Observations and Mechanisms of Regional Sea Level

The German Bight and its Coastline

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1 Introduction

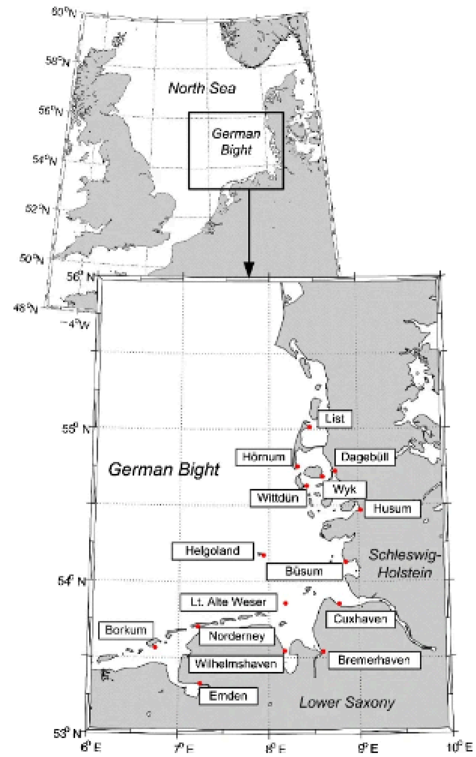
1.1 Background

Sea level rise is one of the most important signals of anthropogenic climate change and globally driven by thermal expansion and addition of freshwater due to the melting of ice sheets (Weissenberger et al., 2015). The rise in global sea level has been well recorded and appears to not be temporally and spatially uniform. Even though the global sea level is rising, locally that must not be the case. Regional sea level is composed of a variety of factors including distribution of water mass from glacial melt, variations in atmospheric pressure, and vertical land movement due to tectonic and anthropogenic processes (Weissenberger et al., 2015). It is challenging to understand the linkages and interplay between all factors. On the regional scale it can be difficult to isolate the specific contribution of each different factor underlying relative sea level change due to their coupling and temporal and spatial variations (Jensen at al., 2014). Focusing on observed sea level trends in a singular specific region will give a chance to understand those underlying mechanisms, a necessity for future projections of sea level rise (Hamlington et al., 2020). Those projections are essential to improve mitigation strategies and coastal management plans.

This essay focuses on the German Bight, covering the southeast part of the North Sea including the East Frisian and North Frisean Wadden Sea (Rasquin et al., 2020). The extent and location of the region is illustrated in Figure 1. The German Bight is an excellent example of a low lying coastal region, which is particularly vulnerable to any changes in sea level and storm surges, and impact of current climate change (Rasquin et al., 2020). Drastic sea level changes in this area, which is already subject to extreme storm surges and floods, will consequently require protection and management efforts (Jensen et al., 2014). Coastal areas are an important part of North Germany as a large amount of the population lives in these regions (Jensen et al., 2014). Current infrastructure is designed based on the existing sea level and shoreline, so any changes in those factors will have a direct impact on the coastal communities. In addition to its social significance and low topography, the German Bight is an ideal study region for investigating regional sea level processes because of the extensive spatial and temporal observational coverage specifically through tide gauge systems going back to the 1840s (Wahl et al., 2013).

Figure 1

Study area German Bight with tide gauge locations



Note. From Albrecht, F., Wahl, T., Jensen, J., & Weisse, R. (2011). Determining sea level change in the German Bight. *Ocean Dynamics*, *61*, 2037-2050.

1.2 Goal of the Essay

As mentioned, global mean sea level trends are only partially useful for coastal adaptation policies because of the observed regional unconformities (Mangini, 2022). Wahl et al. states that changes of relative mean sea level (RSML) an essential parameter to consider when deciding on coastal protection strategies (2011).This essay aims to combine data from different observational systems, tide gauges and satellite altimetry, to determine trends for the long-term regional mean sea level as well as considering non-linear trends on shorter timescales. This also allows comparison of these observational tools, revealing current limitations and potential future developments. After having established the observed mean sea level trends up to the present day, any changes in coastal protection relevant factors, which are changes in the tidal regime, extreme sea levels (ESL), and short term variability due to atmospheric processes, will be identified. Jensen et al. highlight that regional sea level rise that differs from the wider North Sea is most often due to vertical land movement and atmospheric processes (2014). So lastly, the essay will explore the contribution of vertical land movement, bathymetry changes, and sedimentation processes to the observed RSML trends to clarify future expectations and provide information for coastal management and protection.

2 Methods and Observations

2.1 Tide Gauge

The German Bight is extensively covered by a system of tide gauges providing availability of long time series. Tide gauges are a longstanding essential tool in oceanographic observations. Starting in the nineteenth century they have been used to measure sea level and provide time series to identify any long term changes and variabilities for the global sea level as well as in their specific location (Cipollini et a., 2019). Tide gauges measure relative sea level, not the absolute sea level, meaning the measurements are always in reference to a certain location or land point (Intergovernmental Oceanographic Commission, 2006). This clear reference point is called the datum, a vertical datum specifically to measure depths (Intergovernmental Oceanographic Commission, 2006). The datum is the ground plane level, where the tide gauge is calibrated to zero and the measurement taken from the tide gauge is the depth of water above that datum (Intergovernmental Oceanographic Commission, 2006). The observed RSML trends are extremely relevant in regards to coastal management and protection, but trends detected by tide gauges are influenced by the several different regional mechanisms, as highlighted in the introduction. Tide gauge measurements are relative to the earth's crust, so they do also inherently measure the motion of the ground (Dawidowizc et al., 2014). Those vertical movement components have to be subtracted from the tide gauge data to produce mean sea level trends (MSL) (Dawidowizc et al., 2014).

Due to the extensive tide gauge data coverage, there is a variety of studies with statistical analysis of MSL trends from those observations. Three main researchers that have published sea level trends for the North Sea including the German Bight are Wahl, Jensen, and Dangendorf. An early study by Wahl et al. recognizes that the virtual time series they have established for the German Bight differs from global sea level reconstruction by Jevrejeva et al. (2006), highlighting the issue that global mean sea level and therefore also MSL projections for the future might not necessarily be the most helpful for the management of regional coastal regions, including the study region, but rather that there is a definite need for regional sea level projections (2011). A later study by Wahl et al. used 30 tide gauges creating an up to 200 year long record with relatively uniform distribution along the coastline of the north sea (2013). Based on that data the study focused on calculating RSML and for the 20th century also absolute regional sea level, concluding a trend of 1.6 mm/year considering all tide gauges in the period between 1900 to 2011 (Wahl et al., 2013). The longest span of tide gauge data has been recorded in Cuxhaven, for which Wahl et al. have calculated linear trends for different time periods (2013). For the 1850-2011 period they identify a trend of 2.3 ± 0.1 mm/yr, 2.1 ± 0.2 mm/yr for 1900-2011, 1.8 ± 0.5 mm/yr for 1950-2011, 2.8 ± 1.2 mm/yr for 1980-2011, and lastly 3.7 ± 2.3 mm/yr for 1980-2011, indicating that more recent periods seem to show higher sea level rise trends than earlier periods (Wahl et al., 2013). The MSL rate even increases to 4.00 ± 1.53 mm/yr when only considering 1993-2009 (Wahl et al., 2013). The study links periods of accelerated sea level rise mostly to atmospheric pressure changes and especially shorter periods can be representative of short-term variability (Wahl et al., 2013). Even though in more recent periods sea level appears to rise at an accelerated rate, so far it is at precedent rates for this region, especially for the tide gauges with the longest records (Wahl et al., 2013).

Wahl, Jensen, and Dangendorf ultimately combined their findings in a collective paper (Jensen et al., 2014). They summarize that the MSL in the German Bight continuously rose through the 19th century (Jensen et al., 2014). It is also concluded that from the tide gauge data, of 22 tide gauges for the time period between 1900-2011, they detected a stable MSL rise trend throughout the last 200 years which accelerated from the 19th to 20th century (Jensen et al., 2014). Based on the tide gauge data they determine a rate of 1.7 mm/a for the North Sea for this period (Jensen et al., 2014). It is emphasized that short term variabilities hide the expected acceleration due to global warming and climate change (Jensen et al., 2014). The study also highlights a significant amount of MSL variability around ± 600 mm which is most pronounced on the inter-annual scale (Jensen et al., 2014). Jensen et al. agrees with the previous claims that current accelerations and changes are within changes that have been observed in the past and we have not yet seen any unprecedented rates (2014). Additionally, Dagendorf et al. focused on monthly MSL variations utilizing the same tide gauge data as Wahl et al. used for their long-term variation reconstruction (2011), which included 13 tide gauges in German Bight with measurements beginning in 1937 (2013). Their findings highlighted a strong seasonal variability within the region's coastline, that can be within a range of 200-290 mm (Dagendorf et al., 2013). Minimum values were detected for April and May, whereas the maximum values were observed

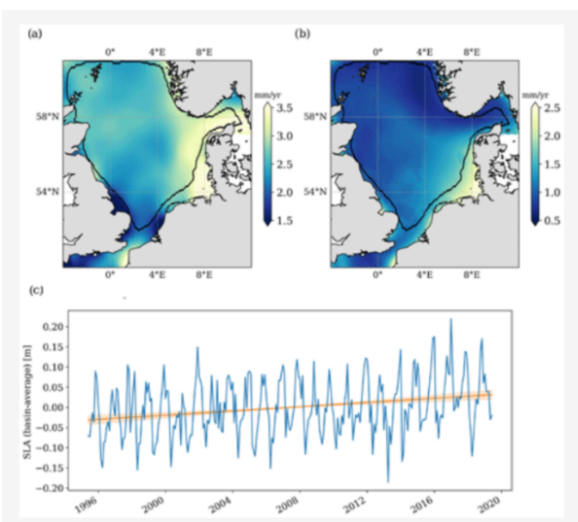
for November (Dangendorf et al., 2013). There are no observed long term changes in the seasonal cycle in regards to amplitude and phase, but the inter-annual variability appears to be large and very prominent, as well is there a slight shift of the maximum values from November and December towards January and February since circa 1988 (Dagendorf et al., 2019)
A more recent study by Benninghof and Winter. on the other hand does find accelerated sea level rise, between 2.2 ± 2.5 to 6.6 ± 3.2 mm/yr, in the German Bight for the most recent decades at rates unprecedented compared to the previous 200 years (2019). A study by Steffelbauer et al. in 2022 finds similar trends that support Benninghoff and Winter claims. Steffelbauer et al. statistically analyzed 8 tide gauges in the north sea and was able to detect a “breaking point”, meaning that in the considered 100 year period sea level rise accelerated at around the early 1990s from 1.7 ± 0.3 mm/yr before the breakpoint to 2.7 ± 0.4 mm/yr after (2022). Despite identifying these accelerated rates, Steffelbauer et al. acknowledges that other studies did not identify any significant accelerations in their respective approach (Steffelbauer et al., 2022). This further highlights that the statistical approach is partially determinant of the type of trends that are being detected, as many of these studies have utilized the same tide gauge data but concluded slightly different results for non-linear and accelerated sea level trends. Linear MSL trends appear mostly in agreement across studies, but results in non-linear trends vary especially between older and more recent studies.

2.2 Satellite Altimetry

Satellite altimetry, which as a technique has been able to provide global sea level measurements since around 1992, measures absolute sea level referencing the sea surface relative to the position of the center of the earth (Wahl et al., 2013). The method has been used to observe global sea level changes of the open oceans for many years now. Early missions Topex/Poseidon and Jason-1 missions have recorded an average global sea level rise and allowed the study of large scale ocean circulation (Schulz-Stellenfleth, 2010). Expected regional unconformities in sea level changes as observed with the tide gauge systems have also been successfully observed with satellite altimetry. The phenomena is observed by Milne et al., who based on satellite altimetry data conclude regional differences on a range of ± 10 mm/yr in comparison to the observed global 3 mm/yr sea level rise (2009). For Jensen et al. those observations are an indication that for the purpose of coastal protection the regional sea levels are of higher relevance than changes in the global mean sea level (2014). Jensen et al. state that since 1993 satellite altimetry data shows accelerated SLR at a rate of 3.2 mm/yr for the German Bight (2014). Based on satellite altimetry data Carret et al. states a SLR of 3.1 mm/yr beginning 1993 (2021), showing agreement with the other satellite altimetry based studies. A new dataset provided by the european Copernicus programme called NorthSEAL uses regionally optimized products for the north sea and creates a collective dataset utilizing all available data from the satellite missions ERS-2, TOPEX, Jason-1, Envis7at, Jason-2, CryoSat-2, SARAL, Jason-2 and Sentinel-3A/B

Figure 2

Altimetry based sea level trends for the period of 1995 to 2019 (a), including uncertainties of those calculations (b), and averaged linear trend of sea level rise over the entire North Sea (c)



Note. From Dettmering, D., Müller, F. L., Oelsmann, J., Passaro, M., Schwatke, C., Restano, M., ... & Seitz, F. (2021). NorthSEAL: A New Dataset of Sea Level Changes in the North Sea from Satellite Altimetry. Earth System Science Data Discussions, 2021, 1-28.

(Dettmering et al., 2021). Focusing on the period between 1995–2019 Dettmering et al. determines a trend of 2.61 ± 0.95 mm/yr for the North Sea which is visualized in Figure 2 (c) (2021). Furthermore, trends within the North Sea vary on a range of 1.5 and 3.5 mm/yr, with the region of the German Bight being identified as having the largest trend (Dettmering et al., 2021). This is illustrated in Figure 2 (a), which highlights the higher sea level rise rates for the German Bight compared to the other regions of the North Sea. The German Bight shows the highest annual cycle amplitude within the North Sea when deriving monthly mean trends across multiple years, indicating strong seasonal variability (Dettmering et al., 2021). This is illustrated in Figure 2 (b), which visualizes associated uncertainties of the satellite altimetry based sea level trends, which are highest for the German Bight compared to the rest of the North Sea, emphasizing that this region relatively more affected by seasonal variability due to atmospheric processes (Dettmering et al., 2021).

2.3 Conclusion and Comparison of Observations

The IPCC report on changes in the ocean and cryosphere concluded a global trend of 1.4 mm/yr for 1901-1990, 2.1 mm/yr for 1970-2015, and 3.2 mm/yr for 2006-2015 based on tide gauge and satellite altimetry data (Hörtner et al., 2019). A study by Albrecht et al. states based on tide gauge data that the global sea level has increased at about 1.7 mm/year during the 20th century (2011)**.** In terms of acceleration, the period between 1993 to 2009 shows significantly higher global MSL rates, 3.2 ± 0.4 mm/yr from altimetry data, then for the period between 1900 to 2009 with rates of only half that value (Wahl et al., 2013). Williams et al. concludes a current rate of SLR at 3.1 mm/year (2013).

Long Term trends for the southern part of the North Sea appeared to be bigger which the authors claimed to be matching GIA movements (Jensen et al., 2014). Overall, the detected trends for the German Bight showed higher standard errors around 3.30 mm/yr compared for example to the southern North Sea with only 0.15 mm/yr, which the authors saw as a strong indication of the interannual and decadal variability mostly related to atmospheric effects (Jensen et al., 2014). Wahl et al. finds that the german North Sea coast shows between 1.6 to 1.8 mm/year of sea level rise but that higher values are observed along the Schleswig-Holsteinischen compared to lower values along the Niedersächsischen coast (Wahl et al. 2010; Albrecht et al. 2011) (Wahl et al., 2013 overall). For the North Sea the long term trends of the 20th century agree well with the global mean sea level, though it does significantly differ on the interannual and interdecadal time scale (Jensen et al., 2014). Brasseur et al. further uses the Wahl et al. 2013 finding that the detected trend of 1.6 mm/year for the time period of 1900-2011 for the German Bight is in line with the observed global trend of 1.7 mm/year for the period 1901-2010 (2023). Overall the German Bight shows similar sea level rise as the global mean sea level rise, but compared to the rest of the North Sea its trends are slightly higher as well as more variable on shorter time scales.

2.4 Critical Analysis of Methodology

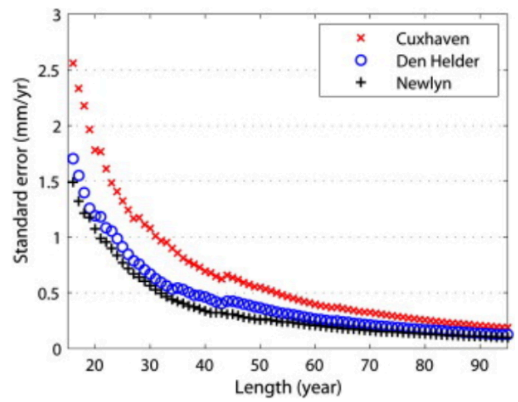
It is important to critically review the two observational methods, as their inherent characteristics affect possible sea level observations and quality of provided data. This comparison is not only indicative on how we should evaluate the study region data, but also offers further implications for other study regions and regional sea level rise in the broader scheme. Overall, most tide gauges are located in the northern hemisphere, creating a discrepancy in available data between the two hemispheres (Intergovernmental Oceanographic Commission, 2006). Tide gauge locations also tend to be biased towards locations like ports, where anthropogenic factors have a higher influence (Pickering et al., 2017). Additionally, it must be acknowledged that tide gauges are spatially biased and more often located along and close to the shoreline, and rather rarely in offshore conditions, meaning the record of global sea level is based on data that mainly represents those conditions (Nerem et al., 2018). This is also the case for the German Bight, as visible in Figure 1, the tide gauges are located closely following the coastline or along islands (Albrecht et al., 2011). Tide gauges themself require a certain kind of conditions and environments to work well, and cannot be placed too close to tectonic activity due to its vertical land movement contribution (Nerem et al., 2018).

The conclusions based on tide gauge records should also be taken with caution as most regions are under the influence of multiple oceanic processes which are not fully represented when only applying a limited number of tide gauges (Vignudelli et al., 2019). Furthermore, not all regions have the same quality records as the German Bight does, constraining observation to decadal and secular scales (Hawkins et al., 2019). Overall, the German Bight does show reliable, accessible, and well distributed tide gauge records, but these difficulties have to be considered for other regions. Tide gauges are operated independently and regionally, meaning quality of tide gauge data can be affected through the inconsistent maintenance of the actual gauges and different reference frames, leading to incomparable data (Intergovernmental Oceanographic Commission, 2006). Given the range of studies that have used tide gauge data for the German Bight without flagging any data quality issues, these potential issues do not seem to be a significant issue for the study region currently.

Most importantly do the conclusions we take from the tide gauge records depend on the applied statistical approach. Trend observations and rates of sea level change depend on fitting a linear or nonlinear approach to the data. Trends also depend on the choice of time series, which in summary or comparative studies have to be aligned, or otherwise can be a source of inconsistency and error. As mentioned before, conclusions about long term sea level changes can only be made for sufficiently long tide gauge records. Records of fifty years or longer are sufficiently long enough to perform long-term trend analysis (Wahl et al., 2013). Figure 3 further supports this, as it illustrates a decrease in standard error of RSML calculations with increasing length of the tide record (Wahl et al., 2013). Many regions, the study region included, are subject to processes that vary on a decadal scale and cover up or possibly enhance any processes going on due to climate change driven sea level rise (Nerem et al., 2018). Depending on the strength of short scale variability, the records required for being able to detect long-term trends have to become longer. Tide gauge records in the German Bight provide extensive temporal coverage, and therefore conclusion of long term sea level trends from the previously summarized studies can be seen as reasonable and justified.

Figure 3

Associated errors for RSML trends of three different tide gauge locations



Note. From Wahl, T., Haigh, I. D., Woodworth, P. L., Albrecht, F., Dillingh, D., Jensen, J., ... & Wöppelmann, G. (2013). Observed mean sea level changes around the North Sea coastline from 1800 to present. *Earth-Science Reviews*, *124*, 51-67.

The disadvantages of satellite altimetry are that substantial long-term coverage currently can only be achieved through combination of different satellite missions, which is very feasible but has to be carefully done due to the characteristic difference between satellites and their missions could potentially be a source of error or inconsistency (Dettmering et al., 2021). The use of satellite altimetry for coastal regions requires certain technical advances and adjustments to overcome current limitations. It has effectively been used for monitoring global sea level, so current efforts focus on developing more fitted applications for coastal regions, as they would benefit from the increased temporal and spatial resolution (Cipollini et al., 2019). Satellite altimetry works well for the open ocean for which it has been designed, but coastal regions are more difficult to measure because both land and water, as well as additional features of coastal environments and more complex atmospheric effects are present (Vignudelli et al., 2019). This can lead to a number of signal interferences, which decrease data quality and cause higher uncertainties (Schulz-Stellenfleth and Stanev, 2010). Current efforts have established coastal altimetry products which can overcome those limitations and provide data for near coast locations (Vignudelli et al., 2019). There have been substantial technical advancements, especially through advanced waveform reprocessing techniques and geophysical corrections which decrease sensitivity to land contamination (Cipollini et al., 2019; Dettmering et al., 2021). For coastal protection purposes it is relevant to specifically identify any near coastal trends. It would also be a valuable addition to current observational systems and tools, as it can access locations that are currently without in-situ coverage (Vignudelli et al., 2019). Those technical advancements currently offer the biggest potential in increasing the ability of determining regional sea level trends.

Next to technological improvements , the combination of tide gauge and satellite altimetry data appears to deliver the most effective results and lower errors than other models using only one of the data sources (Dettmering et al., 2021). Madsen et al. agrees and emphasizes the positive effect of blending tide gauge observations into analysis of coastal altimetry observations (2015). Correlation between tide gauge data and satellite altimetry depends on location, as river mouths, fjords, smaller bays, or closed floodgates showed lowest agreement between the two methods (Dettmering et al., 2021). Especially in shallow water areas are tide gauges currently outperforming altimeter observations (Schulz-Stellenfleth and Stanev, 2010)

3 Coastal Protection Relevant Observations

3.1 Tidal Regime

For the German Bight and the surrounding North Sea it is important to closely investigate the tidal processes to understand what changes can be observed, how that potentially influences mean sea levels as well as extreme sea levels, and most importantly how those changes in the tidal regime correlate to anthropogenic climate change. Additionally, not only MSL is relevant for coastal protection designs but mostly the effects of superposition with tides, surges, and waves, which ultimately lead to the creation of extreme sea levels (Arns et al., 2017). Based on current oceanographic understanding an indirect impact of sea level rise on tides and storm surges as well as directly impacted instantaneous water levels are expected (Idier et al., 2017). The German Bight is based on a shallow continental shelf, in which changes to indirectly affected components are significant, which otherwise are negligible in a deep water setting (Idier et al., 2017). SLR can create larger water depths, which in addition to related frictional changes also impact the required heights of coastal protection measurements compared to solely accommodating for MSL increase (Arns et al., 2017). The tidal dynamics of the German Bight are sensitive to changes of multiple factors, including VLM, MSL trends, morphological changes, or direct human impact like groundwater extraction (Idier et al., 2017; Stengel and Zielke, 1994). An increased water mass will also experience different effects by gravitational forces who drive the tidal regime (Stengel and Zielke, 1994).

In the German Bight two main changes in the tidal system have been observed so far. The Jensen et al. study highlights that since 1950 tidal range has increased, and those changes are significantly bigger than MSL changes (2014). For the area of the Wadden Sea a study by Arns et al. exploring different model simulations for the German Bight highlights an increase of high water levels of more than 10 cm for a sea level rise scenario of only 0.54 m (2015). An early study by Stengel and Zielke shows that the in the North Sea tidal range and high water level have increased over the past 40 years (1994). Between 1953 to 1989 tidal range and tide high water have increased, whereas tide low water levels stayed relatively unchanged, although all three aspects show strong regional variability overall (Stengel and Zielke, 1994). Additionally, using hydrological models they find that sea level rise does indeed impact the tidal dynamics, including tidal range, flow velocities, and tidally-induced residual currents (Stengel and Zielke, 1994). These changes are most pronounced along the coastline of the German Bight and specifically the Elbe Estuary (Stengel and Zielke, 1994). For some coastal regions in the German Bight the tidal range could increase by more than 30% of the mean sea level rise (Stengel and Zielke, 1994). Stengel and Zielke's findings indicate that the implications of tidal changes are relevant for the coastal area, as changes in water velocity due to changes in the tidal system have direct implications for erosion and sedimentation processes, and therefore non negligible for effective coastal management (1994).

A study by Mudersbach et al. focused on the tide gauge record of Cuxhaven and observed that changes in extreme sea level (ESL) are partially due to an increased tidal range (2013). Mudersbach proposes changes in MSL as a driver of changes of the tidal regime, but also mentions that a number of other studies based on hydrological models could not find any significant changes in the tidal dynamics attributed to MSL changes (2013). Other reasons could be human impact or natural variability of the tidal regime (Mudersbach et al., 2013). Projections of changes in the tidal system also depend on the extent of the intertidal area, which equally is connected to mean sea level rise but are very difficult to adequately project (Stengel and Zielke, 1994).

The study by Idier et al. uses a model based approach considering a range of sea levels between -0.25 to 10 m from current level, under the assumption of current day shorelines and with current coastal defense constructions, to understand tidal changes on the European Shelf (2017). The study concludes that independent from the magnitude of the sea level rise scenario, spatially similar changes in the high tide levels can be detected across the shelf (Idier et al., 2017). The German Bight alongside the Irish Sea and southern North Sea shows significant increase in high tide, with patterns proportional to sea level rise if it is below two meters (Idier et al., 2017). Those changes in high tide become less proportional to SLR when the area allows flooding, which can be observed for the German Bight (Idier et al., 2017). This makes it relatively difficult to predict how SLR and the tidal system will change in relation to each. Other regions within the North Sea, for example the English Channel, appear to show much more proportional behavior allowing predictions of high tide level based on SLR (Idier et al., 2017). Changes in water levels in the German Bight do not show uniform spatial distribution (Idier et al., 2017). Benninghoff and Winter observed non-uniform regional patterns of tidal range changes when analyzing 20 tide gauges in the Wadden Sea (2019). The study sees those regional differences as a representation of the morphological and hydrodynamic conditions highlighting the importance of those factors in the mechanism underlying relative sea level changes (Benninghoff and Winter., 2019)

Most importantly concluded across studies is that tide high water levels are increasing, which needs to be accounted for in coastal protection structures. Currently, it is difficult to attribute this solely to the increase in MSL, so further investigation into the potential mechanisms will be an appropriate goal going forward. The tidal system also needs to be well observed to increase certainty of satellite altimetry data as it requires correction for ocean tides (Dettmering et al., 2021). Multiple studies conclude that the biggest change of mean tidal range within all regions of the North Sea is present in the German Bight (Woodworth, 2010; Mudersbach et al., 2013; and Jensen et al., 2014).

3.2 Short Term Variabilities

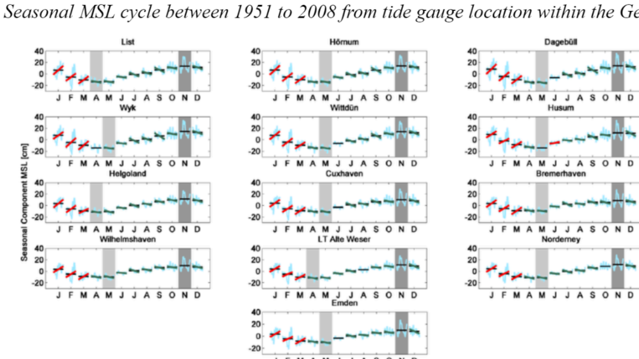
An early study of the region by Wahl et al. had observed strong variability on the short-term scale, especially inter-annually an absolute maximum difference of 150 mm and 50 mm average difference was detected (Wahl et al., 2011). This variability is even more pronounced on the monthly time-scale, with RSML differing up to 770 mm in absolute differences and 140 mm on average (Wahl et al., 2011). Past studies of tide gauge data from Church and White had attributed those inter-monthly variabilities bigger than 250 mm to errors concerning shifts in reference datums and other methodological errors (2006), but Wahl et al. argues that changes on that scale are actually common for MSL observations in the German Bight due to the strong impact of atmospheric processes (2011). Those wind-driven short term variabilities average and cancel out on the global scale leaving the global MSL to be mostly only affected by long-term natural variabilities (Dangendorf et al., 2015). This does not apply on the regional scale, and therefore in regards to sea level changes in the German Bight those factors have to be considered (Dangendorf et al., 2015). The long-term MSL trend does not deviate extremely from the global

MSL trends, but the German Bight shows more pronounced short-term variability (Jensen et al., 2014). As many of the studies have emphasized the importance of long-term trends for accurate future projections, understanding of natural variabilities are important to interpret the observational data correctly and identify the correct long-term signal. As most studies have highlighted, the study region is especially influenced by variability on the short time scale, specifically the seasonal, interannual, and decadal time scale. Those short term variabilities are seen as noise that ultimately limits the signal detection of the long term trends as it interferes with those signals. Dangendorf et al. emphasizes that detecting MSL trends in the German Bight is inherently difficult due to its location on a shallow continental shelf, which is especially vulnerable to atmospheric processes (2014).

If seasonal variability stays constant over the years, it is statistically irrelevant for the determination of long-term MSL trends, as it will average out. Still, it is valuable to understand the seasonal variability that has been strongly indicated by most of the MSL studies, because changes on the seasonal and even the interannual scale are relevant in terms of coastal management and protection. The correlated atmospheric processes need to be understood because the natural variability potentially strengthens or weakens the signal of MSL driven by anthropogenic climate change and anticipated changes in those atmospheric processes will be relevant for future projections. Figure 4 shows the seasonal variability recorded with the tide gauges in the German Bight, highlighting

Figure 4

Seasonal MSL cycle between 1951 to 2008 from tide gauge location within the German Bight

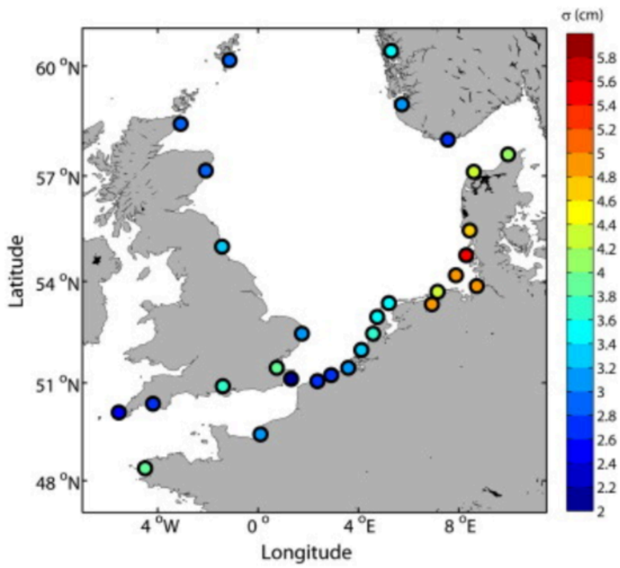


Note. From Dangendorf, S., Wahl, T., Mudersbach, C., & Jensen, J. (2013). The seasonal mean sea level cycle in the southeastern North Sea. Journal of Coastal Research, (65), 1915-1920.

significantly higher sea levels in the winter than in the summer months across all tide gauges (Dangendorf et al., 2013). This agrees with the findings by Dangendorf et al. that the maximum mean seasonal cycle is reached in November (2015). Lang attributes this to the higher wind strengths during those months creating a pronounced wind stress effect on the water surface, and seasonal changes in pressure systems and atmospheric circulation patterns (2020). According to Dangendorf et al. the monthly variability of MSL is 44% due to this seasonal cycle, indicating the strength and significance of seasonal variability in the German Bight (2013). The annual cycle shows higher amplitudes in the German Bight compared to the other surrounding regions within the North Sea within the region of higher amplitude values due to the large seasonal sea level differences (Dettmering et al., 2021). The strong short term variability in the German Bight contributes to uncertainties associated with sea level trends, resulting in higher standard deviation in the tide gauge based RSML time series for the German Bight compared to the rest of the North Sea, which is illustrated in Figure 5 (Wahl et al., 2013).

Figure 5

Standard deviation associated with RMSL time series of entire available data record at each tide gauge location



Note. From Wahl, T., Haigh, I. D., Woodworth, P. L., Albrecht, F., Dillingh, D., Jensen, J., ... & Wöppelmann, G. (2013). Observed mean sea level changes around the North Sea coastline from 1800 to present. *Earth-Science Reviews*, *124*, 51-67.

Short term variability in the North Sea can be attributed to the North Atlantic Oscillation (NOA) and the impact of westerly winds, for up to almost 80% along the southern and eastern north sea coastline, (Jensen et al., 2014). The North Atlantic Oscillation is a dominant pattern of atmospheric variability and has shown to be correlated with MSL trends on the decadal scale

(Lang, 2020). A study by Wakelin et al. explored the correlation between NAO and sea level for the northwest European Shelf relationship between 1955 and 2003 using a 2D model for tides and storm surges, as well as providing validation of the results through tide gauge data (2003). NAO strength is expressed in the form of the NAO index, which measures the normalized sea level pressure difference between the two permanent locations, the Azores and Iceland, (Wakelin et al., 2003). The study finds significant correlation and a detectable spatial pattern for the winter time with a negative trend of -0.7 for the southern part and a positive trend of 0.8 for the northeastern part of the North Sea (Wakelin et al., 2003). Overall, sea level in the southern North Sea appears to be most sensitive to NAO variations with a maximum of 96 mm increase per one unit change of the NAO index (Wakelin et al., 2003). A higher NAO index indicates strong prevailing westerly winds for northern Europe, whereas a negative value indicates weak westerlies combined with episodic easterly winds (Wakelin et al., 2003). Through a regression analysis the study determined the sea level sensitivity to the NAO index, finding that in their model the German Bight shows the largest sensitivity (Wakelin et al., 2003). The study concludes a significant correlation between the NAO and sea level across the North Sea but with changing strength of correlation over time showing higher correlation between 1955 to 2000 than for earlier periods (Wakelin et al., 2003).

Lastly, Wakelin et al. also emphasizes that the sea level in the German Bight is more sensitive to the changes in magnitude and direction of the wind field, and not a response to pressure system changes and an inverse barometer effect (2003). The study emphasizes that it is common for shallow shelf areas, which the German Bight and eastern part of the North Sea are located on (Wakelin et al., 2003). Chen supports those findings, identifying that for the period between 1953 to 2010 the inter-annual variability in the North Sea shows significant correlations with NAO for the winter months, December to March, and that for those months the role of atmospheric forcing is much more significant than thermosteric effects due to the influence of the NAO on the more shallow regions (2014). Dangendorf et al. argues that other parts of the north sea mostly experience sea level changes because of the inverse barometer effect, but that sea level changes the german bight are dominantly due to westerly winds and not the pressure systems (2014). Dangendorf emphasizes that the NAO correlation is strongest along the coastline, indicating that wave formation plays an influential role as well (2014). Hatterman et al. also supports that large scale atmospheric circulation patterns are impacting sea levels in the German Bight, with westerly circulation patterns having strong influence on flood behavior and occurrence (2012). Frederikse and Gerkema agree that wind and pressure are the main drivers of seasonal variability of sea level (2018), but Dettmering et al. warns that since they are based on tide gauge data, which are biased towards coastal regions, those trends cannot seamlessly be transferred to regions off-shore and open ocean (2021). Dangendorf et al. finds that the detected decadal and seasonal MSL variability in the North Sea can be attributed to atmospheric forcings and the interactions between the atmosphere and the sea, attributing MSL changes on the decadal time scale to volumetric and distributional water mass changes (2015).

The study also strongly emphasizes that the selection of statistical methods and the description of the natural variabilities within those approaches ultimately determines the strength of the statistical significance of long-term trends (Dangendorf et al., 2015). This highlights the need for sophisticated statistical analysis and understanding of the processes underlying the short-term variabilities to increase certainty of detected long-term signals, which coastal management strategies primarily rely on. Predictions of global warming related NAO changes will help project MSL rise for the German Bight. The low water depths due to the underlying shallow continental shelf makes the German Bight vulnerable to short term variability induced by westerly winds, creating strong seasonal and interannual variability. These shorter term fluctuations in magnitude are important to anticipate when designing coastal protection infrastructure and management strategies.

3.3 Extreme Sea Levels

Dettmering et al. NorthSEAL data indicates that MSL rise also leads to increased flood and storm surge probability (2021). For the low lying and flood prone region even an increase in sea level by one meter is estimated to increase storm flood probabilities from being one in a hundred to only one in ten, putting coastal communities and economies under increased threat (Sterr, 2008). An increase in storm surges has been observed in addition to the MSL rise related changes in the tidal system (Jensen et al., 2014). Mudersbach et al. strongly supports that the impact of MSL rise will strongly affect periods of ESL, which are created through the right combination of tidal state, MSL, and storm surges (Mudersbach et al., 2013). The tide gauge records in the German Bight reveal an increase in storm floods due to SLR (Brasseur et al., 2023), but the interaction between process due to the characteristics of the shallow shelf and the tidal regime can also potentially contribute to increased ESL (Arns et al., 2015)

Mudersbach used six tide gauges along the German coastline and identified that ESL changes for the Cuxhaven tide gauge record were the same as MSL changes until 1950 and beginning again from 1990, but that in the intermediate period ESL changes differed from MSL changes (2013). This is attributed to changes in the tidal amplitude and storm activity which correlate in timing of onset (Mudersbach et al., 2013). The required water level for storm surges will appear more frequently due to the overall increase in the baseline MSL water level, as well as potentially due to changes in ocean tides,magnitude and spatial patterns of weather systems and storm surge characteristics (Mudersbach et al., 2013). The study summarizes that many other studies have identified the MSL increase as driving the increase of high sea levels as they have increased at rates similar to MSL (Mudersbach et al., 2013). On the other hand, it is also mentioned that other studies have observed increases of high sea levels at faster rates than MSL increase, attributing this to regional wind patterns and long term changes of the tidal system (Mudersbach et al., 2013). Lang attributes changes in ESL magnitude to natural variability, as well as correlates long-term ESL changes with large scale NAO forcing due to shifts in the north westerly wind components (Lang, 2020)

The region of the German Bight is so vulnerable to extreme floods because of the potential and common superposition of tides and storms creating powerful floods for the surrounding coastal region (Lang, 2020) . Lang emphasizes the importance of understanding the mechanisms of long-term variability of strength and occurrence of extreme storm floods and not only single events or recent trends, stating that it will be essential in improving coastal protection measurements (Lang, 2020) . The study also clarifies that making any significant claims about changes in ESL is difficult, because they are rare events by definition and difficult to differentiate from other natural variability of similar shorter timescale due to the limited length of available time records (Lang, 2020). Current data availability limits the ability to robustly identify the mechanisms behind ESL variability (Lang, 2020). Any conclusions on the effect of RMSL rise on ESL are inhibited by the rare nature of extreme events, and studies can only make use of a limited amount of past historical events (Stengel and Zielke, 1994). Lang et al. concluded that they couldn't detect any trends that didn't also lie within the range of changes caused due to natural variability (2020).

4 Relevant Geological Factors

4.1 Vertical Land Movement

Tide gauges measure the sea level relatively to a fixed datum, but the reference point is subjected to the vertical movement of the land (VLM), which is recorded in the tide gauge data (Woodworth, 2006). Those movements can be on the same order of magnitude as changes in MSL themselves and therefore cannot be neglected when looking at tide gauge statistics (Woodworth, 2006). To calculate absolute sea level changes, vertical land movement rates have to be subtracted from the tide gauge data, either by using glacial isostatic adjustment (GIA) models to estimate VLM rates, predicted RSML changes based on geological information, or measured VLM rates through CGPS (Continuous Global Positioning System) employed alongside tide gauges (Wahl et al., 2013). Before the availability of CGPS, GIA models were the only applicable model to correct tide gauge data accurately, but are dependent on correct knowledge of past glaciations including lithospheric thickness and upper and lower mantle viscosity, as well as it is limited to the general uncertainties associated with modeling systems (Woodworth, 2006). Optimally, VLM should be directly measured at the tide gauge, which is possible through the CGPS system (Woodworth, 2006; Wahl et al., 2013). Han et al. mentions the use of CGPS measurements to define VLM rates, as well as the option to combine the use of tide gauge and altimetry data (2015). Because tide gauge data includes the VLM component, subtraction of the absolute sea level provided through the altimetry data allows to determine the VLM component itself (Han et al., 2015). Currently, only the minority of tide gauges are located alongside GNSS stations (Vignudelli et al., 2019). The required spatial and temporal coverage to provide measurements of high enough accuracy from CGPS has been reached since the beginning of the 20th century according to Hawkins et al. (2019). The applications of CGPS are limited because they haven't been employed for a long enough yet and due to noise interference don’t always deliver the required degree of accuracy (Wahl et al., 2013). Hawkins et al. emphasizes that using VLM data provided from CGPS systems significantly reduces the rates of observed sea level rise within the tide gauge records from the initial half of the 21st century (2019). This highlights the importance of VLM approximation choice, as inaccurate rates can lead to wrongful conclusions and falsely detected MSL trends (Hawkins et al., 2019).

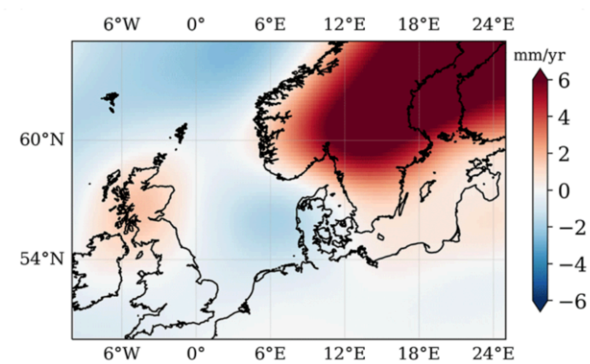
Vertical land movement though can be caused by a number of underlying mechanisms, including natural processes like tectonics and glacial isostatic adjustment or induced by human activity through extraction of fluids like groundwater and oils, ultimately leading to a subsidence of the land (Wahl et al., 2013). GIA is the primary component in regards to understanding vertical land movement in relation to sea level changes. The fifth IPCC report mentions the importance of considering non-GIA movement (Pachauri et al., 2014) which was further highlighted by a study of Han et al. in 2015, which found that for projections for tide gauges along the coast of North America and East Asia the failure to consider non-GIA VLM leads to a significant under- or overestimation. Projections for coastal and regional sea level by the IPCC AR5 do not consider those components (Pachauri et al., 2014), which based on the findings by Han et al. can cause significant changes. Additionally, the rates of relative sea level change due to human impact such as groundwater extraction, especially in landscapes with recent sedimentary deposits, can be significantly higher than the climate change driven sea level change, meaning that any type of vertical land movement mechanism needs to be considered and observed when the study includes mitigation goals and protection of the coastal community in their study objectives (Nicholls et al., 2021). A study by Nicholls et al. wanted to quantify subsidence for coastal regions on the global scale and the study claims that there a large amount of coastal populations are located in subsiding regions and experience sea level rise at an unproportional rate of 7.8 to 9.9 mm/yr (2021). This extreme subsidence is not observed for the German Bight. The statement by Nicholls et al. though can also be interpreted differently, as the heavily populated coastal regions are subsiding more due to the present population and infrastructure demands, especially when processes like freshwater extraction can cause significant subsidence. Those processes do not dominate in the coastal region of the German Bight, meaning their contribution is not significant and neglected in this paper.

Tectonic motion contributing to vertical land movement are viscoelastic relaxation of the mantle due to load changes during melting of ice sheets, which can either cause subsidence or uplift depending on where the study area is located in relation to the previous ice location (Hawkins et al., 2019). If the area was previously under the weight of the glacial mass, melt of the glacier leads to large rates of uplift, whereas if it was located around the glacier melt of the ice will cause subsidence in response (Hawkins et al., 2019). GIA rates show varying spatial patterns with higher VLM rates at higher latitudes, but appear to be rather lineary in time for the time period that is considerable for current sea level changes (Hawkins et al., 2019). Additionally, increasing water volume for example due to the increased freshwater release due to glacial melt leads to subsidence of the sea floor due to the additional weight (Hawkins et al., 2019). VLM is also determined by mantle convection and plate tectonic movements which are more gradual and predictable changes, as well as movement induced through earthquakes, which cause more episodic changes (Hawkins et al., 2019).

GIA is driven by glacial processes on recent decadal and millennial time scales, but most dominantly the long-term is driven by the last glacial period, leading most sea level studies to prioritize this long-term trend in their analysis (Simon et al 2021). Wahl et al. emphasize that the GIA component is most relevant for the North Sea region as changes in RSML seem to be well correlated with the observed VLM patterns (2013). Reicherter et al. concluded through the application of glacio-isostatic models that most of current VLM is due to glacial loading and unloading after last deglaciation during the Pleistocene (2005). Those viscoelastic processes are ongoing (Meier et al., 2022) and Wahl et al. highlighted that for the German Bight subsidence at a rate of 1-2 mm /a is observed in response to the last glacial period (2014). The graph in figure 6 shows the trend patterns of the VLM rates considered for the adjustment of the relative sea level (Dettmering et al., 2021). The VLM trends for the German Bight appear to be either zero or negative, highlighting the pattern of subsidence due to the region's position on the glacial bulge during the last glaciation (Vink et al., 2007). The last glacial period relevant for the study region included the Fennoscandinavian ice sheet, and placed the study region not beneath it but close around its circumference into the peripheral glacial bulge (Vink et al., 2007). The bulge formed as a balancing response to the ice sheets mass weighing down the mantle (Vink et al., 2007). After the ice sheet melts, the mantle underneath German Bight responds with subsidence of the land as the weight distribution is slowly being balanced out again (Vink et al., 2007). The study by Reicherter et al. defined the maximum zone of subsidence due to glacio-isostatic adjustment as located at the center of the peripheral glacial

Figure 6

VLM rates of GIA model used to correct tide gauge data to isolate MSL trends



Note. Modified from Dettmering, D., Müller, F. L., Oelsmann, J., Passaro, M., Schwatke, C., Restano, M., ... & Seitz, F. (2021). NorthSEAL: A New Dataset of Sea Level Changes in the North Sea from Satellite Altimetry. Earth System Science Data Discussions, 2021, 1-28.

forebulge, which mostly covered the Jadebusen regions, Weser and Elbe Estuaries, but excluded Schleswig-Holsteinische coastline (2005). This aligns with the observation that subsidence rates within the German Bight vary inter-regionally. Variations between individual tide gauges and bigger trends observed in the southern north sea align with those GIA movements (Jensen et al., 2014). A study by Vink et al. finds that their analysis of the MSL curves show different altitudes between the data for the Belgian North Sea, compared to the Netherlands, northwest german and southern North Sea part (2007). They state that this is an indication for different VLM rates, showing that the northwest german, netherland, southern parts appear to experience more subsidence compared to the Belgian part (Vink et al., 2007). The study also states that under the assumption that global mean sea level rise is constant across all areas, the component of VLM due to tectonic subsidence appears to be negligible in its contribution to RMSL changes and all significant contributions to VLM are due to isostatic readjustment (Vink et al., 2007). Through comparison with other tectonic and isostatic activity of other parts in the North Sea Vink et al. established that the northwest german coast has undergone subsidence due to isostatic readjustment at about an rate of 10 cal. ka BP. (2007). Subsidence in the German Bight specifically due to GIA is much bigger than in its neighboring Dutch north sea parts (Vink et al., 2007). These numbers have been estimated for the holocene age and the study emphasizes that it could significantly vary for any older ages (Vink et al., 2007).

In terms of current tectonic activity as well as impact of earthquake, this component is not contributing significantly to current VLM movements, as the German Basin only shows low seismic activity (Reicherter et al., 2005). As well is the earthquake probability for earthquakes of larger MSK intensity than five very small, making vertical land movement due to earthquake activity a negligible factor in the sea level analysis of this paper (Reicherter et al., 2005).

Recent changes due to ongoing anthropogenic VLM due to ongoing glacial melt are non-linear and are difficult to include in GIA models, but Frederiksen et al. also concluded trends on the order of mm/year (2019).

For future considerations accurate constraints of the long-term GIA in models can help to identify the present VLM due to water mass redistribution allowing to identify the effect of ongoing recent climate change (Simon et al., 2021). This means that in the future it would be useful to understand long-term GIA as well non-GIA tectonic motion, to be able to observe how current glacial melt is changing the distribution and mass budget (Simon et al., 2021). This is slightly beyond the scope of this paper but further defining the VLM components within the German Bight can deliver useful information for local patterns of glacial melt, changes in the global water budget, and attribution of current climate change to sea level changes. Although studies focusing on climate change induces SLR often subtract vertical land movement data from the tide gauge record to determine MSL trends, current literature also focuses on observing RSML independent of the geological origin or contribution to the VLM component, as ultimately RSML is what determines the region's experience and is what coastal adaptations and mitigation strategies need to be based on on (Nicholas et al., 2021).

4.2 Bathymetry and Sedimentation Processes

Bathymetry is defined as the study of physical characteristics of the seafloor and its geologic features, which is susceptible to changes due to climate change, sea level rise, changing storm patterns, and erosion in the coastal area, ultimately changing the seafloor dynamics (Lang, 2020). The global sea level can rise through an increase in water mass through melt of ice sheets, but even without any change in water volume the sea level can change when the existing water mass is redistributed (Lang, 2020). It is important to consider the SLR and bathymetry relationship, and if the rising sea level caused observable changes in bathymetry or if changes in bathymetry have led to mass redistribution. Defining this relationship will allow more accurate future projections. Sea levels can locally be enhanced when topographic features cause a decrease in water depth (Lang, 2020). Those features can change and vary over the long term partially due to current climate change (Lang, 2020). Changes in sea level also change sediment supply and deposition space availability, which affects sea levels again (Lang, 2020). Additionally, bathymetry is linked with and determines ocean circulation processes, which as established also affect sea level (Lang, 2020).

The bathymetry of the German Bight is a shallow continental shelf, which physically influences interior dynamics and therefore also the sea level (Wise et al., 2018). Jacob and Stanev highlights that the tides and wind determine direction of sediment transport (2021). As established, the tidal system is subject to change due to MSL. Furthermore, water depth increases with SLR and Jacob and Stanev highlight that changes from ebb-dominant to flood-dominant influences the tidal asymmetry and therefore direction of sediment transport ultimately changing the bathymetry and hydrodynamic energy (2021). The German Bight includes the Wadden Sea, a large tidal system, meaning that these interactive relationships due to SLR will be relevant to consider especially in regards to ecosystem conservation efforts. Wachler et al. used a hydraulic model to identify changes in velocities due to tidal and bathymetric changes (2020). The study concluded that current velocities will change when bathymetry is altered and that the bathymetric response has to be considered when projecting tidal changes due to SLR in the region (Wachler et al., 2020). This means that when we consider future projections, one has to keep in mind that erosional and depositional processes can change bathymetry and therefore lead to mass redistribution, especially relevant in coastal areas. Jensen et al. highlights that this component is not very well explored just yet (2014). Current bathymetric data is required to determine storm surge vulnerability due to SLR (Mokhtar et al., 2023). Exemplary for this is a study by Mokhtar et al. which uses satellite imagery, specifically lidar, to produce bathymetric data for the region (2023).

The German Bight and the coastline contains a variety of landscapes as illustrated in Figure 7, including barrier islands, marshlands, estuaries, and river mouths, for which all transgression or regression will look differently due to different rates of sediment supply and accommodation space (Benninghoff and Winter, 2019). These processes will need to be considered as they determine the landscape's reaction to SLR as well as sedimentation rates determine part of the VLM (Benninghoff and Winter, 2019). Additionally, the tidal regime regulates morphological changes, meaning that the observed tidal changes can also influence the morphology of the land and can contribute to relative sea level changes through that (Benninghoff and Winter, 2019). It is important to think about potential morphological changes, especially potential transgression due to fast SLR can lead to overstepping and drowning of the barrier islands, which are inhabited and popular for tourism, as well as changes in the Wadden

Figure 7

Landscape of the German Bight defined by morphology

Note. From Benninghoff, M., & Winter, C. (2019). Recent morphologic evolution of the German Wadden Sea. Scientific reports, 9(1), 9293.

Sea which is a valuable and unique ecosystem (Storms et al., 2008). A detailed analysis of those surface processes is beyond the scope of this particular essay, which has focused more on other mechanisms, but this aspect should be of further interest and consideration when MSL trends are being projected for the future.

More specifically, I suggest a further investigation of the paleoenvironment of the German Bight. Recent landforms in the German Bight are the result of much larger sea level rise, about 110 m sea level rise over the last 15000 years since the last deglaciation, the Weichselian Late Glacial and Holocene period (Streif, 1989). On the long-term scale the mean sea level was significantly influenced by tectonic processes, during the Cretaceous the mean sea level was more than 100-300m higher than currently observed MSL (Jensen et al., 2014). Based on radiocarbon dates, a rise of 46m since 8900 B.P has been reconstructed (Steif, 1989). Approximately since that period the current features include barrier island, tidal flats, and shoal and beach sediments in barrier island zones, which heightened through the addition of salt marsh deposits and dunes which elevated them about 20 m (Steif, 1989). Understanding those past environmental processes during a period of significant sea level rise potentially helps to project how the current landscape can be expected to change with current sea level rise rates.

5 Summary and Outlook

Overall, the coastal RMSL change is more drastic in other regions that often experience more extreme vertical land movement, as the Nicholls et al. study had shown with comparison to global mean sea level rise for coastal regions (2021). Important though is that for each individual region even small changes have a significant impact. Especially for this very shallow region with unique and vulnerable ecosystems and densely populated coastal region, those small changes are significant, even though the region has experienced much more drastic SLR throughout the geologic past. Those magnitudes of SLR will not be a good comparison when considering the current impact on coastal regions as the present coastlines are utilized differently and integrated into communities and infrastructure.

For future predictions long-term records of sea level change have been seen as most relevant, and this does also apply to the study region, but after investigating the different mechanisms underlying this current relative sea level change, short term variabilities are of particular interest. As stated throughout this paper though, the major limitation to precisely determining long-term trends in this region is due to interannual and decadal variability which can interfere and cover the long-term signal.

Data analysis and statistics play a significant role in what conclusions ultimately can be detected. Depending on the statistical approach, different trends can be observed despite using the same data across different studies. Quality observational data of German Bight is provided through tide gauges and altimetry, but it is still difficult to detect non-linear MSL changes or fully attribute ESL and MSL changes to one of the explored mechanism, mostly due to limitations in temporal coverage compared to length of natural variabilities.

Development of better coastal altimetry products will be important because for management of coastal regions, high quality observations from as close to the shoreline as possible will be increasingly more helpful than open water measurements. More research into the shift of the seasonal cycle will be useful because of the potential effect on ecosystems and the lack of extensive information on how that could be linked to MSL rise and climate change in the German Bight. Multiple studies remark that VLM and GIA rates are still relatively uncertain, so improvements in those estimates will better our understanding of the contribution of anthropogenic climate change. It will also simultaneously reveal information on local patterns of glacial melt. This paper did not really acknowledge the influence of the glacial melt patterns and mechanisms, so something that will be essential for future considerations is magnitude and timing of glacial melt. For this paper it was generally assumed that eustatic sea level rise is constant and equal for all areas. Other factors, like thermal patterns and distribution, were also not considered as much in this analysis due to the constricted length of the paper.

Even though this region does not show any extreme changes and there are other regions where sea level change is much more pronounced, it is still very much worthwhile to have analyzed this region. It reveals the interplay of all the different processes which understanding will benefit any further region that will be studied. Any improvement in one region will enable improvement of another region. As much as there are many regions that show extreme observed changes or are predicted to experience extreme change, there are many regions with more moderate change but still impact to the coastal population. Our modern infrastructure and populations tend to maximize use of any available space and therefore even any small change has a direct impact in most regions. Although the current sea level rise does not pose an immediate threat to the coast, for this region in particular we have to consider the effect of sea level rise on the tidal ecosystems included in the study region. This region also requires additional thought due to the different responses of the variety of landform features, including different island types, tidal system, and the coastal mainland. The study area is scaled down to the regional level, but for well fitted mitigation and management strategies that require accurate projections, the chosen area might need to be downscaled even further to fulfill the different needs of the Wadden sea, the barrier islands, or the different estuary systems. A smaller region will allow better analysis and prediction of the impact of morphological changes and vertical land movement, as well as anthropogenic impact. Although observational data of RMSL will be limited to fewer sources, potentially making it vulnerable to operational errors or other variabilities.

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