Still normal? Near-real-time evaluation of storm surge events in the context of climate change~~Still normal? Contextualizing real-time data with long-term statistics to monitor anomalies and systematic changes in storm surge activity - Introduction of a prototype web tool storm surge monitor for the German coasts~~

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Abstract. Storm surges represent a major threat to many low-lying coastal areas in the world. In the aftermath of an extreme event often discussions develop, in which the extent to which the event was unusual and the potential contribution of climate change in shaping the event are debated. Commonly analyzes that allow for such assessments are not available right away but are only provided with often considerable time delay. To address this gap, a new tool was developed and applied to storm surges along the German North and Baltic Sea coasts. The tool integrates real-time measurements with long-term statistics to put ongoing extremes or the course of a storm surge season into a climatological perspective in near-real-time. The approach and the concept of the tool are described and discussed. To illustrate the capabilities, exemplarily several cases from the storm surge seasons 2018/2019 and 2019/2020 are discussed. It is concluded, that the tool provides support in near-real-time assessment and evaluation of storm surge extremes. It is further argued, that the concept is transferable to other regions and/or coastal hazards.~~While most places can cope with or are more or less adapted to present-day risks, future risks may increase from factors such as sea level rise, subsidence, or changes in storm activity. This may require further or alternative adaptation and strategies. For most places, both forecasts and real-time observations are available. However, analyses of long-term changes or recent severe extremes that are important for decision-making are usually only available sporadically or with substantial delay. In this paper, we propose to contextualize real-time data with long-term statistics to make such information publicly available in near real-time. We implement and demonstrate the concept of a "storm surge monitor" for tide gauges along the German North Sea and Baltic Sea coasts. It provides automated near real-time assessments of the course and severity of the ongoing storm surge season and its single events. The assessment is provided in terms of storm surge height, frequency, duration, and intensity. It is proposed that such near real-time assessments provide added value to the public and decision-making. It is further suggested that the concept is transferable to other coastal regions threatened by storm surges.~~

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1 Introduction

For many low-lying coastal areas, storm surges represent a substantial threat. While many of the affected places can typically cope with or are more or less well-adapted to present-day risks, future risks may increase from, for example, mean sea level rise, subsidence, or changes in storm activity (e.g. von Storch et al. 2015; Wahl et al. 2017). This may, in the future, require additional protection or alternative adaptation strategies.

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Storm surges and the h~~H~~igh water levels at the coast associated with them are typically caused by the ~~combination and interaction~~interplay of different factors. These include, for example, ~~the~~ high astronomical tides, the effects of strong winds pushing the water towards the coast (wind or storm surge), or seasonal, interannual, and long-term mean sea level changes. Depending on the region, nonlinear interaction among the different factors occurs and may substantially contribute to the extremes and enhance the risks (Arns et al.~~,~~ 2017). For example, in shallow water, the efficiency of the wind in producing the surge may vary substantially with tidal water levels (phase of the tide), and the propagation of the tidal wave may~~ in turn~~, in turn, depend on surge levels (Horsburgh and Wilson~~,~~ 2007).

The

e~~E~~xtreme sea levels that result~~resulting~~ from such processes pose a major risk to many of the low-lying coastal areas worldwide that are at least seasonally affected by storms (von Storch et al. 2015). So far, t~~T~~he most deadly and devastating storm surges were caused by tropical cyclones. Examples comprise the storm surges generated by the 1970 Bhola Cyclone in Bangladesh that caused approximately 300,000 casualties or by the 2005 Hurricane Katrina ~~storm surge~~ which represents one of the most ~~costly~~ expensive natural disasters in U.S. history (Needham et al.~~,~~ 2015).
Extratropical storm surges, although less severe, still bear a substantial threat (e.g. Weisse et al. 2009; Weisse et al. 2012).

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In the mid-latitudes, the German ~~parts of the~~ North ~~Sea~~ and Baltic Sea coasts are examples of such regions and are highly susceptible to the impacts of extreme sea levels. For instance, in 1953 and 1962 two major disasters occurred at the North Sea coast. Both flooded several thousand hectares of land and ~~killed~~ caused several hundred or thousands of ~~people~~ casualties (Gönnert and Buß~~,~~ 2009; Hall~~,~~ 2013). In 1872, the Danish and the German Baltic Sea coasts were devastated by an extreme storm surge, which still represents the highest on record in many areas (Feuchter et al.~~,~~ 2013).

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Since then, coastal defenses at the German coasts ~~was~~ were improved significantly. Particularly ~~in~~ at the North Sea coast, higher storm surges than those reported in 1953 and 1962 were observed in more recent years. For example, ~~the~~ a storm surge in January 1976 caused higher water levels than in 1962 at many gauges along~~t~~ the German North Sea coast while~~.~~ in December 2013~~In the recent past,~~ the extratropical storm Xaver ~~in 2013~~ caused exceptionally high water levels along the ~~entire~~ coast~~line~~ and within the estuaries ~~of Lower Saxony~~ (Deutschländer et al.~~,~~ 2013; Rucińska~~,~~ 2019)~~, including the cities of Hamburg and Bremen~~. However, c~~C~~ontrary to the devastating events ~~of~~ in 1953 and 1962, ~~later extremes caused~~ no severe damages or casualties were reported due to ~~significantly~~ the reinforced ~~improved~~ coastal protection. Due to the latter, public perception of vulnerability and risk has decreased in recent years (Ratter and Kruse~~,~~ 2010). Nevertheless, the risk still exists, and it may further increase in the expected course of anthropogenic climate change (e.g. Gaslikova et al.~~,~~ 2013; Wahl~~,~~ 2017; Weisse et al.~~,~~ 2014).

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For the German North Sea coast, there is a considerable number of studies analyzing either variability and/or long-term changes in extreme sea levels (e.g. Dangendorf et al.~~,~~ 2014). Such studies focus on either the description of past and present (e.g. Weisse and Plüß~~,~~ 2006) or possible future (e.g. Gaslikova et al.~~,~~ 2013) variability and change in general or link them to some driving mechanisms (e.g. Woodworth et al.~~,~~ 2007). Studies based on observations (Dangendorf et al.~~,~~ 2014), ~~as well as on taking~~ modeling approaches (e.g. Vousdoukas et al.~~,~~ 2016; Woth et al.~~,~~ 2006), or statistical~~s~~ approaches (e.g. Butler et al.~~,~~ 2007) do exist. The main conclusion from the majority of ~~these~~ such studies is that extreme sea levels along the German North Sea coast have increased over the past about 100 years. Primarily, this is suggested to be the~~a~~ consequence of the rising mean sea level. Changes in the wind climate (e.g. Krieger et al. 2021) produced some interannual and decadal variability but no noticeable trend (e.g. Weisse et al., 2012). Changes in the tidal regime may also have contributed to some extent (e.g. Hollebrandse~~,~~ 2005).

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For the Baltic Sea, ~~several~~ numerous studies carried out similar analyses. Based on gauge records, most authors concluded that no significant ~~observed~~ increases in extreme Baltic Sea levels have been observed so far (e.g. Richter et al. 2012; Meinke 1999; Mudersbach and Jensen 2008; Weisse et al. 2021). ~~are mainly due to corresponding increases in the mean sea level of about 10–15 cm within the last century (Marcos and Woodworth, 2018; Meinke, 1999; Ribeiro et al., 2014; Weisse and Meinke, 2016).~~ Some of the northernmost gauges, however, deviate from that picture due to decreasing relative mean sea levels caused by Glacial Isostatic Adjustment (GIA) of the Earth's crust and changes in atmospheric wind patterns (Barbosa~~,~~ 2008; Ribeiro et al.~~,~~ 2014; Weisse et al. 2021). Strong correlations of Baltic Sea level variability with the large-scale atmospheric circulation are reported as well (Hünicke and Zorita~~,~~ 2006; Karabil~~,~~ 2017; Karabil et al.~~,~~ 2017). For the future, however, present studies indicate a further increase in extreme sea levels mainly in response to a further rising mean sea level, while storm-related contributions exhibit considerable uncertainty with the upper bound suggesting an increase of up to a few decimeters (e.g. Vousdoukas et al.~~,~~ 2017; Weisse et al.~~,~~ 2012; Weisse et al. 2021). At some places, the figure may be modified substantially ~~modified~~ by vertical land motions such as subsidence or uplift (e.g. Ribeiro et al.~~,~~ 2014; Richter et al.~~,~~ 2012).

Because of the existing risk and the expected future developments

~~For decision-making~~, information on long-term changes in storm surge activity is of utmost importance for decision making (e.g. Kodeih~~,~~ 2019; Kodeih~~,~~ et al.~~,~~ 2018; Weisse et al.~~,~~ 2015). Mostly, detailed local information is ~~requested~~required, and ~~–~~evaluation and assessment ~~the contextualization~~ of ~~the~~ ongoing storm surge activity in the context of long-term variability and climate change ~~is~~ are increasingly requested~~asked for~~ (e.g. Meinke~~,~~ 2017; Weisse et al.~~,~~ 2019~~20~~). This includes, for example, questions on physically plausible upper limits (Weisse et al. 2019), on probabilities for co-occurrences of storm surges and other hazards (e.g. river floods in estuaries), or, often in the immediate aftermath of an event, on the extent to which this event was "normal" or can be attributed to anthropogenic influences such as climate change. The latter requires evaluating and assessing ~~contextualizing~~ events in near-real-time within a detection and attribution framework. This comprises both, the assessment of~~; that is, to first provide information on~~ how usual or unusual an event has been (detection) and the ~~second to~~ attributione~~e~~ of causes to unusual~~unusable~~ cases (attribution) (e.g. Hegerl~~,~~ 2010). ~~Unfortunately~~Typically, ~~the update of~~ such information becomes available~~occurs more or less sporadically~~ with some delay after a severe event or is provided in~~at~~ regular~~specific~~ ~~time~~ reports published in intervals in the order of years. From our experiences in collaborating with decision-makers and other stakeholders, we suggest that near-~~–~~real-time availability of such localized information and its contextualization may provide substantial added value to ~~professional~~ regional stakeholders and~~or~~ the public discussion in general. Moreover, ongoing monitoring can detect changes in long-term statistics at an early stage.

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In the following, we present a~~n~~ novel ~~approach~~ tool to map and monitor coastal hazards in a detection and attribution framework and describe ~~on~~ how such information may be contextualized and can be made publicly available in near-~~-~~real-time. To start with, t~~T~~he ~~approach~~ tool is ~~initially~~ developed for storm surges along the German North and Baltic Sea coasts and it initially focuses on detection only. We propose that the approach can be easily transferred to other regions and extended to other variables and/or attribution. In s~~S~~ection~~.~~ 2, the tool and its concept are described ~~we introduce the~~

~~approach,~~ which in the following will be shortly referred to as *s~~S~~torm s~~S~~urge m~~M~~onitor*. In t~~T~~his section also ~~describes~~ the data and~~,~~ methods used~~,~~ together with the presently implemented ~~and functionalities~~features are described. In s~~S~~ection~~.~~ 3, the long-term statistics~~development of storm surge activity at the German coasts is analyzed~~ are discussed that provide the background against which ongoing events and seasons are assessed. Additionally, in section 4 cases from two recent seasons are discussed to illustrate the use of the tool for the evaluation and contextualization of storm surge events.~~Moreover, it exemplarily provides a retrospective analysis of the storm surge seasons 2018/19 and 2019/20.~~ The results are summarized and d~~D~~iscussed~~ion and summary are provided~~ in s~~S~~ection~~.~~ 5~~4~~.

2 The s~~S~~torm s~~S~~urge m~~M~~onitor

2.1 General c~~C~~oncept

Information on sea level extremes is typically available and used in several different ways. For example~~,~~ real-time data are used to monitor ~~and forecast~~ extremes ~~; that is,~~ to ~~be~~ support the preparedness and ~~to~~ protection of inhabitants, assets, and infrastructures in~~of~~ coastal regions. Potential long-term changes, which need to be assessed to adopt risk management procedures or coastal protection measures, are typically not assessed in real-time~~,~~ but become available only at fixed time intervals (typically several years) or in the aftermath of an exceptionally extreme case when specific analyse~~i~~s have~~s~~ been carried out. Assessment and evaluation of extremes aiding the public and scientific debate regarding the extent to which such events~~they~~ were unusual ~~and if they may serve as examples of ongoing long-term changes is~~are therefore ~~only~~ possible only with considerable delay. ~~How can these two different sources of information be linked together in near real-time?~~ To address this gap~~issue~~, we propose a concept in which real-time measurements are put~~ting~~ into context with observed long-term conditions; that is, their statistics such as mean conditions, variability, expected extremes, or long-term changes, in near-real-time. By minimizing delays between the occurrence of extremes and their climatological assessment, we propose to add value to the ongoing public and scientific debates. ~~monitoring and assessing ongoing storm surge seasons and their single events.~~

The concept was implemented and tested in a prototype web tool, which in the following is referred to as *s~~S~~torm s~~S~~urge m~~M~~onitor* (or short~~ly~~ as the *m~~M~~onitor*) and which is available in both, a German (https://sturmflut-monitor.de) and an English (https://stormsurge-monitor.eu) version~~ in the following~~. The tool is based on and monitors~~It was developed for~~ several frequently considered

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~~measures~~ parameters describing the storm surge climate such as the height, frequency, duration, or intensity of extreme events. Both, single events and entire storm surge seasons are evaluated against the climatological averages and t~~T~~heir long-term changes.~~, seasonal and single event assessments are provided. The Monitor is available in both English (www.stormsurge-monitor.eu) and German (www.sturmflut-monitor.de).~~

2.2 Tide gauge data

We used historic and real-time water level measurements from 10 tide gauges along~~data from~~ the German North ~~Sea~~ and Baltic Sea coasts and their estuaries (Figure 1) to set up the m~~M~~onitor.~~ Based on the availability of historical and real-time data, in total 10 tide gauges along the German North and Baltic Sea coasts were selected (Fig. 1).~~

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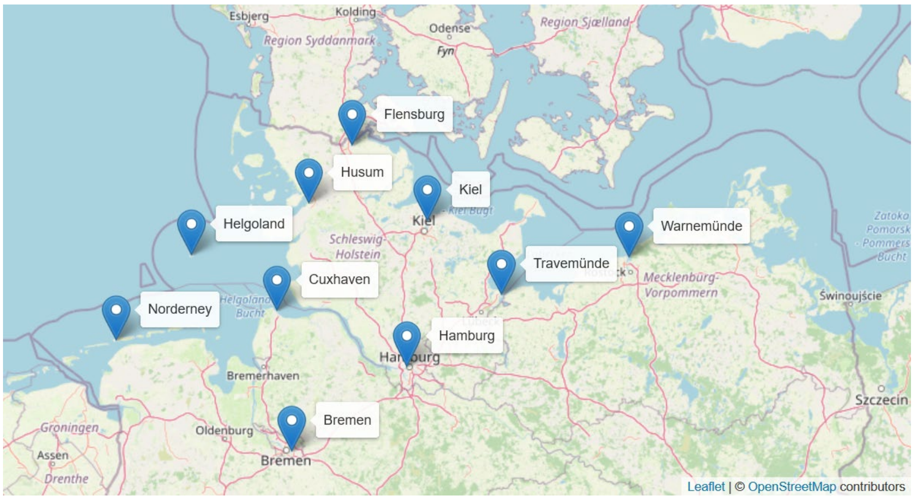

~~**Figure 1.** Location of the tide gauges. (Credit: Leaflet | Maps © OpenStreetMap contributors. Distributed under a Creative Commons BY-SA License)~~

The data processing workflow is illustrated in Figure~~.~~ 2. ~~Two types of data, historical and real-time, were used.~~ The historic~~al tide gauge records~~data were used to derive long-term statistics while the real-time data were used to describe and measure the ongoing events. For the historic data, t~~T~~he available record length, temporal resolution, and source of the data vary (Table 1). Depending on thate ~~data availability and the record length~~, we either used twice-daily high water level or hourly data. ~~While the advantage of using~~When hourly data were available, ~~is the ability to provide~~ information on the duration and intensity of extreme events could be derived.~~,~~ On the other hand, the maxima of extremes may be underestimated due to the sampling frequency. Only tide-gauges with available records starting not later than the 1950s were selected.

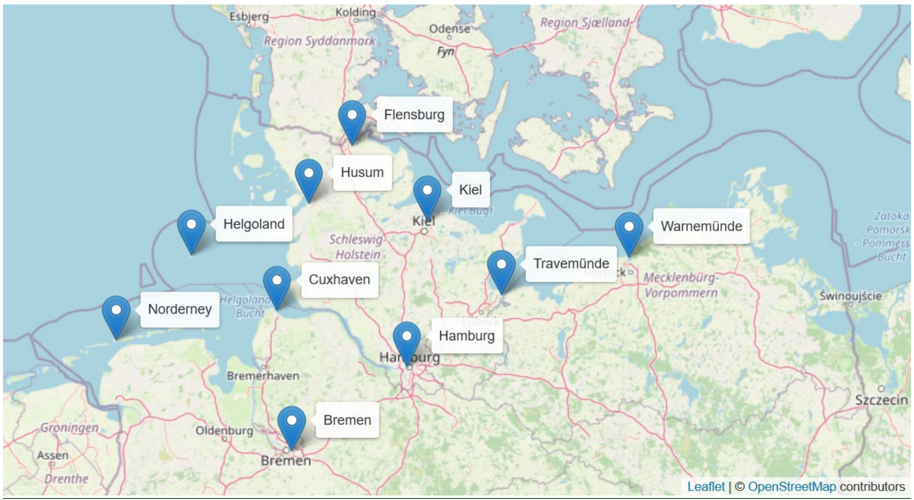

Figure 1. Locations of the tide gauges used in the monitor. (Credit: Leaflet | Maps © OpenStreetMap contributors. Distributed under a Creative Commons BY-SA License.)

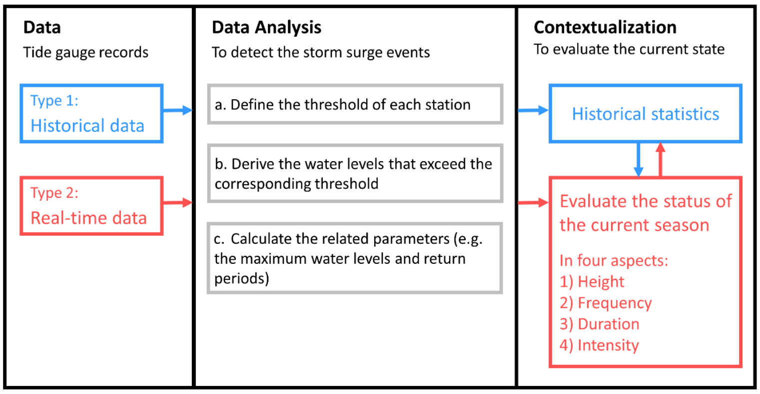

Figure 2. Schematic diagram of the data processing workflow.

Table 1. Summary of the tide gauge records used to calculate the long-term statistics.

Tide gauge	Period	Temporal resolution	Data source

Husum	1936–2018	High water	German Federal Waterways and Shipping Administration (WSV), provided by the German Federal Institute of Hydrology (BfG)
Helgoland Binnenhafen	1953–2018	High water	WSV, provided by BfG
Cuxhaven	1901–2018	High water	WSV, provided by BfG
	1919–2018	Hourly	University of Hawaii Sea Level Center (UHSLC) (*Caldwell et al.*, 2015)
Hamburg St. Pauli	1951–2019	High water	WSV, provided by BfG
Bremen Weserwehr UW	1954–2019	High water	WSV, provided by BfG
Norderney	1901–2018	High water	WSV, provided by BfG and the Coastal Research Station~~Center~~ (FSK) of the Lower Saxony State Agency for Water, Coastal and Nature Conservation (NLWKN)
Flensburg	1955–2019	Hourly	WSV, provided by BfG
Kiel-Holtenau	1955–2019	Hourly	WSV, provided by BfG
Travemünde	1950–2018	Hourly	WSV, provided by BfG
Warnemünde	1954–2018	Hourly	WSV, provided by BfG

~~To assess the characteristics of the ongoing storm surge season and the severity of the latest events, the real-time data are needed.~~ Real-time data for all tide gauges are ~~For this, the data~~ available every minute and are automatically fetched four times daily from PEGELONLINE (https://~~www.~~pegelonline.wsv.de) ~~were used~~. They ~~were~~ are subsequently ~~automatically fetched four times daily and~~ resampled to either ~~to~~ high water levels or hourly values depending on and matching the temporal resolution ~~the~~ of ~~availab~~available~~ility of~~ historical data at each tide gauge. All tide gauges measure

~~The observed water level from tide gauges is measured~~ relative to a land-based reference frame (relative sea level) and the data contain~~s~~ contributions from atmospheric and oceanic dynamics as well as from solid Earth processes (Stammer et al.~~,~~ 2013). As ~~For coastal management,~~ it is ~~the~~ relative sea level that is important for coastal management and protection (Rovere et al.~~,~~ 2016; Stammer et al.~~,~~ 2013), ~~.~~ i~~I~~n our analyses~~,~~ the data are therefore intentionally not decomposed or detrended to retain contributions from sea level rise or subsidence.

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2.3 Near real-time ~~information delivery~~data processing and information provision

To ensure ~~fast~~ near-real-time information provision~~delivery~~, the m~~M~~onitor is automatically updated four times ~~a~~ daily~~y~~ ~~(~~at 1:30, 7:30, 13:30, and 19:30 CET~~)~~. When the water level within the last fetched period ~~at any gauge~~ exceeds a ~~given~~ gauge-specific threshold, a new storm surge event at this particular gauge is ~~recognized~~detected. ~~Accordingly~~Subsequently, new plots are automatically generated to provide the latest information ~~about~~ and a near-real-time assessment of the event and its long-term and seasonal contextualization. While the~~is near real-time~~ availability of such an assessment represents the major purpose of the m~~M~~onitor, it has some limitations ~~on the other hand~~caused by potentially undetected errors in the real-time data. Since ~~the~~ real-time data are normally raw data from measurements, it is possible and unavoidable that, for example, due to instrument failures during a storm no or only erroneous~~urnes~~ data are accessible, which could ~~potentially~~ then affect the detection and classification of an extreme. Also, other technical problems ~~could~~ can occur that ~~,~~ lead~~ing~~ to unusable values over extended periods~~ that can last for hours or months~~. For example, the tide gauge at Norderney experienced a technical problem from May to September 2018. The measurements during that period ~~are~~ were initially invalid with randomly high, ~~/~~low, or missing values~~ or no value at all~~, and ~~the~~ a corresponding notification ~~of the incorrect measurements~~ was posted on the PEGELONLINE website. To deal with such erroneous data in near-~~real~~ real-time, a quick quality control algorithm was implemented that marks and removes ~~values~~ measurements whose absolute values of minute~~e~~ increments exceeded~~were higher than~~ 0.3 m (spikes) or had ~~and~~ values that were not within a reasonable range of ~~(~~1–12 m~~)~~. When updated quality controlled data become available, new plots are produced and figures and assessments may~~ thus~~ change compared to the initial near-~~ to the near~~ real-time assessment.

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2.4 Detection of storm surge events

~~To identify and assess the severity of storm surges, the first step is to~~An important step in detecting and assessing storm surges is the ~~defin~~definition of~~e~~ corresponding ~~the~~ thresholds for the extremes. For the German North and Baltic Sea coast, t~~T~~here are two~~various~~ different methods ~~defining the threshold of storm surge~~used in practice. The DIN 4049-3 defines a storm surge as an event in which regionally defined thresholds are exceeded. These thresholds are defined such that an event with a specific severity can be expected on average once for a given period, e.g. the once in a 20-year event (DIN 4049-3 1994). For their forecasts and to issue public storm surge warnings, on the other hand, the German Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie, BSH) uses uniform exceedance thresholds ~~and in research, e.g. from the DIN 4049 (DIN 4049-3, 1994) or from the Federal Maritime and Hydrographic Agency of Germany (Bundesamt für~~

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~~Seeschifffahrt und Hydrographie, BSH) (Gönnert, 2003). The definition from the DIN 4049 is based on the statistical probability of occurrence, while the one from BSH~~ for larger regions (Gönnert 2003)~~is relatively simple to understand and more related to the public, as the BSH is responsible to issue a public warning.~~ ~~of storm surges.~~ While each method has advantages and disadvantages~~Therefore~~, the ~~definition~~ thresholds from the BSH were~~as~~ used in this study as they are used in public warnings. Accordingly, f~~F~~or the German North Sea coast, a storm surge event is detected when the water level exceeds the local mean tidal high water level (MThw, Table 2) by at least 1.5 m. The event is subsequently further classified as a severe or very severe event when its maximum water level exceeds the MThw by at least 2.5 m or 3.5 m. Because of the different atmospheric and oceanographic conditions, storm surges at the German Baltic Sea coast are divided into four classes. Events ~~of~~ in which the maximum water level exceeds the mean water level (MW) by 1.00~~–1.25~~ m are referred to as storm surge events. Events with water levels of 1.25–1.50 m above MW or 1.50–2.00 m above MW are referred to as medium or severe events. Cases in which the maximum water level is higher than 2.00 m above MW are referred to as very severe events. While for routine practices, MTHws and MWs are regularly updated, we used fixed values ~~In the Monitor, the MThw at the North Sea and the MW at the Baltic Sea tide gauges were~~ calculated over ~~the~~ the ~~standard~~ common reference period 1961–1990 (Table 2) so that events at all gauges can be compared, changes over a longer period can be monitored, and results are presented relative to a fixed reference.~~ defined by the World Meteorological Organization (WMO) so that all events (past and present) at each gauge refer to the same reference (Table 2).~~ ~~Also~~In the following, the period 1961–1990 is referred to as the reference period in the analyses.

Table 2. ~~L~~M~~ist of the m~~ean tidal high water levels (MThw) and ~~the~~ mean water levels (MW) ~~(~~in m relative to the German reference level NHN (Normalhöhennull~~)~~) of the reference period 1961–1990 for the tide gauges along the North Sea and Baltic Sea coasts.

North Sea		Baltic Sea	
Tide gauge~~s~~	MThw	Gauge~~s~~	MW
Husum	1.58 m	**Flensburg**	-0.02 m
Helgoland Binnenhafen	1.07 m	**Kiel-Holtenau**	0 m
Cuxhaven	1.46 m	**Travemünde**	0.02 m
Hamburg St. Pauli	1.93 m	**Warnemünde**	0 m
Bremen Weserwehr UW	2.47 m		
Norderney	1.14 m		

2.5 Definition of storm surge seasons~~ and statistical analyses~~

At the German North Sea and Baltic Sea coasts, storm surge activity is most pronounced in the winter season from October to March (Jensen and Müller-Navarra~~,~~ 2008). In the m~~M~~onitor, the period from July to June of the following year was therefore used to define and characterize a storm surge season.~~,~~ ~~and all analyses and statistics were computed based on these seasons.~~ Each storm surge season is denoted by the year in which the season ends~~ to indicate the latest possible information~~. For instance, the period from July 2018 to June 2019 is referred to as season 2018/19 and marked as 2019 in the ~~annual~~ plots. The course of a storm surge season and the monthly distributions are also derived and shown from July to June of the following year. When the ongoing season ends, new long-term statistics are automatically computed, in which the statistics of the ~~terminated~~ concluded season will be included.

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~~The steps of data processing are shown by the second column entitled Data Analysis in Fig. 2. The first step is to derive the threshold of each gauge. Then, storm surge events are detected when water levels exceed the corresponding threshold. It is possible to have multiple threshold exceedances or pauses during one event. For this, we use a de-cluster interval of four hours to separate one event from another. To estimate the probabilities of storm surges, we apply the generalized extreme value (GEV) distribution to the annual maximum values (Hennemuth et al., 2013). The parameters of the distribution (location, scale, and shape) are derived by using the maximum-likelihood estimation (MLE). A wide range of the commonly used statistical distributions and methods exists for extreme value studies, such as the Gumbel distribution together with block (annual) maxima method, or the Generalized Pareto distribution (GPD) together with a peak over threshold approach (e.g. Muis et al., 2016; Wahl et al., 2017). All these methods have their own merits and can provide good estimations of extreme values. Thus, the selection among the methods is often a trade-off and largely depends on the purpose of the study. As one type of the GEV, the Gumbel distribution has only two parameters (location and scale) and is often used in global-scale research, while a known limitation is that it could underestimate or overestimate the high end of extreme values (Buchanan et al., 2017; Wahl et al., 2017). In this regard, the GEV and GPD are more flexible shaped to better represent the extreme values. Both distributions are considered to have stable and reliable performance for tide gauges along the German coast, while the GPD is suggested when the dataset is short (Arns et al., 2013). Studies have compared various sampling methods in detail, varying the block maxima method with r-largest sampling and the peak over threshold~~

~~method with different threshold selection (Arns et al., 2013; Wahl et al., 2017). The annual maxima method is used in this analysis because it is robust to temporal and spatial variations as well as suitable for the region. The annual maximum is defined as the maximum water level that occurs in an annual period, which is a storm surge season in this analysis.~~

2.6 ~~Structure of the Monitor and m~~Main ~~functionalities~~features presently implemented

The m~~M~~onitor ~~consists~~ was implemented for~~of~~ ten tide gauges so far. ~~Six~~ Four of them are located at the German North Sea coast, two of them in the Elbe and Weser estuaries, and four of them ~~are~~ along~~t~~ the German Baltic Sea coast (Figure 1). ~~The map (Fig. 1) of the Monitor is interactive, so users can access the information by clicking on the tide gauges.~~ For each tide gauge, a~~On the~~ web page is generated ~~of a particular tide gauge, users can view~~providing figures, texts, and interpretations ~~that~~ illustrating~~e~~ (a) the average conditions during the reference period and (b) their long-term ~~development~~ trend. Recent storm surges are contextualized within the long-term development and the ongoing storm surge season is compared to the reference period. ~~of storm surge activity and Underneath each figure, we provide a brief caption and an example interpretation to assist users in reading the figures.the characteristics of the current season in comparison to the historical seasons and long-term statistics.~~ Depending on the availability of ~~real-time and~~ historical data ~~availability~~, different measures and statistics are available~~ccessible~~ for each tide gauge ~~via the navigating items~~. Information on storm surge height and frequency is presented for all gauges, while information on their duration and intensity is provided only for the gauges where~~ith~~ historic hourly data exist (~~, i.e.,~~ Cuxhaven, Flensburg, Kiel, Travemünde, and Warnemünde). To illustrate the main features of the monitor, the figures of the season 2019/20 at the tide gauge Cuxhaven are discussed exemplarily.

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2.6.1 Storm surge height

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~~For each measure, two figures are displayed: the first one shows the time development of that measure over the past few decades, and the second one allows an assessment on whether or not the current storm surge season can be considered unusual when compared to the long-term statistics of the past seasons. Underneath each figure, we provide a brief caption and an example interpretation to assist users in reading the figures. These elements complement each other to reveal a comprehensive description and contextualization of the ongoing storm surge season and recent events.~~

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~~To illustrate the main functionalities of the Monitor, the figures of season 2019/20 at the tide gauge Cuxhaven are discussed exemplarily (Figs. 3 to 5).~~ t~~T~~wo ~~important~~ height indicators ~~addressing the height of extremes are assessed~~is provided, the development of ~~namely~~ the annual maximum water

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level over time and the return period of extremes (Figure~~.~~ 3). Specifically, the maximum water level of the current season (red dot) is compared with the variations of the annual maxima of the previous seasons (black curve) (Figure~~.~~ 3a). The plot allows for ~~a ~~quick visualization of the observed long-term changes and the extent to which the highest water level in the~~an~~ ongoing season is unusual. For easy visualization, the current season is highlighted in all the annual plots by ~~the ~~a vertical red-dotted line. The gray line provides an estimate of the linear trend with the gray shaded area representing the 95~~ ~~% confidence interval. The trend line is shown in solid when the estimated trend is significantly different from zero at the level of 95~~ ~~% and dashed otherwise. The scale on the left axis is labeled as water level relative to the German reference ~~surface ~~level (Normalhöhennull, NHN), while the right axis is labeled ~~in reference to~~about the severity classification of storm surges (water level relative to MThw for the North Sea coast or relative to MW for the Baltic Sea coast).

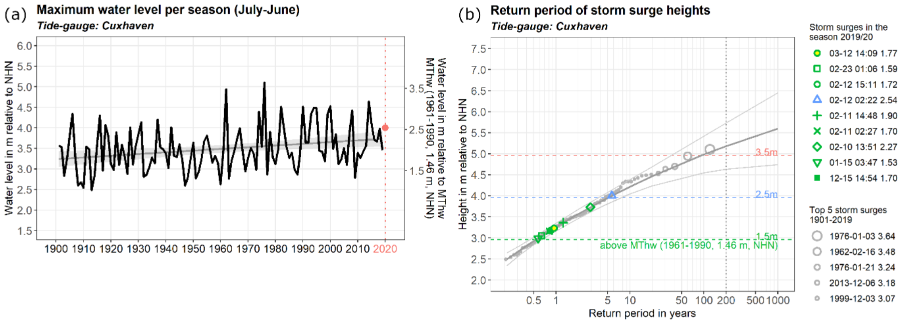

Figure 3. (a) Maximum water level per storm surge season (past seasons – black; ongoing season – red) in m (left ordinate: relative to NHN; right ordinate: relative to the MThw of the reference period) and corresponding~~its~~ linear trend at Cuxhaven~~. The trend~~ (gray line) together~~is shown~~ with the 95 % confidence interval (light gray band). ~~and as a solid line when it is significant at the level of 95 %. The red dot denotes the maximum water level observed in the current season (season 2019/20 here).~~ (b) Return periods of storm surge~~s~~ events at Cuxhaven from the past (gray symbols) and the ongoing season (colored symbols; ~~. The events of the current season are marked by colored symbols according to their heights and the respective severity classifications (~~green – minor; blue – severe; red – very severe events) together with the~~. The~~ estimated distribution (dark gray curve) and the corresponding ~~of the annual maxima (gray points) over the previous seasons was derived using the generalized extreme value (GEV) distribution and the maximum-likelihood estimation (MLE). The gray band shows the ~~95 % confidence band (area between the light gray curves) derived from past annual maxima.~~ interval~~ ~~of the estimation.~~ The events of the ongoing season and the top five severe

historical events in the available period ~~are represented by gray open circles with size indicating their magnitudes~~are listed on the right.

The second plot provides ~~an~~ estimates of the return periods of the storm surges that have~~s~~ occurred in the current ongoing season (Figure~~.~~ 3b). Return periods are widely used to estimate the likelihood and severity of extreme events (e.g., Haigh et al.~~,~~ 2015; Wahl et al.~~,~~ 2017). To estimate the return period of storm surges, we fitted a generalized extreme value (GEV) distribution to the annual maximum values (Hennemuth et al. 2013). Here annual maxima refer to the block maxima within the historic storm surge seasons. The parameters of the distribution (location, scale, and shape) were derived by using the maximum-likelihood estimation (MLE).

~~For example, if an event is referred to as a one in a hundred years event, this means that such an event has a 1:100 (1 %) chance of happening in any given year, no matter when the last similar event has happened.~~ Figure 3b displays the extreme value distribution (dark gray curve) estimated from the historical ~~-~~data for Cuxhaven together with its 95~~-~~% confidence interval (two light gray lines). ~~derived by fitting a GEV to the observed annual maxima.~~ This fit is subsequently used to evaluate the return period of the latest (ongoing) storm surges in near-~~-~~real-time. When an event occurs, ~~it will~~ a colored symbol whose color denotes its severity (green – minor; blue – severe; red – very severe) is added. Additionally, an entry ~~be placed~~ on the top of the list of current events is generated (right)~~the current season list and marked by a colored symbol whose color denotes its severity (green – minor; blue – severe; red – very severe)~~. In the example season (Figure 3b), ~~two minor~~several smaller events with return periods of less than five years and a larger event with a return period between about 5-10 years can be identified ~~(Fig. 3b)~~. To further put the recent events into perspective, a list of the five severest historical events during the available period (seasons 1901–2019 here) is given ~~underneath~~ below the list of events of the current season. These are represented by gray open circles with different sizes indicating their magnitudes.

2.6.2 Storm surge frequency

Similarly, two plots assessing the frequency of storm surges ~~from a long-term perspective and within the current season~~are generated (Figure~~.~~ 4).~~.~~ ~~For~~ To visualize the long-term development, variability, and change~~perspective~~, the number of storm surges per season over time is shown together with its trend (Figure 4a). Generally, in all plots, a trend that is/is not different from zero at the 95% confidence

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level is shown by a solid/dashed line~~(Fig. 4a)~~. The severity of the events is marked with different colors to ~~show~~ illustrate the number of events in the different severity classes in each season. ~~The~~ Again the current season is ~~also~~ highlighted in red ~~as in Fig. 3a~~. While still ongoing, it ~~could~~ can already and preliminarily be put into context with previous seasons, long-term variability, and change.

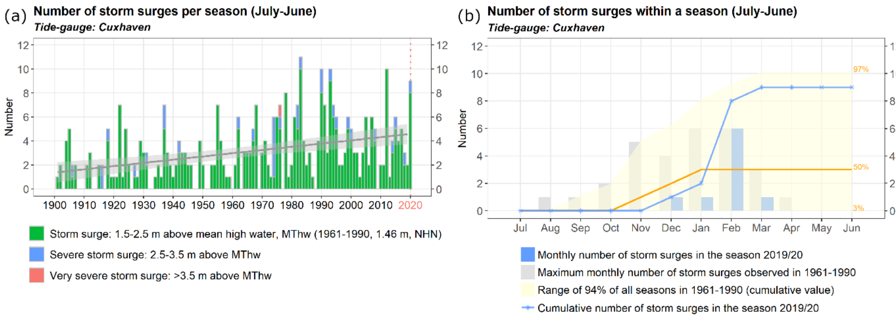

Figure 4. (a) Number of storm surges per season (colored bars; green – minor; blue – severe; red – very severe) and corresponding~~its~~ linear trend (gray line) together with the 95% confidence band (gray shaded) at Cuxhaven. ~~The color of the bars denotes the degree of severity (green – minor; blue – severe; red – very severe). The trend (gray line) is shown with the 95 % confidence interval (light gray band) and as a solid line when it is significant at the level of 95 %. The current season (season 2019/20 here) is highlighted with the red dotted line.~~ (b) Development of the ongoing storm surge season illustrated by the n~~N~~umber of storm surges per month (blue) and their sum since the onset of the season (blue line)~~within a season (July–June)~~ at Cuxhaven. For contextualization, also ~~Bars: the monthly number in the current season is shown as blue bars, and t~~the historical monthly maximum number of events (gray bars) and the 50th percentile (orange curve) and the range between the 3rd and 97th percentiles (yellow shaded area) from the cumulative number of events in the reference period 1961–1990 ~~is shown as~~are ~~gray bars~~ shown. ~~Curves: the cumulative number of events in the current season is shown as a blue curve, in comparison with the 50th percentile (orange curve) and the range of the 3rd and 97th percentiles (yellow shaded area) over the reference period.~~

The second plot (Figure~~.~~ 4b) was designed to illustrate the course of the~~an~~ ongoing season. It can be used to assess, f~~F~~or example, if the onset of a storm surge season was~~is~~ very early or late, if there was~~is~~ an unusual number of events within a particular month, or if the whole season is unusually active or inactive compared to the average ~~in terms of frequency and~~ annual cycle. For this, ~~The analysis is shown for a storm surge season from July to June of the following year.~~ t~~T~~he number of events in each month of the current season (blue bars) can be~~is~~ compared with the maximum number of events in

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the corresponding month over the reference period (1961–1990, gray bars). Further, t~~T~~he blue curve shows the cumulative number of events from the beginning of the ~~a particular~~ current season until the day of the website visit. It can be compared to t~~T~~he reference ~~is~~ given by the 50th percentile (orange curve) and the range between~~from~~ the 3rd and ~~to~~ the 97th percentiles (yellow shaded area) of the reference period. For example, when the blue curve remains below the orange one, this indicates that fewer events than usual were observed so far. If t~~T~~he blue curve is above the orange line but still within the yellow shaded area, this suggests that the frequency of such a season is still within a normal range but already belongs to the more active ones~~seasons~~. If the blue curve exceeds the yellow shaded area, indications for an exceptionally active season do exist.

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2.6.3 Storm surge duration and intensity

In addition to storm surge height and frequency, duration and intensity are widely used measures to describe the characteristics of storm surges (Cid et al.~~,~~ 2016; Zhang et al.~~,~~ 2000) that ~~because height/frequency and duration/intensity of events do not necessarily share a similar variability even though they are related to some extent. Moreover, these two measures~~ are also important from the perspective of coastal protection and risk ~~assessment~~ management (e.g., Kodeih et al.~~,~~ 2018). Therefore, information on ~~duration and intensity statistics are~~both measures was included in the m~~M~~onitor, although ~~they~~ it can only be provided for ~~some~~ those tide gauges where long-term hourly data were~~are~~ available. In the following analyses, duration denotes the number of hours for which the water level exceeds the given storm surge threshold, while intensity refers to the area between the water level measurements and the storm surge threshold and has units of meter × hour.

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Regarding storm surge duration~~, in particular~~, the seasonal sum is a key indicator for coastal erosion. ~~On the other hand, looking at single events~~Regarding intensity, the maximum intensity of storm surges in a season is also critical for potential damages ~~at~~ to coastal infrastructure.

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I~~Thus,~~ n the monitor, the total duration and the maximum intensity of storm surges in each season are both shown ~~from~~ within a long-term context~~perspective~~ (Figure 5~~s. 5a and 5b~~). In both cases, t~~T~~he current season is highlighted with an orange bar to be easily separable from the previous seasons (gray bars). Assessment of ~~the~~ single events within a season can be derived~~is~~ from~~provided in~~ Figures~~s.~~ 5c, d ~~and 5d,~~ in which the events of the current seasons~~events~~ (red dots) are shown relative to the monthly distributions derived from historical data. The historical reference (blue) is illustrated in the form of a box plot bounded by the 3rd and 97th percentiles. The median is given by the solid horizontal blue line, and the historical maximum in each month is denoted by the blue dot. Assessment can be obtained from the relative positions of the red dots, which indicate whether an event lasted longer or was more intense in comparis~~i~~on to the monthly statistics of the reference period.

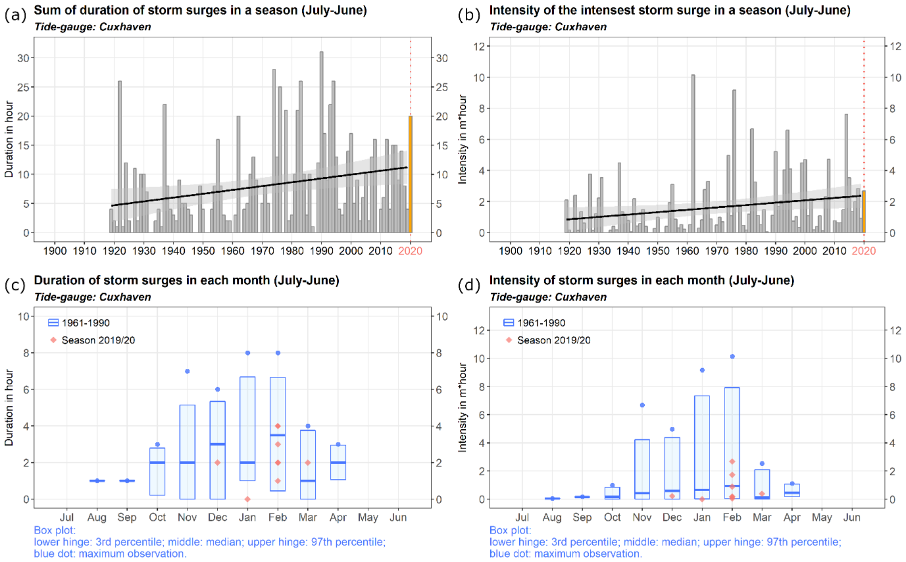

Figure 5. (a, b) Total duration and maximum intensity of storm surges per season at Cuxhaven for past (gray bars) and the ongoing (orange bar) s~~. The gray bars represent the past s~~easons together~~,~~ ~~while the orange bar denotes the current season (season 2019/20 here). The~~ with the linear trend (black line) and~~is~~ ~~shown with~~ the 95~~-~~% confidence interval. ~~and as a solid line when it is significant at the level of 95 %.~~ (c, d) Box plots for~~of~~ monthly~~the~~ duration and ~~the~~ intensity of storm surges in the reference period (blue box: 3rd to 97th percentile; blue line: median; blue point: maximum) together with the events of the ongoing season (orange). ~~in each month at Cuxhaven. Blue shows the statistics (the 3rd, 50th, 97th percentiles, and the maximum) of the events in each month of the reference period 1961–1990, while the red dots signify the events of the current season.~~

3 Long-term changes

In this section, the capabilities of the monitor in supporting assessments of long-term changes are briefly illustrated.~~3 Contextualizing real-time storm surge data with long-term statistics~~

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~~In this section, we demonstrate the capabilities of the Monitor by analyzing the long-term development over the available periods and the two recently concluded storm surge seasons, namely the seasons 2018/19 and 2019/20. Comparing the seasons, both in time and spatially as well as putting them into context with the historical distributions and changes, several inferences can be made. First, the anomalies and systematic changes in storm surge activity at each gauge can be inferred, which also reflects local differences among the tide gauges. Second, the consistency between the observed anomalies and the long-term trend is evaluated in order to distinguish between randomly active seasons and active seasons that exemplarily fit into the long-term development. Third, differences between the North Sea and Baltic Sea coasts can be inferred, which reflect the different key processes and their settings contributing to the storm surges.~~

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3.1 North Sea coast~~ (incl. Elbe and Weser)~~

3.1.1 ~~Long-term development of storm surges~~Height

~~Height~~

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~~Annual ~~The annual maximum water level increased at all~~ selected North Sea~~ tide gauges over the available periods (e.g. Figures~~s.~~ 3a, ~~ and ~~6). Except for Helgoland, the trends are significantly different from zero at the 95~~-~~% confidence level. The mean increase of the annual maximum water level since 1950 is about 20–40 cm at the coastal gauges and about 60–10~~8~~0 cm at the estuarine gauges Bremen and Hamburg~~ and Bremen~~. The reasons for the ~~increasement ~~increases are still discussed in the literature~~not fully explored,~~ but are~~it~~ likely~~could be~~ to be the result of the interplay between several factors, such as mean sea level rise, variability in the wind climate, astronomical tide cycles, and the implementation of ~~hydro ~~hydro-engineering measures with different contributions at the coast and in the estuaries (e.g. von Storch and Woth 2008; von Storch et al. 2008; Hein et al. 2021; Jensen et al. 2021).

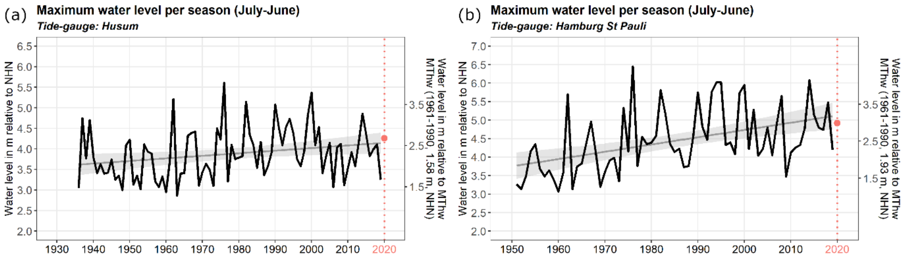

Figure 6. A~~Maximum water level per season same a~~s Fig. 3a but for the tide-gauges Husum (a) ~~Husum~~ and ~~(b)~~ Hamburg St. Pauli (b).

Although the trends are positive, the annual maximum water level strongly varies ~~from~~ between seasons ~~to season~~ and from gauge to gauge. ~~In general, the annual maximum water levels are lower at Cuxhaven, Helgoland, and Norderney, while they are higher at Husum, Hamburg, and Bremen.~~ Among the gauges, either the storm surge of February 1962 (Helgoland, Bremen, and Norderney) or the storm surge of January 1976 (Husum, Cuxhaven, and Hamburg) is the highest since the beginning of data availability. Among the analyzed North Sea tide-gauges, t~~T~~he highest water level since the 1950s occurred on 3 January 1976 at Hamburg St. Pauli with about 4.5 m above MThw. In the last decade, ~~the~~ a storm surge ~~of~~ in December 2013 represents the highest event. At some gauges (Cuxhaven, Hamburg, Bremen, and Norderney), it is among the five highest events over the available periods.

3.1.2 Frequency

Annual storm surge frequency increased at all gauges (e.g. Figures~~.~~ 4a, ~~and~~ 7). Except for Helgoland, the trends are significantly different from zero at the 95~~-~~% confidence level. In the 1950s, about 1–3 storm surges usually occurred in a season. Over the past few decades, the annual number of storm surges has increased by about one at Helgoland and Norderney, and it has nearly doubled at Husum and Cuxhaven. At the estuarine gauges, storm surge frequency has increased even more strongly. On average, there are about five times as many storm surges per season nowadays as there were in the 1950s. In addition to the positive trends, the number of events also varies from season to season and from gauge to gauge. In general, there are fewer events at Helgoland, Cuxhaven, and Norderney, while events occur more frequently at Husum, Hamburg, and Bremen. This may be due to differences in the specific configuration of the coastline and bathymetry relative to the prevailing wind direction during storm surges that make a location more or less susceptible to storm surges (e.g. Gönnert 2003) but also partly an effect of the common threshold used to detect surges in the monitor (see section 2). ~~In~~

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~~the 1950s, about 1–3 storm surges usually occurred in a season. Over the past few decades, the annual number of storm surges has increased by about one at Helgoland and Norderney, and it has nearly doubled at Husum and Cuxhaven. At the estuarine gauges, storm surge frequency has increased even more strongly. On average, there are about five times as many storm surges per season nowadays than there were in the 1950s.~~

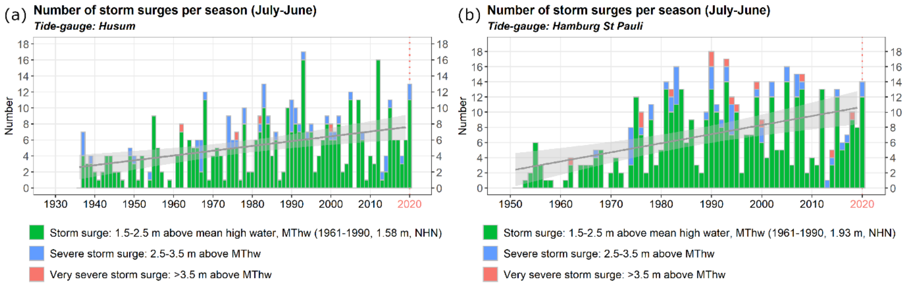

Figure 7. ~~Number of storm surges per season same a~~As Fig. 4a but for the tide-gauges ~~(a)~~ Husum (a) and ~~(b)~~ Hamburg St. Pauli (b).

3.1.3 Duration and intensity

Due to the limited availability of high temporal resolution data, the statistics for storm surge duration and intensity can only be evaluated for Cuxhaven. As introduced in s~~S~~ection~~.~~ 2.6.3, the total duration of all events in a season and the intensity of the most intense event in a season are evaluated (Figures~~.~~ 5a, ~~and 5~~b). For both measures, upward trends significantly different from zero could be inferred. Specifically, both measures have about doubled since the 1920s. The annual total duration increased from about 5 ~~h~~ hours to 12 hours, and the annual maximum intensity increased from about 1 meter × hour ~~m h~~ to about 3 meter × ~~m~~ hour. This is likely caused by an increase in mean sea level that raised the baseline upon which wind-induced fluctuations act rather than a change in storm climate (e.g. Weisse et al. 2012; Weisse and Meinke 2016). Averaged over the reference period, the mean values of the total duration and the maximum intensity were about 10 hours and 2 meter × ~~m~~ hour~~h~~, respectively.

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3.2 Baltic Sea coast

3.2.1 Height

At the German Baltic Sea coast, the annual maximum water levels show strong variability over the available period. Linear trends within this period vary in their signs from gauge to gauge and because of the strong interannual variability, none of the trends is significantly different from zero at the 95% confidence level (Figure 8). This is consistent with the results based on annual data, which cover a longer period (e.g. Meinke, 1999). Although no significant changes in the extremes could be detected, the mean sea level has increased along the German Baltic Sea coast (e.g., Weisse and Meinke 2016; Weisse et al. 2021) and is expected to rise further in the future (e.g., Grinsted 2015; Hieronymus and Kalén 2021). Therefore, it is likely that the annual maximum water levels may increase in the future as well. Thus, ongoing monitoring is important, although no significant trends in the annual maxima water level could be detected so far.

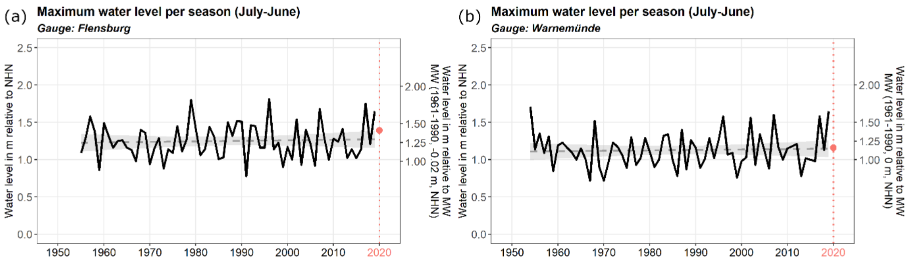

Figure 8. As Fig. 3a but for the gauges Flensburg (a) and Warnemünde (b).

Over the past seven decades, the annual maximum water level varies between about 0.7 m and 2.0 m above MW at the analyzed gauges. The average maximum water level is around 1.2 m above MW. The data in the monitor do not include the highest storm surge at the German Baltic Sea coast that occurred on 13 November 1872 (Jensen and Müller-Navarra 2008; Rosenhagen and Bork 2009; von Storch et al. 2015; Weisse and Meinke 2016) and for which only limited reliable measurements are available. According to these, the maximum water level was about 3.3 m above MW (e.g. Jensen and Müller-Navarra 2008) along the southwestern coast of the Baltic Sea. This is much higher than any extreme event that occurred later in this region. Since the 1950s, none of the water levels at the analyzed Baltic Sea gauges exceeded 2 m above MW (Figure 8). However, this value was nearly hit in Travemünde on 4 January 1954 when the water level reached a value of 1.97 m above MW and in Kiel on 4 November 1995 when the water level reached a maximum of 1.96 m above MW (not shown).

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3.2.2 Frequency

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The storm surge frequency at the analyzed Baltic Sea gauges shows pronounced interannual and decadal variability. Over the available periods since the 1950s, the frequency varies between zero and nine events. Except for Warnemünde, all gauges show a maximum of events observed in the season 1989/90 (e.g. Flensburg, Figure 9a). In Warnemünde the highest number of events in a season was five and was observed in 2001/02 (Figure 9b). Trends in storm surge frequency are not significant at all gauges (e.g. Figure 9). As mean sea level increased over the period (e.g. Weisse et al. 2021), in-significant trends in the extremes may be due to the large inter-annual variability in the extremes that hamper detection in relatively short records. Overall, that the storm climate over the area does not show significant trends (e.g. Weisse et al. 2021). This result is consistent with other studies analyzing different periods (e.g. 1883–1997 in Meinke 1999 and 1948–2011 in Weidemann et al. 2014) and in which the effects of mean sea level rise have been excluded. Moreover, the wind climate over the Baltic Sea shows large inter-decadal variability: For the last six decades, an increase in the number of days with westerly components has been detected during winter (Gräwe et al. 2019; Lehmann et al. 2011), while days with easterly winds have decreased (Gräwe et al. 2019). Since storm surges in the southwestern Baltic Sea are mainly connected with strong easterly winds, this variability in wind climate could further contribute to the in-significant trends in storm surge activity since 1950, against the background of rising mean sea level.

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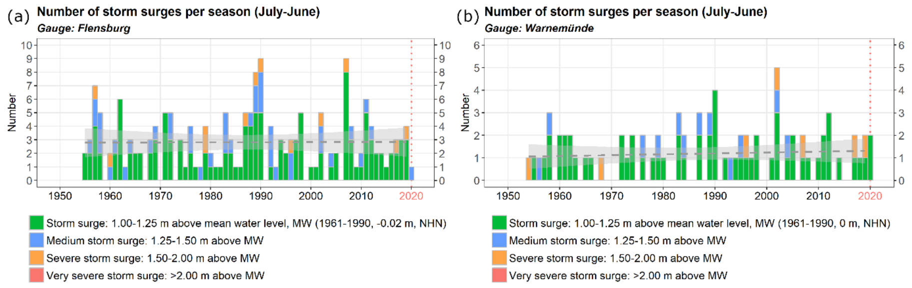

Figure 9. As Fig. 4a but for the gauges Flensburg (a) and Warnemünde (b).

3.2.3 Duration and intensity

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Information on duration and intensity can be derived at all selected Baltic Sea gauges since hourly data are available. The total duration and the maximum intensity of storm surges per season show strong variabilities. Trends at all gauges vary around zero and are not statistically different from zero at the 95% confidence level (Figure 10). This is consistent with the findings from other studies that analyzed data from model hindcasts over different periods (e.g., Weidemann et al. 2014).

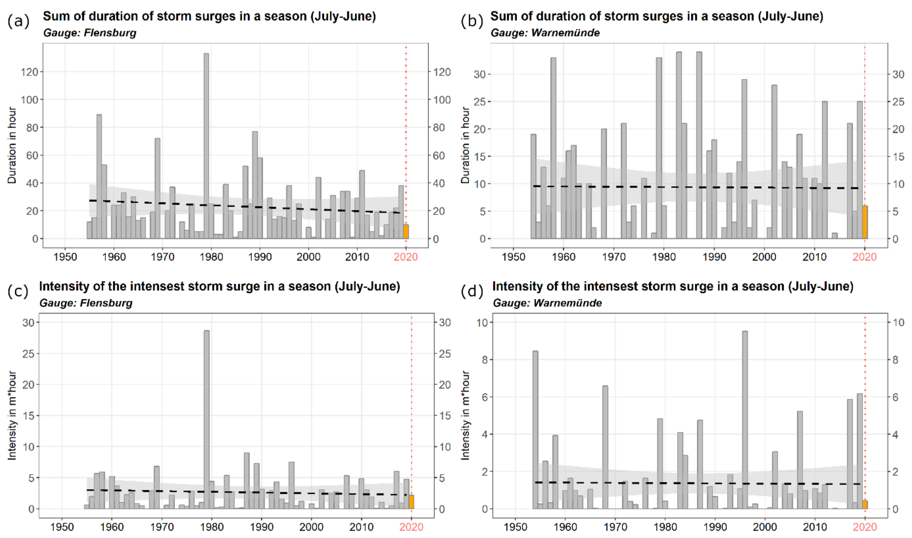

Figure 10. Top: As Fig. 5a but for the gauges Flensburg (a) and Warnemünde (b). Bottom: As Fig. 5b but for the gauges Flensburg (c) and Warnemünde (d).

4 Evaluation of recent storm surge seasons

In this section, cases from two recent storm surge seasons (2018/19 and 2019/20) are exemplarily discussed to illustrate the capabilities of the monitor in aiding the identification of unusual events and/or seasons together with regional differences.

4~~3~~.1~~.2~~ North Sea coast~~Assessment of the two seasons 2018/19 and 2019/20~~

4.1.1 Height

In season 2018/19, the annual maximum water levels at all gauges fell into the lowest category of severity (1.5–2.5 m above MThw) (e.g. Figures 3a,~~.~~ 6). This immediately implies that all events observed in the season were minor (green marks in Figs. 11~~8~~a, ~~and 8~~b). Except for Husum, the highest event in the season occurred on 8 January 2019, and its return period varies between about 1 and 3 years depending on the tide gauge ~~(e.g. about 1 year for Hamburg in Fig. 8b)~~. For Helgoland and Norderney, this was also the only event ~~observed~~ detected in this~~e~~ season using the thresholds

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defined in section 2. It should be noted that the use of different thresholds (e.g. DIN 4049-3 1994) can lead to different results. At other gauges, m~~M~~ore events ~~occurred~~ were registered~~at other gauges~~, but they only slightly exceeded the lowest threshold~~s~~ (e.g. Husum and Hamburg in Figures~~.~~ 11~~8~~a,~~ and 8~~b). On average, such ~~minor~~ events may occur several times a year ~~about twice a year, which are normal for these gauges in~~and the season 2018/19 was not unusual in terms of storm surge height.

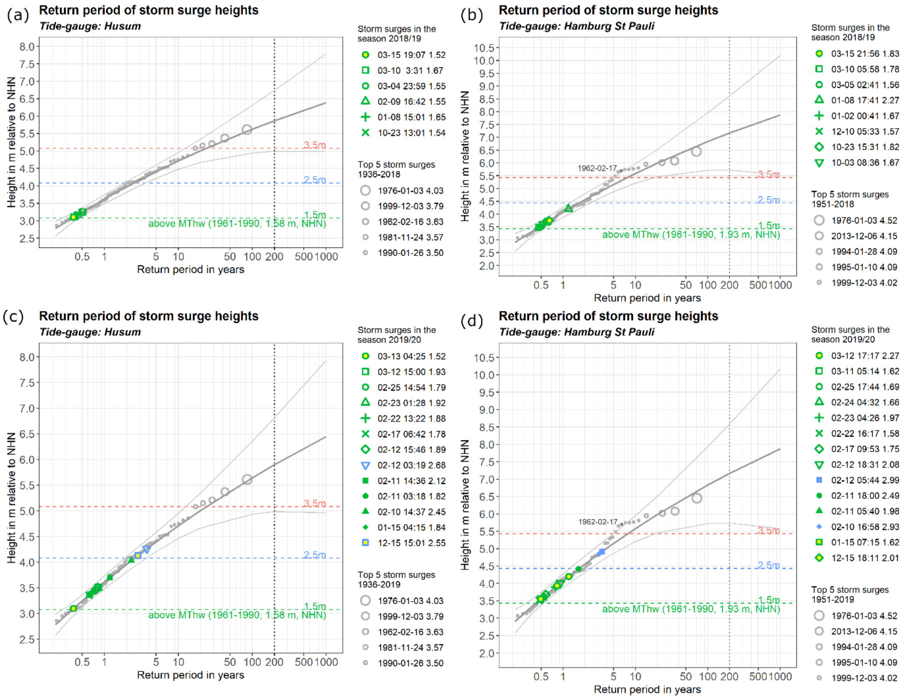

Figure 11~~8~~. ~~Return period of storm surges same a~~As Fig. 3b but for the tide-gauges Husum (a, c) ~~Husum~~ and ~~(b, d)~~ Hamburg St. Pauli (b, d). ~~(~~T~~t~~op: season 2018/19; b~~b~~ottom: season 2019/20~~)~~.

Compared to season 2018/19, higher annual maximum water levels were observed in the following season 2019/20 (Figures 3a,~~.~~ 6). During 10–12 February 2020, the storm Sabine (Haeseler et al.~~,~~ 2020) induced a series of consecutive storm surges. The highest water levels of the season were observed during these days. The estimated return period of the highest event varies from 3 to 8 years at different gauges (~~e.g. about 3.5 years for Husum and Hamburg in~~ Figures~~.~~ 11~~8~~c,~~ and 8~~d). ~~As the maximum water level has increased over the past decades, the highest water levels of the season are consistent with this long-term development. At Helgoland and Husum, the maximum storm surge height may serve as an example of this development since it corresponds to the average of the past~~

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~~years (Fig. 6a).~~ In addition to this series of events, more minor events were ~~observed~~ detected at Husum, Cuxhaven, Hamburg, and Bremen. They are ~~classified~~ categorized as minor events with estimated return periods shorter than one year, indicating that such minor events are common for these gauges. While somewhat more active than the previous season, again the season 2019/20 was not unusual in terms of storm surge height.

4.1.2 Frequency

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In terms of storm surge frequency, the~~se~~ two seasons 2018/19 and 2019/20 differ ~~are~~ significantly ~~different from each other~~. In season 2018/19, storm surge frequency is around the average frequency of the reference period. A total of one or two events was observed at Cuxhaven (Figure 4a), Helgoland~~,~~ ~~Cuxhaven~~, and Norderney (not shown~~Fig. 4a~~), whereas six ~~or eight~~ events were observed at Husum (Figure 12a) and eight events at~~,~~ Hamburg (Figure 12b), and Bremen (not shown~~Fig. 7~~).

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In season 2019/20, the number of events was at least ~~doubled~~ twice as high at five ~~out~~ of the six tide gauges. Especially, the number of 13 events at Husum is remarkable and exceeds the 3-97 percentile of the reference period (Figure 9c). The season ranks among the top three in terms of~~highest~~ storm surge frequencies at this gauge (Figure~~.~~ 7a). ~~As the storm surge frequency has increased over the past decades, the higher storm surge frequency of this season is consistent with the long-term development. However, even compared to the mean annual frequency of the recent years, the number of storm surges in this season was much higher.~~

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A look at the course of the season and the long-term average reveal~~s the reference shows~~, that the first storm surges usu~~s~~ally occur~~s~~ in November or December, and the majority ~~most storm surges~~ occur between November and February (Figure~~.~~ 12~~9~~). The course of the season 2018/19 broadly followed this development along the long-term median (Figures~~s.~~ 12~~9~~a, ~~and 9~~b). For some gauges ~~where~~ frequencies eventually exceeded the long-term median, but the values remained well~~are still~~ below the ~~corresponding~~ 97th percentiles~~s~~. Moreover, the numbers of events in the individual months were nowhere~~t~~ exceptional.

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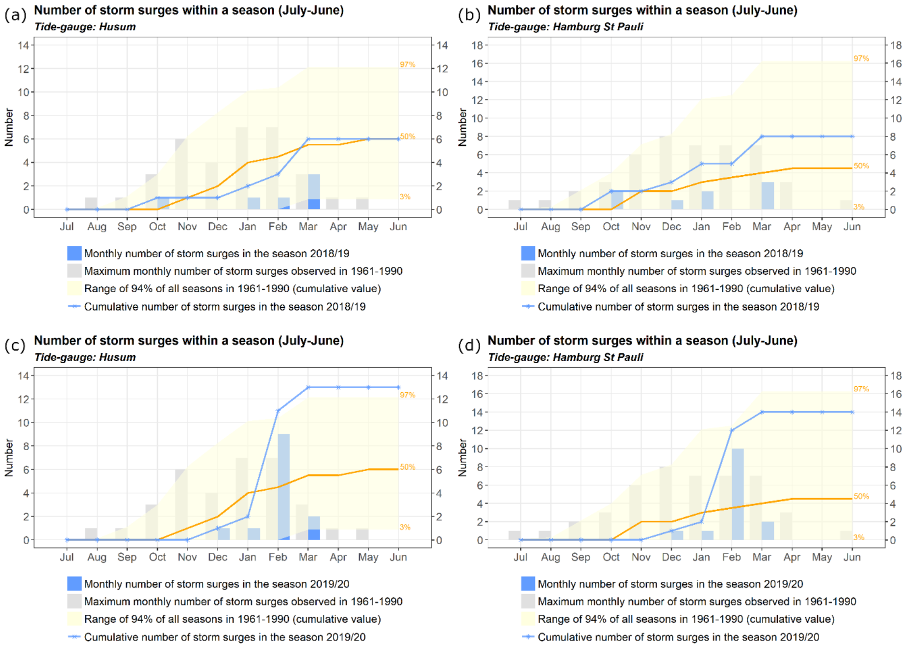

Figure 12~~9~~. ~~Number of storm surges within a season (July–June) same a~~As Fig. 4b but for the tide-gauges ~~(a, c)~~ Husum (a, c) and ~~(b, d)~~ Hamburg St. Pauli (b, d). ~~(T~~top: season 2018/19; bottom: season 2019/20~~)~~.

In contrast, the season 2019/20 was substantially different. The season initially started late~~ initially~~, and the storm surge frequencies~~y~~ were~~as~~ moderate and mostly below the long-term median. This character substantially changed in February when the storm Sabine caused a ~~record~~ large number of events within a relatively short period (Figures~~.~~ 12~~9~~c, ~~and 9~~d). For example at Husum, nine events (five of which were caused within only about two days~~by Sabine~~) were ~~observed~~ registered in February 2020~~ at Husum,~~ which exceeds~~ed~~ the maximum of seven events ~~over the reference period~~detected so far in February (Figure~~.~~ 9c~~a~~). Consequently, the cumulated number of events in the season ~~exeeds~~exceeds the ~~normal~~ 3-97% range and the season eventually represented~~; thus, it is~~ a~~n~~ rather unusual season in terms of storm surge frequency although their height was mostly moderate.~~for Husum. Interestingly, this series of events occurred shortly after the conclusion of the project EXTREMENESS, which considered such a series as an unlikely event with potentially large consequences (Schaper et al., 2020; Weisse et al., 2020).~~

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4.1.3 Duration and intensity

The two ~~consecutive~~ storm surge seasons also differ in terms of their total duration and their maximum intensity. This is demonstrated exemplarily for Cuxhaven (Figure~~.~~ 5). ~~In season 2018/19~~Here, both measures were ~~below the averages of the reference period, while they were~~ significantly higher in the season 2019/20,~~.~~ e~~E~~specially ~~for~~ the total duration.~~,~~ ~~long storm surge hours (20 h) occurred in season 2019/20, which could be attributed to a few long lasting events and/or~~In this case, this can be attributed to the unusually~~a larger~~ large number of shorter events in this~~a~~ season (see ~~. As~~ discussioned~~ed~~ above) while the individual events were neither exceptionally intense nor long-lasting (Figures 5c, d)~~, in the case of season 2019/20, this is due to the latter~~. ~~Regarding the long-term increase of storm surge duration at Cuxhaven, the total duration in season 2019/20 corresponds to this development; however, it is much higher than the average of recent years (Fig. 5a). The maximum intensity of the events in the season is 2.7 m·hour (Fig. 5b). This corresponds to the increased maximum intensity of the recent years and is thus exemplary for the long-term development of storm surge intensity at Cuxhaven.~~

~~In season 2018/19, the two minor events in January and in March at Cuxhaven lasted for about three hours and one hour, respectively. The duration and intensity of both events were around the corresponding median (figures not shown here). In season 2019/20, the duration and intensity of the events were also within the normal monthly range (Figs. 5c and 5d). Though more events were observed, only a few in February and the one in March are slightly above the corresponding median. The rest of the events are shorter or less intense than about 50 % of the events observed in the corresponding month over the reference period. In general, the storm surges at Cuxhaven were not exceptionally long or intense throughout both seasons.~~

In summary, for the German North Sea coast~~gauges~~, the storm season 2018/19 ~~can be considered~~represents ~~as~~ a rather typical storm surge season in all aspects. All detected events~~the storm surges~~ were relatively low~~minor events,~~ and their return periods were~~are~~ mostly shorter than one year. Although the number of events at some gauges was~~is~~ slightly above the average level, it is still far from the upper bound defined by the 97th long-term percentile~~of the normal range~~. In contrast, the s~~S~~eason 2019/20 was more active and unusual in some aspects. ~~, i.e., the height, frequency, and total duration of the events.~~ It was characterized by a slow onset, which was more than compensated by an unusual series of events in February. In consequence, the total number of events at the end of the season wa~~i~~s only ~~around~~ slightly below or even above the upper bound of the long-term

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distribution. While the surges were mostly moderate in height~~normal range~~, t~~ and at some gauges it was exceptional from both monthly and seasonally perspectives. T~~he total duration of the storm surges ~~in the season~~ was also doubled compared to the reference period.

~~3.2 Baltic Sea coast~~

~~3.2.1 Long-term development of storm surges~~

~~*Height*~~

~~At the German Baltic Sea coast, the annual maximum water levels show strong variability over the available period. Linear trends within this period vary in their signs from gauge to gauge, and none of them are significantly different from zero at the 95 % confidence level (Fig. 10). This is consistent with the results based on annual data, which cover a longer period (e.g. Meinke, 1999). Since sea level has risen at the German Baltic sea coast (Weisse and Meinke, 2016) and is expected to rise further in the future (Grinsted, 2015), it cannot be excluded that the annual maximum water levels may increase in the future as well. Thus, an ongoing monitoring is important, although no significant trend in annual maximum water level has been found so far.~~

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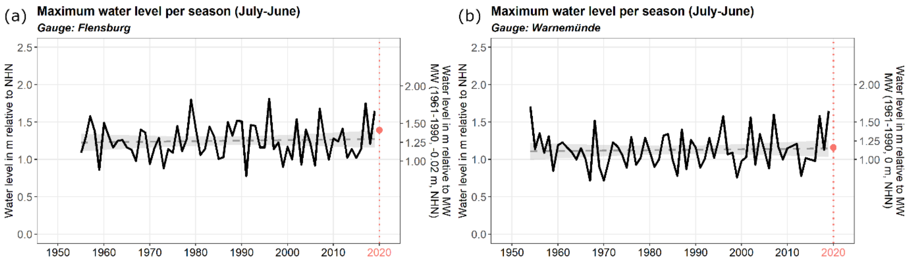
(a) Maximum water level per season (July-June)
Gauge: Flensburg

(b) Maximum water level per season (July-June)
Gauge: Warnemünde

~~**Figure 10.** Maximum water level per season and its linear trend at the gauges (a) Flensburg and (b) Warnemünde. The trend (gray line) is shown with the 95 % confidence interval (light gray band) and as a doted line when it is not significant at the level of 95 %. The red dot denotes the maximum water level observed in the current season (season 2019/20 here).~~

~~Over the past seven decades, the annual maximum water level varies between 0.7 m and 2.0 m above MW at the analyzed gauges. The average maximum water level is around 1.2 m above MW. The highest storm surge at the German Baltic Sea coast since the beginning of the measurements took place on 13 November 1872 (Jensen and Müller-Navarra, 2008; Rosenhagen and Bork, 2009; von Storch et al., 2015; Weisse and Meinke, 2016). The maximum water level was about 3.3 m above MW on the southwestern coast of the Baltic Sea, which is much higher than any extreme event occurred~~

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~~later on in this region. It was a very rare event, which, however, could occur any time again. Since the 1950s, none of the water levels at the analyzed Baltic Sea gauges exceeded 2 m above MW (Fig. 10). However, 2 m above MW was almost reached on 4 January 1954 at Travemünde with a maximum water level of 1.97 m above MW and on 4 November 1995 at Kiel with a maximum water level of 1.96 m above MW. The latter event is among the five highest events at all analyzed Baltic Sea gauges since the 1950s, and it has been the highest event of Flensburg and Kiel since then. At Warnemünde and Travemünde, the highest event in that period has occurred on 4 January 1954.~~

~~*Frequency*~~

~~The storm surge frequency at the analyzed Baltic Sea gauges shows pronounced interannual and decadal variability. Over the available periods since the 1950s, the frequency varies between zero and five events per season at Warnemünde, and between zero and nine events per season at other gauges (e.g. Flensburg and Warnemünde in Fig. 11). On average, there were normally about one event per season at Warnemünde and about two to three at Flensburg, Kiel and Travemünde. At Travemünde and Warnemünde, the storm surge frequency shows a slight but not significant increase over the available periods. This result is consistent with other studies, which analyzed other periods, e.g. 1883–1997 (Meinke, 1999) and 1948–2011 (Weidemann et al., 2014). However, contrary to the Monitor, the impact of sea level rise has been excluded in those studies. At all analyzed gauges, the number of medium storm surges in the last three decades (1991–2020) is lower than in the reference period (1961–1990). In the period of 1991–2020, five severe storm surges occured (in 1995, 2002, 2006, 2017 and 2019). Compared to the reference period, the number of severe storm surges has decreased at Kiel. However, it has not changed at Flensburg (Fig. 11a) and Travemünde and notably increased at Warnemünde (Fig. 11b).~~

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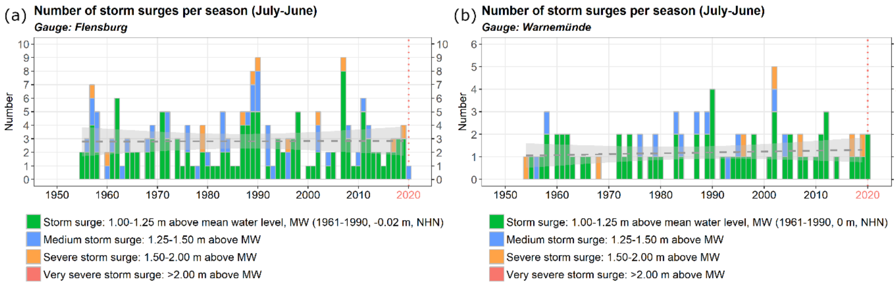

~~**Figure 11.** Number of storm surges per season and its linear trend at the gauges (a) Flensburg and (b) Warnemünde. The color of the bars denotes the degree of severity (green – minor; blue –~~

~~medium; orange – severe; red – very severe). The trend (gray line) is shown with the 95 % confidence interval (light gray band) and as a doted line when it is not significant at the level of 95 %. The current season (season 2019/20 here) is highlighted with the red-dotted line.~~

~~Duration and intensity~~

~~Information on duration and intensity can be derived at all selected Baltic Sea gauges, since hourly data are available. The total duatarion and the maximum intensity of storm surges per season show strong variabilities and slightly negative trends, which are not statisticaly different from zero on a 95% confidence level (Fig. 12). In other studies, the absolute or maximum duration of single storm surges above a certain threshold or within a certain range of different thresholds were analyzed (e.g. Weidemann et al., 2014). These studies show a slight but not significant increase in storm surge duration.~~

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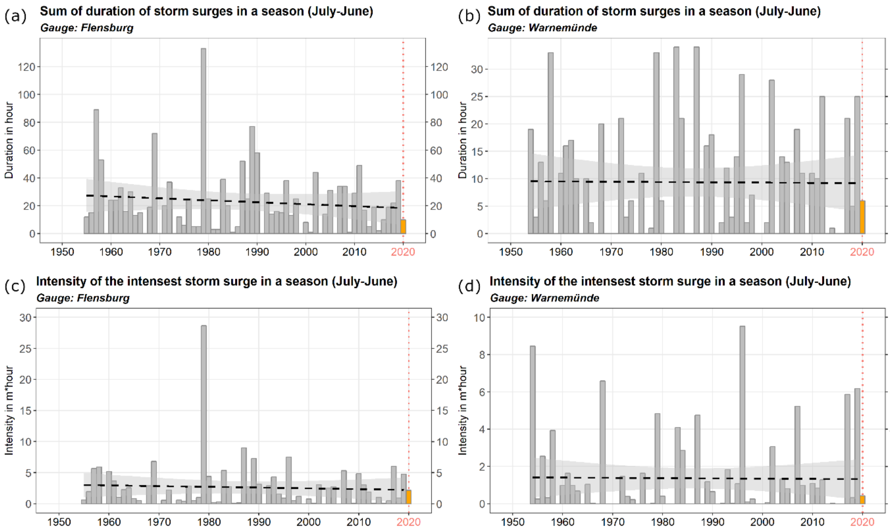

~~**Figure 12.** Total duration of storm surges per season (top) and the intensity of the intensest storm surge per season (bottom) at the gauges (a, c) Flensburg and (b, d) Warnemünde. The gray bars represent the past seasons, while the orange bar denotes the current season (season 2019/20 here). The trend (black line) is shown with the 95 % confidence interval and as a doted line when it is not significant at the level of 95 %.~~

~~The average of the total duration per season is about 20–30 h at Flensburg, Kiel and Travemünde and about 10 h at Warnemünde. The highest total duration per season at Flensburg, Kiel and~~

~~Travemünde occured in season 1978/79, reaching 120–130 h. At Warnemünde, there was no such season with extraordinary long duration of storm surges. Instead, the highest total duration per season lasted 30–35 h, and all these seasons occurred before 1990. The average intensity of the most intense event is about 2–4 m·h. At Flensburg, Kiel and Travemünde, the most intense event during the analyzed period occurred in season 1978/79 with about 20–30 m·h. At Warnemünde, it occurred in season 1995/96 with the intensity of about 10 m·h.~~

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~~3.2.2 Assessment of the two seasons 2018/19 and 2019/20~~4.2 Baltic Sea coast

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4.2.1 Height

Contrary to the North Sea where the two storm surge seasons 2018/19 and 2019/20 were rather similar in height but differed in frequencies, both seasons differed in height in the Baltic Sea with the first season being the stronger one. This illustrates that in both areas different meteorological conditions are required to generate storm surges. The differences between both seasons are sown exemplarily for Flensburg and Warnemünde (Figure 13). ~~Assessing the maximum water levels of the two seasons, it is obvious that the maximum water levels of season 2018/19 are higher than normal at all analyzed Baltic Sea gauges, whereas the maximum water levels of season 2019/20 are close to the averages (e.g. Flensburg and Warnemünde in Fig. 10). Specifically, as shown in Figs. 13a and 13b,~~At both gauges, the highest storm surge in~~of~~ the season 2018/19 occurred on 2 January 2019 and~~, which was induced~~ was caused by the storm Zeetje (Perlet~~,~~ 2019). The maximum water levels reached 1.67 m and~~,~~ 1.65 m respectively ~~, 1.70 m, and 1.65 m above MW~~ at Flensburg ~~, Kiel, Travemünde,~~ and Warnemünde~~, respectively~~. In both cases, the event represented ~~For all gauges, these water levels are classified as~~ severe storm surges ~~(orange mark) in the return period plot (e.g. Flensburg and Warnemünde in Figs. 13a and 13b)~~. In Warnemünde its height was very close to the highest value of 1.71 m in the record and t~~T~~he estimated return period of ~~this severe~~the event in January 2019 was between about~~event is~~ 50–60 years. At the other gauges, the frequency of such events is somewhat larger and the return periods of the January 2019 event vary between ~~at Warnemünde (Fig. 13b)~~ about ~~and~~ 10–20 years. Regarding height, the season 2019/20 was less active with events having return periods well below 5 years (Figure 13).~~at the other three gauges (e.g. Flensburg in Fig. 13a). In addition to this severe event, there were other minor events in this season (green marks). The estimated return periods of these minor events are about 0.5–2 years, which are normal at these gauges.~~

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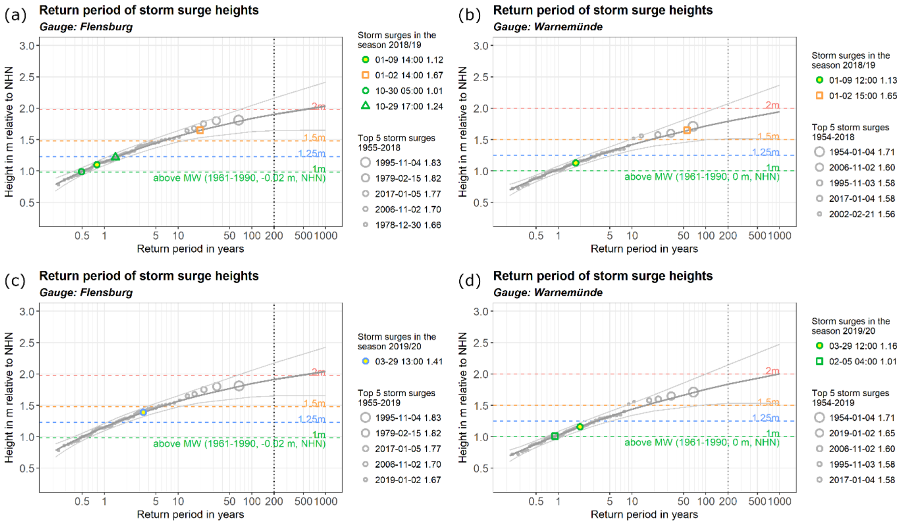

Figure 13. As Fig. 3b but for the gauges Flensburg (a, c) and Warnemünde (b, d) for the seasons 2018/2019 (top) and 2019/2020 (bottom).~~Return period of storm surges at the gauges (a, c) Flensburg and (b, d) Warnemünde. The events of the "current" season (top: season 2018/19; bottom: season 2019/20) are marked by colored symbols according to their heights and the respective four severity classifications (green – minor; blue – medium; orange – severe; red – very severe). The estimated distribution (dark gray curve) of the annual maxima (gray points) over the previous seasons was derived using the generalized extreme value (GEV) distribution and the maximum-likelihood estimation (MLE). The gray band shows the 95 % confidence interval of the estimation. The top five severe historical events in the available period are represented by gray open circles with size indicating their magnitudes.~~

~~In season 2019/20, the maximum water levels of most gauges fall into the second category of severity (1.25–1.50 m above MW) (e.g. Flensburg Fig. 13c), while the maximum water level at Warnemünde is in the lowest category (1.00–1.25 m above MW) (Fig. 13d). This highest event of the season occurred on 29 March 2020 at all gauges. It is classified as a medium storm surge (blue marks) at Flensburg, Kiel, and Travemünde with an estimated return period of 3–4 years. At Warnemünde, it is denoted as a minor storm surge (green mark) with an estimated return period of 2 years. Note that the highest storm surge of the previous season on 2 January 2019 is now on the historical lists of the five highest events at Flensburg and Warnemünde, as the historical lists have been updated automatically when season 2019/20 began (Figs. 13c and 13d).~~

4.2.2 Frequency

In contrast to the North Sea, both seasons in the Baltic Sea were relatively typical in terms of storm surge frequency. This is again shown exemplarily for Travemünde and Warnemünde (Figure 14). While i~~I~~n ~~season~~ 2018/19~~,~~ the storm surge frequency at ~~all analyzed~~both gauges ~~are~~ was slightly above the average of the reference period, in 2019/20 it was below average in Flensburg and above average in Warnemünde. In all cases, values fell within usual ranges, except for the maximum number of surges observed in October 2018 in Flensburg. Note, however, that total numbers are small which makes comparisons less robust. ~~but within the normal range. Taking Flensburg as an example, there were three minor events (green marks) and one severe event (orange mark in Fig. 11) among the four events in the season. With these four events, the storm surge frequency is above the average frequency but still in the normal range (Fig. 14a, blue line above orange line but within the yellow area).~~

~~In season 2019/20, only one event occurred at Flensburg and Kiel, which lables the season less active in comparison to the median over the reference period (e.g. Flensburg in Fig. 14c, blue line below orange line). At Travemünde and Warnemünde, two events were observed, which is equal to the median for Travemünde and above the median of one event for Warnemünde (e.g. Warnemünde in Fig. 14d, blue line above the orange line). This reveals that the same storm surge season can be less active (Flensburg and Kiel), normal (Travemünde) or more active (Warnemünde) at the German Baltic Sea coast, depending on the location of the respective gauge.~~

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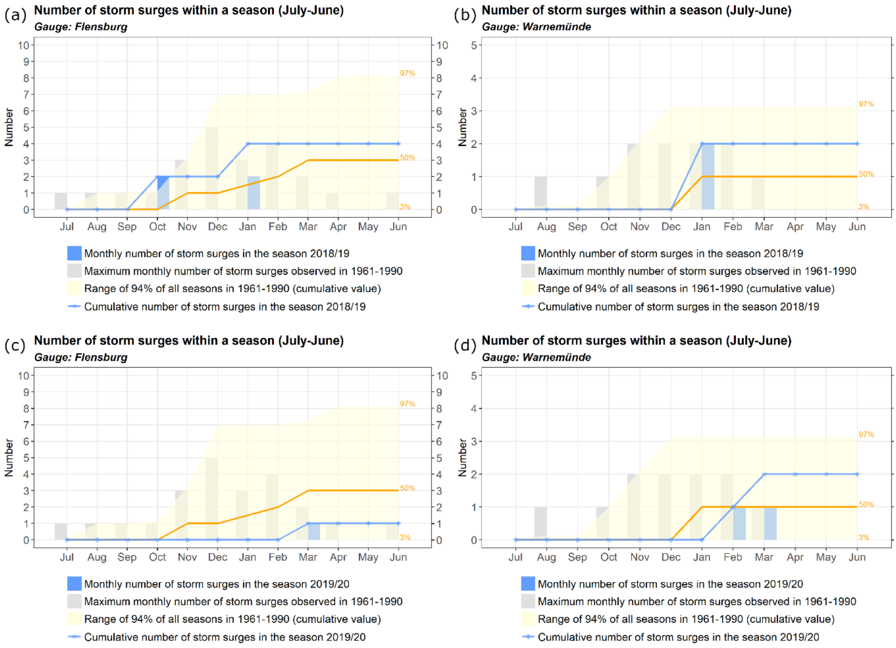

Figure 14. As Fig. 4b but for the gauges Flensburg (a, c) and Warnemünde (b, d) for the seasons 2018/2019 (top) and 2019/2020 (bottom).~~Number of storm surges within a season (July–June) at the gauges (a, c) Flensburg and (b, d) Warnemünde. Bars: the monthly number in the "current" season (top: season 2018/19; bottom: season 2019/20) is shown as blue bars, and the historical monthly maximum in the reference period 1961–1990 is shown as gray bars. Curves: the cumulative number of events in the current season is shown as a blue curve, in comparison with the 50th percentile (orange curve) and the range of the 3rd and 97th percentiles (yellow shaded are) over the reference period.~~

~~As the orange line in Fig. 14 indicates, the first storm surge of a season normaly occurs in November at Flensburg and in January at Warnemünde. The two events in October 2018 at Flensburg indicate a relatively early start of season 2018/19, whereas it was a rather late start in the following season, when the first and only event at Flensburg occurred in March (Figs. 14a and 14c). At Warnemünde, however, it was rather normal for both seasons, with the first event in January and February (Figs. 14b and 14d).~~

4.2.3 Duration and intensity

Contrary to the North Sea, the~~In~~ season 2018/19 was more active than 2019/20 in terms of ~~, the~~ total duration and intensity (~~of storm surges is almost double the average over the reference period (e.g. Flensburg and Warnemünde in~~ Figures~~s~~. 10~~2a and 12b~~). While for the North Sea, the season 2019/20 was outstanding in terms of duration due to a series of moderate events, for the Baltic Sea the season 2018/19 stands out in terms of intensity caused by a major event in January 2019 (Figure 15). In Flensburg also the duration and intensity of the event on 29 October 2918 were exceptionally high (Figure 15a, c). Again this illustrates that different atmospheric conditions are required to trigger storm surges along the German North and Baltic Sea coasts. ~~As discussed in Sect. 3.1.2, long duration could be caused by a few long lasting events and/or many shorter events. In this season, both factors contribute to the long duration. As described above, the storm surge frequency of this season is higher than normal. Moreover, several events lasted longer than the monthly average of the reference period (Figs. 15a and 15b, red dot above the median). The storm surges in October and January also show higher intensity than the monthly average of the reference period (Figs. 15c and 15d).~~

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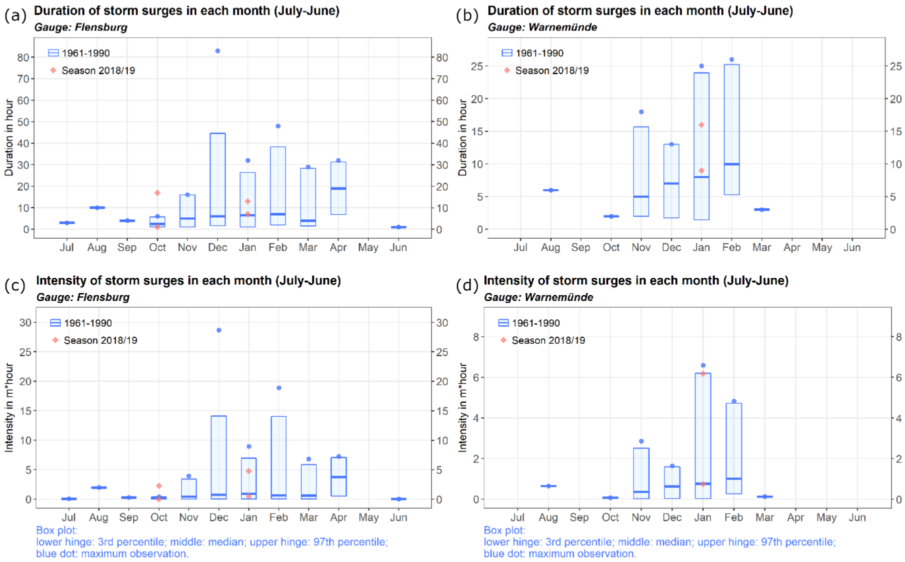

Figure 15. Top: As Fig. 5c but for the gauges Flensburg (a) and Warnemünde (b). Bottom: As Fig. 5d but for the gauges Flensburg (c) and Warnemünde (d).~~Box plot of the duration (top) and the intensity (bottom) of storm surges in each month for season 2018/19 at the gauges (a, c) Flensburg and (b, d) Warnemünde. Blue shows the statistics (the 3rd, 50th, 97th percentiles, and the~~

~~maximum) of the events in each month of the reference period 1961–1990, while the red dots signify the events of the current season.~~

~~In particular, duration and intensity of the severe event on 2 January 2019 are between the corresponding median and the 97th percentile of the January events over the reference period at all gauges, except for the intensity at Warnemünde. As shown in Figs. 15b and 15d, although the duration of the event is not exceptionally long, the intensity was as high as the 97th percentile, as intensity reveals combined information of height and duration. For the event on 29 October 2018, which mainly affected the western gauges, the duration and intensity exceed the maximum values of all October events at Flensburg in the reference period (Figs. 15a and 15c).~~

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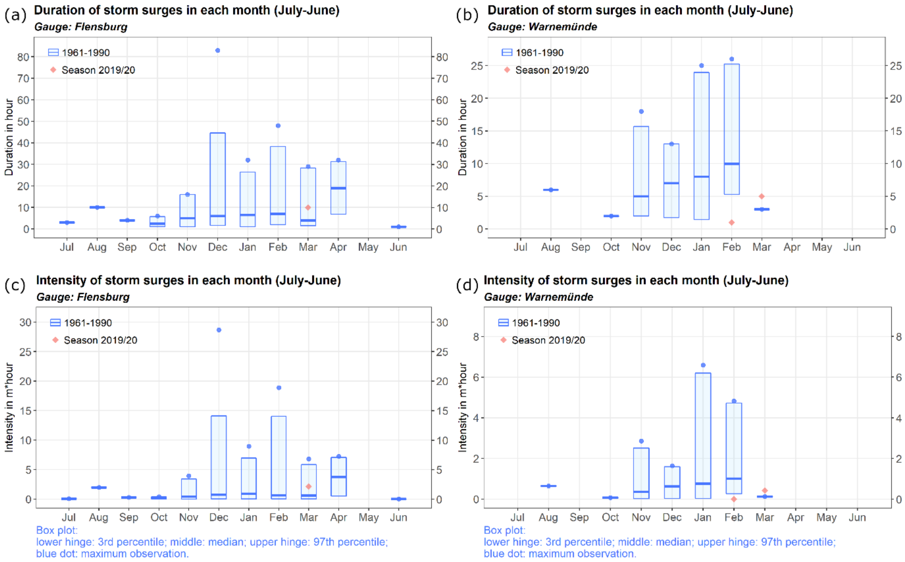
~~In season 2019/20, the total duration and the maximum intensity of storm surges are mostly below the long-term average (Fig.12), and the duration and intensity of the events are low in general (Fig. 16). At Flensburg, the duration and intensity of the event in March 2020 are higher than the medians of the March events in the reference period, while the values are higher than the maxima at Warnemünde (Fig. 16). Note that storm surges in March are common for Flensburg, but much rare for Warnemünde, indicating the local differences among gauges.~~



Box plot:
lower hinge: 3rd percentile; middle: median; upper hinge: 97th percentile;
blue dot: maximum observation.

Box plot:
lower hinge: 3rd percentile; middle: median; upper hinge: 97th percentile;
blue dot: maximum observation.

~~**Figure 16.** Same as Fig. 15 but for season 2019/20.~~

~~In summary, for the Baltic Sea gauges, season 2018/19 could be described as an active season in all aspects, though it is still within the normal ranges derived over the reference period. This is particularly due to the severe event on 2 January 2019, which is among the severest historical events since the 1950s. In contrast, season 2019/20 has fewer storm surges with lower heights and shorter duration, which is an example of a normal storm surge season for the Baltic Sea coast.~~

5~~4~~ Discussion and summary

A new tool and approach for~~To~~ monitoring the ~~potentially increasing~~ storm surge hazard~~s~~ in the context of long-term variability and climate change were proposed. They aim at providing near-real-time information for evaluation and contextualization of ongoing extremes and at bridging the gap between the availability of real-time data and the considerable time delay before assessments are published. ~~and to assess changes in near real-time, we propose an approach that puts recent extremes and the ongoing storm surge season into a historical prespective.~~ The~~is~~ approach was implemented into a prototype web tool (~~we called~~ the *s~~S~~torm s~~S~~urge m~~M~~onitor*) and implemented exemplarily for the German North Sea and Baltic Sea coasts. With the help of the m~~is M~~onitor, storm surges ~~at tide gauges~~ are ~~instantaneously~~ detected in real-time and are in near-real-time set into a climatological context.~~the long-term context of varying storm surge activity.~~ This way, not only an assessment of the current storm surge season or~~and~~ ongoing events is achieved but also the development over the past seasons is documented. The tool aims at providing easily accessible~~Understandable~~ information to the public, science, and stakeholders that aid in the evaluation of extremes, for example, ~~is provided to users~~ to assess in near-real-time if and to what extent an event or a season is unusual compared to the statistics of the extreme events in the past decades. M~~oreover, m~~easures to assess long-term changes can also be inferred from the m~~M~~onitor~~. Note that no attribution is made so far, but only the extent to which the measures are within previously observed ranges is assessed~~. Because of the existing risk and the expected future developments, such information can be highly relevant for decision making (e.g. Kodeih 2019; Kodeih et al., 2018; Weisse et al. 2015) or within the public debate.

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The monitor also documents long-term changes in storm surge climate. Such ~~The observed long-term~~ changes ~~at the German North Sea coast (e.g. the annual maximum water level in Fig. 3a)~~ can~~ould~~ in principle originate from various factors, such as changes in storm activity, astronomical tide cycles, or sea level rise. Locally, water-works may also play a role. To date, there is no clear evidence suggesting a significant long-term change of storm activity in the German coastal~~this~~ regions (Feser et al.~~,~~ 2015;

Krieger et al.~~,~~ 2020; Krueger et al.~~,~~ 2019; Stendel et al.~~,~~ 2016; Weisse et al.~~,~~ 2012). For the North Sea gauges, likely,~~It is likely that~~ the observed ~~long-term changes~~changes in storm surge climate are largely related to the local mean sea level rise (e.g. Weisse et al.~~,~~ 2012; Woodworth et al.~~,~~ 2011). ~~Moreover, it should be noted that the~~ R~~r~~ising relative sea levels in the area, for the most part, are related ~~is not necessarily fully related~~ to global mean sea level rise and climate change~~,~~ but ~~partly due to~~also contain contributions from non-climatic~~e~~ factors such as~~, e.g.~~ land subsidence. ~~As tide gauge is land-based, the observed water level contains the contribution from crustal motions, which may be~~The latter may result from ~~induced by~~ natural phenomena (e.g. GIA) ~~and~~ or local anthropogenic activities (e.g. groundwater extraction, dredging, waterworks, etc.) (e.g., Rovere et al.~~,~~ 2016; Stammer et al.~~,~~ 2013; Tamisiea and Mitrovica~~,~~ 2011).

At the analyzed gauges at the German Baltic Sea coast, no ~~trend~~ significant long-term change in storm surge activity could be detected~~ly different from zero at the 95% confidence level has been found~~ so far. F~~As f~~or the annual maximum water levels, this is in agreement~~ccordance~~ with the e.g. the results of Meinke (1999) and the review in Weisse et al. (2021). S~~light but~~imilarly, non-~~t~~significant trends have been found ~~in~~ for storm surge frequency~~ at Travemünde and Warnemünde~~, also in agreement with previous studies (e.g. ~~Meinke, 1999;~~ Weidemann et al.~~,~~ 2014).~~ The total duration and the maximum storm surge intensity show slight decreases, which are not significantly different from zero at the 95% confidence level. Beside these findings related to long term trends, further monitoring is necessary.~~

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~~Although severe storm surges are rare events and their number has mostly not changed, they have mayor impact to coastal communities. In case of damages, the Monitor helps to distinguisch different sources: if damages occur while the storm surge is within the normal range, it may indicate deficiencies of actual coastal protection; if damages occur because the storm surge was unusually high or intense, this indicates that coastal regions are not adequately prepared, even though the occurance of very unusal events is plausible as the storm surge of November 1872 shows. Moreover,~~ I~~i~~t is plausible that storm surge height, frequency, duration, and intensity may change in the future, as sea level continues to rise along~~t~~ the German North and Baltic Sea coasts (e.g., Grinsted~~,~~ 2015; Weisse and Meinke~~,~~ 2016; Hieronymus and Kalén 2021; Weisse et al. 2021). Thus, continuous monitoring of the storm surge climate in a climatological context may foster early detection and attribution and support adaptation and the public debate. ~~n seasonal anomalies contextualized in the long-term development of storm surge characteristics is very important. After each storm surge season, the long-term trends are automtacally recalculated and tested if they are significantly different from zero at the 95% confidence~~

~~level. This helps to contextualize local long-term statistics with future sea level scenarios and thus may serve as a scientific basis for regional adaptation strategies of coastal ptrotection measures.~~

~~Discussing these two recent and subsequent seasons, it can be inferred that severity and activity vary across regions. A season can be normal or less active to one coastal region but more active or even unusual to another. This is due to the different regional meteorological conditions that are responsible for generating the storm surges. For example, season 2018/19 was largely typical for the North Sea coast, while it was relatively active for the Baltic Sea coast mainly because of one severe event. Vice versa the following season 2019/20 was more active at the North Sea coast mostly because of a series of events in February, which did not cause corresponding events in the Baltic Sea due to the wind direction and the track of the storm systems. Furthermore, water levels at different tide gauges also react differently, which depends largely on the local wind conditions and the shape of the coastline (Jensen and Müller-Navarra, 2008).~~

Nowadays, web-based applications are frequently used tools to develop links between the results of scientific research and public demands. For sea level extremes, various such efforts do exist. These~~Such~~ tools provide online access to the statistics of extreme water levels or ~~and~~ document the severity and consequences of historical flooding. Examples are the Extreme Water Levels site from NOAA (https://tidesandcurrents.noaa.gov/est/)~~,~~ or the SurgeWatch site for the UK coast (https://www.surgewatch.org/, ~~) (~~Haigh et al.~~,~~ 2015). ~~Building~~ We built upon experiences from developing such tools, but contrary to existing ones ~~and adding to previous applications,~~ our storm surge monitor ~~tool~~ focuses on the near-~~-~~real-time evaluation and contextualization of extremes ~~the current season and its events~~ against the background of long-term variability and change ~~with the intention~~ to provide an up-to-date and continuously available piece for~~of~~ coastal climate services. ~~Looking back in time helps to improve the understanding of the past and to better evaluate the state of the present. Monitoring the present enables us to update the statistics and to detect the changes at the earliest possible stage.~~ Both,

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t~~T~~he m~~M~~onitor and the statistics are freely available online. They are expected to be useful and meaningful to the public. I~~and i~~n particular, the monitor was found to be useful to the media, since it fits their needs to focus on actual threats and to contextualize them within a scientific frame. After the implementation of the monitor, numerous interview requests were served and background information was provided based on the monitor ~~who are concerned about storm surges~~.

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The monitor~~It~~ is further~~also~~ relevant to ~~the~~ multi-sector coastal stakeholders who demand such~~this~~ information for coastal flood risk management and planning. For example, presently a discussion is ongoing with users asking for an extension including also thresholds following the definitions given in the DIN 4049-3 (DIN4049-3 1994). Further and interestingly, the series of storm surges that made the season 2019/20 outstanding along the North Sea coast, occurred shortly after the conclusion of the transdisciplinary project EXTREMENESS (Weisse et al. 2019) in which physically plausible but yet unobserved extremes and their potential impacts were discussed and modeled. One type of such potentially high-impact events identified by stakeholders was a series of storm surges that, even when only of moderate heights, may provide challenges for coastal protection (Schaper et al. 2019; Weisse et al. 2019).

~~Moreover,~~The monitor ~~it~~ can~~ould~~ further serve for educational purposes, for example, illustrating changing storm surge activity at the German coasts. ~~Last but not least~~Finally, it can also be useful to researchers as auxiliary information~~ in the presentations of their scientific results, or as pre-knowledge for furthe~~ supporting their~~r~~ research~~ especially on the most recent extreme events~~.

~~The up-to-date information in collecting and analyzing storm surges is currently in need at local to regional scales for coastal climate service. This work has demonstrated a way to make real-time data more meaningful and accessible to the public as well as a way to deliver more up-to-date information.~~ We argue that the tool ~~It~~ has the potential to be developed into a larger suite of tools including, for example, other regions or other coastal hazards such as~~ a network of tide gauges that covers the coasts under threat of storm surges. Our attempts started with the storm surges on the German coasts and focused on event detection and description. We propose that the concept can also be used to other variables (e.g.~~ sea level rise or~~and~~ storm activity~~), and can be developed further to include attribution~~.

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Author contributions

RW and IM initiated the idea of the storm monitor~~web tool~~ and designed it. XL processed the data, performed the analyse~~i~~s, and programmed the web tool. All authors equally contributed to the preparation of the manuscript. The revised version including the suggestions from the reviewers was prepared by RW and IM.

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Competing interests

The authors declare that they have no conflict of interest.

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