Estuarine, Coastal and Shelf Science 156 (2015) 31–41

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

How to quantify long-term changes in coastal sea storminess?

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ARTICLE INFO

Article history:
Accepted 4 August 2014
Available online 15 August 2014

Keywords:
wind climate
storm surges
cyclones
wave hindcast
coastal change
multiple stressors
Baltic Sea

ABSTRACT

The paper discusses various aspects of local and regional storminess, as well as challenges in quantifying its tendencies in the eastern section of the Baltic Sea. The study is based on various long-term data sets, such as wind and sea level observation data from coastal stations and tide gauges of Estonia (1899–2013). It also discusses long-term wave hindcasts (1966–2013), reconstructions of shoreline changes, as well as the limitations and possible shortcomings in each of the data sets. Mostly located on the westerly exposed and windward coast of the semi-enclosed Baltic Sea, the case study area is sensitive to wind and storm climate changes. Different manifestations of storminess delivered somewhat specific results. When analyzed together, the first principal component of storminess was connected to the intensity of regional cyclonic activity along the polar front and had relatively high stages in 1920s–1940s, 1980s–1990s and probably also from 2010. The second component carried a local and more random imprint. Appearing independently of the high NAO or general "storminess" phases, the most notable event-driven extremes in the record were related to this component. Based on our data, we cannot confirm the existence of any general increasing long-term trends for storminess. Wherever the increase exists, it has occurred as a winter-time increase accompanied by the shift of the stormy season from autumn to winter. The spatially contrasting results for westerly and northerly exposed coasts reflect the corresponding variations in local wind, which are connected to the changes in storm track activity above northern Europe and a poleward shift of cyclones' trajectories.

1. Introduction

Considered as a hazardous result of global climate warming, increasing storminess has been reported in different parts of the world (Easterling et al., 2000; Matulla et al., 2008). It affects coastal and bottom habitats, near-shore ecology and various aspects of human activity (Beniston and Stephenson, 2004; Emanuel, 2005). Recent influential hurricanes like Katrina (2005) and Sandy (2012) in the USA and the Philippines Typhoon Haiyan (2013) have repeatedly called for a better understanding of storms in order to adapt to and mitigate their impacts (e.g. Hill, 2012). At the same time, recurrence statistics of storms have often been ridiculed by the frequent appearance of "once a century" or "once a millennium" type events (Suursaar et al., 2006; Needham et al., 2012). Moreover, even if the immediate approach of a catastrophic event can nowadays be satisfactorily forecasted, its various parameters are frequently unexpected and the adjoining consequences remain unmitigated (McCallum and Heming, 2006).

The perception and manifestations of "storminess" may vary regionally. Apart from tropical cyclones (typhoons, hurricanes) and extra-tropical cyclones, some specific but regionally important storm types, as well as their accompanying phenomena like storm surges, wave storms and river floods in lower reaches should be kept in mind (Schernewski et al., 2011; Esteves et al., 2011). A windstorm above the ocean or a continent may be dangerous, but the largest devastation usually occurs in the coastal zone. For instance, the tsunami-like storm surge of Typhoon Haiyan, the 10 m surge of Hurricane Katrina or numerous floodings at the Bangladeshi coast have vastly aggravated the impacts of windstorms. Quite similarly, the remarkably powerful (magnitude 9) Tōhoku 2011 earthquake did not cause any prominent losses until the tsunami hit the coastal region of Sendai and the Fukushima Daiichi Nuclear Power Plant. Coastal zones are the most threatened yet the most densely populated areas on the Earth. Consequently, it is justified that attempts are made to analyze coastal zone storm events as combined wind-, wave- and surge events.

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http://dx.doi.org/10.1016/j.ecss.2014.08.001
0272-7714/

There is no overall agreement whether the frequency and intensity of storms has increased or will increase in the future. Some argue that a trend in the frequency of cyclones is hard to prove owing to the large natural variability compared to the sample size (e.g. Trenberth, 2005) but others find that the warming may indeed lead to cyclones becoming more powerful (Easterling et al., 2000; Emanuel, 2005). Quantifying long-term developments in coastal zone storminess is not a straightforward task, since one must deal with multiple stressors and data sets of mixed representativeness. The relatively compact, cyclone-prone and practically tideless Baltic Sea is an ideal model area for testing interdisciplinary approaches to the analysis of impacts of climate change and storminess (Meier, 2006; Schernewski et al., 2011). Extratropical cyclones occasionally pass from the west to the east along the North Atlantic storm track and create considerable fluctuations in the Baltic Sea level and its wave conditions, topple woods and cause substantial financial losses (Soomere et al., 2008; Lehmann et al., 2011). The most straightforward way to investigate wind extremes would seemingly be to analyze records of wind observations. However, only coastal stations at very exposed locations or small islands are most likely to show long-term homogeneity (Heino et al., 1999). Data quality may be lowered by gaps and possible changes in instrumentation, as well as by changes in vegetation and infrastructure around the station. Hence it is recommendable to have alternative estimates by calculating geostrophic winds from sea-level pressure records (Krueger et al., 2013), station-based low air pressure indices (Bärring and von Storch, 2004), as well as some indirect approaches by analyzing wave climate (Tuomi et al., 2011) or storm surges (Bijl et al., 1999).

In terms of climatology, increasing storminess in northern Europe was analyzed by, for example, Alexandersson et al. (1998), and Bärring and Fortuniak (2009). They link changes in cyclonic activity to variations in large-scale atmospheric circulation. The data show that the number of cyclones moving over northern Europe has increased in winter, suggesting a poleward shift of the storm track (Sepp et al., 2005; Pinto et al., 2007). As a consequence, the percentage of anti-cyclonic conditions in winter described by low temperature, little precipitation and weak winds has decreased in Estonia, and cyclonic weather with higher temperatures, precipitation and wind speeds have become much more common (Jaagus, 2006).

Focussing on the Estonian (Fig. 1) case study, the Estonia-based air pressure data describe storms only partially (Post and Kõuts, 2014). Owing to Estonia's small size (approximately 250 × 200 km^2), the most influential storms over the coastal sea pass to the north of the territory of Estonia. The calculation of geostrophic wind speed is too generalizing and does not take into account local conditions such as land-sea proportions within the model grid-cells. It seems that the pressure-based indices of Kajaani or Härnösand (Finland) may be more helpful for characterizing storms affecting Estonia (BACC, 2008). Still, local wind data from the exposed coastal stations still remain a valuable source for describing storms.

Decadal variations in regional wind conditions are closely related to the increase in storm surge heights near the Estonian coast and probably also to the variations in mean sea level (Suursaar and Sooäär, 2007). The sea level rise was concentrated on the season of higher cyclonic activity from November to March. Variations in the Baltic Sea wave climate, including rough sea conditions along the eastern section of the Baltic Sea were studied by e.g. Soomere et al. (2008), Tuomi et al. (2011), and Suursaar et al. (2014). Besides spatial differences, a possible consensus for trends seems also to be compromised by the different wind forcings used (i.e. station-based measured data, geostrophic model winds, or re-analysis data).

Various, sometimes contradicting opinions and quantifications of different aspects of storminess (meteorology, sea level, waves, coastal change; e.g. Esteves et al., 2011) even for one and the same region introduce the problem of reliability and representativeness of the estimates. The quality and limitations of each data set should be assessed. The present study makes use of the Estonian wind, sea level, wave and coastal change data and extends previous work (Jaagus, 2006; Tõnisson et al., 2008; Jaagus and Suursaar, 2013; Suursaar, 2013) to 2013. The study also attempts to present a more integrated, critical review of various aspects of storminess by revising and joining up different data series of Estonian origin.

The main objectives of the study are to: (1) identify the types, manifestations and combinations of storms that are most

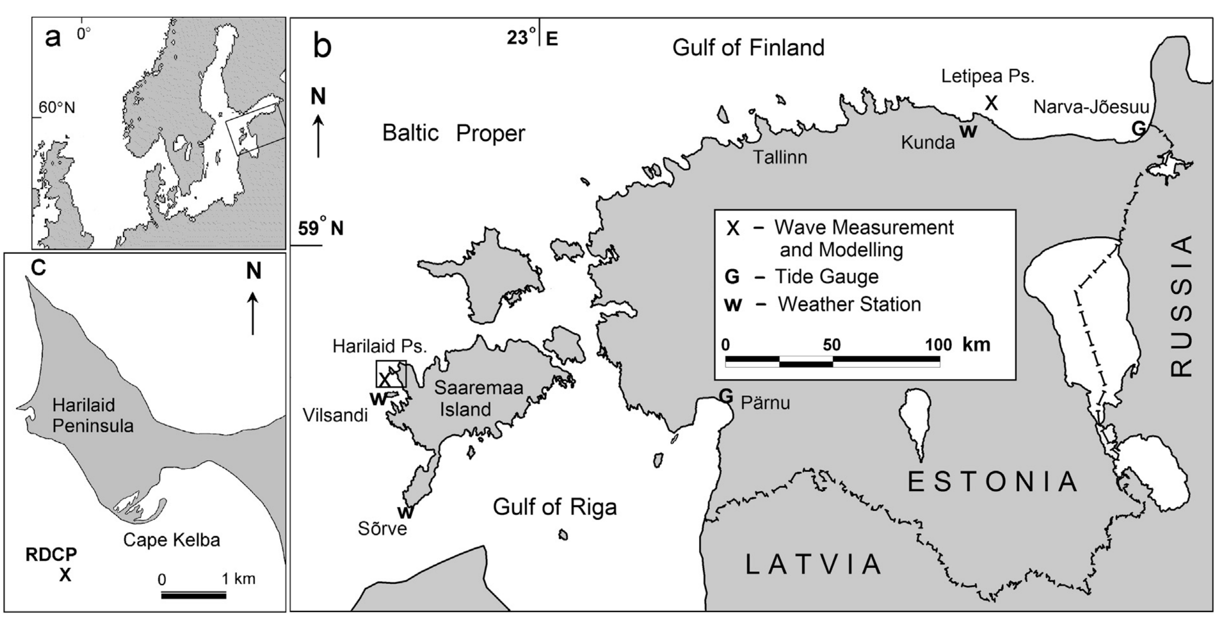

Fig. 1. Map of the study area with the sea level, wind and wave observation sites.