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Global reconstructed daily surge levels from the 20th Century Reanalysis (1871–2010)

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ABSTRACT

Studying the effect of global patterns of wind and pressure gradients on the sea level variation (storm surge) is a key issue in understanding the recent climate change effect on the dynamical state of the ocean.

The analysis of the spatial and temporal variability of storm surges from observations is a difficult task to accomplish since observations are not homogeneous in time, scarce in space, and moreover, their temporal coverage is limited. A recent global surge database developed by AVISO (DAC, Dynamic Atmospheric Correction) fulfilled the lack of data in terms of spatial coverage, but not regarding time extent, since it only includes the last two decades (1992–2014).

In this work, we use the 20th Century Reanalysis V2 (20CR), which spans the years 1871 to 2010, to statistically reconstruct daily maximum surge levels at a global scale. A multivariate linear regression model is fitted between daily mean ERA-interim sea level pressure fields and daily maximum surge levels from DAC. Following, the statistical model is used to reconstruct daily surges using mean sea level pressure fields from 20CR. The verification of the statistical model shows good agreements between DAC levels and the reconstructed surge levels from the 20CR. The validation of the reconstructed surge with tide gauges, distributed throughout the domain, shows good accuracy both in terms of high correlations and small errors. A time series comparison is also depicted at specific tide gauges for the beginning of the 20th century, showing a high concordance.

Therefore, this work provides to the scientific community, a daily database of maximum surge levels; which correspond to an extension of the DAC database, from 1871 to 2010. This database can be used to improve the knowledge on historical storm surge conditions, allowing the study of their temporal and spatial variability.

1. Introduction

The storm surge is one of the main variables that describe the dynamical state of the ocean. It is defined as the sea level variation due to wind stress and sea level pressure gradients over the sea surface. The storm surge magnitude has a large spatial variability and can reach extremely high values associated to tropical and extra-tropical storms (extreme storm surge events).

The storm surge is one of the sea level components, and can be extracted from tide gauge records; but since many of the world areas are ungauged, the global coverage is scarce. Besides, areas where instrumental records are available, normally present short time records and hence only recent analysis can be carried out. Nevertheless, there is a global assessment from long centennial records (Marcos et al., 2015) focus on sea level extremes, although it is limited to areas with available tide gauges. One option to overcome these shortcomings is the use of numerical models. They enable us to simulate the magnitude of the storm surges at a global scale or in an specific area. In fact, there is a global surge database, the Dynamic Atmospheric Correction from AVISO (hereinafter DAC database, http://www.aviso.altimetry.fr/), that provides global records from 1992 and onwards (a description of the numerical configuration can be found in Carrère and Lyard, 2003). Nevertheless, DAC database is not long enough to address inter-decadal climate variability or likely long-term trends. The numerical modelling at a global scale and for a long period of time requires an extremely high computational effort.

An alternative to numerical models is the statistical modelling; different techniques of statistical reconstruction are widely used in

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climate or ocean variables. Statistical downscaling techniques can be classified into: transfer functions, weather-type approaches and stochastic weather generators (Giorgi et al., 2001). Regarding marine climate, linear transfer functions (regression models) have been applied to downscale the significant wave height at global (Wang et al., 2012) and at regional scale (Casas-Prat et al., 2014). Also, a weather-type model has been proposed to downscale multivariate wave climate (Camus et al., 2014b; Espejo et al., 2014).

The application of statistical downscaling approaches is usually limited to specific locations. Calafat and Gomis (2009) used a reduced space optimal interpolation analysis to reconstruct the sea level in the Mediterranean Sea. For storm surges specifically, Dangendorf et al. (2014) compared, in the North Sea, the long-term behavior of surges to that of reanalysis wind fields by means of a statistical-empirical formulation (Müller-Navarra and Giese, 1999).

The goal of this study is to perform a global reconstruction of the storm surge by means of a statistical model in order to extend the DAC temporal coverage. For achieving this purpose, we define the statistical relationship between the storm surges from DAC database and their drivers (pressure and wind fields from ERA-interim reanalysis, Dee etal., 2011) using multiple linear regression. In this work, although using the term storm surge, we are not reconstructing specific strong events but to a continuous time series of daily values. Once the statistical model is calibrated and verified, we use a global atmospheric database that starts at the end of the 19th century (20th Century Reanalysis V2, Compo et al., 2011) to reconstruct the storm surge at a global scale and for a long period of time (1871–2010).

The work is structured as follows. Section 2 describes the three global databases and the tide gauges used in this study. The methodology of the statistical model is explained in depth in Section 3 and its accuracy is shown in Section 4, where the verification results are depicted. Finally, the global reconstruction of the surges and its validation with tide gauges is shown in Section 5. Main conclusions are summarised in Section 6.

2. Databases description

The surge database corresponds to the Dynamic Atmospheric Correction (DAC), produced by CLS Space Oceanography Division using the MOG2D model from Legos and distributed by Aviso, with support from Cnes (http://www.aviso.altimetry.fr/). MOG2D (2 Dimensions Gravity Waves model) is a finite element, barotropic, non-linear, two-dimensional shallow water hydrodynamic model, derived from Lynch and Gray (1979). The model is forced by pressure and wind fields from the European Centre for Medium-range Weather Forecasts (ECMWF) analysis, with a temporal resolution of 6 h and including shallow water areas and marginal seas. Barotropic sea level outputs span from September 1992 to present and are provided on a regular grid of 0.25° × 0.25° every 6 h. The operational DAC database is made of the high frequencies (i.e. less than 20 days) obtained from MOG2D barotropic model and the low frequencies of the inverse barometer (IB) assuming a static response of the ocean to the atmospheric forcing, and neglecting wind effects for low frequency (i.e. more than 20 days). Therefore, a 20 days high pass (respectively low pass) filtering is applied to separate high and low frequencies (see Eq. (1)).

$$DAC = MOG2D(T < 20 \text{ days}) + IB(T > 20 \text{ days}) \quad (1)$$

Regarding the atmospheric forcing, sea level pressure fields (SLP) were selected from two different global atmospheric databases: ERA-interim reanalysis (Dee etal., 2011) from the ECMWF, which is the DAC forcing field, and the twentieth Century Reanalysis V2 (20CR, Compo et al., 2011).

SLP fields from ERA-interim, consist of 6-hourly atmospheric data at 0.75° of spatial resolution and spanning from 1 January 1979 to present. In this work, only data covering DAC period (1992–2014) are selected. These data are used to calibrate and verify the statistical model (see Section 3).

SLP fields from the 20CR are available every 6 h at a spatial resolution of 2°, covering the period between 1871 and 2010 (i.e. 140 years). These data are used for the statistical reconstruction of surge levels (see Section 5).

Concerning instrumental data, all available tide gauges from the University of Hawaii Sea Level Center (UHSLC, http://uhslc.soest.hawaii.edu/data/download/rq) were downloaded at hourly scale. From the total amount of 643 tide gauges, only those with more than one year of data before 2010 are used to validate the reconstructed surge from 20CR. In order to compare both signals, the tide gauge residuals are obtained by subtracting the astronomical tide (computed using t-tide, Pawlowicz et al., 2002) to the hourly values, and subtracting a 30-day moving average to both, modelled and measured data. This leads to a validation of the storm surge reconstruction at 386 tide gauge locations distributed worldwide.

3. Statistical modelling methodology

3.1. Predictor and predictand definitions

The aim of the statistical reconstruction is to estimate surge levels (predictand) from local atmospheric conditions (predictor) based on a statistical relationship. Specifically, our interest consists in finding the statistical relationship between mean daily atmospheric conditions and maximum daily surge levels. Following this purpose, the predictand is defined as the maximum of the 4 daily DAC values (DAC has a 6-hourly temporal resolution) at each grid point. The spatial resolution of the statistical reconstruction is determined by the 2° resolution of the 20CR. This spatial resolution is considered sufficient to represent the surge variability at a global scale. Therefore, surge levels are selected from DAC database every 2°.

As mentioned in Section 2, SLP fields from ERA-interim are used to obtain the statistical relationship between these atmospheric fields and surge levels. Although both, surface wind and pressure fields, are the drivers of the storm surge, in this work we are only extracting SLP fields from the atmospheric reanalysis. This is because in global circulation models, sea wind fields are not as well reproduced as sea level pressure fields (Wang et al., 2010); but since the geostrophic wind speed is proportional to the square pressure gradient, SLP gradients are calculated, and taken into account in the statistical modelling, to also have an estimation of the wind speed.

Although SLP from ERA-interim reanalysis has a horizontal resolution of 0.75°, SLP fields and the calculated gradients have been re-arranged in a 2° grid at a daily scale. The final step in the definition of the predictor is the establishment of the spatial coverage. Taking each of the predictand grid points, a local area of 4° × 4° enclosing this target point is defined. As a result, the predictor is composed of 9 SLP values and 9 SLP gradients (18 components) centred in the predictand location.

The same process is carried out for the definition of the predictor from 20CR SLP fields, with the only difference that in this case, data are already in a 2° grid.

Therefore, the predictand consists of daily maximum values of surge levels from September 1992 to December 2014 in a 2° global grid; the predictor for the statistical model configuration consists of daily means of SLP fields and square SLP gradients from ERA-interim, covering an area of 4° × 4° centred at the predictand location. Once the statistical model is defined, 20CR daily predictors are used to reconstruct surge levels from 1871 to 2010 at each location (10,594 locations).