe ANOVA results in Figure 13b, show that the variance ofin the maximum surge depends mostly onis more influenced by the simulatedspecific hurricane (i.e., on the location) rather than onby the atmospheric forcing. This meansresult suggests that in regionsareas with less accurate reanalysis data, parametric wind models might serve as anbe a viable alternative. For instance inexample, Wood et al., 2023, reported that the Dynamicdynamic Holland Model performs better compared tomodel outperformed ERA5 in the southern China Sea, where ERA5 struggled in accurately capturingto capture typhoon dynamics, probably due to the smaller amount accurately, likely because of assimilatedlimited data. However, assimilation. Nevertheless, ERA5 clearly performs better in terms of the correlation and duration of extreme events, using ERA5 to model storm surges significantly outperforms the various parametric wind models. This trend is consistent across all simulated hurricanes which isas illustrated by a large part of the significant variance dominated by the attributed to atmospheric forcing in Figure 13c. When intercomparingcomparing parametric wind models, none appearsappear superior since their performance highly depends on the hurricane being simulated, and only four are simulated. This result is highlighted by the large interactions between tropical cyclones and parametric winds in the variance analysis onin Figure 13d. An alternative approach could involve a combination of reanalysis and parametric models based on the specific region or the prevalence of tropical cyclones to consider the strength of each approach (Dullaart et al., 2021). To mitigate biases associated with meteorological forcing, potential strategies could involve the application of bias correction techniques (Li et al., 2019; Lemos et al., 2020)Potential strategies to mitigate biases associated with meteorological forcing could involve bias correction techniques (Li et al., 2019; Lemos et al., 2020) or the use of statistical or dynamical downscaling at higher resolutions to capture processes that are not resolved in global or regional reanalyses (Dullaart et al., 2024)(Dullaart et al., 2024). In recent developments, data-driven techniques, such as those employed by Tadesse et al., 2020 and Qin et al., 2023, utilizehave utilized satellite products to quantify the relationships between storm surges and key atmospheric variables likesuch as wind speed and mean sea level pressure. These

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diverse methodologies offer a range of options for improving storm surge modelling accuracy and addressing region-specific challenges.

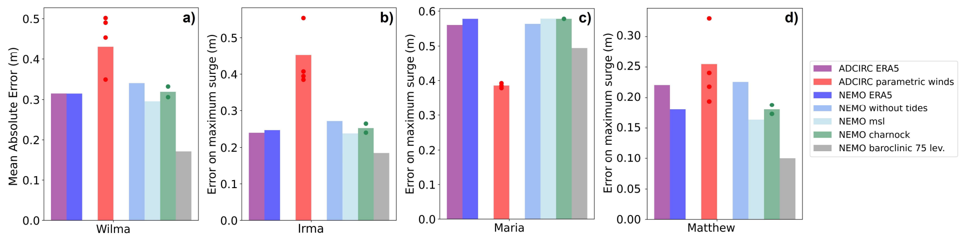

Figure 14: Mean absolute ~~error on~~errors of the maximum surge values for all the different experiments performed (Tab. 3). The dots represent the errors of each experiment when they are grouped in a bar~~;~~ for the parametric wind models (DHM, Chavas, Willoughby, and GAHM) and for the wind stress (constant and variable ~~charnock~~Charnock parameters).

~~Non-linear~~Nonlinear interactions of tides and the mean sea level with storm surges, as well as ~~different~~ wind stress formulations, have shown ~~a~~ minimal ~~impact~~impacts on ~~the~~ storm surge estimates ~~induced by~~during hurricane events (~~Fig~~Figs. 13b, ~~Fig.~~ 14). ~~The~~This limited simulated tide~~-~~–surge interaction ~~simulated~~ could be attributed to the small tidal range within the domain, which rarely ~~exceeding~~exceeds 2 meters. The impact of interactions with tides ~~would be probably larger with a higher resolution in the coastal regions (Hsiao et al., 2019) or considering~~is likely greater in other regions dominated by tides, such as in the English Channel ~~(Fernández-Montblanc et al., 2019; Arns et al., 2020),~~with extratropical cyclones (Fernández-Montblanc et al., 2019; Arns et al., 2020) or in Asia with typhoons ~~(Idier et al., 2019; Hsiao et al., 2019).~~(Hsiao et al., 2019; Idier et al., 2019). Although the effect of mean sea level forcing appears small, its significance may become more pronounced in ~~a~~the long-term context, particularly when accounting for the mean sea level rise (Fox-Kemper et al., 2021). The inclusion of wetting and drying in NEMO, which was not employed in this study, ~~would~~could also contribute to better resolving ocean dynamics in shallow water areas, where storm surges are the ~~biggest~~greatest (O'Dea et al., 2020). In general, improving storm surge estimates by resolving more relevant components and their interactions may require the incorporation of additional processes and the use of a higher resolution ~~model,~~in coastal regions (Hsiao et al., 2019), together with a refined coastline and bathymetry. For ~~instance~~example, improving storm surge modelling could involve ~~a~~ coupling with a wave model to simulate wave setup and associated interactions, as existing for ADCIRC with the SWAN wave model ~~(Marsooli and Lin, 2018; Dietrich et al., 2018; Hsu et al., 2023) or for NEMO with~~(Dietrich et al., 2018; Marsooli and Lin, 2018; Hsu et al., 2023) or for NEMO with the WAM (Staneva et al., 2021) or WW3 wave model (Couvelard et al., 2020). Additionally, ~~the consideration of~~including river inflows ~~would also be important to include the~~to account for significant precipitation ~~associated with hurricane passages. To go further, employing~~during hurricanes may also be important. Employing a fully coupled ocean~~-~~–atmosphere~~-waves-~~wave model~~,~~ or ~~alternatively,~~ a ~~simpler~~simplified atmospheric boundary layer model ~~with a lower computational cost, would~~could further enable the simulation of the ~~processes~~interactions and feedback mechanisms between the ocean and atmosphere (Lemarié et al., 2021). When coupled with increased resolution, adjustments based on land cover data, including the use of the Manning coefficient, canopy coefficient to mitigate wind stress from vegetation, and directional effective roughness length, could also be applied to refine surge amplitudes ~~at~~near the coast and inland (Dietrich et al., 2018).

The inclusion of the baroclinic response ~~have notably impacted~~significantly impacts storm surge amplitudes for all hurricanes (Fig. 13b~~)~~), with ~~less underestimated amplitudes as shown~~ notable reductions in model underestimates and smaller MAEs depicted in Figure 14 ~~with smaller MAE values.~~. For ~~instance, the model~~ example, maximum surge underestimations ~~of the maximum~~ are reduced by up to 40 cm ~~for~~at a station in the southeastern Florida peninsula (USA). ~~The~~However, the correlation ~~however~~with tide gauge data remains unchanged, as shown ~~with~~by the negligible variance contribution of the baroclinic simulation ~~to the variance~~ for this metric in Figure 13b. These improvements are attributed to large changes in ~~the~~ general

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~~surface~~ocean circulation caused by ~~the~~ hurricane passage. ~~It is however important to note that~~However, these simulations are computationally very expensive ~~(around~~ approximately 70 times longer~~),~~ and require 15 times more computational resources ~~—~~posing challenges not only for large~~-~~scale studies ~~or~~, long-term ~~applications, such as global to regional~~ hindcasts or projections~~,~~ but also for operational ~~purposes~~applications requiring efficient results. Alternative ~~methods could be considered~~approaches to incorporate these baroclinic processes without simulating the entire ~~3-D~~3D column~~, such as~~ include using ~~the~~ models in a ~~2-D~~2D baroclinic mode (Westerink and Pringle, 2018) or adding ~~the baroclinic contribution as a post-processing step (Zhai et al., 2019).~~ baroclinic contributions as a postprocessing step (Zhai et al., 2019; Pringle et al., 2019).

6. Conclusions

This study aimed to ~~explore multiple~~examine various factors affecting the performance of ~~the~~ numerical ~~modelling of~~models in simulating extreme sea levels dominated by ~~large~~ storm surges induced by hurricanes. The factors explored encompassed the choice of numerical ~~model~~models (ADCIRC and NEMO)~~, the choice of the~~ oceanic and atmospheric forcings, physical parameterizations for wind stress, and baroclinic/barotropic modes. ~~Four~~The study simulated four historical hurricanes ~~were simulated~~ in the tropical Atlantic region~~, — Wilma (2005), Matthew (2016), Irma (2017), and Maria (2017) —~~ covering the Caribbean Sea and Gulf of Mexico~~. The~~ and evaluated the modelled storm surge maxima and ~~the behavior of the~~ hourly time series ~~were evaluated~~ against tide gauge data.

The analysis of the ~~different~~ numerical experiments revealed some interesting insights. ~~Both~~ Compared with tide gauges, both the ADCIRC and NEMO ~~numerical~~ models can simulate storm surges due to tropical cyclones in a similar ~~way compared to tide gauges.~~manner. The ~~performance~~accuracy of these models is ~~however~~ highly dependent ~~of those of the~~ on atmospheric forcing ~~hence varying across regions.~~, leading to regional variations. In the ~~analyzed~~ tropical Atlantic region studied here, the ERA5 atmospheric reanalysis ~~forcing~~ generally outperforms ~~the various~~ parametric wind models ~~for storm surge modeling,~~ in terms of the maximum surge values, ~~correlation~~correlations, and ~~duration~~durations of extreme events. The inclusion of the baroclinic response significantly improves storm surge amplitudes, i.e~~.~~., significantly reduces underestimates, in ~~some~~ regions such as along the southeastern Florida peninsula (USA). ~~However, non-linear~~Conversely, nonlinear interactions of tides and the mean sea level with storm surges, as well as different wind stress implementations ~~show very small contribution to the~~ , have minimal impacts on storm surges induced by hurricanes. These methodological insights ~~can have key implications for the development of~~will guide future research, especially in refining regional hindcast and projections~~, but~~ for the tropical Atlantic. By integrating these results and addressing uncertainties in the model and the configuration development, we aim to enhance the accuracy and reliability of storm surge estimates. Furthermore, these findings may be also ~~for~~used in coastal impact assessment~~, particularly for understanding and predicting~~ to better understand and predict hurricane-induced coastal flooding and erosion. ADCIRC provides a wetting/drying option, which is crucial for coastal impact studies, such as floodplain inundation. NEMO also has this capability (O'Dea et al., 2020) and incorporating it for future coastal studies using NEMO would be highly beneficial.

These results rely primarily ~~rely~~ on the available tide gauge data, which are scarce and occasionally out of service during hurricane events. Currently, ~~there is a lack of~~ alternative observational products ~~to~~for accurately ~~measure~~measuring storm surges are lacking, and satellite data ~~remains~~are insufficient for capturing local surge details near the coast (Lobeto and Menendez, 2024).

##

Appendix ~~1~~A: Model settings

Model	ADCIRC	NEMO	NEMO baroclinic

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Version	v53	v4.0.4	v4.0.4
Resolution	From 3 km to 70 km	1/12º (~ 9 km)	1/12º (~ 9 km)
Type	2-D Barotropic	2-D Barotropic	3-D Baroclinic
Number of elements	63568	544*342 = 186048	544*342 = 186048
Number vertical levels	1	2 (only one active)	75
Time step	18 s	18 s (barotropic motions), 600 s (baroclinic time step)	18 s (barotropic motions), 600 s (baroclinic time step)
Time of calculation for 1 tropical cyclone	~20 min	~35 min (1 node)	~2.5 h (15 nodes)
Vertical coordinates	sigma	sigma	z levels (partial steps)
Bathymetry and coastline	NOAA Operational Model with ADCIRC	NOAA Operational Model with ADCIRC interpolated on curvilinear 1/12 º grid	NOAA Operational Model with ADCIRC interpolated on curvilinear 1/12 º grid
Minimum bathymetry	3 meters	3 meters	3 meters
Bottom stress	Quadratic friction (constant drag=2.5e-3)	Quadratic friction (constant drag=2.5e-3)	Quadratic friction (constant drag=2.5e-3)
Atmospheric forcing:	ERA5: hourly winds and pressure	ERA5: hourly winds and pressure	ERA5: hourly winds, pressure, temperature and specific humidity, radiative fluxes, precipitation, snow cover
Wind stress	S&B scheme: Cd=(0.75+0.067U)e-3	S&B scheme: Cd=(0.75+0.067U)e-3	Charnock (alpha=0.018)
Lateral boundary forcing: Ocean	no	constant tracers	GLORYS (1/4 º), daily tracers (temperature and salinity), currents, sea level
Lateral boundary forcing: Tides	8 primary constituents TPXO9	8 primary constituents TPXO9	8 primary constituents TPXO9
Initial conditions:	no	constant tracers	GLORYS (1/4 º) temperature and salinity of the day before the hurricane
Runoff	no	no	no (but the impact on the tracers is accounted for)
Sea level accounted for	Tides, storm surges	Tides, storm surges	Tides, storm surges, mean sea level (due to oceans circulations and variations in sea level budget)

Table A1: Table of the different configurations developed and settings used in them.

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Code availability

The NEMO 4.0 version used was developed by the NEMO consortium (https://doi.org/10.5281/zenodo.3878122, Madec et al., 2019). All specificities included in the NEMO code are freely available (NEMO, 2024: https://www.nemo-ocean.eu/). The ADCIRC code is available from the project website (http://adcirc.org/) under the terms stipulated there and is free for research or educational purposes.

Data availability

The tide-gauge data used for validation are available on the GESLA website (at www.gesla.org). ERA5 atmospheric forcings are available on the Climate Data Store (https://cds.climate.copernicus.eu) in the context of the Copernicus Climate Change Service (C3S). The tidal forcing is available on the OSU TPXO Tide Models website (https://www.tpxo.net/home). The GLORYS ocean reanalysis product was obtained from the Copernicus Marine Services (https://marine.copernicus.eu/).

Author contributions

MM and AAC designed the study. AAC prepared the regional ocean configurations and performed the simulations. MRP prepared the parametric wind models forcings and helped to set-up the ADCIRC ocean configuration. AT and AAC designed the variance decomposition analysis. AAC did the analyses of the simulations. MM and AT supervised the project. ACC wrote the first draft of the manuscript, and MRP wrote the parametric wind models sections. All authors contributed to manuscript revisions and read and approved the submitted version.

Competing interests

The contact author ~~has~~ declared that ~~none of~~all the authors ~~has any~~have a competing ~~interests~~interest with Editor Mauricio as they all work in the same institute.

Acknowledgments

The authors are grateful to Clare O'Neill and Jeff Polton for sharing the NEMO barotropic code and to Chris Wilson for sharing the NEMO baroclinic Caribbean configuration. The tide ~~-~~gauge data used for validation are available on the GESLA website (at www.gesla.org). Analyses were carried out with Python (utide and statsmodels packages). The unstructured mesh has been designed with SMS software.

Financial support

AAC and AT would like to thank the Government of Cantabria through the FENIX Project GFLOOD. MM and MRP acknowledge the financial support from the ThinkInAzul programme, with funding from 761 European Union NextGenerationEU/PRTR-C17.I1 and the Comunidad de Cantabria. AT acknowledges financial support from the Ministerio de Ciencia e Innovación (MCIN/AEI and NextGenerationEU/PRTR) through the Ramon y Cajal Programme (RYC2021-030873-I).

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