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Natural Hazards and Earth System Sciences
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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 in coastal areas. The FP7 IncREO project aims to understand the impact of climate change on coastal areas and also to assess the predictability of such extreme events. Reproduce efficiently past events is the fisrt step to reach this purpose. This paper shows the use of atmospheric downscaling techniques in order to improve waves and storm surge hindcasts. Past storms which caused damages on European coastal areas are investigated using atmosphere, wave and storm surge numerical models and downscaling techniques are based on existing ECMWF reanalyses. The results show clearly that the 10 km resolution wind forcing provided by the downscaled atmospheric model gives better waves and surges hindcast against using wind from the reanalysis. Furthermore, the analysis of the most extreme mid-latitude cyclones indicates that a 4D blending approach improves the whole process as it includes small scale processes in the initial conditions.

1 Introduction

One of the most vulnerable areas affected by winter storms are coastal regions as their soil are often eroded and they are also densely populated (Barredo, 2007; Clarke and Rendell, 2009; Ferreira et al., 2009; Ciavola et al., 2011; André et al., 2013). Such events are frequently responsible for severe damages, huge economic losses and many casualties. Storm surges can reach 250 cm along the Atlantic coasts (Marcos et al., 2009). The Western Black Sea coast is also vulnerable to high storm surge and highest surge ever recorded in the Black Sea reached 150 cm (Ryabinin et al., 1996). Most winter storms that affect western Europe are associated with mid-latitude cyclones that originate in the Atlantic ocean (Klawa and Ulbrich, 2003; Della-Marta et al., 2009; Usbeck et al., 2010), whereas the Bulgarian coasts are beset by cyclones whose origin lies in the Mediterranean. Intense storms in conjunction with high winds generate high and powerful swells, which, associated with high tides, have disastrous consequences. Furthermore, the cumulative effects of deep low pressures, dynamical action of winds and spring tides lead to a strong rise of sea level causing coastal flooding. This kind of combination occurred during the Xynthia storm

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which hit the western part of the French coast on February, 27^{th} 2010. Hence, meteorological services must improve timely waves and storm surges warning systems to ensure the delivery of reliable off shore and near the coasts safety bulletins.

A better knowledge of the variability of these events is of primary interest and the trends in the frame of global change are thus critical as well. Some studies already investigate the consequences of climate change on storm surge and sea level rise. Among others, Woth et al. (2006) used an ensemble of atmospheric regional simulations to analyse the present and future climate over the North Sea. They highlighted a potential increase of North Sea storm surge extremes. Lozano et al. (2004) worked on North-Atlantic coasts and pointed out a trend to fewer but more intense storms. Similar study for the Black Sea (Kislov et al., 2016) pointed out that under RCP8.5 scenario the storm frequency in the Black Sea will increase but that does not necessarily mean a change in the storms intensity. Moreover some papers focused on assessment and economic consequences of these trends (*i.e.* Hallegatte et al., 2011; Pinto et al., 2012). The Increasing Resilience through Earth Observation (IncREO) project funded by the Seventh Research Framework Programme (FP7) of the European Union was designed to address the same issue. The project has brought together Earth observation data gathered through the European Union's programme Copernicus, which makes it available to emergency planning services and disaster management missions. One major component of the project is the mapping of the coastal vulnerability using a series of wave and surge extreme events.

Due to the lack of long-term wave records based on in-situ measurements and surge archives for the whole 20^{th} century, it is necessary to reconstruct these data using numerical models. Waves and surge hindcasts are driven by 10-m surface winds provided by the atmospheric model. A straightforward approach consists in using global reanalyses to study historical extreme storms. However, such winds are not fully resolved and have a coarse resolution which is not suited to extreme convective systems generating very high winds. Therefore downscaling strategies have been implemented in order to provide better wind forcing at a 10 km resolution. The technique is based on an interpolation of the data from a low resolution grid into a higher one, taking or not into account small-scales informations, followed by short-term forecasts. This study aims to develop a downscaling method and evaluate the impact on high waves and storm surges along the Bulgarian and French coasts during past extreme events. Consequently this will improve our sampling of extremes that occurred in the past. The numerical suite is based on reanalyses provided by the European Centre for Medium-Range Weather Forecasts (ECMWF; Dee et al., 2011; Poli et al., 2013; Stickler et al., 2014) and dynamical downscaling in order to fully resolve the horizontal scales involved in the mid-latitude cyclone development process (e.g. Reistad et al., 2011; Li et al., 2016). Waves and surge models are then run using both the interpolated reanalyses and the obtained downscaled meteorological fields.

The paper is organized as follows. Section 2 describes the methodology and data used for the downscaling strategies. Section 3 gives a short description of wave and surge models configurations. Section 4 discusses the results and the validation with wave observations and tide gauges. Finally section 5 summarizes the concluding remarks.

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2 Methodology and data

Atmospheric forcing plays a key role to ensure an accurate waves and surge hindcasts. It is then needed to generate the best wind conditions in order to run models for historical storms. The downscaling technique is a good candidate to fulfil this condition. This process is applied on ECMWF reanalyses. Hereafter more details on the process are given.

2.1 Downscaling methodology

With their coarse resolution (larger than 80 km), reanalyses did not fully resolve the windstorms. Two downscaling strategies aiming at providing forcing conditions at 10 km resolution for atmospheric models are suggested.

The first downscaling method (hereafter referred to as D1) consists in using reanalyses interpolated from the native truncation (here about 125 km or 80 km) to T798 (about 10 km) as initial conditions. 12-hour atmospheric model runs are performed using these initial conditions.

A more elaborate downscaling method (hereafter referred to as D2) was deemed necessary as the first method gave no information to wavelengths matching the reanalysis truncation. Furthermore it was noted that, after a short period of time (3 hours), non-linearities triggered small scales which were consistent with the large scale. As a mean of improvement, it was decided to use this small scale information provided by the 6-hour forecast and to blend it with the large scale given by the interpolated reanalysis (Fig. 1). This procedure was cycled 4 times. Therefore, the determination of one single initial condition uses 4 reanalyses and is then, in some sense, 4-dimensional.

2.2 Reanalyses

A meteorological reanalysis is the result of assimilating historical observations in an analyse produced by an atmospheric numerical model. ECMWF has been producing global atmospheric reanalyses (ERA) for several years. They are used as initial conditions for some wave and storm surge hindcasts simulations and also with fine mesh atmospheric models for the downscaled approach described previously. These reanalyses have evolved with time and several versions of them are available for different periods. A quick description is presented hereafter.

The ERA-40 reanalysis considers a 45-year period from 1 September 1957 to 31 August 2002 (Uppala et al., 2005). It was produced using the June 2001 version of the ECMWF Integrated Forecast Model (IFS Cy28r3). The spectral resolution is T159 (about 125 km) and there are 60 vertical levels, with the model top at 0.1 hPa (about 64 km). Observations are assimilated using a 6-hourly 3D variational analysis (3D-Var). Satellite data which were used include Vertical Temperature Profile Radiometer radiances which started in 1972, followed by TOVS, SSM/I, ERS and ATOVS data. Cloud Motion Winds are used from 1979 onwards.

ERA-Interim was originally planned as an ’interim’ reanalysis in preparation for the next-generation extended reanalysis intended to replace ERA-40 (Dee et al., 2011). It uses the December 2006 version of the ECMWF Integrated Forecast Model (IFS Cy31r2). It initially covered dates from 1 January 1989 but an additional decade, from 1 January 1979, was added later. ERA-Interim can still be considered as a reference dataset. The spectral resolution is T255 (about 80 km) and there are 60 vertical levels, with the model top at 0.1 hPa (about 64 km). The data assimilation system is based on a 12-hourly four-dimensional variational analysis (4D-Var) to which was added an adaptive estimation of satellite radiance biases (VarBC).

ERA-20C produces a global atmospheric reanalysis of the atmosphere, land, and ocean waves from 1900 to 2010 (Poli et al., 2013). It employs the ECMWF model and data assimilation system at a 125 km global resolution with 91 vertical levels extending from the surface up to 0.01 hPa (approximately 80 km). The assimilated dataset consists of surface pressure and marine wind observations, including many observations provided by ERA-Clim data rescue activities. For the most recent period, data denial is applied to homogenize the system.

For each storm studied, the most recent available version of ERA reanalyses was selected for downscaling procedures. As a consequence, ERA-Interim was used for cases after 1979, ERA-40 for the 1958 to 1979 cases and ERA-20C for oldest storms.

3 Description of models

Three types of numerical models are required for this study: atmospheric, wave and storm surge numerical models. The first one provides forcing conditions to the other two. Different models are used with respect to the area of interest to consider the more appropriate combination of models. The models characteristics are described hereafter and listed in Table 1.

3.1 NWP models

ARPEGE (Action de Recherche Petite Echelle Grande Echelle; Courtier et al., 1991) is the operational global primitive-equation numerical weather prediction (NWP) system used at Météo-France and based on the ARPEGE-IFS software developed in collaboration with ECMWF. The version used here has 70 hybrid vertical levels between 17 m and about 70 km. A stretched grid allows a finer horizontal resolution over France (around 10 km) with a coarser one at the antipodes (60 km). The model is initialized with the best available reanalysis, namely ERA-40 and ERA-Interim for the most recent cases and ERA-20C for the 1930th and 1950th cases.

Over western Europe, it makes sense to couple wave and surge models with atmospheric forcing predicted using this configuration. However, over Bulgaria, the ARPEGE grid is too coarse and requires further downscaling. ALADIN (Aire Limitée, Adaptation dynamique, Développement InterNational), a limited-area model based on the ARPEGE system (Radnóti et al., 1995) is used for that purpose. To be consistent with Western Europe simulation we run ALADIN over Bulgaria and the Black Sea at a 10 km resolution using ARPEGE lateral boundary conditions.

Since we run models using initial conditions built from a different system, the first six hours are not taken into account to prevent model spin up. Only +06 h to +12 h forecast ranges are kept for the wave and surge model forcing.

3.2 Wave models

Two domains were set to evaluate the impact of using downscaled winds on waves and surge hindcasts. The first domain is set for the Western European coasts and the wave MFWAM model was implemented to examine events coming from the North

Atlantic, North Sea and the Mediterranean Sea. While the second domain is set for the Black Sea and the wave SWAN model is implemented to investigate extreme events.

The MFWAM model is a third-generation model of the operational wave forecasting system of Météo-France. This model is based on the ECWAM code (IFS-CY36R4) 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 and a direction-dependent part that controls the directional spread of the resulting wave spectra. It includes a cumulative effect describing the smoothing of big breakers on small breakers. The term also uses a wave turbulence interaction part, which is weak as indicated in Ardhuin et al. (2010). The MFWAM model uses a quadruplet non linear interaction term based on the discrete interactions approximation as indicated in the ECWAM model. In this study, a nested MFWAM model is implemented with a grid size of 0.1° for western European seas including the Mediterranean Sea. The domain boundaries are 20° N-72° N, 32° W-42° E for latitude and longitude, respectively. 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 winds reanalyses.

The SWAN (Simulating Waves Nearshore; Booij et al., 1999) model is used for Bulgarian cases. It is a third-generation wave model that is especially designed to simulate waves in near shore waters and is very often applied to enclosed and semi-enclosed seas, estuaries and lakes. 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-capping, bottom friction and depth-induced breaking. The model performance, the parameterizations of the wave generation and dissipation processes and other aspects of SWAN applied to the Black Sea have been studied by Akpinar et al. (2012); Arkhipkin et al. (2014); Rusu et al. (2014). The model domain, BUL, that is used for the simulations of 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; 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 is based on Hasselmann (1974) with the δ coefficient (which determines the dependency of white-capping on wave number) set to 1 (according to the study by Rogers et al., 2003). This specific set of parameterizations was chosen to have the lowest bias, root mean square error (RMSE) and scatter index when comparing results from the model and the along-track satellite altimetry data.

3.3 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 (Bleck, 2002; Baraille and Filato, 1995). The HYCOM code is managed by an international consortium: 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: ATL and MED (Fig. 2). ATL corresponds to the North-East Atlantic (Bay of Biscay, English Channel and North Sea), from 9° W to 10° E and from 43° N to 62° N; MED defines the Mediterranean Sea domain, from 9° W to 37° E and from 30° N to 46° N; with a grid size of around 1 km on the French coast (curvilinear grid). The tides are computed thanks to 17 harmonic components from NEA Optimal 2011 (Laboratoire d'études en géophysique et océanographie spatiales; LEGOS) imposed at the marine boundaries; the bottom friction coefficient is spatially variable and has been optimized to properly reproduce the propagation of tides. Tides are discarded in the storm surge computation, and another computation of the tides, based in harmonic components obtained from measurements by SHOM, is added to the storm surge in order to know the sea level with more accuracy, at specific locations. The bottom friction coefficient is constant and taken 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 the Black Sea by Mungov and Daniel (2000). 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 covers the entire Black Sea. The bottom friction coefficient is 1.5 10^{-3} over the shelf and 1.5 10^{-5} over the liquid bottom. 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). 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 models for the Black Sea would fail to simulate any surge even if very strong, constant winds were used as an input. The bathymetry data for the storm surge model (and the wave model) are obtained by digitalization of proprietary maps provided by the Bulgarian military hydrographic service.

4 Results

4.1 Evaluation of D1 and D2 on meteorological fields

Fig. 3 shows the comparaison of the downscaling strategies applied to an extreme cyclogenesis event, Lothar storm. This storm occurred a few hours before the Martin storm in December 1999 and it is the most extreme storm in terms of pressure gradient, surface wind and displacement velocity to hit France to this day (Wernli et al., 2002; Rivière et al., 2010). D1 improves the ERA-Interim reanalysis fields but D2 better reproduces the weak cyclone over Northern France than D1 and the ERA reanalysis. Given the size of the simulation area and the small area affected by this storm, statistics were performed with the 12 meteorological stations available on a domain including the area of the weak depression (48° N-50° N; 2° E-4° E). Table 2 shows that downscaling is noticeably better than using an ERA-Interim reanalysis in regard to surface observations. Also highlighted, the slight improvement of results by the use of D2.

The use of D1 generally allows a better agreement between simulated meteorological fields and surface observations in terms of mean sea level pressure and 10-m wind for the French and Bulgarian coasts. Nevertheless, the use of D2 leads to slightly better results than that of D1, with, most of the time, stronger surface winds and deeper cyclones.

4.2 Impact of D1 and D2 on waves and surge hindcasts

NWP models with downscaling provide wind forcing at the ocean surface with a satisfactory fine resolution which enable the investigation of the features of main waves, especially in coastal areas. To evaluate the impact of downscaled winds on waves and surge hindcasts, we firstly use the ALADIN model (Bulgarian cases) to compare D1 winds and ERA reanalyses. Then, we use the ARPEGE model (French cases) to compare D1 winds and ERA reanalyses. Thirdly, we investigated whether the use of D2 winds versus D1 was more efficient. In the following subsections, results for some specific cases are presented before more general conclusions.

4.2.1 Validation of Bulgarian cases

Wave hindcasts are evaluated by using all the available data, such as in-situ observations and satellite altimeter data. The subsection is devoted to one single event. The wave model is validated by comparing the output for the significant wave height with along-track data measured by the Jason-1 and ENVISAT satellite altimeters on 7 and 8 February 2012. Statistics show that the use of D1 forcing improves hindcasts (Table 3). The highest waves, obtained with 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, the SWAN model output, in terms of significant wave height, was compared with in-situ wave measurements by ADCP (Acoustic Dopler current Profiler) located at Pasha Dere beach. The data was provided by the Bulgarian Institute of Oceanology (Valchev et al., 2014). Fig. 4 presents a comparison of the wave measurements with the SWAN model outputs, obtained using the two wind inputs as an atmospheric forcing. Clearly the use of D1 slightly overestimates the measured wave heights. The use of ERA-Interim underestimates significantly modeled values of significant wave height, while the use of D1 winds leads to better matching of the simulated and measured wave heights. The SWAN model output was also compared to the satellite altimetry 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 the number of data points was limited this was the only opportunity to evaluate the model. For the Black Sea, the occurrence of a storm case when more than one satellite track crosses the area with the highest waves seldom happens. The results of the comparison of the significant wave heights simulations with the ENVISAT satellite altimetry along-track data are presented in Table 3 and Fig. 5. The conclusion is that 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 storm.

For the eight storms along the Bulgarian coasts with surge measurements, no obvious evidence is highlighted regarding using ERA or D1 forcing for surges hindcasts. Indeed, with D1 forcing, surges are usually higher than with ERA forcing. For example, for the 1997 storm, with an observed maximum of 1.30 m surge hindcast with D1 forcing is closer to observations with with ERA forcing (Fig. 11). In the other hand, surge hindcast for the 1996 storm lead to similar results with both forcings (not shown).

4.2.2 Validation of French cases

Runs of the MFWAM model are performed with interpolated reanalyses and D1 winds for historical storms. The validation of the results is mostly based on significant wave height (SWH) provided by the satellite altimeters available during the storms. The model wave heights are collocated with the altimeters tracks with a time window of 3 hours. For 2004, 2007, 2008 and 2010 storms, data are collected from three altimeters: Jason-1, Envisat and Jason-2. Fig. 7 shows the scatter plots between model and altimeters wave heights. This clearly indicates that the use of D1 winds induces a better fit with a strong reduction of normalized root mean square error (NRMSE) from 17.1 to 13.1%. The bias is also significantly reduced from -35 to -4 cm. The best performance of the MFWAM model with D1 winds is obtained for the 2008 storm, where the NRMSE of significant wave heights is significantly reduced from 15.9 to 11.8%, as illustrated in Fig. 8. For the 1998, 1999 and 2000 storms, altimeters wave heights from Topex and ERS2 are collected for the validation of the results. The same tendency is found with a strong decrease of NRMSE of significant wave heights from 16.2 to 14.1 %, and the bias is well reduced from -32 to 10 cm (not shown). Comparisons between model and buoys significant wave heights were also performed for more recent storms. Fig. 9 shows time series of significant wave heights from model and buoys at the peak of the storm on February 2010 at Nice (43.4° N and 7.8° E) on the coast of the Mediterranean Sea. This indicates the good fit on significant wave height induced by using D1 winds in regard to interpolated ERA winds.

A network of 25 tide gauges around the French coasts is maintained to validate surge model implemented at Météo-France. In this study particular attention is taken for the storm happened on December 2004 which affects mostly the British Channel and the North Sea. Following a deep low of 980 hPa which crossed from West to East the North French coasts, the wind increased veering north-westerly on nearby seas, generating high waves and surge along the coast. The maximum surge exceeds 1 m at St Malo and Dunkerque, and fortunately under average tide, as illustrated in Fig. 10. During this event it is clearly shown that the use of downscaled ARPEGE forcing catch perfectly the peak of the surge in St Malo and Dunkerque (Fig. 10). While the use of ERA winds induces an underestimation of the surge by roughly 60 cm and 20cm at St Malo and Dunkerque, respectively.

Using D1 instead of ERA forcing mainly improves wave hindcasts, even if for the 1998 storm it leads to an overestimation of significant wave heights. For storm surge hindcasts, it has a positive impact on the quality of the storm surges simulations, but at various degrees.

4.2.3 Impact of D2 forcing

To find out how the D2 impact the storm surge and waves hindcasts, additional runs with D2 wind forcing were performed for selected storms where altimeters and tides gauges data were available (Tab. 4).

Fig. 8 shows histograms of biases and NRMSEs of significant wave heights from runs with D1, D2 and interpolated ERA winds for the considered storms. The statistical analysis reveals that the use of D2 winds leads to better results than the use of interpolated ERA winds. Biases of significant wave heights are slightly better improved using D2 winds rather than when using

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D1 winds. However D2 winds slightly increases the NRMSE of significant wave height for the 2004, 2007 and 2008 storms. Only for the storm Xynthia of 2010, the D2 winds improves slightly the NRMSE of significant wave height. The validation with altimeters did not show clearly a gain from using the advanced D2 technique against the simpler D1. It seems that the advanced D2 is better skilled for higher winds such as the Lothar storm.

For December 2004 storm, Fig. 10 indicates that the use of D2 winds induces an overestimation of the surge of 20 cm at St Malo. However at Dunkerque the storm surge from D1 and D2 gives almost the same surge. November 2007 storm affected the whole domain of North Sea (Dunkerque and Calais on the French coast), and slightly the East British channel. It is associated to a strong north-westerly flux on the North Sea and lasted near 24 hours. At the peak of the storm event a surge of 2.30 m is recorded at Dunkerque, as illustrated in Fig. 11. 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 the surge by 80 cm (Fig. 11). One can see for this storm that D2 winds give slightly better surge on 11 November 2007 at 00 UTC. These two storms are an example of the various response of the storm surge hindcast with both types of downscaling: no significative trend could be highlighted.

4.3 Historical case hindcast using ERA-20C

ERA-20C reanalyses were just available at the beginning of the study. They allow to examine extreme events which occurred during the last century by using them to initialize the downscaled technique. Consequently, the response of wave and storm surge models to the use of issued winds have been then analysed. Here, focus is put on the major storm which occurred in the North Sea in February 1953 (Fig. 12), which caused severe damages to the Dutch, Belgian and English coasts. Wind intensity around force 10 on the Beaufort scale (around 50 kt) were reported in Scotland and Northern England. The winds and the low pressures combined with exceptional spring tides and the funnel shape and shallowness of the North Sea were responsible for the surge. The Netherlands was worst affected, recording 1,836 deaths and widespread property damage (Gerritsen, 2005). Most of the casualties occurred in the southern province of Zeeland. 307 people were killed in England, 19 in Scotland and 28 in Belgium.

The MFWAM results using the D1 winds indicated significant wave heights 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 powerful swell with a peak period of 20 s, which hit the Dutch coasts inducing wave flooding. The storm surge simulation showed a very high surge which was very unusual for this area: along the Dutch and Belgian coastlines storm surges exceeded 3 m (Fig. 14). This reveals clearly that when using the D1 forcing, storm surge is significantly higher than when using the ERA-20C. Fig. 15 shows the comparison of the storm surges obtained with ERA-20C and D1 forcings with observations recorded at four locations. The improvement induced by D1 forcing particularly marked at Ijmuiden, Ostend, Brouwershavn and Dieppe where recorded peaks of storm surge are well caught when compared to ERA-20C.

For these cases, there were no available wave observations needed for the validation. However it seems that the use of the D1 winds reduces the overestimation of wave parameters obtained from the model runs with ERA winds. Finally, the interest of the D1 forcing to better simulate the storm surges appears clearly but it is not systematic: it is necessary to validate the quality of the downscaling before using it as forcing in the storm surge models.

5 Conclusions

ECMWF reanalyses are widely used for many climate applications. However, its coarse spatial and temporal resolution generates strong uncertainties for high wind features associated to extreme mid-latitude cyclones. To overcome this problem, dynamical downscaling techniques have been implemented and applied to reproduce high resolution historical atmospheric fields for coastal areas of France and Bulgaria. The ECMWF ERA reanalysis of wind at 10 m and mean sea level pressure were downscaled using 10 km NWP models to force wave and storm surge numerical models.

This study shows a significant improvement of wave and storm surge hindcasts when using downscaled winds for both French and Bulgarian coasts. The validation with independent wave observations such as wave heights from altimeters has indicated the strong reduction of bias and improved RMSE of significant wave height for extreme waves events during the past 20 years. The study has shown that the chosen downscaling technique was well suited to storm surge extreme events, such as the 1953 storm and also clearly demonstrated the good fit of storm surge with recorded data at the Belgian and Dutch coasts. The advanced downscaling method, D2, generally led to an improvement, especially for cases with small-scale, intense, mid-latitude cyclones.

Among the perspectives of this work, because of lack of tide gauges during past events, the use of a downscaled technique with ERA-20C will be efficient and very helpful way to build up a data base of storm surges. Consequently this will open applications for coastal protection and risks management.

Downscaling is a very promising technique to provide an accurate reanalysis of waves and storm surges for the 20th century. After validation and calibration with observations, these model outputs can be very useful to give trends for wave climate and improve the thresholds used in the wave submersion warning system. Further, regional climate modelling is expected to address the response of wave and surge extreme variability to the global change.

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Table 1. Outline of the numerical models required for wave and storm surge hindcasts.

Purpose	Model	Resolution	Coupling - Initial conditions data	Domain
Atmosphere	ARPEGE D1	T 798	ERA	global
	ARPEGE D2	T 798	ERA + ARPEGE	global
	ALADIN	10km	ARPEGE D1	Bulgaria
Wave	MFWAM	0.1°	ARPEGE D1/D2	Western Europe
	SWAN	0.1°	ALADIN	Bulgaria
Surge	HYCOM	1 km	ARPEGE D1/D2 + bathymetry	ATL
	HYCOM	1 km	ARPEGE D1/D2 + bathymetry	MED
	HYCOM	0.0333°	ALADIN + bathymetry	Black Sea

Table 2. Statics for MSLP from ERA 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 (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	993	10	12	18
D1	980	1	6	6
D2	977	1	5	5

Table 3. Comparison of SWAN wave model SWH (m) and altimeter data from ENVISAT and JASON1 satellites for the 2012 case over Bulgarian coast.

Time of satellite track		Pairs	Mean			Biais		RMSE		Scatter Index	
			Obs	ERA	D1	ERA	D1	ERA	D1	ERA	D1
7 Feb. 2012	08 UTC	44	3.9	3.5	4.1	-0.43	0.21	0.60	0.37	0.15	0.10
	14 UTC	76	3.6	3.2	3.8	-0.41	0.15	0.66	0.57	0.18	0.16
	20 UTC	51	6.4	5.3	6.3	-1.08	-0.09	1.14	0.37	0.18	0.06
8 Feb. 2012	14 UTC	43	5.6	4.4	4.7	-1.22	-0.94	1.37	1.16	0.24	0.21

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Table 4. 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.

Coast	Date	Tide gauges	Storm surge	Downscaling method	ERA 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

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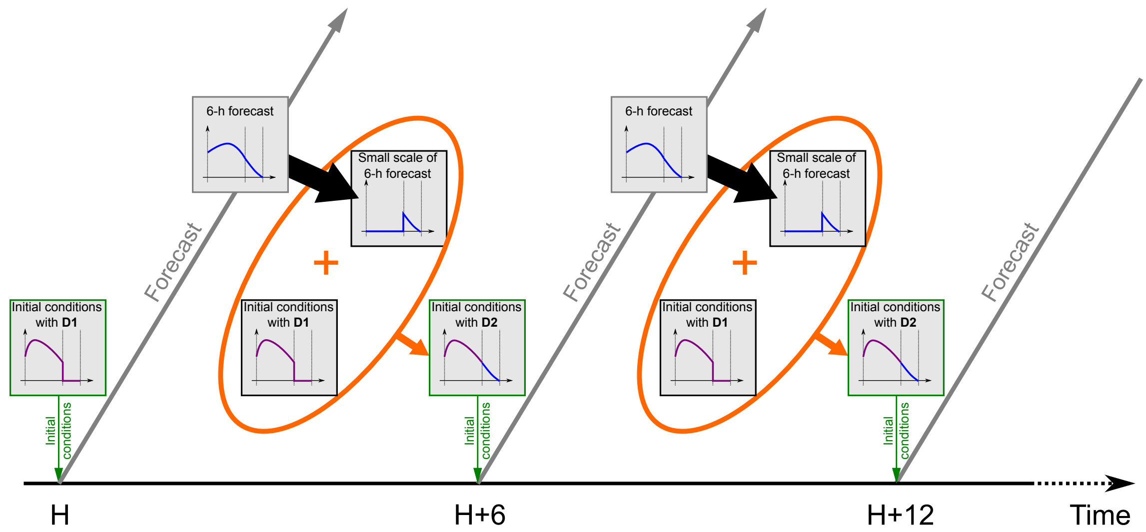

Figure 1. Schematic representation of the production of the new initial file used for the more elaborate downscaling. Energy spectra are within small stamps.

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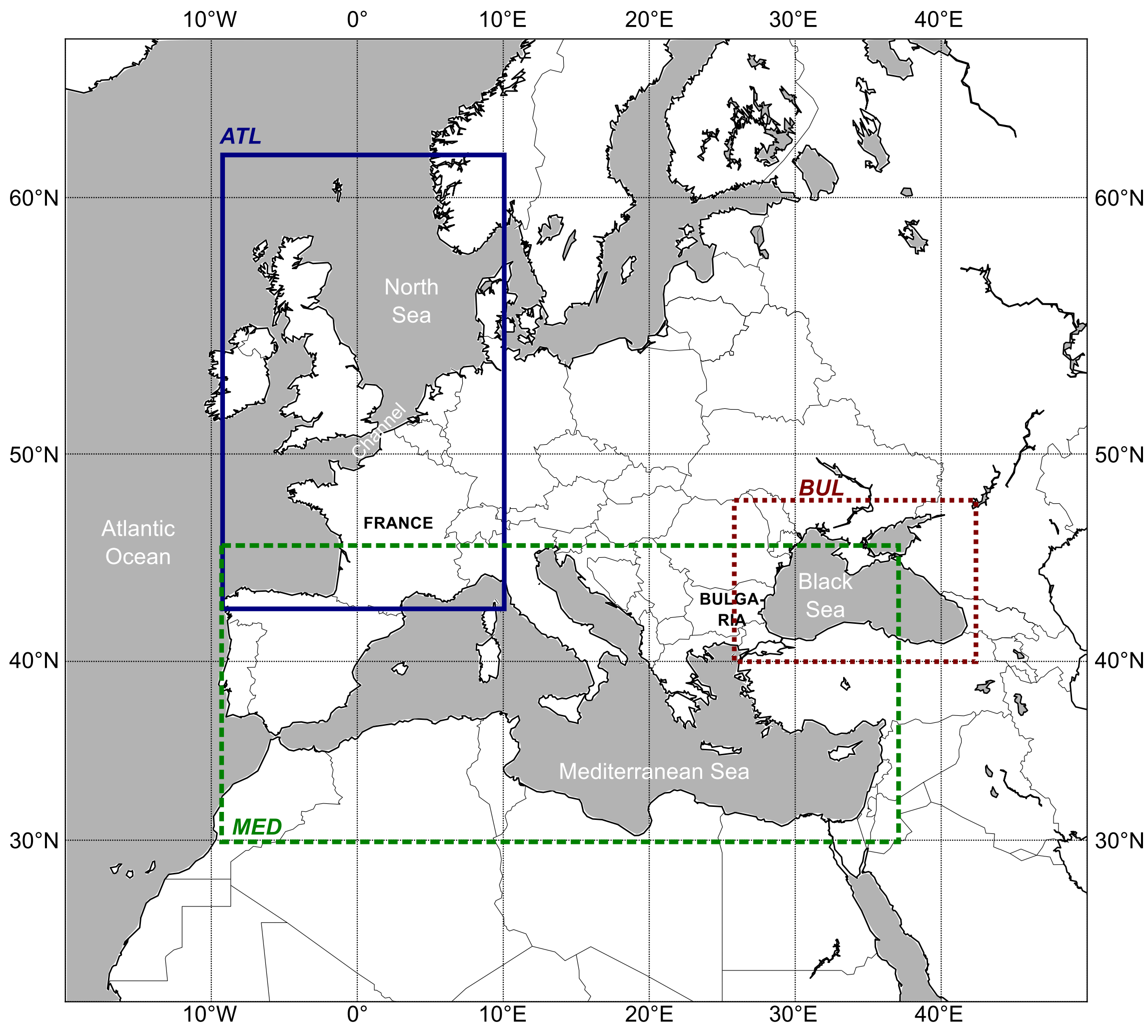
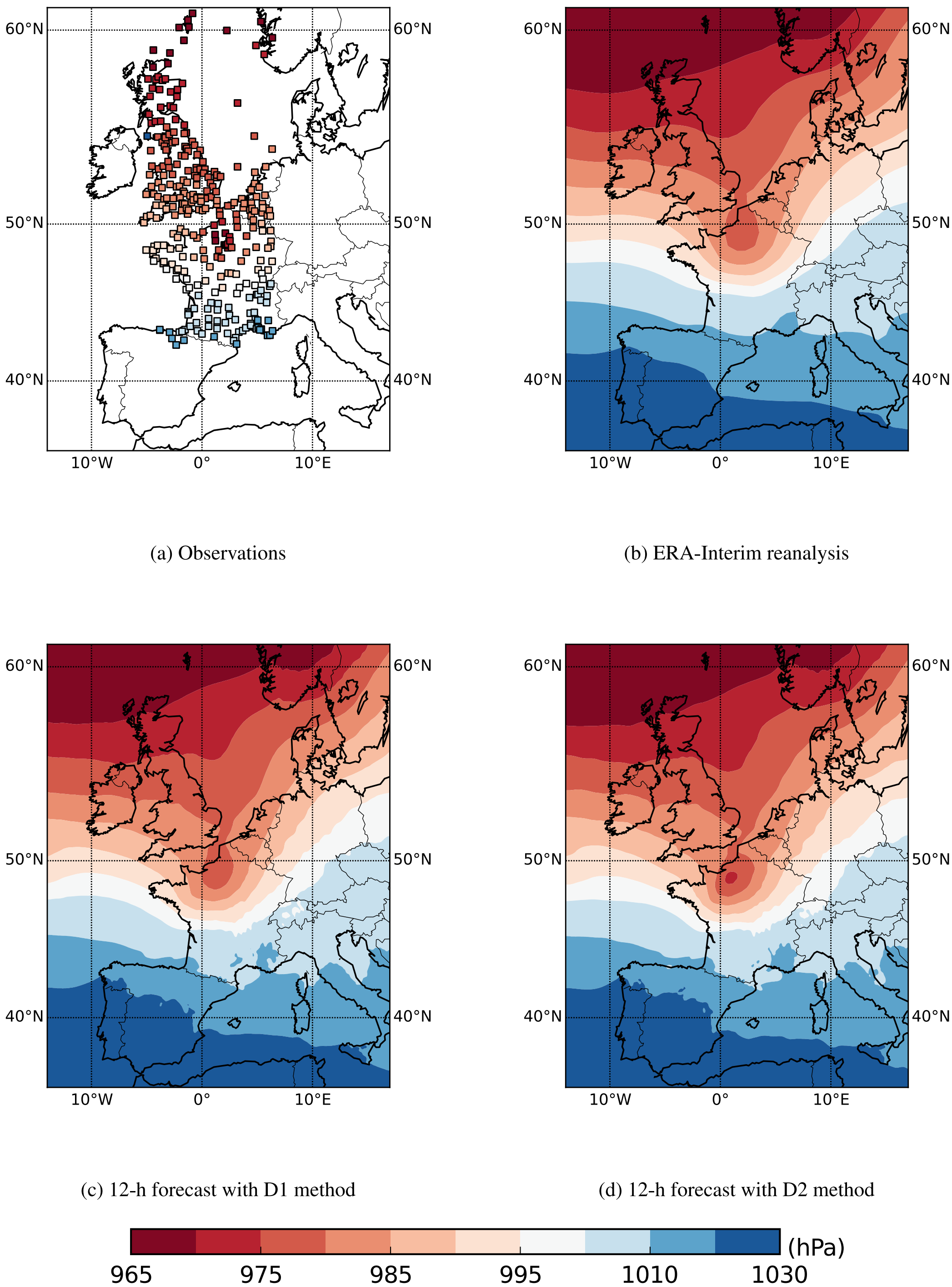


Figure 2. Locations of ATL (blue), MED (green) and BUL (red) domains used in the study, respectively for Atlantic, Mediteranean and Bulgarian domains.



(a) Observations

(b) ERA-Interim reanalysis

(c) 12-h forecast with D1 method

(d) 12-h forecast with D2 method

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.

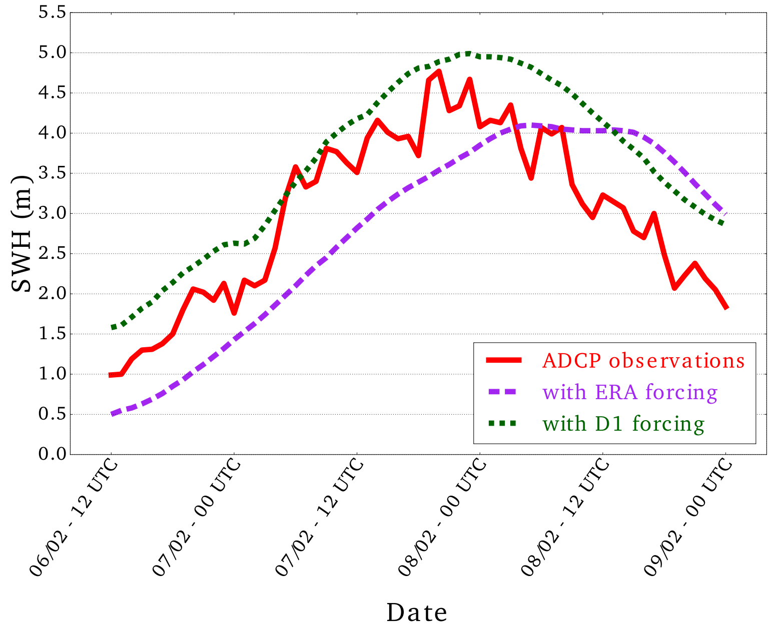


Figure 4. Comparison of the simulated significant wave heights using the two wind inputs (downscaled wind input D1 and ERA-Interim) with the data by ADCP located in the Western Black Sea coast at 20 m depth, during the storm of 7-8 February 2012. ADCP location coordinates: 43°04'49.13" N - 28°01'39.63" E.

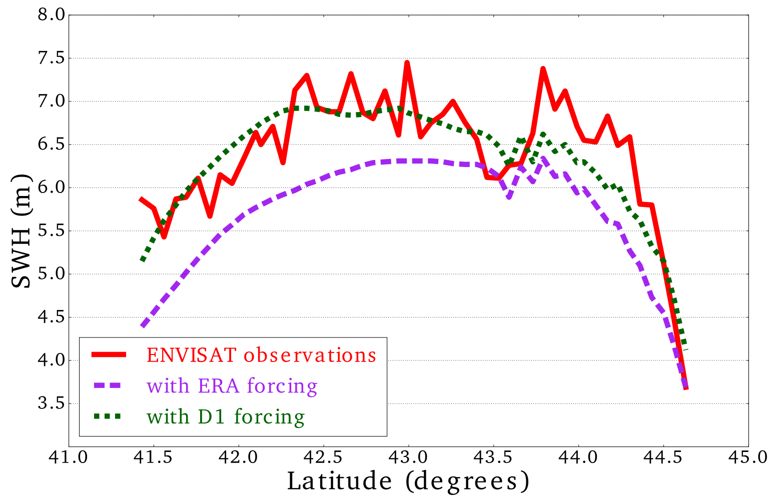


Figure 5. Comparison of the simulated significant wave heights with downscaled wind input and ERA wind input with the data from the ENVISAT track crossing the Western Black Sea at 20 UTC 7 February 2012.

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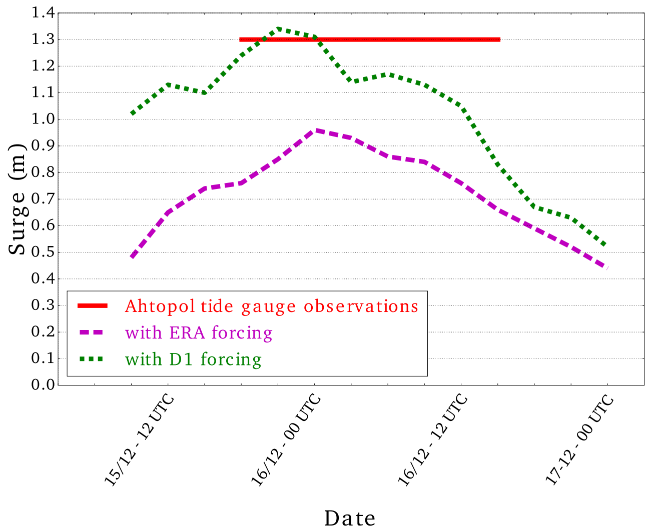
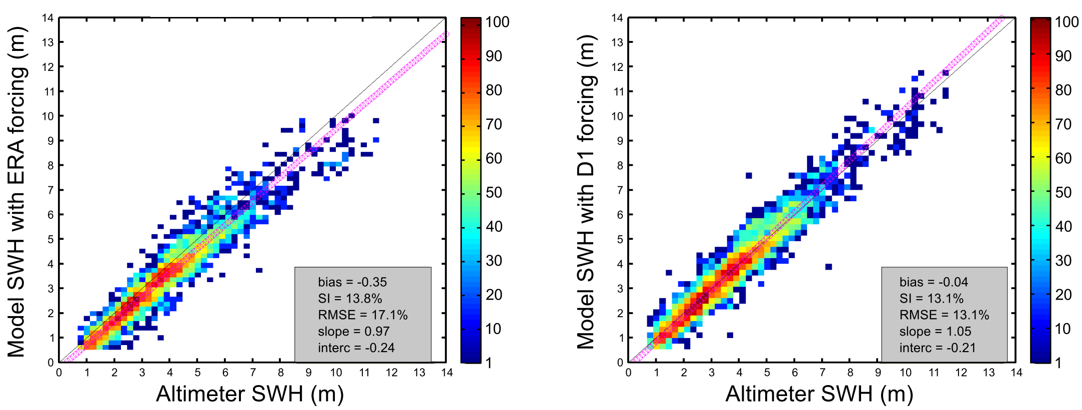


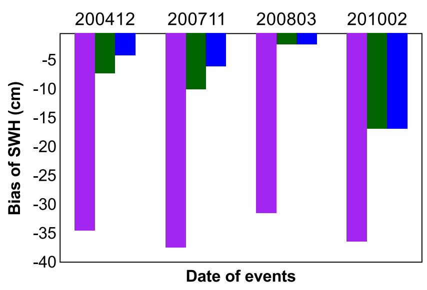
Figure 6. Temporal series of surge maximum observed (red) and simulated with ERA (purple) and D1 (green) forcing, at Ahtopol (42°06' N - 27°56' E) for the 15-19 December 1997 storm.



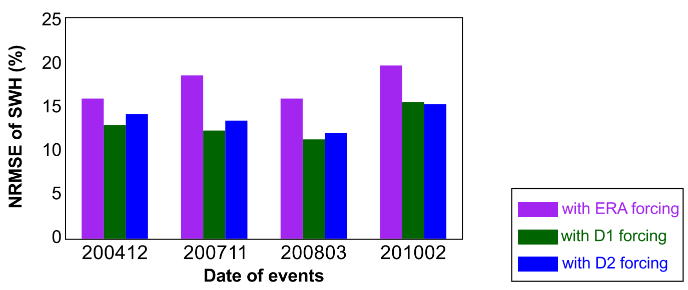
(a) with ERA-Interim forcing

(b) with D1 forcing

Figure 7. Scatter plots of significant wave heights of model MFWAM and altimeters (ENVISAT et Jason-1) for the 2004, 2007, 2008 and 2010 French storms. (a) and (b) stand for runs with interpolated ERA and D1 wind forcing, respectively.



(a) Bias



(b) NRMSE

Figure 8. 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.

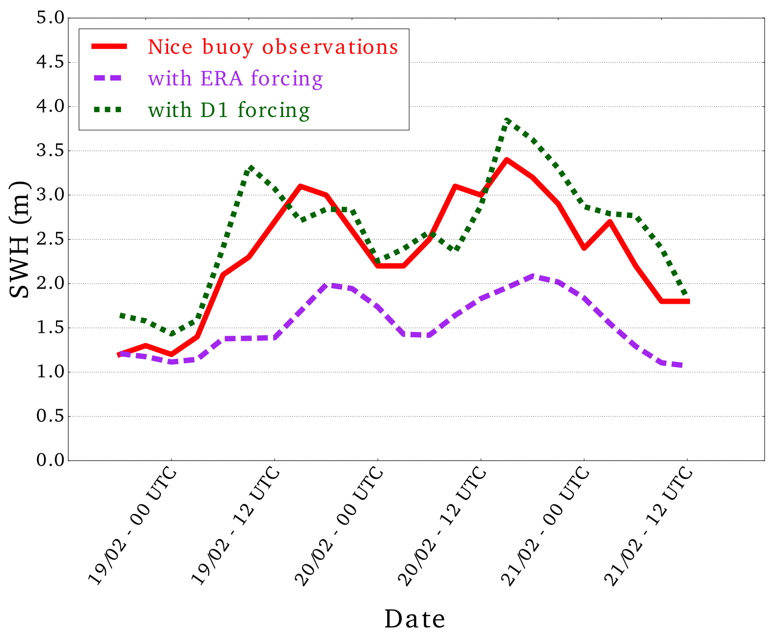
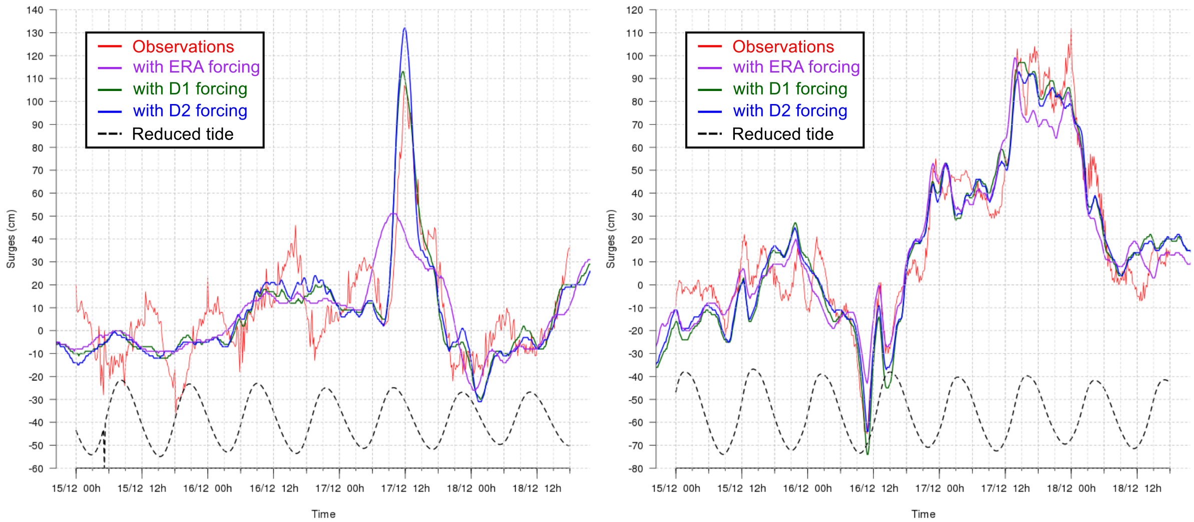


Figure 9. Time series of significant wave heights for the storm on February 2010 at Nice location (43.4° N and 7.8° E) in the Mediteranean sea. Blue and red colors stand for ERA and D1 forcing, respectively. Black line stands for Nice buoy observations.



(a) St Malo

(b) Dunkerque

Figure 10. Storm surges (cm) at St Malo (a) and Dunkerque (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.

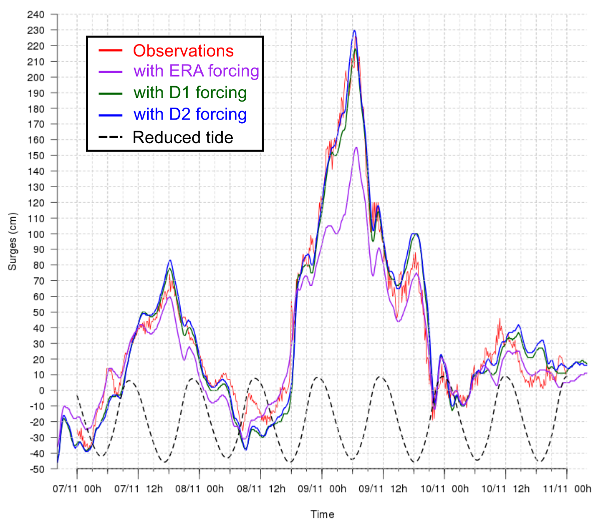


Figure 11. Storm surges (cm) at Dunkerque from 7 November 2007 at 15 UTC to 19 December 2004 at 06 UTC. The measured surge (red), the reconstructed surge by using the ERA forcing (purple), the D1 forcing (green) and the D2 forcing (blue) are superimposed. The little oscillatory dotted line in the lower part of the graph is used to indicate the time of high and low tides.

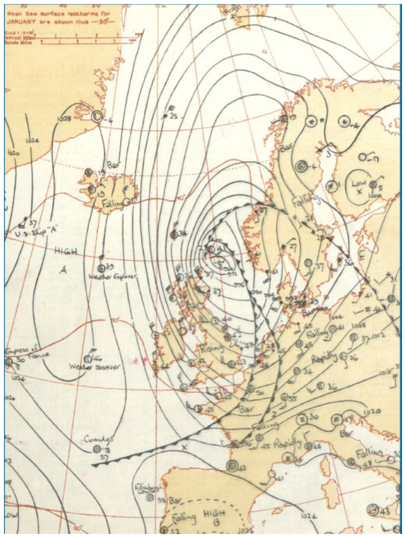
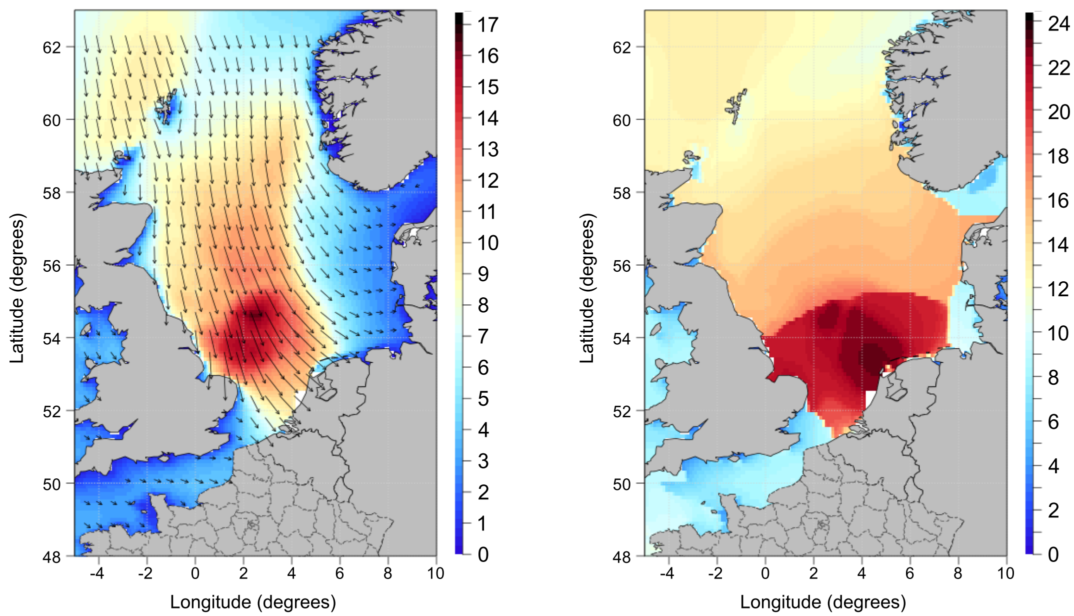


Figure 12. Surface pressure chart (hPa) at 06 UTC 1 February 1953. From hhtp://www.metoffice.gov.uk



(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 downscaled winds on the peak of the storm at 00 UTC 1 February 1953. Mean Wave Direction is shown with black arrows in (a) when significant wave height are greater than 1.5 m.

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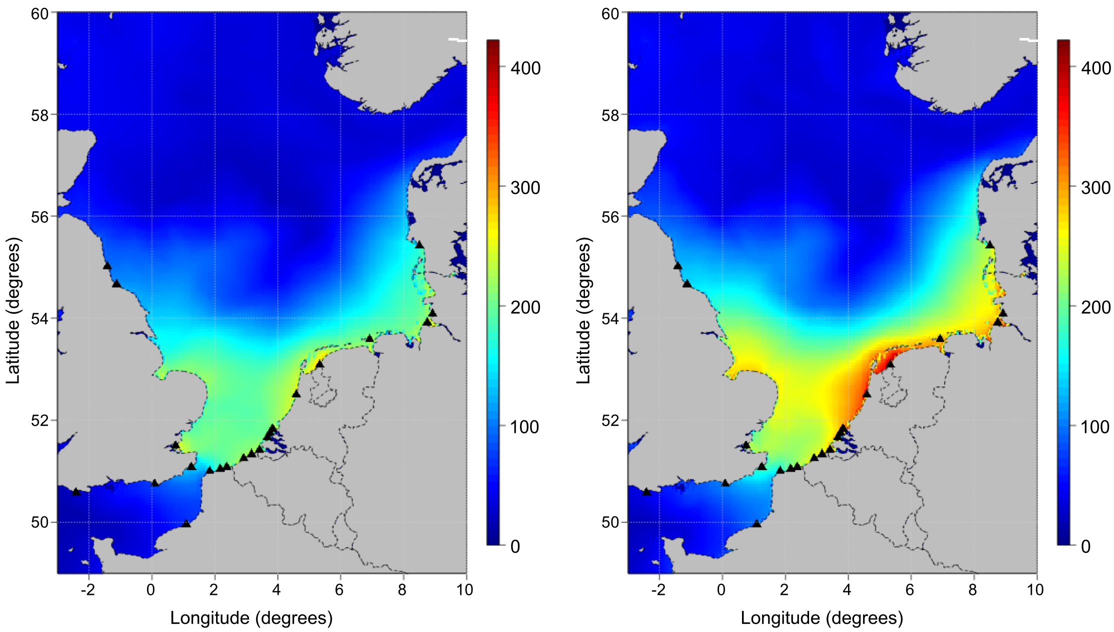
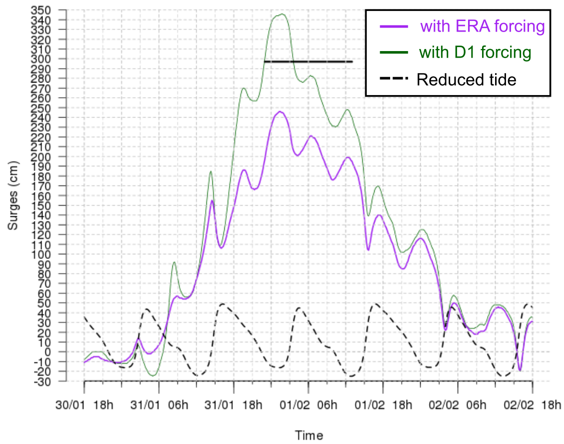


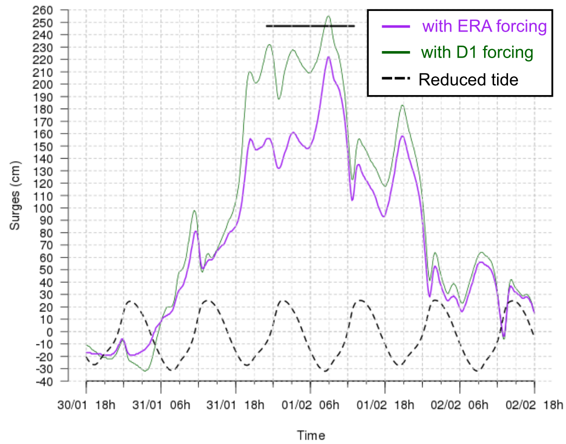
(a) with ERA-20C forcing

(b) with D1 forcing

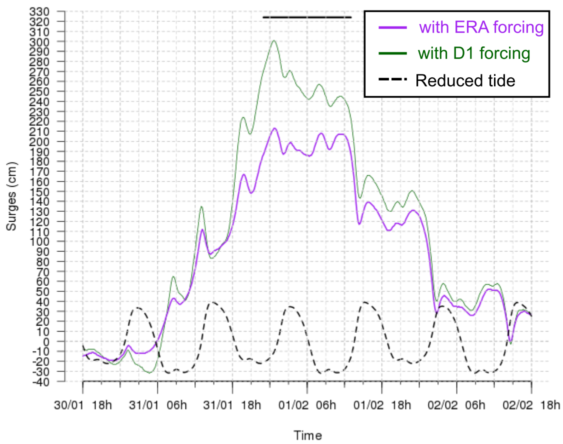
Figure 14. Highest simulated storm surges (cm) obtained for the period from 30 January to 2 February 1953, with the ERA-20C forcing (a) and with the downscaled ARPEGE forcing (b) along the southern part of the North Sea coast.



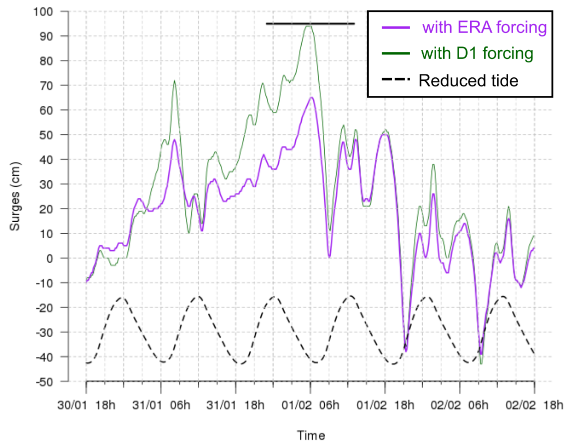
(a) Ijmuiden



(b) Ostend



(c) Brouwershavn



(d) Dieppe

Figure 15. Storm surges (cm) at Ijmuiden (Netherlands; a), Ostend (Belgium; b), Brouwershavn (Netherlands; c) and Dieppe (France; d) from 18 UTC 30 January to 18 UTC 2 February 1953. Two surges are represented: resulting of forcing with ERA-20C (purple) and with the downscaled ARPEGE (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).