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Baltic Sea extreme sea levels 1948-2011: Contributions from atmospheric forcing

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Abstract

Extreme sea levels in the Baltic Sea are usually analyzed from tide-gauge data covering more or less extended periods. More comprehensive spatial or systematic analyses are less frequently available. Data from a high-resolution tide-surge model driven by high-resolution reanalyzed atmospheric fields reconstructing Baltic Sea sea levels from 1948 to 2011 on an hourly basis are analyzed. Meteorologically induced sea levels are characterized by pronounced annual to decadal fluctuations and a typical seasonal distribution comparable to the variability in regional wind climate. No substantial long-term trends over the considered period could be detected. Wind set-up represents the most dominant factor, however, short term variations in the filling levels of the basin and seiches contributed substantially to some of the observed peak water levels in the past. For the tide-gauge Wismar at the German Baltic Sea coast, it is exemplarily demonstrated that storm surges during periods with and without high filling levels occurred at about equal shares. When high filling levels were present, lower wind speeds were generally needed to sustain comparable peak water levels. Seiches also contributed to some of the observed extremes usually with a preferred phase shift. For Wismar, in about one third of the cases contribution from seiches at peak water level was found to exceed 10 cm.

Keywords: Baltic Sea; storm surges; seiches; filling levels; hindcast; extreme sea level; climatology

1. Introduction

Coastal flooding is usually associated with extreme sea levels. The latter are often caused by a coincidence of contributions from different sources such as large meteorologically induced surges (storm surges) or large or even moderately high tides[1]. Seasonal or longer time scale variations in the frequency, duration or intensity of such events

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may occur due to, for example, corresponding variations in the atmospheric forcing. On the long run, changes in relative mean sea level such as caused by geological factors, water works, or anthropogenic climate change may have an impact as they change the base line upon which wind-induced changes may act.

In the semi-enclosed Baltic Sea, wind set-up certainly is the most dominant atmospheric process affecting extreme sea levels and their variability[2]. There are, however, some additional atmospherically driven processes that may influence extreme sea levels and their distribution. First, fluctuations in water exchange through the Danish Straits and to a smaller amount in river runoff and precipitation may lead to variations in the degree of filling of the basin[3,4] and to corresponding sea level or filling level (FL) variations of up to 50 cm on time scales of days to weeks[5]. Second, seiches are a typical phenomenon for semi-enclosed basins such as the Baltic Sea[6]. When favorably coupled with wind driven sea level variations (storm surges) seiches may substantially contribute to extreme sea levels[3]. The relation between these two phenomena in the Baltic Sea is still discussed controversially[7,8].

In the following we analyze the relation between these atmospherically driven sea level components in the Baltic Sea and consider their long-term variability and change. The analysis is based on a high-resolution multi-decadal tide-surge hindcast[9] providing a comprehensive and consistent met-ocean data set for the analysis. In section 2 the hindcast is briefly described while the main results and conclusions are presented in sections 3 and 4.

2. Data and methods

For our analyses we used hourly sea level data derived from a multi-decadal (1948-2011) tide-surge hindcast[9]. Data are available at a hierarchy of grids ranging from 12.8 x 12.8 km in the North Sea to 1.6 x 1.6 km in western Baltic Sea. The hindcast was driven by hourly values of near-surface marine wind and pressure fields obtained from a corresponding high-resolution atmospheric hindcast[10]. Validation of the atmospheric forcing and the tide-surge hindcast is described in the literature[10,11].

To determine the effect high filling levels may have on extreme sea levels we used model time series of sea levels near Landsort in the central Baltic Sea. To identify periods with a high degree of filling (FL-H) we used the available definition where modelled sea level near Landsort need to exceed the local long-term mean by at least 15 cm over at least 20 consecutive days[12].

Contributions from seiches were estimated using local Fourier decomposition (see appendix) with pre-defined frequencies from theoretical considerations[3]. According to theory, such oscillations may either represent manifestations of basin-wide seiches or of an ensemble of weakly coupled local oscillations[13]. As in both approaches the local frequencies remain virtually the same and since we are primarily interested in the contribution of seiches to local sea level extremes, these differences in interpretation of the origin of the oscillations will not affect our results.

Because seiches occur only occasionally, a moving analysis technique was used in which Fourier decomposition was applied subsequently on shifted (by one hour) windows of 96 hours length. This corresponds to roughly three times the period of the longest seiche and is about twice the decay or e-folding time of seiche amplitudes in the Baltic Sea[14]. This way hourly time series of amplitudes and phases were obtained from which the contributions of seiches to extreme sea levels and their changes could be analyzed.

3. Results

Generally we found the storm surge climate well represented in the model data. On a seasonal scale, extremes are generally highest and more frequent in winter and lowest and less frequent during the summer season. Values are generally small for open waters and increase towards the coast[15]. There is considerable variability on annual to decadal time scales with the early decades showing below averaged conditions while the decades around the 1990s were characterized with on average higher than normal extremes. Over the 64 year hindcast period some increase in storm surge extremes can be inferred, most pronounced in the northern to northeastern parts of the basin.

Periods with high filling levels (FL-H) occurred on average about 60 days per year. Generally there is pronounced inter-annual to decadal variability with below average conditions in the early decades. Again the decades around the 1990s were characterized by above normal conditions (Fig. 1). The frequency of FL-H periods