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Separation of the Baltic Sea water level into daily and multi-weekly components

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ABSTRACT

Storm surges and changes in the water volume of the entire sea, with typical time scales about a day and a few weeks, respectively, are the largest contributors to the water level variations at the eastern Baltic Sea coasts. Our analysis employs time series of sea levels numerically reconstructed using the RCO (Rossby Center, Swedish Meteorological and Hydrological Institute) ocean model for 1961–2005. The distribution for the weekly-scale water level, defined as a running average over a certain time interval, has an almost Gaussian shape. For the 8-day average the distribution of the residual, interpreted as the frequency of occurrence of local storm surges of different height, almost exactly matches the exponential distribution that can be considered as reflecting the time between events of the underlying Poisson process. The distribution of the total water level contains a few outliers that often do not match the classical statistics. All extreme values (outliers) of water level are a part of the exponential distribution of storm surges for averaging intervals longer than about 3 days. Such separation of phenomena on different temporal scales is universal for the entire eastern Baltic Sea coast. The slopes of the exponential distribution for low and high water levels are different, vary markedly along the study area and provide a useful quantification of different coastal sections with respect to the probability of coastal flooding.

1. Introduction

Coastal flooding is one of the most devastating natural hazards. Although no clear trend has been recorded in its intensity and frequency over the last decades (Weisse et al., 2014), its projections show a rapid increase in the related losses (Hallegatte et al., 2013). The combination of the global sea level rise (Cazenave et al., 2014), increase in the storminess (Alexandersson et al., 2000; Jaagus et al., 2008) or properties of cyclones (Sepp et al., 2005; Sepp, 2009) in the Baltic Sea region has reinforced the need for better understanding of how the water masses react to such changes.

The total water level in a serious flood event is normally the joint result of the impact of several drivers. The largest contributions usually stem from tides and low atmospheric pressure (inverted barometric effect), wind-driven surge and wave-induced set-up. The resulting values may be to some extent modified by meteorologically driven long waves such as meteorological tsunamis (Monserrat et al., 2006; Pattiaratchi and Wijeratne 2014; Pellikka et al., 2014) [also called squall line waves in the USA (Sallenger et al., 1995) and baric waves in some studies of the Baltic Sea (Wiśniewski and Wolski, 2011)], seiches, tide–surge interactions (Batstone et al., 2013; Olbert et al., 2013) and other site-specific phenomena.

It is usually assumed that contributions from different mechanisms to the resulting water level are basically independent. This assumption makes it possible to single out the signal of each mechanism from the overall course of water level and to analyse separately its progression, timing and contribution to the flooding (e.g., Losada et al., 2013). It also allows in-depth analysis of gradual changes in the averages and extremes caused by a single driver (e.g., Howard et al., 2014; Weisse et al., 2014) and finally constructing a projection of joint changes in mean and extreme water levels and return periods of dangerous events.

This approach is a standard tool in areas where local water level is driven by changes in the long-term mean, properties of storms and tidal activity (Pugh and Vassie, 1978, 1980). In such cases it is customary to decompose the water level time series into periodic (or dynamic) and random components, and to analyse their contribution separately (Haigh et al., 2010).

The situation is more complicated in locations exhibiting

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substantial aperiodic variations in sea level at daily to monthly scales (called subtidal water level variability, Buschman et al., 2009). This component may be significant along the open ocean coast (e.g., near Crescent City, California) (Percival and Mofjeld, 1997) where it is driven by atmospheric pressure patterns. It is often much more pronounced in semi-enclosed estuaries and basins such as the Delaware estuary (Wong and Moses-Hall, 1998), Galveston Bay (Guannel et al., 2001), Tampa Bay (Wilson et al., 2014) or the Baltic Sea (Leppäranta and Myrberg, 2009), where it is associated with changes in the overall volume of water in the basin.

The fundamentally aperiodic components have a typical time scale of a few weeks in the Baltic Sea. This is due to the impact of sequences of storm cyclones (Post and Kõuts, 2014) that may bring substantial amounts of water into the sea and lead to a 1 m increase in its water level (Johansson et al., 2001) similarly to Chesapeake Bay (Bosley and Hess, 2001). This value is comparable or even larger than the all-time maximum height of the local storm surge in the eastern Baltic Sea measured from the average water level in the entire sea. The local impact of storms (the classical storm surge) develops on the background of this (elevated or depressed) water level. For example, in north-western Estonia the all-time highest total water level is about 1.5 m (1.48 m at Dirhami, 1.52 m or 1.55 m at Tallinn according Suursaar et al., 2006b and Averkiev and Klevanny, 2010, respectively), whereas the magnitude of the local storm surge is about half of it. For this reason the most devastating surges occur in the eastern part of the Baltic Sea when a strong storm approaches after a sequence of previous storms has considerably increased the overall water volume of the Baltic Sea (Johansson et al., 2001).

The presence of this large-amplitude aperiodic component leads to a major problem in the construction of projections of future extreme Baltic Sea water levels. The total water level time series contains a few very large positive outliers in many locations. Their presence not only deviates from the predictions of the classical statistical distributions but may also substantially affect the properties of the “tail” of these distributions and render the standard methods for the evaluation of return periods of high water levels essentially meaningless (Suursaar et al., 2006a, 2015). This situation calls for more detailed studies of the mechanisms behind such outliers and of the possibilities of their separation into a specific population of events.

Previous attempts to separate sea level variations on different scales in the Baltic Sea largely focus on establishing long-term trends in mean and extreme water levels (Barbosa, 2008; Johansson et al., 2011) and on distinguishing tidal, annual and semi-annual (Ekman, 1996; Stramska, 2013) phenomena and the so-called pole tide or Chandler peak (about 14.3 months, Ekman, 1996; Medvedev et al., 2014). Long-term changes in water level along the Estonian coasts are usually separated into two parts: the joint impact of global sea-level rise and postglacial land uplift (called external impacts, Suursaar et al., 2006a) and changes driven by atmospheric forcing. The external impacts led to the total (annual mean) sea level rise in the range of 7.5–15.3 cm at different locations in 1950–2002.

The strongest periodic signal in the water level time series is the annual variation in sea level (Johansson et al., 2001). It ranges between 20 and 25 cm in the Gulf of Finland (Raudsepp et al., 1999) and has increased by about 5 cm in Pärnu and Narva-Jõesuu (Suursaar et al., 2006a, 2015). This variation is usually less than 10% of the total range of water level variations (Suursaar et al., 2006a) and about 50% of the typical (annual) standard deviation of the instantaneous water level recordings (Johansson et al., 2001; Suursaar et al., 2006a). The contribution from diurnal tides is usually a few centimetres, reaching 10 cm in selected locations of the Gulf of Finland (Leppäranta and Myrberg, 2009) and 17–19 cm in the easternmost region of this gulf (Neva Bay, Medvedev et al., 2013).

Several drivers with different temporal and spatial scales may contribute to subtidal variations in the water level. Although intra-seasonal variations in freshwater inflow may add a few centimetres to the water level in the neighbourhood of large river mouths (Leppäranta and Myrberg, 2009), subtidal variations in the Baltic Sea mostly result from atmospheric pressure and direct wind impact. Storm surges have a typical time scale of 1 day. The above-mentioned sequences of storms (Post and Kõuts, 2014) may add up to 1 m to the level of the entire sea over a typical time scale of a few weeks (Feistel et al., 2008; Leppäranta and Myrberg, 2009).

Therefore, even if various harmonic components have been singled out, as has been done in common models of water level (e.g., Raudsepp et al., 1999), the residual signal is a mixture of reactions of water level to at least two strong drivers (single storms and subtidal variations) with different temporal scales and contains a substantial aperiodic component.

In this paper we make an attempt to separate the major components of the course of water level based on the difference of their typical time scales. The problem would be relatively simple if we had at our disposal the correct time series of the overall water volume of the Baltic Sea and a necessary correction procedure to calculate the associated values for the idealised calm water level (e.g., taking account of the spatial distribution of air pressure or changes in salinity) at each site of interest. These data are usually not available. Our aim is to develop a meaningful and easy-to-use method for such a separation based on local (measured or modelled) time series of water level.

As the subtidal and storm-driven components of water level are fundamentally aperiodic in the Baltic Sea basin, the application of Fourier analysis is problematic because a very large number of harmonics are usually necessary to properly describe the properties of an aperiodic signal. We rely on the classical technique of the running average of water level time series with a properly designed length of the averaging interval. Interestingly, for a particular choice of this length the distribution of the frequency of occurrence of local storm surges of different height becomes the exponential distribution with the probability density function $\sim \exp(\lambda x)$. Such distributions describe inter alia the time between events in a Poisson process (in which events occur continuously and independently at a constant average rate). This property opens a way to systematically characterise the exposedness of different sections of the coast to local storm surges using just one parameter – the exponent of this distribution, equivalently, the rate parameter λ (or, more conveniently, the associated scale parameter $1/\lambda$) of the exponential distribution.

The paper is structured as follows. Section 2 provides a short overview of the circulation model, the output of which is used in the analysis, and describes the spectral composition of the water level time series. Section 3 introduces the scheme used for the separation of short-term (surge-driven) and weekly-scale (associated with the volumetric changes of the entire Baltic Sea) variations in water level. An estimate of the proper length of the averaging interval that allows for meaningful separation of the processes is provided in Section 4 and an overview of spatial variations in the scale parameter of the resulting exponential distribution is available in Section 5.

2. Material and method

The analysis relies on numerically simulated water levels sampled once in 6 h at nearshore locations along the eastern Baltic Sea coast. These locations (Fig. 1) were chosen as the closest grid