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Response to reviewer' comments

Dear Editor,

First, we want to warmly thank the reviewer for her/his very constructive comments and suggestions. Her/his involvement have enabled us to consistently improve the clarity and, hopefully, the quality of our manuscript.

We conducted five main actions to improve our manuscript:

- The structure of the introduction was modified for more fluency. The introduction now follows a clearer thread: context, motivation, purpose of the study. We hope we provided more clarity for the aim of the study.
- Our study has two goals: first, comparing surge and wave reconstruction against observations while using either ECMWF reanalysis data or D1 data as forcing; then examining if using D2 has an added-value compared to using D1 data as forcing. In the Results section, the text in the sections 3.2 and 3.3 has been reorganized in order to answer these two questions, one after the other.
- The two downscaling methods (D1 and D2) descriptions are now more detailed and supported by the modified Fig. 1. The figure highlights the similarities and differences between D1 and D2. We also explained more explicitly our choice of testing D2 method only on 10 cases instead of the whole 30 historical storms studied.
- The term "ERA" now only referred to the acronym of ECMWF Re-Analysis. In the other cases, the confusing term of "ERA" was replaced by the name of the ECMWF reanalysis (i.e. ERA-20C, ERA-40 or ERA-Interim) when only one type of ECMWF reanalysis is considered or by "ERA-x" when two or more types of ECMWF reanalysis are used.
- At the end of our revision, the manuscript has been reviewed by a colleague with English as native language who paid a particular attention to grammar, structure and fluidity of the text.

Here is a detailed answer to all comments from the reviewer. We hope the new version of our manuscript will please the reviewer and you, and is of publishable standard for your journal. We remain at your disposal and will gratefully receive any additional comments and suggestions.

Best regards, On behalf of the co-authors, Émilie Bresson

Response to Anonymous reviewer #1

Unfortunately the concerns regarding the methodology, and the quality of the text are still present. The text still feels more like a technical report, and still needs improvement. I raise some questions below, but there are much more to be addresses. The text is also full of grammatical errors that should have not been passed to a second review iteration. Please revise once more.

We want to thank you for your involvement in the revision for our manuscript. Your comments and suggestions highlight very well the mistakes and the disorganization present in the previous version of the manuscript.

The introduction was reorganized and the aim of our study is now, hopefully, clearer. The analysis of our wave and storm surge reconstructions is now following the two points of our goal.

In order to prevent grammatical errors and other language mistakes, we ask a colleague with English as native language to revise and correct our manuscript.

We hope that the new version of our manuscript would answer all your concerns and that it will offer you the opportunity to evaluate in a more pleasant and fluid way our study.

P1-L5: Add the ECMWF reanalysis acronyms you are using between curly brackets after "reanalyses".

We modified the abstract following this point: the ERA-20C, ERA-40 and ERA-Interim acronyms have been added between curly brackets in the abstract.

P2-L8-9: Are you doing this? "A global atmospheric reanalysis is built using a data assimilation system and historical observations spanning an extended period."

This sentence aims at giving a definition of a global atmospheric reanalysis, but the way we express this point was confusing. It has been replaced in the introduction by: "Several weather forecast centers produce these global atmospheric reanalysis, including the European Centre for Medium-Range Weather Forecasts (ECWMF). The ECMWF Re-Analyses (ERA) include different products that have various date ranges, spatial resolutions and assimilated datasets (Tab. 1; Poli et al., 2013; Uppala et al., 2005; Dee et al., 2011)."

P2-18: ERA is not "European Reanalysis" but "ECMWF Re-Analysis".

The definition of the ERA acronym as "ECMWF Re-Analysis", and not "European Reanalysis", has been corrected in the revised manuscript.

P2-20: The ECMWF reanalyses were not produce using a "coupled climate system, including atmosphere, land surface and ocean". They have been produced by older versions of IFS, the ECMWF operational forecasting coupled model system. By "older" is meant a previous version, compared to the present (at the time) operational version.

The definition of the ECMWF reanalysis has been corrected in the revised manuscript in the section 2.1.

P2-24: ERA-Interim is not "the reanalysis with the highest resolution". There are several other reanalyses with higher resolution, like CFSR, MERA2, JRA-55, etc. ERA-Interim is the highest resolution reanalysis at ECMWF, so your statement is misleading.

We totally agree with you and we add more details about this point in the introduction: "ERA-Interim, one of the higher-resolution reanalyses available from the ECMWF."

P3-L2-5: This sentence (first paragraph on page 3) is full of inaccuracies and misleading statements: "Mean sea level pressure and surface wind are needed as atmospheric forcing to forecast wave and storm surges. In the present study, these two variables are obtained through reanalyses built using a given data assimilation system constrained by past observations. A dynamical downscaling is applied on global atmospheric reanalyses since their resolution is too coarse to deliver accurate information for hindcast."

1. Not "obtained through" but "obtained from".

Done.

2. The "downscaling" is not "applied" but a "dynamical downscaling of the global reanalyses is produced, since the global reanalyses are too coarse to force the regional wave and storm surge models".

The sentence has been corrected in the revised manuscript.

P6-L21-22: Stating the goal of the study in the results section is not correct. Move it to the introduction.

Done.

P8-L19: Which ERA?

For this storm (November 2007), the ECMWF reanalysis used is ERA-Interim.

In the new version of the manuscript, we explicitly use the name of the ECMWF reanalysis considered if only one type of reanalysis is used (ERA-20C or ERA-40 or ERA-Interim). When more than one type of reanalysis is used, ECMWF reanalysis are named ERA-x.

P1-L1: Replace "analysis" with "reanalysis".

Done.

P16-16: Why coarse resolution generates "strong uncertainties"?; What is a "strong uncertainty"?

The correct words were "significant bias" instead of strong uncertainties. The modification has been made. With this "significant bias", we refer to the mesoscale features associated with mid-latitude cyclone development which are not represented in the coarse resolution reanalysis.

On the improvement of waves and storm surge hindcasts by downscaled atmospheric forcing: Application to historical storms

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Abstract. Winds, waves and storm surges can induce severe damages inflict severe damage in coastal areas. To improve the preparedness to crisis due to such eventsa better knowledge of their statistical distribution is required. A better knowledge of past events is the first step to reach this purpose. This paper shows In order to improve preparedness for such events, a better understanding of storm-induced coastal flooding episodes is necessary. To this end, this paper highlights the use

- 5 of atmospheric downscaling techniques in order to improve waves and storm surge hindcasts. Downscaling techniques The downscaling techniques used here are based on existing European Centre for Medium-Range Weather Forecasts reanalyses (ERA-20C, ERA-40 and ERA-Interim). The results show elearly that the 10 -km-resolution wind-data forcing provided by the a downscaled atmospheric model gives a better waves and surges hindcast against using wind compared to using data directly from the reanalysis. Furthermore, the analysis of the most extreme mid-latitude cyclones indicates that a 4-dimensional
- 10 <u>four-dimensional</u> blending approach improves the whole processas it includes small scale, as it assimilates more small-scale processes in the initial conditions. Our approach has been successfully applied to ERA-20C (the twentieth century reanalysis).

1 Introduction

One of the most vulnerable areas affected by winter storms are coastal regions, as their soils are often <u>easily</u> eroded and their population density is high (Barredo, 2007; Clarke and Rendell, 2009; Ferreira et al., 2009; Ciavola et al., 2011; André

- 15 et al., 2013). Such storm events are frequently responsible for severe damages, huge significant economic losses and many casualties. Storm surges can reach 250 cm. In Europe, sensitive regions include the Atlantic, Mediterranean and Black Sea coasts; in particular, storm surges as high as 2.5 m have been recorded along the Atlantic coasts and 150 cm along the Western 1.5 m along the western Black Sea coasts (Marcos et al., 2009; Ryabinin et al., 1996). Most winter storms. These extreme events are often associated with winter low pressure systems; those that affect western Europe are associated with principally
- 20 mid-latitude cyclones that originate in the Atlantic ocean (Klawa and Ulbrich, 2003; Della-Marta et al., 2009; Usbeck et al.,

2010). The , and the Bulgarian coasts are hit by cyclones whose origin lies generated in the Mediterranean region (Bocheva et al., 2007). The cumulative effects of deep low pressures, dynamical action of winds and spring tides lead to a strong rise of sea levelcausing amplification of wind-generated waves and surge by equinox tides within deep low pressure systems can also produce a significant rise in sea level, resulting in coastal flooding.

- For example, during the Xynthia storm, which hit the western part of the French French Atlantic coast on February -27^{th} . 2010, this kind of combination occurred with a coastal flooding scenario occurred as a result of a tide coefficient of 102 - that coincided with a highest astronomical tide between 0.96 m and 1.15 m - and maximal recorded and wind gusts of 160 km h⁻¹ over coastal regions and about 120 km h⁻¹ over land (Rivière et al., 2012). Noteworthy storm surge reached more than As a result of these conditions, a damaging storm surge crested above 1.60 m at La Rochelle and Les Sables d'Olonnefor this storm.
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A-<u>d'Olonne</u>. This example demonstrates that a better knowledge of the variability of these events is of primary interest to improve waves and storm surges extreme coastal events is needed to improve high surf and storm surge warning systems. The trends in the frame of climate change are criticalas well. Due to the In addition, evaluating the frequency and severity of these events within the framework of ongoing climate change is equally critical. Consequently, a 20th century climatology of wave and storm surge would provide a useful baseline for coastal protection and risk management.

The lack of long-term wave records based on in-situ measurements and surge archives for the whole prevents the development of a completely observational 20th century, these -century climatology for waves and storm surges. Therefore, reconstructing wave and storm surge extreme events have to be reconstruct by hindcast using numerical models . A straightforward approach for hindcasting consists in represents an alternative approach toward establishing a climatology. One straightforward method

- 20 for hindcasting involves using global atmospheric reanalyses as the atmospheric forcing conditions of in wave and storm surge numerical models (Reistad et al., 2011). A Several weather forecast centers produce these global atmospheric reanalysisis built using a data assimilation system and historical observations spanning an extended period. The Increasing Resilience through Earth Observation (IncREO) project offered the opportunity to test this approach for a limited number of wind storm cases studies. This project, funded by the Seventh Research Framework Programme (FP7) of the European Union, has brought
- 25 together Earth observation data gathered through the European Union's programme Copernicus. This project makes those data available for emergency planning services and disaster management missions. One major component of the project consists in mapping of the coastal vulnerability using a series of past wave and surge extreme events.

In this study, we assess wave and storm surge hindcast for extreme events between 1924 and 2012. Thirty cases are selected to offer a large panel of extreme events with various affected areas (French Atlantic and Mediterranean coasts; Bulgarian

30 Black Sea coasts), more or less extended impacted zones, different cyclone trajectories and amplitudes and varied highest astronomical tide (Tab. 2). The different European reanalyses, including the European Centre for Medium-Range Weather Forecasts (ECMWF).

The ECMWF Re-Analyses (ERA), produced by European Centre for Medium-Range Weather Forecasts (ECWMF), have various period lenghts, model include different products that have various date ranges, spatial resolutions and assimilated

35 datasets . ERA-20C, ERA-40 and ERA-Interim datasets are produced with a coupled climate system, including atmosphere,

land surface and ocean (Tab. 1; Poli et al., 2013; Uppala et al., 2005; Dee et al., 2011). Although we can use the finer finer-scale reanalysis as initial conditions for a given event, it turns out that period, a dynamical downscaling of the global reanalyses is also necessary, since they are too coarse to force the regional wave and storm surge models. Furthermore, certain mesoscale processes related to the formation of strong winds surface winds, such as sting jets (Hewson and Neu, 2015), are absent even

- 5 in ERA-Interim, the reanalysis with the highest resolution. As described in Reistad et al. (2011); Li et al. (2016)one of the higher-resolution reanalyses available from the ECMWF. Therefore, in order to better resolve mesoscale features associated with mid-latitude cyclone development and their interaction with locally-complex coastal topography, a dynamical downscaling can be applied on these reanalyses using a high resolution numerical model to better resolve the horizontal scales involved together in the mid-latitude cyclone development processes and interaction with fine resolution coastal topography. The purpose
- 10 of this study is to present different downscaling approaches leading to better atmospheric forcings for wave and storm surge models and to assess the added value of those proposed approaches.

The paper is organized as follows. Section 2.1 describes (e.g., Reistad et al., 2011; Li et al., 2016).

In this study, we apply two different downscaling methods on ERA datasets. The first one is a simple dynamical downscaling approach beyond the reanalysis truncation, whereas the second is more complex. We evaluate to what extent the mesoscale

- 15 features resolved by the first downscaling technique impact our surge and wave reconstruction over the French and Bulgarian coasts, followed by an examination of the added-value of the second downscaling method against the first, simpler one. As observations are spatially and temporally scattered in these regions, we focus on thirty extreme events between 1924 and 2012 that targeted the French and Bulgarian coasts. The selected cases offer a large panel of observed extreme events with various affected areas (in particular, the French Atlantic and Mediterranean coasts and the Bulgarian Black Sea coast), including cases
- 20 with more or less extended impacted zones, different cyclone trajectories and amplitudes and varied highest astronomical tide (Tab. 2). In the present paper, we first describe the methodology and data used for the downscaling strategies ; Section 2.2 presents (Section 2.1) and then the wave and surge models configurations - (Section 2.2). In Section 3discusses the results: first examining the impact of , we first compare the results from the two downscaling techniques on a deep cyclone development; a second part is devoted to wave hindcasts evaluation; then reconstructing an intense cyclone's development, then we evaluate
- 25 <u>wave hindcasts and storm surge model outputs skillis addressed; last part is dedicated to skill, followed by an analysis of our</u> early 20th century cases. Finally, Section 4 summarizes the take-home messages our conclusions.

2 Methodology

Mean sea level pressure and surface wind are needed as atmospheric forcing to forecast wave and storm surges. In the present study, these two variables are obtained through reanalyses built using a given data assimilation system constrained by past

30 observations. A dynamical downscaling is applied on global atmospheric reanalyses since their resolution is too coarse to deliver accurate information for hindcast.

2.1 Dynamical downscaling of reanalyses

The general method of a dynamical downscaling uses a coarse resolution dataset, like global atmospheric reanalysis <u>data</u>, as initial conditions for a numerical atmospheric model. Three ECMWF reanalyses are selected for this study: ERA-20C, ERA-40 and ERA-Interim (Tab. 1). They are all produced with a coupled climate system, incorporating atmosphere, land surface and

- 5 ocean systems by older versions of the Integrated Forecasting System (IFS), the ECMWF's operational forecasting coupled model system. ERA-40 includes conventional observations (e.g. surface stations, buoybuoys, radiosondes), polar satellites and geostationary satellites. ERA-Interim datasets benefited of benefit from improvements in assimilation methods and large increase a large expansion of available data. It turns out that , with observation quantity and quality increased with time. Therefore in increasing over time. In order to mitigate the inhomogeneity of this inhomogeneity in the 20th century reanalysis,
- 10 only observations of surface pressure and surface marine winds are assimilated in the ERA-20C dataset. To In order to provide the best possible atmospheric conditions for wave and storm surge hindcast, the following ERA datasets are downscaled for each stormevent: ERA-20C for cases study before 1957, ERA-40 for 1957–1978 period, the 1957–1978 period, and ERA-Interim for storms occurring in 1979 and after thereafter (Tab. 2). The designator "ERA-x" is used in this manuscript to describe a group of cases where more than one ERA reanalysis product is applied.
- 15 Over both Hereafter, this study focuses on the advantages of downscaling global atmospheric reanalysis for the development of wave and storm surge hindcasts. Over both the French and Bulgarian domains, numerical weather prediction (NWP) models need to assure high enough horizontal and time resolutionrequire high horizontal and temporal resolution, especially for the storm surge model hindcast. For French events, the selected model, ARPEGE (Action de Recherche Petite Echelle Grande Echelle), is the operational global primitive-equation NWP system used at Météo-France and is based on the ARPEGE-IFS
- software developed in collaboration with ECMWF (Tab. 3; Courtier et al., 1991). A stretched grid allows for a finer horizontal resolution over France (around 10 km)with a coarser one at the antipodes (60 km). The version used here has 70 hybrid vertical levels from 17 m to about 70 km height. The Bulgarian events are hindcast thanks to from ALADIN (Aire Limitée, Adaptation dynamique, Développement InterNational) for more consistency as the ARPEGE grid is too coarse over this region. ALADIN model, which is a limited-area model based on the ARPEGE system (Radnóti et al., 1995). Its The model's core characteristics are the same as for ARPEGE.

Two dynamical downscaling methods (D1 and D2) are examined here, hereafter referred to as D1 and D2, where D2 represents an improved version of D1. For D1, the necessary part data from the global fields of ECMWF reanalysis ERA-x are interpolated to the plane model domain both on horizontal and vertical scale for each NWP system, ARPEGE and AL-ADIN. The upper-air initialization step is using uses the spectral coefficients of ERA reanalysesERA-x data. Then we apply

30 the Schmidt transform transformation, which is well defined in spectral space to project the fields into the ARPEGE stretched grid. The land-surface initialization is not straightforwardsince many differences of, since there are many differences between the ERA reanalysis and the NWP models in terms of the applied land-surface parametrizations parameterizations and physio-graphic databasesbetween the two land-surface schemes can be found. For instance, the Tiled ECMWF Scheme for Surface Exchanges over Land (TESSEL) scheme of ERA-ERA-x uses four soil layers with fixed thicknesses, each layer having its own

water content. The land-surface scheme of ARPEGEuses only, however, only uses two layers in our experiments,; the top layer with has a fixed size of 1 -emcm, and the second layer overlaps the first one and has a variable depth. For Furthermore, for a given grid point, soil types are often very different in the two land-surface schemes. Therefore, using the raw land-surface datasets from ERA-ERA-x as initial conditions would be troublesome, since the water saturation fraction depends on the soil

- 5 type. Thus, we interpolate the surface fields so as to preserve as much as possible the <u>ERA-x</u> surface heat and momentum fluxes (Boisserie et al., 2016). The procedure is based on the conservation of the Soil Wetness Index (a relevant indicator for soil water availability) during the interpolation process, since soil water availability is supposed to regulate the partition of latent and <u>sensible</u> heat fluxes, which, in turn, influence energy and water exchanges between the atmosphere and the land-surface. The resulting files are initial conditions for NWP forecasts and (IC-1) for the NWP forecasts (Fig. 1, top). Then, hourly forecasts are
- 10 produced twice a day(, at 00 UTC and at 12 UTC), starting from H+06 to H+18. The first six hours are not taken into account to prevent model spin up, and after H+18, the next forecast time is considered (Fig. 1, top). Forecasts are produced from a week (d-7) before to two days (d+2) after the day (d) that the storm impacted the coastline. The D2 method helps is more complex than D1 (Fig. 1, bottom). The D2 method also uses hourly forecasts produced twice a day, at 00 UTC and at 12 UTC, starting from H+06 to H+18, and the forecast start nine days (d-9) before and continue until two days after (d+2) the the day (d) that
- 15 the storm impacted the coastline. Instead of using independent initial conditions (IC-1) like in D1 for the 00 UTC and 12 UTC forecasts, the initial conditions for D2 (IC-2) include information from the last 6-h forecast (Fig. 1, bottom). Consequently, the D2 method allows us to evaluate the importance of taking into account small wavelengths beyond the reanalysis truncation , that are not considered in D1. Furthermore, after a short period of time (3 hours), non-linearities trigger small seales scale processes which are consistent with the large scale. This small scale small-scale information provided by the 6-hour forecast
- 20 is blended with the large scale information given by the interpolated reanalysis (IC-1) (Fig. 1, bottom). This procedure was cycled 4 times two days before the first 00 UTC forecast used as forcing for the wave and storm surge models. Therefore, the determination of one single initial condition (IC-2) uses 4 reanalysesand is then, in some sense, 4-dimensional. The D2 technique is apply on applied to 10 French events recent French coastal flooding events (Tab. 2). These 10 cases represent a diverse panel of events affecting different coastlines with adequate observational data (satellite altimeters and tide gauges) to
- 25 evaluate the reconstruction of the wave and storm surge observations and to enable a comparison between D1 and D2.

2.2 Description of wave and storm surge models

For more consistency, In order to ensure consistency in our case studies, the selected wave and storm surge models used here have share similar general characteristics while being adapted to either, despite being adapted specifically either the French or Bulgarian coasts.

30 2.2.1 Wave models

The French coast extreme wave events are hindcast with the Meteo-France WAve Model (MFWAM), a third-generation model of the operational wave forecasting system of Météo-France (Tab. 3). This model is based on the IFS-CY36R4 of the European wave model (ECWAM) with modified source terms for the dissipation by wave breaking and the air friction dedicated to swell

damping as described in Ardhuin et al. (2010). The MFWAM model uses the wind input term developed as defined in Bidlot et al. (2005). The dissipation by wave breaking is directly related to the wave spectrum with a saturation rate of dissipation. The source term is a combination of an isotropic part component and a direction-dependent part component that controls the directional spread of the resulting wave spectra. It also includes a cumulative effect describing the smoothing of big breakers

- 5 on small breakers. The term also additionally uses a wave turbulence interaction part, which weak component, which, as indicated in Ardhuin et al. (2010), is of secondary importance. The MFWAM model uses a quadruplet non-linear non-linear interaction term based on the discrete interactions approximation as indicated defined in the ECWAM model. In this study, a nested MFWAM model is implemented with a grid size of 0.1° for western European seas-Western Europe, including the Mediterranean Sea. The domain boundaries are 20° N-72° N longitude, 32° W-42° E for latitude and longitude, respectively
- 10 latitude (EURAT01 domain in Fig. 2). The wave spectrum is discretized in 24 directions and 30 frequencies starting from 0.035 to 0.58 Hz. This regional model is forced by boundary conditions provided by the global MFWAM model with a grid size of 0.5°. The global MFWAM model is driven by 6-hourly ERA windsreanalyses.

ERA-x winds. The SWAN (Simulating Waves Nearshore) model is used for the Bulgarian cases (Tab. 3). It is a third-generation wave model that is especially designed to simulate waves in near-shore near-shore waters and is very often applied to enclosed and semi-enclosed seas, estuaries and lakes (Booij et al., 1999). The model computes random, short-crested, wind-generated waves in coastal regions and inland waters. SWAN accounts for wave propagation and transitions from deep to shallow water at finite depths by solving the spectral wave action balance equation, which includes source terms for the wind input, non-linear interactions, white-cappingwhitecapping, bottom friction and depth-induced breaking. The model performance, the parameterizations of the wave generation and dissipation processes and other aspects of SWAN

- 20 applied to the Black Sea have been studied by Akpinar et al. (2012); Arkhipkin et al. (2014); Rusu et al. (2014)basin have been addressed in previous studies (Akpinar et al., 2012; Arkhipkin et al., 2014; Rusu et al., 2014). The model domain that is used for the simulations of our historical Black Sea storms is based on a numerical grid covering the entire Black Sea area (40° N-47° N and 27° E-42° E; hereafter named BUL; Fig. 2) with a mesh size of 0.0333° in latitude and longitude. The spectral discretization is based on 36 directions and 30 frequencies logarithmically spaced from 0.05 Hz to 1.00 Hz.
- The wind input parameterization follows Komen et al. (1984)and white-capping, and whitecapping is based on Hasselmann (1974), with the δ coefficient (which determines the dependency of white-capping whitecapping on wave number) set to 1 (according to the study by Rogers et al., 2003)(following Rogers et al., 2003). This specific set of parameterizations is chosen to have the lowest bias, root mean square error (RMSE) and scatter index when comparing compared to results from the model and the along-track satellite altimetry data. The bathymetry data for the wave model are obtained by the digitalization
- 30 of proprietary maps provided by the Bulgarian military hydrographic service.

2.2.2 Storm surge models

The operational surge model of Météo-France (Daniel et al., 2001) is a barotropic 2-dimensional version of the HYCOM model (HYbrid Coordinate Ocean Model) implemented by SHOM (Service Hydrographique et Océanographique de la Marine) from the 3-dimensional version (Tab. 3; Bleck, 2002; Baraille and Filatoff, 1995). The HYCOM code is managed by an international

consortium:, including COAPS (Center for Ocean-Atmospheric Prediction Studies;, USA), NRL (Naval Research Laboratory; , USA), SHOM (France), DMI (Danish Meteorological Institute;, Denmark) and NERSC (Nansen Environmental and Remote Sensing Center;, Norway). The model is run on two domains (as shown in Fig. 2);; ATL corresponds to the North-East Atlantic area (Bay of Biscay, English Channel and North Sea), from 9from 43° W to 10N to 62° E and from 43N and from 9° N to 62W

- 5 to 10° N; E, and MED defines the Mediterranean Sea domain , from 9 from 30° W to 37N to 46° E and from 30N and from 9° N to 46W to 37° N; with E. In both domains, the model runs on a grid size of around approximately 1 km on the French coast (curvilinear grid). The tides imposed at the marine boundaries are computed thanks to according to the 17 harmonic components from the COMAPI (COastal Modelling for Altimetry Product Improvement project) regional atlas implemented in the North East Atlantic Ocean area (Cancet et al., 2010); the , The bottom friction coefficient is spatially variable and has
- 10 been optimized to properly reproduce the propagation of tides. Tides are discarded in the storm surge computation, and for which another computation of the tides, based in harmonic components obtained from measurements by SHOM, is added to the storm surge in order to know-more accurately represent the sea level with more accuracy, at specific locations. The bottom friction coefficient is constant and taken as equal to 0.002. For both HYCOM configurations (ATL and MED), the drag coefficient used to compute the wind stress, follows the Charnock (1955) scheme with a constant Charnock parameter of 0.025.

The simulations of storm surges for Black Sea cases are based on the storm surge model of Météo-France (Daniel et al., 2001)adapted to-, which was adapted for the Black Sea by in Mungov and Daniel (2000) (Tab. 3). The model is depth-integrated, and tides are not taken into account, as their amplitude is less than 9 cm in the Black Sea. The model grid for the Black Sea is a regular spherical grid with a spatial resolution of 0.0333°. The model domain that covers the entire Black Sea. The bottom

- 20 friction coefficient is $1.5 10^{-3}$ over the shelfand $1.5 \cdot 10^{-5}$ over the liquid bottom. The In addition, the depth of the Black Sea mixed layer is considered as a liquid bottom (given the very stable stratification of the Black Sea waters and the shallowness of the mixed layer depth), and as such, the bottom friction coefficient is defined as $1.5 \cdot 10^{-5}$ over the liquid bottom. Data about the seasonal variations of the Black Sea mixed layer depth are taken from the study by Kara et al. (2009). Without this specific set-up of a liquid bottom, the depth integrated liquid bottom setup, the depth-integrated models for the Black Sea would fail
- 25 to simulate any surgeeven if very, even if strong, constant winds were used as an are used as input. The bathymetry data for the storm surge model (and the wave model) are obtained by digitalization of were obtained by digitizing proprietary maps provided by the Bulgarian military hydrographic service.

3 Results

3.1 Impact of the two downscaling techniques on a deep cyclone development

30 The effects of the two downscaling techniques on the reconstruction of intense storms are presented with an example of a deep cyclone development. The Lothar stormwas for the case of the Lothar storm, an extreme cyclogenesis event (occurring a few hours before the Martin storm described further in Sections 3.2 and 3.3) in December 1999. It is the most extreme severe storm in terms of pressure gradient, surface wind winds and displacement velocity to hit France to this day within the

observational record (Wernli et al., 2002; Rivière et al., 2010). This storm did not produce extreme wave and storm surge, and thus it was not selected for hindcasts. Nevertheless, it is interesting to look at the behaviour oh of both downscaling strategies for this case where the particular case due to its uniquely tight horizontal pressure gradientare so strong. Fig. 3 shows the comparison of the downscaling strategies applied to this storm. For this storm, the D1 method slightly improves the ERA-

5 Interim reanalysis fieldsbut, but the D2 downscaling better reproduces the cyclone structure over Northern France than D1 and the ERA reanalysis. Statistics are (Fig. 3). A statistical analysis using the mean, the bias, the root mean square error (RMSE) and the standard deviation error (STD) is performed with the 12 meteorological stations available on in an area encompassing the low pressure system (48° N-50° N; 2° E-4° E). Table 4 confirms that downscaling is noticeably better than This analysis confirms that the use of D1 forcing is an improvement compared to using an ERA-Interim reanalysis in regard with respect to

10 surface observations. Table 4 also highlights the slight improvement of results by the The use of D2 -

The purpose of the paper is to measure to what extent the mesoscale features built by the downscaling techniques beyond the reanalysis truncation have an impact in terms of surge and wave reconstruction slightly improves the reconstruction of the observations ((Table 4)).

3.2 Wave hindcasts

- 15 Significant wave heights For the wave reconstruction evaluation, simulated Significant Wave Heights (SWH) hindcasts can be evaluated by using, for example, in-situ observations and are compared against observations from satellite altimeter data and in-situ observations. Several satellites operated while some selected stormsoccurred over the French and Bulgarian coasts during the storms: TOPEX-Poseidon (1992–2005), ENVISAT (20021000ERS2 (199510002012), Jason-1-2011), ENVISAT (2002–2013) and Jason-2 (200810002012) and Jason-1 (20021000). Buoys 2013). In addition, buoys and Acoustic Doppler
- 20 Current Profiler (ACDP) ADCP) in-situ provide SWH informationas well. Caveats remaining in . The limited scope of each of these observations datasets observational datasets, together with the coarse resolution of altimeter measurements do not enable a comprehensive verification, preclude a comprehensive validation for all the selected cases. For an initial evaluation of our modelling approach, the results from the wave model driven by ERA-x and D1 data is compared to available altimeter data. The simulated wave heights are collocated with the altimeter tracks with within a time window of 3 hours. For the 2004, 2007, 2008
- 25 and 2010 stormsFrench Atlantic coast storms and the 2012 Bulgarian storm, data are collected from three altimeters: Jason-1, Envisat and Jason-2. Fig. 4 shows the two satellite altimeters, Jason-1 and ENVISAT. The scatter plots between model and altimeter wave heights . This clearly indicates indicate that the use of D1 winds induces provides a better fit with a strong reduction of to the data (Fig. 4). In particular, when compared to the results for the wave model driven by ERA-Interim initial conditions, the use of D1 data reduces the normalized root mean square error (NRMSE) from 17.1 to 13.1 %. The bias is also
- 30 significantly reduced, largely owing to a significant reduction of bias from -35 to -4em. The best performance of the MFWAM model with D1 winds is obtained for the 2008 storm, where the NRMSE of SWH is significantly reduced from 15.9 to 11.8 % with D1, as illustrated in cm (Fig. 8. The statistical analysis reveals that the use of D2 winds leads to better results than the use of interpolated ERA winds. Biases of SWH are slightly improved using D2 winds rather than when using D1 winds. However, D2 winds slightly increases the NRMSE of SWH for the 2004, 2007 and 2008 storms. Only for the storm Xynthia (February)

2010), the D2 winds improve slightly the NRMSE of significant wave height. The evaluation with altimeters does not show elearly a gain from using the advanced D2 technique against 4). The D1. It seems that D2 shows better skills for higher wind speeds such as the ones observed during the Lothar stormdownscaling also leads to a better fit for high SWH, providing an important validation for extreme wave events. For the 1998, 1999 and 2000 storms, altimeters wave heights from TOPEX and

- 5 ERS2 are also used for the evaluation of the modelled wave heights. The SWH, and the same tendency is foundwith a strong decrease of NRMSE of SWH from 16.2 to 14.1 %, and the bias is well reduced from -32 to 10 cm, with an improvement of the reconstruction of SWH using D1 winds over ERA-x winds (not shown). The SWH hindcast and measured by the buoys are also compared for the most recent storms. Fig. 7 shows time series of SWH from model and buoys at the peak of the storm on February 2010 at Nice (43.4° N and 7.8° E) on the Mediterranean coast. This indicates a good fit on SWH induced by using D1
- 10 winds comparing to interpolated ERA winds. The February-

As satellite altimeters provide data along a track, these observations can be useful for mapping the spatial distribution of the SWH. For further examination, we present the 2012 storm is presented Bulgarian storm as an example of evaluationa more detailed evaluation of the reconstruction against observations. The wave model outputs are evaluated by comparing the simulated SWH with using ERA-Interim or D1 initial conditions are first compared to the 214 along-track data points.

- 15 measured by the Jason-1 and ENVISAT satellite altimeters on 7 and 8 February, 2012. The SWAN model output is compared to the satellite altimeter data from the Jason-1 and ENVISAT satellites. Four satellite tracks crossed the area with high waves in the western Black Sea (the total number of data points along the tracks was 214). Although this small number of data points, this event is the only opportunity to evaluate the SWAN model outputs. For the Black Sea, the occurrence of a storm seldom happens when more than one satellite track crosses the area with the highest waves. The results of the comparison of
- 20 the modelled SWH simulations with the ENVISAT satellite altimetry along-track data are presented in Table 5 and Fig. ??. Statistics have shown that the use of D1 forcing improves the wave hindcast (Table 5). The highest waves, obtained with wave reconstruction given by D1 forcing, reached about 7 m south of Ahtopol, where unfortunately the storm destroyed the tide gauge and the measurements were therefore lost. As a consequence, forcing more closely matches the satellite observations, especially in terms of wave intensity over the southern part of the SWAN model output, in terms of significant wave height,
- 25 is compared with satellite track (Fig. 5). However, the maximum observed SWH value is not reached by the model for both the ERA-Interim winds and the D1 winds. Regarding the temporal evolution of the 2012 Bulgarian storm, we can use insitu wave measurements by acoustic Doppler current profiler (ADCP) to check if the peak SWH occur at the same time in the observations and the reconstruction. In Fig. 6, we compare the SWH data from the ADCP located at Pasha Dere beach at 20 m depth . The data was provided by the Bulgarian Institute of Oceanology (Valchev et al., 2014) . Fig. 6 presents a
- 30 comparison of the wave measurements with the SWAN model outputs, obtained using the two wind inputs as an atmospheric forcing. Clearly the to our wave model outputs. The use of D1 slightly generally overestimates the measured wave heights. The SWH, while the use of ERA-Interim underestimates drastically the modelled values of significant wave height, while the wave heights. However, the use of D1 winds leads to a better matching of the simulated and measured waveheights. To conclude, temporal structure of the wave. The overall improvement of the SWH reconstruction by using D1 is confirmed by the statistical
- 35 analysis in Table 5. The temporal evolution of a storm can also be evaluated with in-situ buoys. For example, for the 2010

Mediterranean storm, we compare the time series of SWH from model and buoy data (43.4° N and 7.8° E) off the coast of Nice, France, at the peak of the storm (Fig. 7). The results show that the SWH induced by using D1 data more closely match the buoy observations when compared to the ERA-Interim data forcing. Given our validation of the D2 approach discussed in Section 3.1, the D2-driven SWH hindcast of the 2004, 2007, 2008 and 2010 French Atlantic storms are also compared to

- 5 satellite altimeter data. The statistical analysis (bias and NRMSE) reveals that the use of D2 winds leads to better results than the use of D1 winds considerably improved the bias, the root mean square error and the scatter index of significant wave height for this severe (Fig. 8). Biases of SWH are slightly improved using D2 winds over D1 winds; however, D2 winds slightly increase the NRMSE of SWH for the 2004, 2007 and 2008 storms. The D2 method only slightly improves the NRMSE of SWH for the storm Xynthia (February 2010). While the application of the D2-method winds does not lead to an improved
- 10 result over D1 in all cases, D2 appears to show better skill for events with higher wind speeds, such as the ones observed during the Lothar storm.

3.3 Storm surge hindcasts

Storm surge hindcasts can be evaluated by tide gauges gauge measurements. A network of 25 tide gauges around along the French coasts is maintained to validate the surge model implemented at Météo-France; Furthermore, an additional 12

hydro-meteorological stations are located along the Bulgarian coasts - Depending of the storm spread for validation purposes. Depending on the storm extent and instrument condition, the number of available data points is different for each storm (Tab. 2). For a global evaluation of hindcast regarding tide gauges, all the available measurements with a peak in storm surge are selected. A Weighted Normalized Observation Error (WNOE) is calculated to highlight over the overestimation and underestimation of the simulated maximum storm surges regarding measurements. It with respect to available measurements, and it is defined
by ÷

$$WNOE = 100.\alpha(t). \left(\frac{X_{sim} - X_{mea}}{X_{mea}}\right)$$

with $\alpha(t) = 1.1$ if $t_{mea} - 3 < t_{sim} < t_{mea} + 3$ and $\alpha(t) = 0.9$ otherwise. the following equation:

 $WNOE = 100.\alpha(t_{sim}).\left(\frac{X_{sim} - X_{mea}}{X_{mea}}\right)$

In this simple calculation, $t_{sim(mea)}$ is time related to the simulation outputs (measurements) (in hours), $X_{sim(mea)}$ is the 25 simulated (measured) value of maximum storm surge (in cm); $t_{sim(mea)}$ is the corresponding time (in hours); , and α is the weighting coefficient. The value of α is equal to 0.9 if the simulated maximum of storm surge is in a falls within a time window of +/- 3 h regarding h with respect to the observed peak time; if it is sooner or later, the bias is multiplied by weighting coefficient is set equal to 1.1 to reflect greater bias. For some cases, when no time information is available, no weighting is applied, and thus $\alpha = 1$. Fig. 11 presents the percentage of events regarding their WNOE value. A tendency of underestimation

30 by using ERA forcing is highlighted in comparison of forcing models with When ||WNOE|| < 20%, we consider errors to be low or moderate. Moreover, the values are evaluated regarding the number of samples (Tab. 6). First, we evaluate the impact of using wind and mean sea level pressure data from D1 or D2 atmospheric outputs. When considering extreme cases only, those instead of from ERA-x. The storm surge outputs using ERA-x forcing have a tendency to underestimate maximum storm surge compared to D1 forcing (Fig. 9, 10 and 11). Cases with low or moderate errors (say ||WNOE|| < 20%) represent respectively 18% represent a larger proportion of storm surge events when D1 data are used. In particular, 63% and 69% for ERA, D1 and

- 5 D2. Dispersion of D2 results is larger then for D1. Table 7 presents the portion of cases in the satisfactory range (*WNOE* + <20%) for each coastline and of storm surge events were associated with low and moderate error in the ATL basin, 54% for BUL and 100% for the MED domain. This represents a general improvement over the ERA-x data, which had low/moderate errors for 21% of storm surge events for ATL, 0% for cases studied with the three different forcing. Values have to be evaluated regarding the number of samples presented in BUL and 100% for the MED domain (Tab. 6. For each coastline, D1 and D2 lead</p>
- 10 to better result than with ERA. Atlantic cases are better performed with D2. The ability of D2 to simulate very deep cyclones could explained this point. 7).

A special focus is now made on the storm occurring on December Second, the D2 method is applied on two examples of storm surge reconstruction (the Atlantic 2004 and 2007 storms in France) with a corresponding statistical analysis. For the December 2004 which mostly affects the British Channel and the North Sea. Following storm, a deep low of 980 hPa which

- 15 crossed from West to East the North French coasts, the wind increased veering north-westerly on nearby seascrossed the northern French coasts from west to east, generating high waves and surge along the coastBritish Channel and the North Sea coasts due to strong northwesterly winds wrapping behind the system. The maximum surge exceeds observed surge exceeded 1 m at St Malo and Dunkirk, and fortunately under average tide, as illustrated in during a period of below-average tide (Fig. 9. During). Over the course of this event, it is clearly shown that the use of D1 forcing captures the peak the application
- 20 of ERA-Interim winds result in an underestimation of the surge in-by roughly 60 cm at St Malo and 20 cm at Dunkirk (Fig. 9)whereas ERA winds induces an underestimation. However, the use of D1 forcing successfully captures the peak of the surge by roughly 60 cm and 20 cm at in St Malo and Dunkirk, respectively. The use of D2 winds induces an overestimation of the surge of 20 cm at St Malo . At Dunkirk, the storm surge from D1 and D2 gives almost and roughly the same surge -Another as D1 at Dunkirk. The second example of storm surge hindcast is provided by the November 2007 storm. It This event
- 25 affected the whole domain of North Sea (including Dunkirk and Calais on the French coast), and slightly the East and parts of the eastern British channel. It is associated to a strong north-westerly flux was associated with a strong northwesterly wind on the North Sea and lasted nearly 24 -hours. At the peak of the storm event, a surge of 2.30 m is was recorded at Dunkirk, as illustrated in (Fig. 10. This also shows the good fit obtained by the model with the two wind forcing D1 and D2. However the ERA forcing was significantly underestimating). While the ERA-x forcing significantly underestimates the surge by 80 cm
- 30 (Fig. 10). One can see for this storm that , a good fit is obtained by the model with both the D1 and D2 data forcing. For this particular storm, the D2 winds give slightly better surge results on 11 November, 2007, at 00 UTC. These two storms are DIFdelan example examples of the various response responses of the storm surge hindcast with both types of downscaling: no significant trend could be highlighted. Overall, the dispersion of WNOE values for the D2 results is larger than for D1 (Fig. 11), and Atlantic cases are better hindcasted with D2 forcing data (Table 7). The ability of D2 to simulate very deep cyclones could
- 35 explain this point, since the mesoscale processes involved in strong wind are better described with the D2 approach.

3.4 Evaluation of early 20th century cases hindcast using ERA-20C

Twentieth The 20th century extreme events which that occurred before 1957 can be hindcast by using ERA-20C, the 20th century reanalysis ECMWF project (Poli et al., 2013). For these cases, even if there were no available wave observations, a storm surge evaluation is possible thanks to reliable sea level due to the availability of reliable sea-level observations.

- ⁵ To validate the concept of downscaling using ERA20C analyses, a focus is made ERA-20C reanalyses, we concentrated on the major storm which that occurred in the North Sea in February, 1953 (Fig. 12), which caused severe damage along the Dutch, Belgian and English coasts. Wind intensity around force 10 on the Beaufort scale (around 50 kt90 km h⁻¹) were measured in Scotland and Northern England. The winds and the low pressures atmospheric pressure combined with exceptional spring tides and equinox tides were responsible for the surge, which was exacerbated as
- 10 well by the funnel shape and shallowness of the North Seawere responsible for the surge. The Netherlands were the worst affected worst-affected, recording 1,836 deaths and widespread property damage (Gerritsen, 2005). Most of the casualties occurred in the southern province of Zeeland. Three hundred and seven people were ; an additional 307 people were reported killed in England, 19 in Scotland and 28 in Belgium . The as a result of the storm. The most striking feature along the Dutch coast was a long swell with a peak period of 20 s, which induced wave flooding. In our reconstruction of the event, the MFWAM
- 15 results using the D1 winds indicate SWH exceeding 16 m in the western part of the North Sea at 00 UTC on 1 February, 1953 (Fig. 13). The most striking fact is the long strong swell with a peak period of 20 s, which hit the Dutch coasts inducing wave flooding. The storm surge simulation shows a very storm surge hindcast produces a high surge which is very unusual for this area: in particular, along the Dutch and Belgian coastlines storm surges exceeded 3 m either with ERA-20C or D1 data forcing (Fig. 14). Fig. 15 shows the comparison of the storm surges obtained with ERA-20C and D1 forcing with observations
- 20 recorded at four locations. The improvement induces The improvement of storm surge reconstruction induced by D1 forcing was particularly marked at Ijmuiden, Ostend, Brouwershavn and Dieppewhere, where the recorded peaks of storm surge are well caught when compared to better represented than for ERA-20C (Fig. 15).

4 Conclusions

ECMWF reanalyses data are widely used for many climatological studies. However, their due to the coarse spatial resolution

- 25 and the limited access in term of time frequency of model output generate strong uncertainties temporal resolution of reanalysis model output, there is significant bias for high wind speed speeds associated with extreme mid-latitude midlatitude cyclones. To overcome this problem, dynamical downscaling techniques are implemented and applied to reproduce high resolution historical atmospheric fields. ERA-20C, ERA-40 and ERA-Interim data are used to encompass the studied period of 1924 – 2012 studied period. 2012. Very short range forecasts using 10 km resolution and hydrostatic models initialized with ERA analyses provide
- 30 downscaled MSLP and 10 m wind fields ERA-x analyses provide the downscaled data, which are used in turn to force wave and storm surge numerical models. This approach was already experimented tested for the North Sea coast for a long period using only ERA-40 -

To evaluate such a data. In order to evaluate such downscaling technique on different initial conditions, thirty cases are selected over French and Bulgarian coastlines to offer a large panel of characteristics: diverse selection of storm characteristics in terms of location, intensity, highest astronomic tide , and meteorological context. Some early 20^{th} century cases generating extreme storm surge and waves are part of this selection thanks to ERA-20C recent availability due to the recent availability

- 5 of ERA-20C. This study shows a significant and quasi-systematic improvement of wave and storm surge hindcast when using downscaled winds. The evaluation with independent wave observations (such as wave heights from altimeters) shows the strong reduction of bias and improved RMSE of significant wave height for extreme waves events. The downscaling techniques are also well-suited to-well-suited for storm surge extreme events, such as the 1953 storm, since the storm surge reconstruction using the present presented approach fits with the recorded data at from the Belgian and Dutch coasts. The D2 method, generally
- 10 leads to an improvement in comparison with D1, especially for cases with small-scale, intense, mid-latitude cyclones.
 Downscaling is a very promising technique to provide Dynamical downscaling is a promising technique for providing an accurate reconstruction of waves and storm surges for the whole 20th century. After evaluation and calibration with observa-

tions, these model outputs can be very useful to analyse the inter-annual variability of the coastal consequences of useful to analyze the interannual variability of coastal wind-storms and to improve the thresholds used in the wave submersion warning
system. Further, regional climate modelling Regional climate modelling in future studies is expected to address the response

- of wave and surge extreme variability to storm-track modifications due to global <u>climate</u> change. A further step towards this objective would be to use interactive <u>model models</u> of wave and storm surge to enhance <u>hindcast</u>. <u>Consequently, all these points</u> will open applications the hindcast. We expect that these approaches to reconstructing extreme events will prove valuable for coastal protection and risk management.
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 Table 1. List of the 30 cases selected for this study. Coast: Atl. - Med. for Atlantic and Mediterranean. Tide gauges: number of available and useful tide gauges. Storm surge (m): maximum storm surge recorded. Star is for unknown information
 Characteristics of ERA-20C, ERA-40 and ERA-Interim reanalyses. 4(3)D-Var: 4(3)-dimensional variational analysis; VarBC: Variational Bias Correction of surface pressure observations.

	ERA-20C	ERA-40	ERA-Interim
Time period	1900 - 2010	1957 – 2002	1979 – present
IFS version	Cy38r1	Cy23r4	Cy31r2
Data assimilation system	24-hour 4D-Var; VarBC	6-hour 3D-Var	12-hour 4D-Var; VarBC
Spectral resolution	T159 (~ 125 km)	T159 (\sim 125 km)	T255 (~ 80 km)
Number of vertical levels	91	60	60
Vertical scale (from the surface up to)	0.01 hPa (~ 80 km)	0.1 hPa (\sim 64 km)	0.1 hPa (\sim 64 km)
Pressure levels	37	23	37
Reference	Poli et al. (2013)	Uppala et al. (2005)	Dee et al. (2011)

Table 2. Characteristics of ERA-20C, ERA-40 and ERA-Interim reanalyses. 4(3)D-Var: 4(3)-dimensional variational analysis; VarBC: Variational Bias Correction of surface pressure observationsList of the 30 cases selected for this study. Coast: Atl. - Med. for Atlantic and Mediterranean. Tide gauges: number of available and useful tide gauges. Storm surge (m): maximum storm surge recorded. Star is for unknown information.

Coast	Date	Tide gauges	Storm surge	Downscaling	ERA-ECMWF reanalyses
Atlantic	8 Oct. 1924	*	*	D1	ERA-20C
	14 Mar. 1937	*	*	D1	ERA-20C
	31 Jan - 1 Feb. 1953	*	> 3	D1	ERA-20C
	13 Feb. 1972	10	1.83	D1	ERA-40
	30 Nov 2 Dec. 1976	12	1.36	D1	ERA-40
	11 - 13 Jan. 1978	7	1.65	D1	ERA-40
	15 - 16 Oct. 1987	12	1.72	D1	ERA-Interim
	26 Feb 1 Mar. 1990	6	1.67	D1	ERA-Interim
	2 - 4 Jan. 1998	5	1.60	D1 / D2	ERA-Interim
	6 Nov. 2000	8	1.00	D1 / D2	ERA-Interim
	17 Dec. 2004	7	1.30	D1 / D2	ERA-Interim
	9 Nov. 2007	2	2.20	D1 / D2	ERA-Interim
	10 Mar. 2008 (Johanna)	7	1.30	D1 / D2	ERA-Interim
	23 - 24 Jan. 2009 (Klaus)	10	1.29	D1	ERA-Interim
	28 Feb. 2010 (Xynthia)	8	> 1.60	D1 / D2	ERA-Interim
Mediterranean	6 Nov. 1982	*	*	D1	ERA-Interim
	6 - 7 Feb. 2009	7	0.60	D1 / D2	ERA-Interim
	24 - 25 Dec. 2009	6	0.50	D1 / D2	ERA-Interim
	19 Feb. 2010	6	0.50	D1 / D2	ERA-Interim
Atl Med.	27 Dec. 1999 (Martin)	4	1.60	D1 / D2	ERA-Interim
Bulgarian	5 - 21 Oct 1976	2	1.00	D1	ERA-40
	16 - 21 Jan. 1977	1	0.60	D1	ERA-40
	13 - 23 Feb. 1979	3	1.43	D1	ERA-Interim
	7 - 10 Jan. 1981	0	*	D1	ERA-Interim
	24 - 31 Dec. 1996	2	1.00	D1	ERA-Interim
	15 - 19 Dec. 1997	1	1.30	D1	ERA-Interim
	20 - 27 Jan. 1998	2	0.90	D1	ERA-Interim
	1 - 3 Jul. 2006	2	0.60	D1	ERA-Interim
	8 - 11 Mar. 2010	2	0.90 - 1.00	D1	ERA-Interim
	7 - 9 Feb. 2012	2	*	D1	ERA-Interim

Table 3. Outline of the numerical models required for wave and storm surge hindcasts.

Purpose	Model	Resolution	Coupling - Initial conditions data	Domain
Atmosphere	ARPEGE D1	T798 (~ 10 km)	ERA-ERA-x	global
	ARPEGE D2	T798 (~ 10 km)	ERA-ERA-x + ARPEGE	global
	ALADIN	10km	ARPEGE D1	Bulgaria
Wave	MFWAM	0.1°	ARPEGE D1/D2	Western Europe
	SWAN	0.1°	ALADIN	Bulgaria
Surge	НҮСОМ	1 km	ARPEGE D1/D2 + bathymetry	ATL
	HYCOM	1 km	ARPEGE D1/D2 + bathymetry	MED
	MF model	0.0333°	ALADIN + bathymetry	Black Sea

Table 4. Statics for MSLP from ERA-ERA-Interim reanalysis at 06 UTC 26 December 1999, 12-h forecast using the D1 and D2 at 18 UTC 25 -December 1999, versus observations at 06 UTC 26 -December 1999. Mean (hPa), standard deviation error (STD; hPa), bias (hPa), Root Mean Square Error (RMSE; hPa). Calculations are done for the nearest point. Small domain corresponds to 48° N-50° N; 2° E-4° E and includes 12 pairs of data and model values.

	Mean	STD	Bias	RMSE
Obs	973	2	_	_
ERA-ERA-Interim	993	10	12	18
D1	980	1	6	6
D2	977	1	5	5

Table 5. Comparison of SWAN wave model SWH (m) and altimeter data from ENVISAT and JASONI-Jason-1 satellites for the 2012 case over the Bulgarian coast.

Time of sate	llite track	Pairs		Mean		Biais		RMSE		Scatter Ind
			Obs	ERA-ERA-Interim	D1	ERA-ERA-Interim	D1	ERA-ERA-Interim	D1	ERA-ERA-Interin
7 Feb. 2012	08 UTC	44	3.9	3.5	4.1	-0.43	0.21	0.60	0.37	0.15
	14 UTC	76	3.6	3.2	3.8	-0.41	0.15	0.66	0.57	0.18
	20 UTC	51	6.4	5.3	6.3	-1.08	-0.09	1.14	0.37	0.18
8 Feb. 2012	14 UTC	43	5.6	4.4	4.7	-1.22	-0.94	1.37	1.16	0.24

	ERA-ERA-x	D1	D2
ATL	34	34	15
MED	13	13	13
BUL	9	9	0

Table 6. Portion of cases (%) with ||WNOE|| < 20% for each coast (ATL: Atlantic; MED: Mediterranean Sea; BUL: Bulgarian; commoncases: cases using D1 and D2 forcing)Number of observations used for calculations of WNOE for each region and each forcing.

Table 7. Number of observations used for calculations of WNOE for each region and each forcing.Portion of cases (%) with ||WNOE||< 20% for each coast (ATL: Atlantic; MED: Mediterranean Sea; BUL: Bulgarian; common cases: cases using D1 and D2 forcing).</td>

	ERA-ERA-x	D1	D2
ATL	21	63	80
MED	0	54	38
BUL	33	100	_
Common cases	18	64	61



Figure 1. Schematic representation of D1 and D2 techniques. Energy spectra are within small stamps. The red part of forecast are the forecast data used as input forcing in the wave and storm surge models.



Figure 2. Locations of EURAT01 (black), ATL (blue), MED (green) and BUL (red) domains used in the study, respectively for European 0.1° resolution grid and Atlantic, Mediterranean and Bulgarian domains.



Figure 3. Mean-sea level pressure (hPa) from observations (a) and ERA-Interim reanalysis at 06 UTC 26 -December 1999 (b), from 12-h forecast using the D1 (c) and D2 (d) downscaling methods at 18 UTC 25 December 1999.



Figure 4. Scatter plots of significant wave heights (SWH) of model MFWAM and altimeters (ENVISAT et and Jason-1) for the 2004, 2007, 2008 and 2010 French storms. (a) and (b) stand for runs with interpolated ERA-ERA-interim and D1 wind forcing, respectively.



Figure 5. Variation of the bias (a) and the normalized root mean square error (NRMSE; b) of significant wave heights from the model MFWAM in comparison with the altimeters (ENVISAT et Jason-1) for the 2004, 2007, 2008 and 2010 French storms. Purple, green and blue colors stand for ERA, D1 and D2 forcing, respectively. Comparison of the simulated significant wave heights (SWH) with downscaled wind input and ERAERA-Interimwind input with the data from the ENVISAT track crossing the Western Black Sea at 20 UTC on 7 February, 2012. Purple and green colors stand for ERA and D1 forcing, respectively. Red line stands for ENVISAT observations.



Figure 6. Comparison of the simulated significant wave heights using the two wind inputs (downscaled wind input D1 and ERA-Interim) with the data by ADCP located in on the Western western Black Sea coast at 20 m depth, during the storm of 7-8 February 2012. ADCP location coordinates: $43^{\circ}04'49.1349''$ N - $28^{\circ}01'39.6340''$ E. Purple and green colors stand for ERA-ERA-Interim and D1 forcing, respectively. Red The red line stands for ACDP represents the ADCP observations.



Figure 7. Comparison of the simulated significant wave heights with downsealed wind input and ERA wind input with the data from the ENVISAT track crossing the Western Black Sea at 20 UTC 7 February 2012. Purple and green colors stand for ERA and D1 foreing, respectively. Red line stands for ENVISAT observationsTime series of significant wave heights (SWH) for the storm on February 2010 atNice location (43.4° N and 7.8° E43°24'0" N - 7°48'0" E) in the Mediterranean sea. Purple and green colors stand for ERAERA-Interim and D1 forcing, respectively. Red line stands for Nice buoy observationsThe red line shows the time series of theNice buoy observations.







Figure 9. Percentage of cases depending of their *WNOE* range when using ERA (purple), D1 (green) or D2 (blue) forcing. All the available observations with a maximum storm surge measurement are taken into account. Storm surges (cm) at St Malo (a) and Dunkirk (b) from 14 December 2004, at 15 UTC to 19 December, 2004, at 06 UTC. The measured surge (red line), the reconstructed surge by using the ERA forcing (purple line), the D1 forcing (green line) and the D2 forcing (blue line) are superimposed. The little-oscillatory dotted line in the lower part of the graph is used to indicate the time of high and low tides.



Figure 10. Storm surges (cm) at <u>St Malo (a) and</u> Dunkirk (b) from <u>14 December 2004 at 15 UTC to 19 December 20047 November, 2007, at 15 UTC to 11 November, 2007, at 06 UTC. The measured surge (red-line), the reconstructed surge by using the <u>ERAERA-Interimforcing</u> (purple), the D1 forcing (green-line) and the D2 forcing (blue-line) are superimposed. The <u>little</u> oscillatory dotted line in the lower part of the graph is used to indicate the time of high and low tides.</u>



Figure 11. Storm surges (cm) at Dunkirk from 7 November 2007 at 15 UTC to 11 November 2007 at 06 UTC. The measured surge (red), the reconstructed surge by using the ERA forcing (purple), the D1 forcing (green) and the D2 forcing (blue) are superimposed. The little oscillatory dotted line in the lower part of the graph is used to indicate the time of high and low tides.Percentage <u>The percentage</u> of cases depending of their *WNOE* range when using ERA-x (purple), D1 (green) or D2 (blue) forcing. All the available observations with a maximum storm surge measurement are taken into account.



Figure 12. Surface pressure chart (hPa) at 06 UTC on 1 February, 1953. From hhtp://www.metoffice.gov.uk



(a) Significant wave heights with D1 forcing

(b) Peak wave period with D1 forcing

Figure 13. Significant wave heights (m; a) and peak wave period (s; b) from the wave model MFWAM with D1 winds outputs on the peak of the storm at 00 UTC-<u>1 February 1953 on 1 February 1953</u>. Mean Wave Direction is shown with black arrows in (a) when significant wave height are greater than 1.5 m.



Figure 14. <u>Highest The highest simulated storm surges (cm) obtained for the period from 30 January to 2 February</u>, 1953, with the ERA-20C forcing (a) and with the D1 forcing (b) along the southern <u>part of the</u> North Sea coast.





(d) Dieppe

Figure 15. Storm The storm surges (cm) at Ijmuiden, Netherland (Netherlands; a), Ostend(, Belgium; (b), Brouwershavn(, Netherlands; (c) and Dieppe(, France; (d) from 18 UTC on 30 January to 18 UTC on 2 February, 1953. Two surges are represented: those resulting of foreing with from ERA-20C forcing (purple) and with from the D1 outputs (green). The maximum observed storm surge is added (horizontal plain black line). The tide level is indicated by the dashed black line (at a reduced scale).