# Sea Level Dynamics and Coastal Erosion on the Baltic Sea Region (BEAR Report)

**_Author Team:_**
*Ralf Weisse, Inga Dailidiene, Birgit Hünicke, Kimmo Kahma, Kristine Madsen, Anders Omstedt, Kevin Parnell, Tilo Schöne, Tarmo Soomere, Wenyan Zhang, Eduardo Zorita*

## 1. Introduction (1-1.5 pages)

- *General introduction to the topic* ***(Ralf Weisse 0.25 pages)***
- *General, global and regional relevance for societies, why should we care beyond scientific curiosity…* ***(Ralf Weisse 0.25 pages)***
- *Historical background, early findings, methodological developments…* ***(Andres Omstedt 0.5 pages)***
- *BALTEX contributions* ***(Birgit Hünicke 0.25 pages)***

The Baltic Sea is a semi-enclosed, small intracontinental sea in northern Europe connected to the Atlantic Ocean only via the narrow and shallow Danish Straits. With an area of about 406,000 km$^2$ and a volume of about 20,900 km$^3$, it contributes less than a tenth of a percent to the area and the volume of the global ocean (Eakins & Sharman, 2010). Geologically, the Baltic Sea region is divided into the uplifting Fennoscandian Shield in the North and the subsiding lowland parts in the South (Harff et al., 2007).

In the past, sea level dynamics and coastline changes in the Baltic Sea received considerable attention because of three reasons: First, from a regional perspective regional mean and extreme sea level changes and erosion represent important indicators of regional climate variability and change. Second, processes and forcing contributing to Baltic sea level dynamics and erosion substantially vary on short spatial distances (Harff et al., 2017) and time scales of processes and forcing vary considerably ranging from seconds to millennia. Third, the availability of some of the longest tide-gauge records provides an excellent basis for the analysis of long-term variability and change. Finally, any long-term change in mean or extreme sea levels as well as in erosion and accretion will have an immediate impact on society influencing sectors such as coastal protection, shipping, or development of offshore renewable energy resources among others (e.g. Weisse et al. 2015).

Historically, changes in sea levels and coastlines have influenced harbors and settlements during millenniums. Early observations around the shores of the Baltic Sea indicated that sea levels were sinking. Stones carved with runic texts were found quite far from the shore where they were believed to be carved and shallow harbors were gradually abandoned as the water level apparently declined. In the 18th century, Celsius (1743) could estimate the rate of sinking water based on so-called *seal rocks* (Figure AO1), which were economically important places for seal hunting and therefore described in written records (Ekman, 2016).

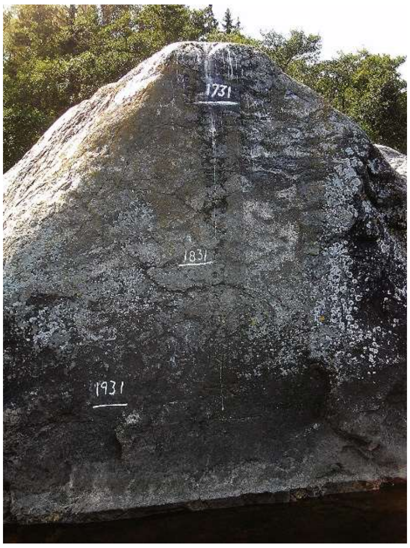

**Figure AO1**: A Celsius seal rock at Lövgrunden outside the Swedish city of Gävle on the Bothnian Sea coast (M. Ekman, 2016); the water nowadays is about 2 meters below the 1731 mark (photo courtesy of Martin Ekman).

Why the water level was sinking around the Baltic Sea could not be determined until it was understood, that in the past thick layers of ice had covered Scandinavia. Early ideas about ice ages came from observation that mountain glaciers could transport large blocks and form long moraines. Sea levels were not sinking but instead land was rising elastically after being ice covered. The idea of postglacial uplift was proposed in the mid-19th century by Jamieson (1865) and then later by others, though the causes of the uplift were strongly debated. Another major shift in ideas was not possible until new knowledge of the thermal history of the earth due to changes in sun–earth orbital motions was available in the 19th century. Later Milanković (1920) made his mathematical contribution by explaining the earth's movement around the sun. The observations of sea level change and land rise is illustrated by an almost 250 year's record from the Stockholm in Figure AO2.

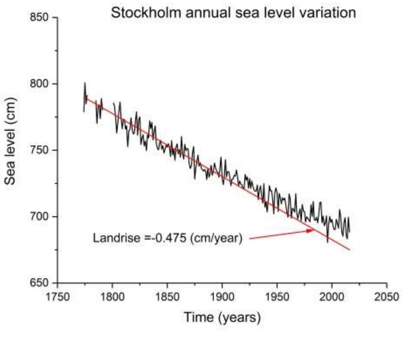

**Figure AO2**: Stockholm annual sea level variations (black) and land rise (red) according to Ekman (2003) (redrawn from Omstedt, 2015).

Changes and variability of Baltic Sea levels result from a combination of processes acting on a large range of spatial and time scales (Figure RW1). Processes contributing to Baltic Sea water level variability and change can be separated into processes that alter the volume of the Baltic Sea and/or the total amount of water in the basin, and processes that redistribute water within the Baltic Sea (Samuelsson & Stigebrandt, 1996). Processes with characteristic time scales of about half a month or longer can change the volume of Baltic Sea water while, due to the limited transport capacity across the Danish Straits, processes with shorter time scales primarily redistribute water within the Baltic Sea (Johansson, 2014). On longer time scales, the Baltic Sea SWLs are thus affected by global and North Atlantic mean sea level rise, and the effects from changing large-scale atmospheric conditions and, measured relative to land, by changes in the earth crust due to the glacial isostatic adjustment (GIA)[1]. On shorter time scales, atmospheric factors such as precipitation and wind are also the primary drivers of sea water level variations occurring within the Baltic Sea.

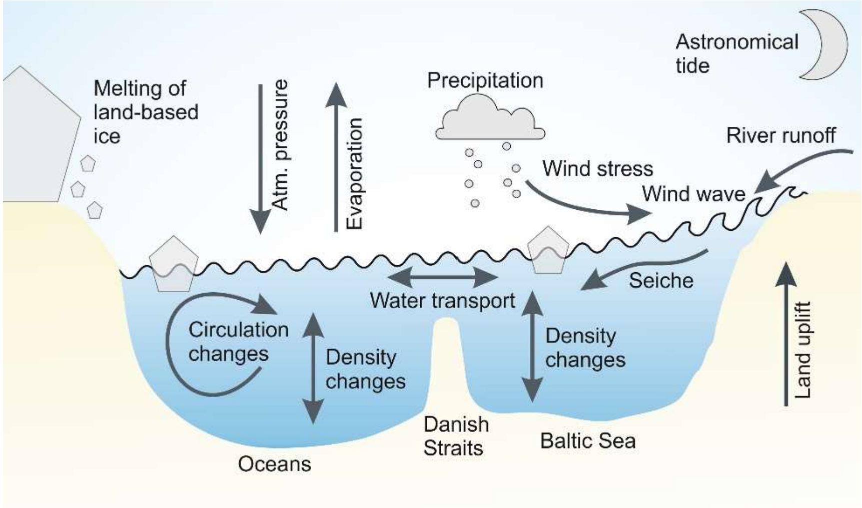

**Figure RW1**: Schematic sketch of processes contributing to SWL variability and change in the Baltic Sea (redrawn from Johansson, 2014).

# 2. Current state of knowledge (6 pages)

## 2.1 Mean Sea Level

***(Birgit Hünicke, Eduardo Zorita, Kristine Madsen, Tilo Schöne)***

*Please contribute to the following points: Current methods and concepts: advantages and shortcomings; Past and present state (observations, hindcasts, re-analyses); Projected future states; Possible implications for society; any other relevant issues*

The primary sources for measuring mean sea level changes are tide gauges and radar altimetry from satellites. Both measure two different quantities, namely *relative* and *absolute* sea levels. *Relative sea level* (RSL) is the height of the sea surface relative to the sea floor and is estimated using tide gauges or sea level reconstructions. Contrary to *absolute sea level*, that refers to the height of the sea surface relative to a geocentric reference such as the reference ellipsoid and that is obtained from satellite altimetry, relative sea level is influenced not only by variations in the height of the sea surface but also by land uplift or subsidence.

**The tide gauge network** of the Baltic Sea is one of the most densely spaced and longest running networks in the world. Many stations are in continuous operation since the early 19th century and some stations provide monthly averages for more than 200 years (e.g. Ekman, 2009; Bogdanov et al., 2000; Kowalewska-Kalkowska and Marks, 2011). There are at least about 45 operational tide gauges with more than 60 years of data and with a very good coverage of the whole Baltic Sea area (Hünicke et al., 2015). While monthly averaged data is often provided to and available open access through the Permanent Service for Mean Sea Level (PSMSL), there is so far no Baltic Sea wide database that combines all long-term monthly and higher frequency Baltic sea level measurements. Tide gauge data is measured relative to specific reference levels that differ between Baltic countries for historical reasons (Ekman, 2009). Further uncertainties in local reference levels are introduced by, e.g. different measuring techniques and sampling frequencies (Ekman, 2009), changes in the reference points due

---

[1] *Glacial Isostatic Adjustment* refers to the viscous rebound of the Earth' crust after the depression caused by the weight of the Scandinavian glacial ice-sheets that started retreating about 18.000 years ago and that finally disappeared about 9.000 years ago.

to relocation of landmarks, or man-made changes of the tide-gauge surroundings, such as coastal or port construction activities (e.g. Bogdanov et al., 2000). Phenomena occurring on timescales of years to decades, such as sinking of piers due to unstable foundations or land sinking due to groundwater extractions can be other sources of uncertainties (Hünicke et al., 2015).

**Radar satellite altimetry** from different satellite missions is available since 1991. The longest and most qualitative dataset is derived from a combination of the consecutive dual-frequency missions Topex/Poseidon, Jason-1, -2, and -3. The orbit repeats itself every 10 days allowing the construction of continuous time series since 1993. The missions form a pattern of ascending and descending orbits with an average cross-track distance of 100 km (at 60°N). Starting in 1991 with the European mission ERS-1 (followed by ERS-2, and the dual-frequency mission ENVISAT (ESA) and AltiKa (India/France)) the Baltic Sea is mapped too every 35 days with an average cross-track distance of 55 km (at 60°N). With the launch of ESA's CryoSat-2 in 2010 a new altimetry concept was established using a synthetic aperture interferometric radar altimeter (SAR/SARin) to especially map ice parameters but also sea surface heights closer to the coastlines. In 2016 the European COPERNICUS program launched a mission on Sentinel-3A (followed in 2018 by Sentinel-3B) carrying forward the uninterrupted altimetry program with 27 day repeat periods to the next decade.

While radar satellite altimetry in open-ocean areas provides reliable results for sea level trends and sea level variability, studies in enclosed or semi-enclosed areas such as the Mediterranean or the Baltic Sea are more complex. Especially in the Baltic Sea, difficulties are arising from various aspects. The most obvious is the sea ice coverage in winter preventing a year-around estimation of sea level in many of the sub-basins and close to the coast. In addition, the proximity of land or small islands to most satellite passes may hinder the analyses. A secondary aspect is the closed basin characteristics, which makes some of the more globally oriented correction models unsuitable for radar altimetry studies in the Baltic Sea.

**Long-term changes in Baltic Sea mean sea level** are the result of a number of processes including thermo- and halosteric effects, long-term changes in wind and surface air-pressure, ocean currents, variations in freshwater input and gravitational effects. Effects may arise from contributions outside and inside the Baltic Sea (Figure RW1).

Global mean sea level rise since the beginning of the last century was estimated from tide gauge records with a rate of about 1.8 mm/year (e.g., Douglas, 1991, 2001). For the era of continuous operated satellite radar altimeters beginning in 1991 much higher estimates of about 3.2 mm/year are reported. Inhomogeneous data, comprising a few tide-gauge records in the 19th and early 20th centuries and satellite data with nearly global coverage in the 21st century, hamper quantification and comparability of trends (Jevrejeva et al., 2008).

For the Baltic Sea, available multimission satellite altimetry data (1992-2012) was used to estimate the trend in Baltic Sea mean sea level with a rate of about 3.3 mm/year (Stramska and Chudziak, 2013) broadly consistent with the global average rate. Current (1993-2015) altimetry derived Baltic Sea mean sea level trend are still comparable with the global average, but reveal trends increasing from South to North[2]. In addition to the purely climate factors, RSL in the Baltic Sea is also affected by land movements. Due to GIA, long-term land movements that imprint the secular trends of relative sea level are particularly strong in the Baltic region. They are of the order of several mm/year and therefore are comparable to the sea level rise caused by climate change in the 21st century. Numerous studies analyze Baltic RSL trends on a national basis (e.g. Suursaar et al., 2006; Dailidienė et al., 2012). Different observation periods and analysis techniques hamper the comparison of results from such studies. A basin wide map of RSL trends, based on tide gauge measurements over 100 years, was developed by Richter et al. (2012) and updated by Groh et al. (2017). RSL trends show a distinct north-south gradient,

---

[2] https://www.eea.europa.eu/data-and-maps/figures/trend-in-asbolute-sea-level-1; ESA, 2017

reflecting the crustal deformation rates due to GIA. In the northern parts, RSL decreases with a maximum rate of about 8.2 mm per year in the Gulf of Bothnia. This corresponds to the area with predicted maximum GIA-induced crustal uplift (Peltier, 2004). In the southern Baltic Sea, RSL increases at a rate of about 1mm per year with a gradient in northeasterly direction (Richter et al., 2012).

Atmospheric forcing in the form of wind and precipitation may affect the basin average sea level through changes of the total volume of water, but also the internal distribution of water volume within the Baltic Sea basin.

Winds, and more particularly the strength of the westerly winds, modulate the exchange of water masses with the North Sea (Gräwe et al., 2019). This is due to the orientation of the connection straits between the Baltic and the North Seas and the prevailing wind directions in this region. Stronger than normal westerly winds push water masses into the Baltic Sea, raising sea level overall. Another atmospheric factor that may affect Baltic sea-level is precipitation and the corresponding changes in salinity and water density. In the mean, there is a strong salinity increase from the Northeast to the Southwest of the Baltic Sea. This mean gradient gives rise to a sea level gradient of about 50 cm. Therefore, long-term changes in the salinity gradient, or large changes at short time scales, caused by stronger or weaker riverine input or in the surface evaporation balance have the potential to change the sea level gradient within the Baltic Sea significantly.

The relation between the state of the large-scale atmospheric circulation and Baltic sea level has been subject of numerous studies. Indices such as the phase of the North Atlantic Oscillation (NAO)[3] during wintertime (Kahma 1999, Johansson et al. 2001, Andersson 2002, Johansson et al. 2003, Jevrejeva et al. 2005, Dailidiene et al. 2006, Hünicke and Zorita 2006, Suursaar et al. 2006), or geostrophic wind near Bornholm Island (Johansson and Kahma 2016) were used. No consistent long-term trend in the wind-induced component of the sea level could be identified.

Correlation between interannual variations of the NAO and Baltic Sea level has been rather variable over the 20th century, with periods with very weak correlation. Also, this correlation strongly varies regionally, with strong values around 0.7 in the North and East of the Baltic sea and more weaker correlations around 0.2 in the Southern Baltic Sea. A more detailed analysis (Karabil et al., 2018) has unveiled a slightly different atmospheric sea-level-pressure pattern associated with a with a gradient more oriented along the southwest to north-east directions. The two centers of action of this sea-level pressure dipole lie over the Baltic Sea and over the bay of Biscay. The statistical link of Baltic sea-level with this pattern with has been temporally and spatially much more stable than with the NAO, suggesting that the new sea-level-pressure pattern is also physically more closely linked to drive Baltic sea-level. The physical mechanisms that are behind the statistical link are not so much the direct effect of wind on the ocean surface but the inverse barometer effect (Karabil et al., 2018). Lower surface pressure over the Baltic Sea and higher pressure in the Western North Atlantic cause a rise of Baltic sea level, and vice versa. Other possible mechanisms, like atmospheric heat flux into the ocean due to air-mass advection or precipitation play a smaller role in terms of explained variability.

The contribution of the mechanisms behind current sea-level trends, apart from the global sea-level rise, can be also estimated from the analysis of simulations with regional ocean models driven by observed atmospheric forcing (Gräwe et al., 2019). This approach has the advantage that it is free of the disturbing effect of land-movement, either at long-time scales (GIA) or at shorter time scales. The simulated rate of Baltic average absolute sea level rise over the past 50 years estimated from these simulations is about 2 mm/year, slightly larger than the global average. Most of this signal is caused by sea-level rise in the North Atlantic Ocean. However, the model results also indicate a spatially

---

[3] The *North Atlantic Oscillation* NAO basically describes a meridional pattern in sea level pressure (SLP) with higher than normal SLP around the Azores and lower than normal SLPs over Island and vice versa. Variability of this pattern is physically linked to the intensity of the westerlies in the European region.

heterogeneous pattern of sea level trends, with stronger rates in the northwest and weaker rates in the southeast. The spatial structure is, according to these model simulations, the result of the poleward shift of pressure systems, and thus it is compatible with the statistical analysis of observations of tide-gauges and sea-level-pressure field.

If this link between the atmospheric circulation and Baltic sea level can be extrapolated to future trends, the contribution of the atmospheric circulation can be estimated by looking into projections of sea-level pressure changes in climate simulations. In general, the associated Baltic sea level trends are small, since the sea-level-pressure trends caused by anthropogenic greenhouse gas forcings are found to be small. Therefore, it is expected that most of the future Baltic sea level rise will be linked to large-scale factors that also modulate the sea level rise in the North Atlantic. During the 20th century, apart from the overall thermal expansion of the water column, one of these main factors has been the variability of the Atlantic Meridional Circulation, and its imprint is also detected in the variations of Baltic average sea level (Börgel et al., 2018). These factors are namely the expansion of the water column and the melting of the Antarctic ice-sheet.

Stronger winds and increased run-off may further contribute to future Baltic sea level rise in the order of some cm (e.g. Hünicke, 2010; Meier, 2006; Meier et al., 2004; Karabil, 2017; Johansson et al., 2014; Pellikka et al. 2019). Future salinity changes due to precipitation and river run-off changes may lead to changes in the salinity gradient of the Baltic Sea, which in turn could lead to a change of the gradient in Baltic MSL topography. Changes in the freshwater budget of the Baltic Sea brought about by climate changes may strongly affect the regional distribution of Baltic MSL by a magnitude comparable with the expected increase of the water column due to thermal expansion only (Hünicke et al., 2017). This implies that effects of regional climate changes in the Baltic Sea need to be considered in Baltic MSL projections. Generally, global mean sea level rise is expected to have the largest impact on future Baltic mean sea level changes. As GIA continues and will persist to dominate RMSL in the northern parts, the northern parts of the Baltic Sea, are expected to see a continued, although decelerated, decrease in RMSL (Räisänen 2019) while the southern parts are expected to experience a RMSL rise slightly exceeding the global average.

**Baltic sea level acceleration.** One of the implications of anthropogenic climate change is not only a sea level rise with approximately constant rate, but rather an increase of this rate over the course of the 21st century. The present rate of global mean sea level seems to have accelerated from around 1.5 mm/year in the mid 20th century to current rates of the order of 3 mm/year. The acceleration rate is, however, difficult to ascertain since the measurement devices over much of the 20th century were coastal tide-gauges, whereas since 1992 sea level is measured globally with satellite altimetry. The Baltic sea level records are among the longest and best quality controlled records, and so the question arises whether an acceleration can be detected with only these, temporally more homogeneous, records. On the other hand, Baltic sea level is subject to many other regional drivers that may mask the global climate change signal. A statistical analysis of the acceleration of Baltic sea level records (Hünicke and Zorita, 2016) indeed result in a detection of an acceleration of the rate of sea level rise. This detection is robust against different definitions of 'acceleration'. However, the overall magnitude of the acceleration is so far small, and if continued unchanged over whole 21st century would add just a few centimeters to the sea level rise resulting from a constant rate.

The acceleration of Baltic sea level also displays a spatial pattern, with accelerations in the Northeast than can be three times as large as in the Southwest. This within-Baltic spatial pattern acceleration cannot be explained by the diminishing sea-ice cover - more tide-gauges readings being reported now than some decades ago. Its spatial structure is compatible with what would be expected with an expected deceleration of the Glacial Isostatic Adjustment. However, this deceleration can be calculated with models of the dynamics of the Earth's crust (Spada et al., 2014), and the resulting order of magnitude is too small to explain the detected acceleration. The origin of the spatial distribution of acceleration remains, therefore, unclear.

## 2.2 Extreme Sea Levels

***(Inga Dailidiene, Tarmo Soomere, Kimmo Kahma, Ralf Weisse)***

*Please contribute to the following points:* ***Wind waves, storm surges, sea level extremes, Baltic Sea volume; wave-set up; meteo-tsunamis****; Current methods and concepts: advantages and shortcomings; Past and present state (observations, hindcasts, re-analyses); Projected future states; Possible implications for society; any other relevant issues*

Short-term fluctuations and extremes in Baltic sea levels are generated mostly by meteorological and to some extent by astronomical factors (Weisse and Hünicke 2019). From a climate perspective, this indicates that any relevant change in meteorological conditions may be associated with corresponding changes in Baltic sea level extremes. The most relevant phenomena contributing to sea level extremes are storm surges, wind waves, and a preconditioning of the Baltic Sea leading by to high water volumes in the Sea associated with periods of prevailing westerly wind conditions that increase the sea level gradient across the Danish Straits. In turn, these gradients lead to higher inflow and higher Baltic Sea water volumes (Samuelsson and Stigebrandt, 1996). Flows across the Danish Straits can reach values of up to about 25 km/day in both directions (Leppäranta & Myrberg, 2009), which corresponds to a sea level change of about 6 cm/day over the entire Baltic Sea (Johansson, 2014). Major inflow events are associated with typical volumes in the order of about 100 km$^3$, corresponding to a Baltic sea level increase of about 24 cm (Matthäus & Franck, 1992). Typically, such variations have time scales of about 10 days and longer while atospheric variability on shorter time scales primarily leads to a redistribution of water masses within the Baltic Sea basin (Kulikov et al. 2015).

Changes in Baltic Sea volume are tightly coupled with storm surges and extreme sea levels. Using model simulations and analyses of historical data, Weisse and Weidemann (2017) showed that under identical wind conditions and surge heights, higher Baltic Sea volumes lead to higher extremes. More specifically, they showed, that westerly storms cause surges on the eastern Baltic Sea coast. At the same time, these storms increase the volume of the sea. During subsequent storms, extreme sea levels are then higher than without such preconditioning.

Storm surges represent a threat for the low-lying coastal areas of the Baltic Sea, in particular in the southwestern parts and in the Gulf of Finland, the Gulf of Riga, and the Gulf of Bothnia (Wolski et al., 2014). They are caused primarily by strong onshore winds during storms and secondarily by the action of spatially varying atmospheric pressure on the sea surface. They may last from several hours to almost a day. Because of the seasonal cycle in wind speed, storm surges are highest and most frequent during fall and winter (Weidemann, 2014). The presence of sea ice may substantially reduce the effectiveness of wind in generating storm surges. In winter in the Gulf of Bothnia the piling-up of water is strongly suppressed by existence of sea ice (Zhang & Leppäranta, 1995).

The highest water levels in the eastern Baltic Sea occur in the northern Bay of Bothnia, the eastern end of the Gulf of Finland and on the eastern shores of the Gulf of Riga (Averkiev and Klevanny, 2010; Hünicke et al., 2015). The highest surges in the Baltic Sea may occur near Saint Petersburg (Averkiev and Klevanny, 2010). The highest reported water level in the Gulf of Finland was 421 cm on 19 November 1824 (Verkiev and Klevannyy 2010). For the western Baltic, the extreme event that occurred on 12-13 November 1872 and that hit large parts of the Danish, German, and Polish coastlines still represents the largest on record for most parts of the western Baltic Sea, with reported peak water levels of more than 3.2 m above the long-term mean (Feuchter et al., 2013).

Under certain atmospheric conditions, seiches with periods of up to tens of hours and e-folding times of up to two days may emerge in the Baltic Sea and contribute to sea level extremes (Leppäranta & Myrberg, 2009). Details of these oscillations are still debated and not fully understood. From numerical studies, Wübber and Krauss (1979) proposed a series of basin-wide seiches with periods of up to 31 hours. Other authors argued that the existence of such basin-wide oscillations is not fully supported by data. Alternatively, they suggested that the sea level oscillations in the Baltic Sea could be considered as an ensemble of weakly coupled local seiches with periods between 17 and 27 hours in the Gulf of Riga, the Gulf of Finland, and the Belt Sea (Jönsson et al. 2008). When favorably coupled with storm surges or in resonance with atmospheric forcing, they may contribute to very high sea level extremes at the coast (Suursaar et al., 2006; Weisse and Weidemann, 2017).

Meteotsunamis generated by moving atmospheric disturbances triggering resonant sea level fluctuations are not extremely frequent in the Baltic Sea, but have been described by Pellikka et al. (2014, 2018) for the Guld of Finland or by Holfort et al. (2016) for the western Baltic Sea. Amplitudes may be in the order of one meter (Pellikka et al. 2014, 2018).

The contribution from tides to extreme sea levels in the Baltic Sea is mostly small as the connection to the open ocean and thus co-oscillation is limited. Tidal amplitudes are therefore generally small and in the order of a few centimeters at most places. Locally generated tides, albeit small also, may therefore contribute in the same order of magnitude as co-oscillations at some places (Schmager et al. 2008). Overall, tidal ranges are mostly between about 2 and 5 cm (Leppäranta & Myrberg 2009). Only in the western sea areas are tidal ranges of up to 10–30 cm observed (Leppäranta & Myrberg, 2009). Due to resonance, tidal ranges of up to 20 cm are also found near St. Petersburg at the end of the Gulf of Finland (Medvedev et al. 2013). In the western Baltic Sea, tidal conditions are predominantly semi-diurnal while in the Gulf of Finland and the Gulf of Riga, diurnal tides prevail (Medvedev et al., 2013; Schmager et al., 2008).

Wind waves in the Baltic Sea show a pronounced seasonal cycle, with higher values in winter and smaller values in summer associated with a corresponding seasonal behavior of wind speed (Augustin, 2005). Generally waves are higher in open than in coastal waters. The highest measured waves in the Baltic Sea occurred at a wave buoy in the northern Baltic Proper. During a storm in December 2004 this buoy recorded a significant wave height of 8.2 m (Björkqvist et al. 2018; Tuomi et al. 2011). Measured extreme significant wave heights during wind storm Gudrun in 2005 reached 7.2 m in the Baltic Proper and 4.5 m in the Gulf of Finland. Away from sensors, model simulations suggested a maximum significant wave height of 9.5 m off the coast of Latvia (Soomere et al. 2008). In the northern Baltic Sea, the seasonal ice cover strongly modifies the wave climate since the highest waves occur in the same season as freezing (Tuomi et al. 2011)

In the coastal zone, the height of the wave extremes is considerably smaller, but other wave-related processes can make substantial contributions to short-term sea level extremes. This includes wave set-up, which is a wave-induced increase in mean water level caused by energy dissipation of breaking waves, and swash, which is caused by the run-up of waves on the beach (Melet et al. 2018). Potential contributions from wave set-up to extreme coastal sea levels were found to be substantial for some regions. For selected areas in the Gulf of Finland, Soomere, Pindsoo, Bishop, Käärd, and Valdmann (2013) estimated maximum wave set-up values of up to 70–80 cm. Finally, the level of the flooding and erosion at the shore depend on the wave set-up and wave run-up. The wave climate at the coast and its long-term changes are thus very location-dependent and the shape of the shoreline and the irregular bottom topography modify local wave conditions (Tuomi et al 2012, 2014).

**Long-term changes in Baltic extreme sea levels** may occur for various reasons. First, any change in RMSL will be associated with a corresponding change in the extremes through a change of the baseline. Second, any change in driving atmospheric conditions will be associated with a corresponding change in phenomena contributing to the extremes discussed above. Third, there are and will be non-linear interactions among the various components and local features such as bathymetry making the overall effects highly non-additive (e.g. Arns et al. 2015).

Based on tide gauge data, a number of studies reported increasing trends in Baltic Sea extreme sea levels over various periods. They found that these trends could to a large extend be explained by corresponding changes in the mean (Marcos and Woodworth 2018; Barbosa 2008; Ribeiro et al. 2014). Only for some of the northernmost stations, trends in the spread was indicative of higher extremes in recent years that are likely associated with corresponding large-scale changes in atmospheric circulation and regional wind patterns (Barbosa 2008; Ribeiro et al. 2014).

Extreme sea levels in the Baltic are positively correlated with the NAO (Johansson 2014; Marcos and Woodworth 2018). Processes contributing to such a correlation are the linkage between NAO and mean sea level in the northwestern European shelf seas (Woolf et al. 2003) such that positive NAO phases go along with enhanced mean sea levels that increases the baseline upon which wind-induced extremes may act; the relation of positive NAO phases with increased frequency of westerly winds that may lead to on average higher-than-normal water volume in the Baltic Sea; and potential relations between NAO and changes in regional wind patterns contributing to corresponding changes in wind surge and waves. Using tide gauge data, Johansson (2014) and Marcos and Woodworth (2018) showed that the positive correlation between NAO and Baltic sea level extremes persisted even when long-term MSL changes were removed. This indicates that NAO influences on Baltic sea level extremes are not only limited to the effects of changes in the mean, but have contribution from NAO effects on Baltic Sea volume and/or locally generated wind surge and waves. This conclusion was further supported by a model study in which a coupled North and Baltic Sea model was forced solely by wind and sea level pressure from 1948–2011, thereby explicitly excluding effects from global mean sea level rise and rising temperatures (Weidemann, 2014). In this experiment, periods of high water volume in the Baltic Sea occurred more often during positive NAO phases and vice versa and lower wind speeds were generally needed to sustain higher sea level extremes when the volume was above normal (Weisse and Weidemann, 2017).

Long-term changes in the wave climate may further contribute to changing extremes through corresponding adjustments of wave transformation in the surf zone (e.g., wave set-up and swash). For the Arkona Basin, Soomere et al. (2012) analyzed wind wave variability and trends based on 20 years of observation and a 45-year wave hindcast. They concluded that the wave height in this area exhibits no long-term trend but reveals modest inter-annual and substantial seasonal variations. Inter-annual variability was about 12% of the long-term mean of 0.76 m (Soomere et al., 2012). For shorter periods, estimates from satellite altimetry data, show a slight, tentative increase in annual mean significant wave height in the order of 0.005 m/year. Spatially, wave height increased in the central and western parts of the sea and decreased in the eastern parts. This pattern signals a rotation of wind directions since the 1990s (Kudryavtseva et al., 2017). Nikolkina et al. (2014) analyzed a multi-ensemble wind wave hindcast covering the entire Baltic Sea. Ensemble members with different atmospheric forcing for 1970–2007 and 1957–2008 with and without sea ice information in the wave model integrations were considered. Comparing spatial patterns and trends of mean and extreme wave heights, Nikolkina et al. (2014) found that the hindcasts consistently described the known spatial patterns, with relatively severe wave climate in the eastern parts of the Baltic Proper and its sub-basins, but could not make a consistent conclusion on long-term changes mainly due to differences in the atmospheric forcing.

Future changes of short-term sea level extremes crucially depend on future developments in large-scale atmospheric conditions, in particular on changing wind patterns. For the Baltic Sea, potential future changes in long-term mean and extreme wind speeds are highly uncertain (Räisänen, 2017). Climate model simulations investigated for the Second Assessment of Climate Change for the Baltic Sea Basin (BACC 2) were highly inconsistent with respect to projected changes in wind speeds at the end of the 21st century (Christensen et al. 2015). Projections of future wind waves and storm surges in the Baltic Sea are thus highly dependent on the atmospheric scenario, climate model, and realization used for the projection.

## 2.3 Coastal Processes and Erosion

***(Tarmo Soomere, Inga Dailidiene, Kimmo Kahma, Kevin Parnell, Wenyan Zhang)***

*Please contribute to the following points:* ***Coastline change, erosion, etc***.*; Current methods and concepts: advantages and shortcomings; Past and present state (observations, hindcasts, re-analyses); Projected future states; Possible implications for society; any other relevant issues*

The Baltic Sea region can be geologically divided into the uplifting Fennoscandian Shield in the North and the subsiding lowlands – parts of the Central European Basin – in the South (Harff et al., 2007). Coastline change of the Baltic Sea coast is characterized by the associated North-South gradient along which the main driving force is gradually shifted from the glacio-isostatic adjustment to the atmospheric and hydrodynamic forcing. The gradient from an uplift of max. 9 mm/a in the North to a subsidence of min. -2 mm/a in the south have caused a persistent marine regression at the Northern Baltic coasts and a marine transgression along the southern coasts since the onset of the Holocene (Harff et al., 2007; 2011). The southern coast of the Gulf of Finland marks the transitional area between the northern uplift and the southern subsidence (Rosentau et al., 2017).

About half of the shores of the Baltic Sea are comprised of either extremely resistant bedrock or relatively slowly changing cliffs of limestone or morainic materials. In Finland and the majority of Sweden, coastal erosion is regarded as not being an issue of concern, due to the geology and continued isostatic uplift (Pranzini and Williams, 2013). The other half of the Baltic Sea shores are sedimentary and susceptible to coastal change (erosion and accretion). The subsiding southern Baltic Sea coast is characterized by a series of barrier islands and sandy dunes connected with soft moraine cliffs. Owing to variation in aero- and hydrodynamic conditions (winds, waves and longshore currents) as well as underlying geological structure along the coast, diverse dune patterns have developed along the Baltic Sea coast. When subject to certain hydro-meteorological loads or changes in sediment supply, erosion and accretion occur with only a very few areas (most notably in Denmark) accreting (http://www.emodnet-geology.eu/). Many shore segments exhibit rapid retreat rates that may have large impacts on coastal infrastructure and cause extensive loss of land.

As with other (semi-) enclosed seas, dominant processes on Baltic Sea shores differ from those described in the classic coastal process literature, in particular the lack of tides, the possibility of seasonal ice cover, and the lack of long (length and period) wind generated swell. Because of a dominant role by the westerly winds that take up more than 60% of the year (Zhang et al., 2011a) and a sheltering effect by the land in the west, wind-waves are more developed in the south eastern Baltic Sea than in the south western part. As a result sediment transport and dune development are more facilitated along the south eastern coast. For example, the coastal dunes with the maximum size and height are developed along the Polish coast. A typical cross-shore profile at the southern Baltic coast features an established foredune ridge or a series of foredune ridges (under favorable condition of aeolian sand accumulation) with a general height between 3 and 12 m above the mean sea level (Łabuz, 2018). At the backshore behind the established foredune ridges, drifting or stabilized dunes in transgressive forms, mainly parabolic or barchanoid types are commonly developed. The source of sediment for dune development includes fluvioglacial sands from eroded cliffs, river-discharged sands, and older eroded dunes (Łabuz, 2015).

The major supplier of energy to the nearshore and the driver of sediment transport are surface waves. The properties of this energy supply and the resulting wave-driven transport in large parts of the Baltic Sea shores are described in (Soomere and Viška, 2014; Kovaleva et al., 2017; Björkqvist et al., 2018) and generalised to the entire Baltic Sea context in (Hünicke et al., 2015; Harff et al., 2017a,b).

The short-term average water level at the shoreline at the time of high waves is the primary influence in determining the extent of erosion due to storm wave attack. Tidal stage (not relevant to the Baltic Sea), storm surge (pressure and wind set-up), wave set-up, the presence or absence of sea ice, and the presence of long-period wave energy (infragravity or edge waves), all influence the location on the beach profile where sediment is able to mobilize and erosion may occur.

While the most massive alongshore and cross-shore sediment transport in the nearshore (surf and swash zones) takes usually place during extreme wave events, the most rapid shoreline changes (both erosion and accretion) occur when high waves attack the shore at relatively large angles, particularly when the angle of wave approach is unusual for that particular location. The most significant erosion events will occur when this combination of events combines with high (normally storm-surge related) water levels.

The presence of ice is an important moderating feature. Storm surges are much higher during ice-fee times than on the shores of even partially ice-covered water. The hydrodynamic forces are particularly effective in reshaping the shore when no ice is present and sediment is mobile (Orviku et al., 2003; Ryabchuk et al., 2011), when strong waves reach unprotected and unfrozen mobile sediment during extreme storm surges on higher sections of the shore that are out of reach of waves during usual water levels (Orviku et al., 2003).

On open-ocean facing beaches, periods of wave energy able to transport significant quantities of sediment and cause coastal change occur throughout the year, and due to remote locations of storms, long wave periods and consequently relatively intense wave refraction, waves approach the shoreline from a low range of angles. The Baltic Sea wave climate, however, is substantially anisotropic (wave directions following the anisotropy of wind directions) and highly intermittent. Only about 1% of the total onshore annual energy flux arrives within the calmest 170–200 days. About 60 % of the flux arrives within 20 days and as much as ~30% of the energy flux during the 3–4 most stormy days (Soomere and Eelsalu, 2014).

A simple consequence of the intermittency and anisotropy of wave fields and of the complicated geometry of the coast is that the evolution of Baltic Sea shores is a step-like process (Soomere and Healy, 2011). A few events cause rapid changes when strong waves arrive from specific directions during high water level events (e.g. Tõnisson et al., 2013), but for most of the time changes are very slow requiring high-resolution measurements (e.g., laser scanning techniques, Eelsalu et al., 2015; Sergeev et al., 2018) to detect. The nature of the coastal change (erosion, accretion or stability) at particular locations is highly dependent on the wave direction, as well as wave energy.

Storm waves often approach the shore at relatively large attack angles (Soomere and Viška, 2014; Pindsoo and Soomere, 2015). The presence of such wave systems means that single shore segments may be sensitive only with respect to a particular approach direction. Small pocket or headland confined beaches with very small amounts of sand may remain unchanged for long periods of time until a storm from an unusual direction causes massive change. Waves approaching the shore at high angle can also drive much more intense alongshore transport on the open shores of the Baltic Sea Proper (Figure TS1) compared to open ocean waves of comparable height that approach the shore almost perpendicularly. When the approach angle exceeds a certain threshold (about 45 degrees, Ashton et al., 2001), the predominance of high-angle waves can create explosive development of large spits and sand ridges. The growth of such structures has recently been observed in the eastern part of the Gulf of Finland (Ryabchuk et al., 2011).

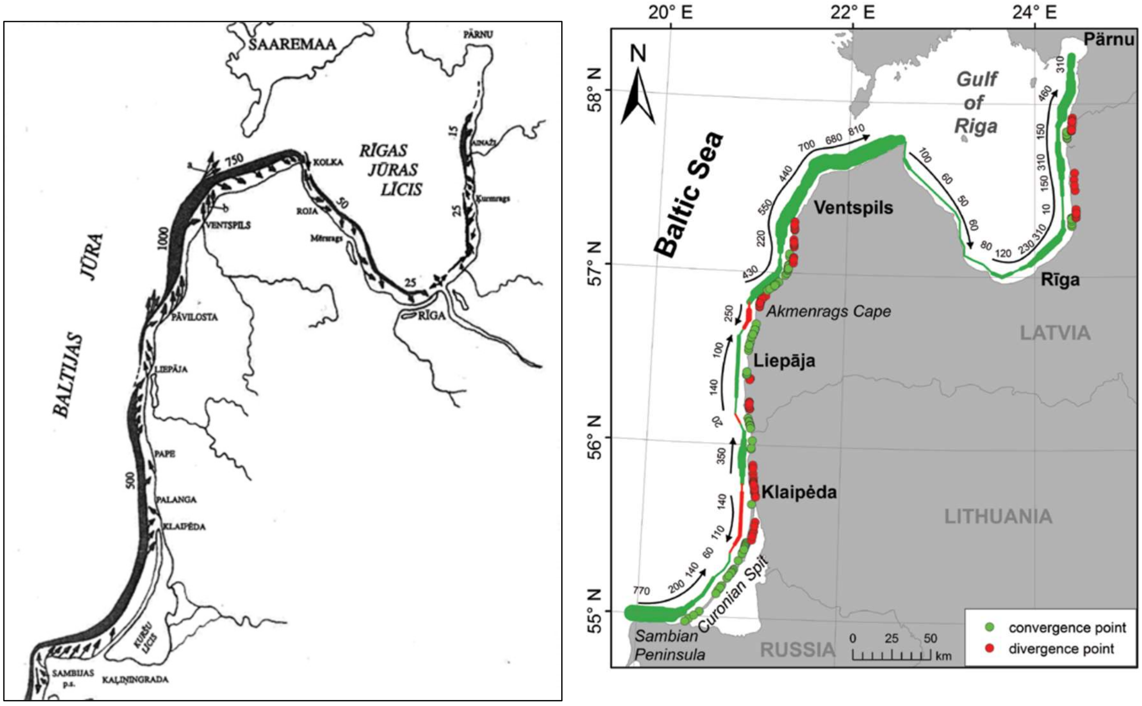

**Figure TS1**. Direction (arrows) and magnitude (numbers at arrows, in 1000 m$^3$) of net sediment transport: left – original scheme by R. Knaps, amended by V. Ulsts (1998); right – simulated potential net sediment transport (Viška and Soomere, 2013).

If alongshore, rather than onshore/offshore, sediment transport prevails due to high angles of wave approach, the classic cut-and-fill cycle of beach change does not occur as mobile sediment is moved along the shore to another location. In addition, the small proportion of low intensity swell waves (when sediment is mobile and waves are constructive rather than destructive) in the Baltic Sea means that natural beach recovery is slow or missing.

The asymmetry of the wave climate gives rise to a similar asymmetry of sediment flux (that is mostly counter-clockwise on the shore of the Baltic Sea proper, Soomere and Viška, 2014, Fig. A). Owing principally to the overall sediment deficit on the Baltic Sea sedimentary shores (Pranzini and Williams, 2013) actual sediment transport is frequently limited by the availability of suitably sized sediment. Thus, the real sediment flux is only a few percent of the potential flux (Soomere and Viška, 2014). This means there is only slow sediment accumulation in flux convergence areas (Figure TS1) but also that accumulation features may be easily destroyed as sediment transport in a single storm from an uncommon direction can be much more intense. This reinforces the fact that in the Baltic Sea, the properties of single storms and the timing of storms in sequences can be the controlling factor for sediment transport and coastal change.

Conceptually, the Baltic Sea shores should be very vulnerable to erosion because of the deficit of sand suitably sized for beach building, while being open to large hydrodynamic loads over short periods of time but with almost no low and long-period swell that is typically associated with beach accretion. Glacio-isostatic rebound in some parts of the Baltic Sea region helps stabilize beaches in some locations. Many beaches of the Baltic Sea are explicitly or implicitly stabilized by the (mis)match of the directions of predominant strong storms and the geometry of the shoreline meaning that they are relatively infrequently hit by storms, being protected by their bayheads. Waves in the Baltic Sea are relatively short meaning that the surf zone is narrow and wave run-up is less powerful than on the open ocean shores. As a consequence, many Baltic Sea beaches with very small amount of sand are in a fragile yet almost equilibrium state.

Unlike many open ocean beaches, where onshore/offshore directed processes are more significant, and sediment transport occurs into deeper water due to long wave lengths and periods, sediment transport direction on Baltic Sea beaches and its convergence (accumulation) and divergence (erosion) areas (Figure TS1) are highly sensitive with respect to the wave approach direction. Even a minor climate-change-driven rotation of the predominant wind directions over the Baltic Sea may substantially alter the structural patterns and pathways of wave-driven transport and functioning of large sections of the coastline (Viška and Soomere, 2012).

Coastal morphogenesis along the southern Baltic Sea has been studied by numerous authors since more than a century ago (e.g. Keilhack, 1912; Kolp, 1978; Kliewe, 1995; Lampe et al., 2007; Zhang et al., 2010, 2014; Tonisson et al., 2013; Furmanczyk and Musielak, 2015; Harff et al., 2017; Deng et al., 2019). Existing literature reveal that short-term and small-scale processes inducing the morphological change of the sandy Baltic Sea coastline, namely the shoreface-beach-dune system, are strongly hinged on a variety of local state variables including wind velocity and direction, water level, waves as well as the antecedent state of the system, while long-term and large-scale development of the coastline is primarily controlled by sediment supply modulated by large-scale processes, notably mean sea level, storms, the regional wind and wave pattern, and engineering structures (Harff et al., 2017; Zhang et al., 2017). Barrier coasts are resilient to a changing climate provided that they are able to maintain physical dimension (elevation, width and volume) and ecological function (vegetation growth) (Zhang et al., 2014). The foredunes form a natural barrier for coastal protection along a major part of the southern Baltic coast. The part of the Baltic coastline that is protected by engineering structures or newly formed foredune ridges has been able to sustain its general shape and function (both ecological and economical) in the past decades, while most of the rest parts, including the soft cliffs and old dune sections, have been subject to continuous and increased erosion (Łabuz, 2015). Most coastline erosion along the southern Baltic Sea is caused either by storms or human-induced depletion of sediment supply (e.g. side effect of engineering structures). Existing studies reveal a highly nonlinear relationship between storm intensity and the rate of coastline erosion along the southern Baltic Sea coast (Zhang et al., 2011b; 2015). The complexity of relationship between coastline change and storm is further enhanced in certain circumstances when storms are found to rework sediment onto the beach, thus, generating accretion (Zhang et al., 2017). Additionally, a strong correlation exists between rates of coastline change and relative level of human development. Even local and modest level of development (e.g. beach nourishment and pier construction) is found to influence the long-term coastline change at large spatial scale (100-km) (Deng et al., 2014; Dudzinska-Nowak, 2017).

The activities of people, and the coastal management policies and practices that have been developed have become significant drivers of coastal processes. With sediment transport largely confined to shallow water, even small coastal construction works such as small boat harbors, can significantly disrupt natural sediment transport pathways, leading to significant local (and frequently undesirable) coastal changes. Ship traffic, with the advent of strongly powered and fast large vessels, has become a significant driver of coastal processes and has caused erosion locally (Soomere et al., 2009). As is the case worldwide (UNEP 2019), the demand for coastal sand for construction, industry and beach nourishment will become increasingly significant for sediment supply. People will play an increasingly important role in what our shorelines will look like in the future. As noted by Vitousek et al (2017), the future coastline under climate change may 'be what we engineer it to be.'

## 3. Knowledge gaps (2-3 pages)

***(Birgit Hünicke, Eduardo Zorita, Kristine Madsen, Tilo Schöne, Inga Dailidiene, Tarmo Soomere, Kimmo Kahma, Ralf Weisse, Kevin Parnell, Wenyan Zhang)***

*Please contribute to the following points: Knowledge gaps and research needs (what we do not know and what we need to know); Methodological needs, shortcomings and challenges*

**Decadal variability and predictability.** Baltic mean and extreme sea levels are strongly influenced by sea level in the North Atlantic and by the atmospheric circulation. The decadal predictability of Baltic sea levels is therefore linked to the predictability of the dynamical state of the North Atlantic ocean and of the large-scale sea level pressure patterns. Decadal predictions are admittedly difficult and are still in an initial state of skill. However, decadal prediction schemes based on initialized simulations with Earth System Models display a moderate skill in the prediction of sea-surface temperatures in the North Atlantic Ocean (Müller et al., 2014). A knowledge gap is the estimation of decadal predictability of Baltic sea level based on decadal predictions provided by Earth System models, possibly down scaled with statistical methods or with regional models of the Baltic Sea.

**Long-term trends.** A range Baltic relative sea-level rise by the end of the 21st century assuming a scenario (RCP8.5) of strong emissions of greenhouse gases has been provided by Grinsted et al., (2015). These estimations include contributions of the thermal expansion of the water volume in the North Atlantic, the transfer of water mass towards the coastal regions, the land movement caused by the GIA, and the contribution of the melting of Antarctic and Greenland ice sheets. The melting of the land-ice sheets is the most uncertain factor, since its quantification currently relies in a mixture of model simulations that are difficult to validate and expert assessments (Bamper et al., 2019). Due to the self-gravitational effect, the Baltic Sea is much more strongly affected by the melting of the Antarctic ice-sheets and very little by the melting of the Greenland ice-sheets (Mitrovica et al., 2001). Therefore, the most important uncertainty for long-term Baltic sea-level rise is the Antarctic melting. This is a process that is complex to simulate, as it includes the dynamics of marine glaciers that are affected by not only by the surface heat flux but also by ocean temperature variability and trends ate very fine spatial scales. This difficulty is reflected in the very large range of uncertainty of Antarctic melting for the end of the 21st century (Bamper et al., 2019). The non-linear interplay between mean and extreme sea level changes in front of ongoing coastline changes represent another major knowledge gap. In addition, estimation and assessment of trends for extremes over centuries is still limited due to observational constraints and rareness of extremes. Digitalization of still available historical data from analogue archives or proxy analyses may provide a way foreward.

While coastal process knowledge and its application to solve problems is advancing rapidly, in the Baltic Sea and other (semi-) enclosed seas specific (and often more complex) methods of research need to be used. As coastal changes are integrally tied to extreme sea-levels and strong wave conditions, continued development of methods to model and predict wave properties and sea-levels at fine resolution are needed, particularly as it is known that various drivers in combination that cause extreme water levels in the Baltic Sea and in its subbasins are not well described by classic statistical distributions (Johansson et al., 2001; Männikus et al., 2019). There is urgent need for improved modelling of extreme sea-levels at finer resolution that are applicable to small coastal segments, which are sensitive to minor shifts in wind directions and intensities. This also applies to modelling of wave properties as the spatial resolution of wave fields about 500 m and even finer is necessary for an adequate replication of the magnitude and role of wave set-up in the total water level. Moreover, there are indications that the empirical distribution of set-up heights in single coastal sections follows an inverse Gaussian distribution. This feature substantially complicates the construction of joint probability distributions of different components of extreme water levels.

Another important source of uncertainty for the estimation of long-term trends in relative sea level is the quantification of land vertical velocities caused by the GIA. Vertical velocities relative to the geoid can be measured using the Global Positioning Systems (GPS) but the GPS records are short, so that other types of short-term vertical land movements (such as …) overlay the long-term GIA signal. This is reflected in a rather patchy pattern of land vertical velocities (Richter et al.,) whereas the GIA effect should in theory display a rather smooth pattern over the Baltic Sea region. Trends of vertical positions of GPS antennae separated a few hundred of kilometers and calculated over two decades of available data may yield differences of 2 mm/year, which is comparable to the climate change signal. Extrapolating this uncertainty until the end of the 21st century yields relative sea-level rise uncertainties of the order of 20 cm, which for some applications can be substantial. Therefore, a more accurate estimation of the GIA is necessary, perhaps by combining observational data with the result of Earth crust deformation models.

**Coastline Changes**. Despite intense research activities for understanding coastline dynamics along the Baltic Sea, there are still knowledge gaps to fill. One of them is a comprehensive view of alongshore sediment transport and associated spatial and temporal variability along the subsiding southern Baltic coast (Harff et al., 2017). It is known that the major transport pathway along the southern Baltic coast is determined jointly by the angle of incidence of the prevailing waves and the alongshore currents. In general, an eastward transport dominates along a major part of the southern Baltic coast due to the impact of the prevailing westerly winds. However, the intensity of secondary transport induced by easterly and northerly winds is much less understood. Its combination with storm surge along the southern coast driven by northerly winds further complicated the understanding because in such circumstance the sandy dunes and cliffs are exposed to highest erosional impact (Musielak et al., 2017). Alongshore transport along some parts of the Baltic Sea coastline is very sensitive to the angle of incidence of the waves due to the orientation of the coastline. For example, the incidence angle of westerly wind-waves at the western part of the Wolin Island in Poland (Dudzinska-Nowak, 2017) and the coast of Lithuania and Latvia (Soomere et al., 2017) is very small and even a slight change in the wind direction (by 10 degrees) could lead to a reverse of the alongshore transport direction. Coastline change at these sections is characterized by high variability and extremely sensitive to future changes in wind wave climate.

Another knowledge gap in understanding coastal erosion in response to future climate change is on the impact of water levels and the submergence of the beach. It is known that water level plays a key role in dune toe erosion and also limits aeolian sand transport on the beach. During storms, the relationship between the intensity of the forcing (wave energy, run-up) and the morphological response (erosion at the beach and dunes) are not straightforward (Dudzinska-Nowak, 2017; Zhang et al., 2017). At some sites (e.g. Miedzyzdroje), dune erosion is well correlated with maximum storm surge level and storm frequency, whilst at some others (e.g. Swinoujscie), it is found that the antecedent beach morphology is more important in determining the state of erosion than the storm surge level.

Anthropogenic activities for protection or recreation purposes have transformed the coastline landscape substantially and impose further uncertainty in predicting coastal erosion. An engineering structure (e.g. pier, seawall) influences coastline change at a much larger spatial scale than the dimension of the structure itself. A profound understanding of the coastline change of the Baltic Sea requires an understanding of the controlling factors that are responsible for formation of the various types of coastal dunes and their interaction with adjoining morphological features such as cliffs, innets and engineering structures.

There are major gaps in the understanding of the functioning of sedimentary compartments and cells and of the wave-driven mobility of sediment between these cells in the eastern Baltic Sea (Soomere and Viska, 2014). Although many of the cells are quite large, many are small, requiring modelling and measurements at a much finer scale than are currently available. Local variations are typically much more significant than for segments of open-ocean shores, where onshore/offshore directed processes tend to dominate alongshore processes. A prospective way for comprehensive quantification of sediment budgets in this region is to combine (airborne and terrestrial) laser scanning measurements of the coastal zone (Eelsalu et al., 2015) and detailed nearshore bathymetric data with detailed simulations of the nearshore wave climate, and to use approximation techniques for estimating underwater sediment transport and distribution changes using, e.g., an inverse Bruun’s Rule (Eelsalu et al., 2019).

The existing modelling efforts of shoreline evolution have all focused on relatively short coastal sections of the Baltic Sea (e.g. Zhang et al., 2015) and have (implicitly or explicitly) assumed that the wind and wave climate has been stationary over the modelling time interval (e.g., Deng et al., 2015). The morphodynamical models heavily rely on the properties of hydrodynamic loads (first of all waves) and are not yet suitable for capturing details of coastal evolution (Deng et al., 2017). However, they are already capable of replication (i) the main statistical properties of alongshore sediment transport and (ii) directions, relative magnitudes and alongshore changes of sediment fluxes in different coastal segments.

The largest gap in our knowledge is the scarcity of in situ data about changes to the coastline. These data are mainly collected by the national geological and coastal surveys and have not been systematically available (Madsen et al., 2018). They are the backbone of estimates of sediment fluxes and identification of sediment compartments, extremely useful for filling the gaps in the data about shoreline relocation and understanding and forecast of coastline changes.

There is yet to be a universally accepted model of coastal change under sea-level rise (Ranasinghe, 2016; Le Cozannet et al., 2019). Indeed, even the assessment of the current state of the world’s beaches is incomplete including in Europe and the Baltic Sea (Luijendijk et al., 2018), and approximate methods such as the ‘Bruun-rule’ continue to be applied despite being widely criticised (Cooper and Pilkey, 2004; Le Cozannet et al., 2016). While there have been significant improvements in the development of coastal morphological models that can be adapted to a range of situations, there remains a need for considerable conceptual and methodological development (Hinkel et al., 2013; Ranasinghe, 2016; Vitousek et al., 2017) that is specific to the unusual process drivers of the Baltic Sea, where even minor climate change related variations (particularly with respect to wind) can be extremely influential (Viška and Soomere, 2012). Major advances, that will enable early and appropriate responses for the benefit and protection of people can only be achieved with research that integrates modelling, measurement and monitoring (Vitouseket al., 2016).

**Coastal satellite altimetry.** The estimation of sea level trends and sea level variability from satellite altimetry requires a number of auxiliary data and environmental corrections to the radar measurements. Beside the internal measurement errors, these corrections account for most of the uncertainties in altimetry. While for most oceanographic applications the correction models are mature in the open ocean, these are under research near the coast and in enclosed or semi-enclosed seas. In respect to the Baltic Sea, most important corrections to be discussed are the wet tropospheric attenuation correction, the ionospheric corrections, the barometric corrections, and, to a minor extend, ocean tides. The wet troposphere correction is estimated employing radiometers carried on most modern satellites (except ERS-1 & -2). This correction is deteriorated near land as the radiometer footprint is much larger than the altimeter footprint. As part of the ESA CCI initiative a new composite product was developed (GPD+; Fernandes et al., 2015) which combines different observations (radiometer, GNSS, etc.) in the vicinity of the satellite measurements. The estimation of ionospheric corrections is based on dual-frequency measurements of the altimeters. Also this correction fails near the coast and models, such as Global Ionospheric Maps (GIM), are widely used to replace wrong values near the coast especially in areas with a good GNSS coverage. The estimation of the mean sea level also requires a correction of barotropic pressure change effects. A high resolution barotropic model (Carrère and Lyard, 2003; Carrère et al., 2016) forced with ECMWF model pressure and wind fields including inverse barometer corrections are used. Although the model operates on finite element grids with improved resolution also for the Baltic Sea, the available product is gridded on a 0.25°x0.25° grid only. Of minor importance, but especially important for variability studies, are ocean tides. The Baltic Sea has minor tides which may increase the errors or introduce aliasing effects in variability studies. A recent study (Esselborn et al., 2018) is aiming on the importance of the quality of satellite orbit solutions and found surprisingly large annual error signals also for the Baltic Sea when comparing orbit solutions provided by different originators.

Studies of coastal vulnerability, erosion or the hazard potential along coastlines require sea level estimation as close as possible to the coastline. The conventional radar altimetry is available at a 1 Hz interval (~6.7 km) along-track, the illuminated footprint varies between 2 and 25 km diameter depending on the surface roughness. A number of studies using high-rate data (10 to 40 Hz depending on the altimeter mission), often in combination with advanced signal processing technologies, such as the so-called retracking of individual radar pulses, allowing the extraction of water levels closer to the shore. In recent years in radar altimetry the SAR/SARin technology was developed and employed. The first altimeter with SAR/SARin capability is CryoSat-2 (launch 2010), and now is also used for Sentinel-3A and -3B. A study of Dinardo et al. (2018) for the North and Western Baltic Sea using CryoSat-2 data demonstrated the possibility to map the mean sea surface with reasonable quality to as close as 2 km to the coast. A similar study by Idžanovi et al. (2018) for Norway also demonstrated the ability to map the sea surface close to the coast and under difficult topographic conditions, e.g., in fjords. Both studies also emphasized on the importance of improved environmental corrections replacing standard products.

## 4. Conclusions and key messages (1-1,5 pages)

***(All)***

*Please list any issue that you would like to see here.*

Inga: In the Baltic Sea region sea level rise is likely to exceed its global average, particularly in the south and south eastern parts of the sea area. A faster mean and short-term maximum sea-level rise in winter periods could be affected by the processes that are connected with the changes of the cold period climate, with more frequent transmission of moist and warmer western air masses. The regional analysis of long-term variations of sea level in the Baltic Sea is directly connected to the problems concerning the extreme sea levels, erosion of coasts, land flooding, security of hydro-technical devices, and development of infrastructure in ports, sea-side towns, stability of ecosystem.

Tarmo: Most sediment transport and erosion occurs over a very few days of the year, when high waves, particularly waves from an unusual direction, occur during periods of extreme sea-levels. Indications of changes in the directional structure of strong winds are alarming because even minor climate-change driven changes in wind direction and/or intensity can have significant coastal morphological impacts, and storm waves from uncommon directions can have very significant morphological consequences for apparently stable coastal segments.
Alongshore sediment transport is frequently supply limited, and limited to a relatively narrow nearshore.

… TBC …

## References

***(All)***

*Please provide a list of your references.*