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Research papers

Spatial variability in the trends in extreme storm surges and weekly-scale high water levels in the eastern Baltic Sea

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A B S T R A C T

We address the possibilities of a separation of the overall increasing trend in maximum water levels of semi-enclosed water bodies into associated trends in the heights of local storm surges and basin-scale components of the water level based on recorded and modelled local water level time series. The test area is the Baltic Sea. Sequences of strong storms may substantially increase its water volume and raise the average sea level by almost 1 m for a few weeks. Such events are singled out from the water level time series using a weekly-scale average. The trends in the annual maxima of the weekly average have an almost constant value along the entire eastern Baltic Sea coast for averaging intervals longer than 4 days. Their slopes are ~4 cm/decade for 8-day running average and decrease with an increase of the averaging interval. The trends for maxima of local storm surge heights represent almost the entire spatial variability in the water level maxima. Their slopes vary from almost zero for the open Baltic Proper coast up to 5–7 cm/decade in the eastern Gulf of Finland and Gulf of Riga. This pattern suggests that an increase in wind speed in strong storms is unlikely in this area but storm duration may have increased and wind direction may have rotated.

1. Introduction

The risks and damages associated with coastal flooding show a rapid increase (Hallegatte et al., 2013) and are one of the largest concerns of countries with extensive low-lying nearshore areas. Although the course of the local water level, the main agent of the relevant risk, does not follow any simple rule (Weisse et al., 2014), the analysis of its linear trends based on its past behaviour is still a powerful tool to obtain a first approximation of the future projections. The relevant efforts have not only confirmed the overall sea level rise (Cazenave et al., 2014) but also established contribution of this rise to local water level maxima (Mudersbach et al., 2013; Xu and Huang, 2013). These efforts have also highlighted an increase in the magnitude of local storm surges for a number of locations round the globe. These processes occur on the coasts of the open ocean (Sun et al., 2013; Talke et al., 2014), in shelf seas (Weisse et al., 2012) and in semi-enclosed basins (Ullmann et al., 2007; Wiśniewski and Wolski, 2011; Masina and Lamberti, 2013).

It is not always clear beforehand which component of the water level (or its physical driver) is responsible for an increase in the maxima in question. For example, on the German North Sea coast prior to the mid-1950s and from about 1990 onwards, changes in high sea levels matched mean sea level changes but from the mid-1950s to 1990 were significantly different from those observed in the mean sea level (Mudersbach et al., 2013).

The contributions from different forcing factors to the total water level are often considered as mostly independent. This assertion is equivalent to the linear superposition principle and makes it possible to analyse separately the course and timing of water level variations caused by each driver (e.g., Losada et al., 2013). More importantly, it allows in-depth analysis of changes in the contributions caused by each single driver (e.g., Howard et al., 2014; Weisse et al., 2014).

Analysis of the behaviour of single components is particularly convenient in locations where the water level reacts to contributions that act at greatly different time scales. A separation of the water level into three components driven by fundamentally different mechanisms – the long-term mean and its slow variations, tides and storm surges – is a classic approach for research into water level dynamics (Pugh and Vassie, 1978, 1980; Haigh et al., 2010a). Likewise, it is traditional to analyse separately the periodic and random components of water level (Haigh et al., 2010b). Attempts of this kind have been also made for locations that contain a substantial range of subtidal (time scales from diurnal to

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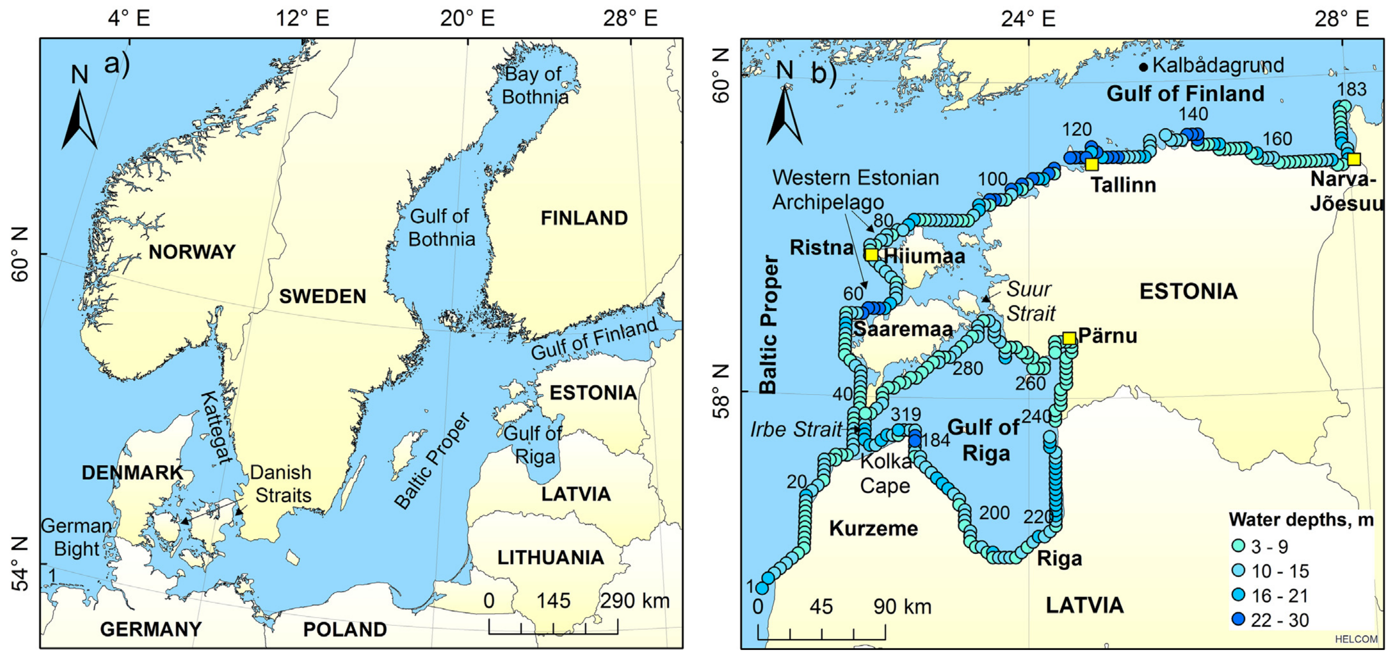

Fig. 1. (a) Scheme of the Baltic Sea and the study area, (b) Water depth at the selected RCO model grid cells in the eastern Baltic Sea (colour scale) and locations of water level gauges (yellow squares at Pärnu, Ristna, Tallinn and Narva-Jõesuu) used in the analysis. The grid cells are numbered consecutively from the western coast of Latvia to eastern Gulf of Finland, and then counterclockwise along the coast of the Gulf of Riga starting from Kolka Cape. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

seasonal) water level variability (Percival and Mofjeld, 1997; Wong and Moses-Hall, 1998; Guannel et al., 2001; Wilson et al., 2014).

The issues of water level are particularly challenging in semi-enclosed water bodies such as the Baltic Sea (Fig. 1a) where the sea-level rise may be faster than in the adjacent regions (Stramska and Chudziak, 2013). The properties of the course of water level depend here on specific factors such as local salinity (Ekman and Mäkinen, 1996) or spatial variations in the tectonic motions (Richter et al., 2012). The latter feature leads to substantial variability in properties of the observed (relative) water levels in different locations of the Baltic Sea (Scotto et al., 2009). The northern part of this basin experiences a rapid postglacial uplift and an associated relative sea level decrease (Johansson et al., 2001). The central part of the sea feels a weak relative sea level rise (Dailidienė et al., 2004, 2006) whereas the southern part is affected by a faster sea level rise owing to a gradual crustal downlift on the order of 0.2 cm/decade (Harff and Meyer, 2011).

These trends are often superposed by variations in the properties of short-term water level fluctuations. These variations appear different in different part of the sea. For example, short-term sea level variability has clearly changed in the northern Baltic Sea (Johansson et al., 2001) whereas no clear trend in the height of storm surges seems to exist for the German Bight (although the frequency and duration of storms have increased in this part of the sea, Gönnert, 2003). The pattern of trends is asymmetric: the trends in minima of water levels are much smaller than similar trends in maximum water levels (Barbosa, 2008).

The possibility of extensive variations in the water volume of the entire Baltic Sea substantially complicates the analysis of the future projections of the course of local water level and of its extremes. These fundamentally aperiodic variations are driven by atmospheric impact and usually occur on time scales of a few weeks (Feistel et al., 2008; Leppäranta and Myrberg, 2009). Even moderate winds from certain directions can reverse the typical estuarine circulation in the Baltic Sea with respect to the Atlantic Ocean. In particular, westerly winds over the Danish straits (Fig. 1a) with speeds of only 2–5 m/s can block the outflow of brackish water from the Baltic Sea (Lehmann et al., 2012). The overall freshwater surplus (Leppäranta and Myrberg, 2009) will then cause an increase in the water volume in the Baltic Sea.

The largest impact to the Baltic Sea water volume arises from sequences of storm cyclones (Post and Kõuts, 2014) that force large amounts of the North Sea water to flow into the Baltic Sea over a few weeks (Stigebrandt and Gustafsson, 2003; Lehmann and Post, 2015). The associated water level increase in the entire sea may reach 1 m (Johansson et al., 2001) similarly to Chesapeake Bay (Bosley and Hess, 2001). For many coastal segments this value is comparable with the all-time maximum storm surge height (Averkiev and Klevanny, 2010). The most devastating surges in this sea are created by strong storms that approach when the overall water volume of the Baltic Sea is unusually large (Johansson et al., 2001). The combination of an increased water level of the entire sea with strong local storms is a probable reason for a few local water level recordings that appear as statistically unpredictable outliers, but are nevertheless caused by storms of reasonable strength (Suursaar and Sooäär, 2007; Suursaar et al., 2015). Another interesting feature of water level maxima along the eastern coast of the Baltic Sea is the massive variation (from about 2 to 9 cm/decade, Suursaar and Sooäär, 2007) in the slopes of their trendlines whereas almost no correlation exists between the changes in the mean and maximum water levels.

These features call for the further analysis of the processes driving water level in the Baltic Sea and similar water bodies. Several efforts have been made to single out the components of water level and to analyse separately their variability and long-term trends. The relevant approaches range from straightforward filtering and averaging techniques up to the use of wavelet methods (Percival and Mofjeld, 1997; Bastos et al., 2013). The state-of-the-art of these approaches is presented in (Johansson, 2014). The analysis in the current paper is motivated by the observation that the weekly-scale average water level in a large section of the eastern Baltic Sea coast represents a quasi-Gaussian process while the residual (the total water level minus the weekly average), interpreted as the local storm surge (Haigh et al., 2010a),