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EFFECTS OF REGIONAL CLIMATE CHANGE ON THE LONGSHORE SEDIMENT TRANSPORT AT THE GERMAN BALTIC SEA COAST

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ABSTRACT

In this study the effects of regional climate change on the future longshore sediment transport at the German Baltic Sea coast are analysed. On the basis of hourly wave conditions both directional and net transport rates are calculated between 1960-2100 and the long-term changes of the transport rates are analysed over time periods of 30years for the future emission scenarios A1B and B1. A tendency towards higher values of the 30year averages of the net transport capacities (with maximum changes of +50%) is found at locations exposed to westerly wind directions. In contrast, a trend towards lower values exists at locations which are sheltered against westerly winds (with maximum changes of -50%). Moreover the climate change signal is more pronounced to the end of the 21st century and for the emission scenario A1B. Due to the projected changes of the regional climate model it can be concluded that local accumulation and erosion processes can be intensified especially at westerly wind exposed coastal stretches.

Keywords: *Longshore sediment transport, regional climate change model Comso-CLM, sediment transport model GENESIS, wave model SWAN*

1. INTRODUCTION

The outer German Baltic Sea coast is approximately 800km long and each 400km are belonging to the two federal states Schleswig-Holstein (S-H) and Mecklenburg-Vorpommern (M-V). The outer coastline is exposed to the Baltic Sea and consists of low-lying shallow coast sections (ca. 2/3) and cliff coasts (ca. 1/3) which have been formed in the latest postglacial time period. The morphological development of the coastline is dominated by coastal erosion (46% in S-H and 65% in M-V) and accumulation of sediments takes place along 32% (S-H) resp. 13% (M-V) of its length. The average rate of retreat of the coast in M-V is about 35m/100a with a maximum of 210m/100a east of Warnemünde, Germany (MV, 2009). In S-H an maximum retreat of the coastline nearby Brodten (north of the city of Travemünde, Germany) in the magnitude of 100m/100a has been observed (SH, 2012). A balance of the sediment budget can be found along 22% of the total length of the German coastline.

The morphology of the coast is mainly influenced by long-term wave characteristics and short-term resp. long-term variations of the regional sea-level. Due to the absence of strong swell waves and tides (the tidal range is less than 15cm for most parts of the German Baltic Sea) the local wave climate is mainly influenced by the prevailing wind conditions.

The nearshore-sediment transport takes place in intermediate resp. shallow water depths and is caused by nearshore-currents which are a result of the waves breaking in limited water depths on the foreshore and on the beach.

In coastal engineering practice the sediment transport at the coast is often characterized by the cross-shore and longshore transport processes. The cross-shore sediment transport moves sand normally to the coast and can be important during (short-term) storm periods. Without any longshore sediment transport the transported sediment (sand) would remain in the cross-shore profile section. Due to the energy input of wind and waves oblique to the coast sediments are moreover transported along the coast towards the opposite direction of the wind. Both transport processes are influencing the morphology of the coast but the long-term changes of the coastline are mainly a result of the longshore sediment transport.

Since the most disastrous flooding event in 1872 in the Baltic Sea the local authorities which are responsible for coastal and flood protection have constructed a very efficient and safe coastal protection system along the whole German coastline consisting of different methods and measures (for details see MV, 2009; SH, 2013). The sediment transport is exemplarily influenced by active measures (beach nourishments) and constructions (offshore breakwaters, groins, harbours and marinas etc.).

The maintenance of the system has become more and more expensive during the past decades hence the protection measures have to be prioritized and adapted to the hydrodynamic changes. Moreover the availability of marine sands as a natural material for coastal protection measures is limited and has its (re-)use has to be optimized.

From recent assessments of climate change and its impacts (e.g. IPCC, 2013; BACC, 2008) changes of the hydrodynamic conditions in the area of the Baltic Sea like e.g. the rise of the regional sea-level and changes of local wind and wave conditions can be expected. The changes are depending on the approach used for the calculation of the changes and on the assumed future greenhouse gas emission scenarios, resulting in a high uncertainty of the results.

For the development of future coastal and flood protection strategies and methods and for the future safe constructional design of the coastal and flood protection structures, coastal engineers need to know possible changes of the hydrodynamic conditions for the assessment of the changes of the loads on the structures. Moreover for the future safe functional design of the coastal protection structures and measures that influence the sediment transport and for the assessment of future morphological changes of the coast is also necessary to analyse effects of regional climate change on the sediment transport processes like e.g. the longshore sediment transport.

2. APPROACH

2.1 Sediment Transport Model

In this study the Generalized Model for Simulating Shoreline Change (GENESIS) Hanson and Kraus (1989) is applied for the calculation of long-term annual sediment transport capacities along the German Baltic Sea Coast. The model has been set-up for selected sections along the German Baltic Sea coast (cp. Figure 1 and Table 1). The coastal sections and the basic model parameter e.g. the:

- Effective grain size of 0.2mm
- Transport coefficients K1=0.6 and K2=0.4
- Average berm height=2m
- Closure depth=10m

that were used in previous assessments of the potential longshore sediment transport (Jankowski and Schlamkow, 2011; Fröhle and Dimke, 2008; MV, 2007) have been used again to account for the comparability of the results.

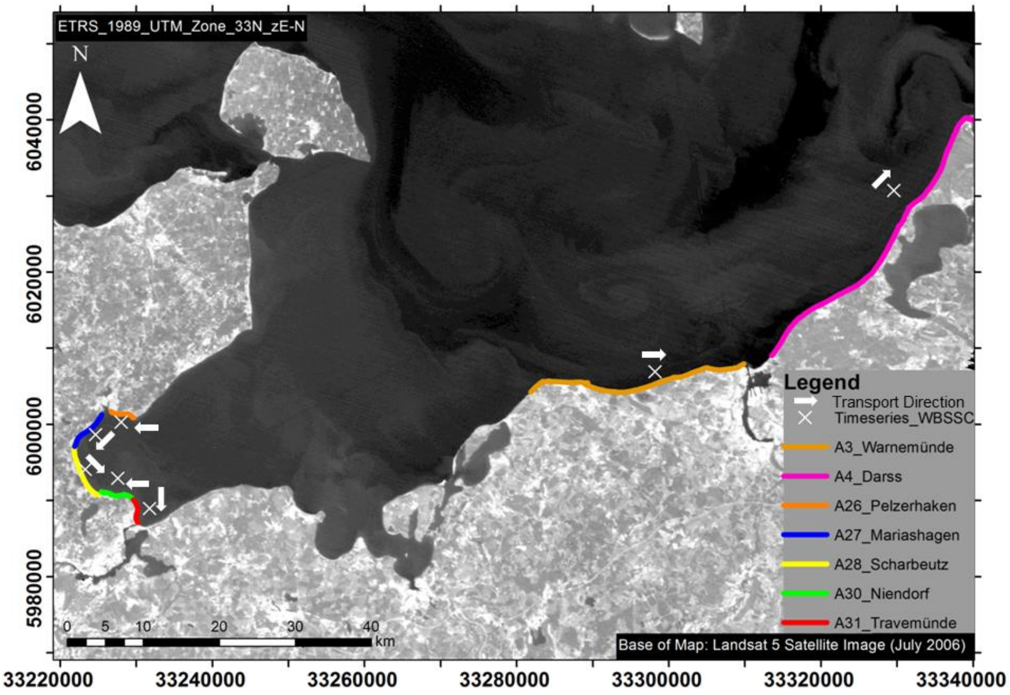

Figure 1. Coastal Sections of the Study Area and Locations of Time Series of Wave Parameter (white crosses). The average direction of the net sediment transport capacity is indicated by white arrows.

Table 1. Coastal Sections of the Study Area and Locations of the Time Series of Wave Parameter.

	Lat [°]	Lon [°]	Depth [m]
A03_Warnemünde	54.171	11.908	12.3
A04_Darss	54.396	12.375	9.8
A26_Pelzerhaken	54.079	10.842	11.4
A27_Mariashagen	54.063	10.792	7.7
A28_Scharbeutz	54.021	10.775	8.7
A30_Niendorf	54.013	10.842	16.7
A31_Travemünde	53.979	10.908	11.4

Genesis uses a modified CERC (Coastal Engineering Research Council) approach for the calculation of the sediment transport. Following this approach the longshore sediment transport is related to the wave induced energy flux. The model does not take into account the availability of sediments at a given location, thus assuming that sediments are always available and transportable. As one of the outputs both net and bi-directional sediment transport capacities are calculated for each grid cell of the model domain.

The model has some advantages when compared with other approaches for the prediction of sediment transport rates like e.g. the original CERC (1984) or Kamphius (1991) approach as shown by Eversole and Fletcher (2003). Firstly it can account for short-term changes of the nearshore wave parameters and different characteristics of sediment like e.g. the mean grain size diameter can be applied. Secondly, the model is able to include costal protection structures and measures that influence the longshore sediment transport within the model domain (e.g. groins, offshore breakwater and active measures like beach nourishments). On the basis of the accumulated or eroded sediment the model is also able to account for the long-term morphological changes in each section of the coastline due to wave and wind impact.

In previous assessments of the potential longshore sediment transport along the German Baltic Sea Coast (Jankowski and Schlamkow, 2011; Fröhle and Dimke, 2008) it was found that the magnitude of the calculated sediment transport capacities are in a good agreement with field observations. Existing coastal protection structures and measures that might influence the local sediment transport characteristics are unattended in this study to analyse the trend of future changes of the longshore sediment transport rates due to the changes of the future wind conditions rather than to focus on possible future morphological shoreline changes.

The numerical simulations of the sediment transport were done on the basis of long-term time series of hourly wave parameters (significant wave heights, mean wave periods and wave directions) which have been derived from numerical simulations of the wave climate at reference points for each coastal section (cp. Figure 1 and Table 1) between 1960-2100 for different scenario runs of the regional climate model (see next section, cp. Table 2). The locations of the reference points were chosen in accordance to Jankowski and Schlamkow (2011) for the comparableness of the results.

2.2 Wave and Regional Climate Model

On the basis of hourly simulated wind data of the regional circulation model Cosmo-CLM (Lautenschlager et al., 2009; Rockel et al., 2008) wave conditions from 1960 to 2100 are calculated for two realisations each of the global emission scenarios A1B and B1 (cp. Table 2) from the Special Report On Emission Scenarios (Nakićenović et al., 2000) of IPCC, AR4 using the numerical wave model SWAN (Booij et al., 1999) for the area of the Western Baltic Sea (cp. Figure 2).

Table 2. Cosmo-CLM model runs and combined transient data sets (remark: ‘x’ denotes no experiment).

20th century (1960-2000) observed anthropogenic forcing	21st century (2001-2100) forced by emission scenario A1B	21st century (2001-2100) forced by emission scenario B1	transient data set (1960-2100) of near-surface wind parameter (10m above surface)
C20_1	A1B_1	x	C20_1+A1B_1
C20_1	x	B1_1	C20_1+B1_1
C20_2	A1B_2	x	C20_2+A1B_2
C20_2	x	B1_2	C20_2+B1_2

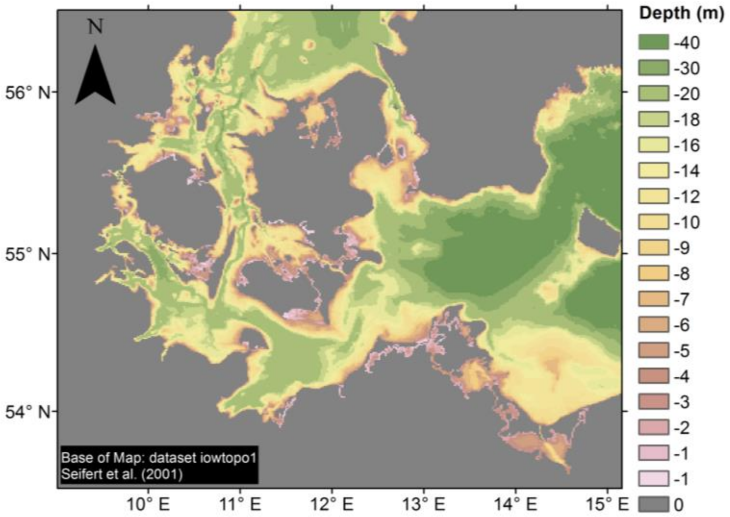

Figure 2. Bathymetry of the Western Baltic Sea.

The fine model was run with a spatial resolution of approx. 1km and nested into a coarse wave model for the whole Baltic Sea on the basis of the wave model WAM (Hasselmann et al., 1988). The coarse model was run with a spatial resolution of approx. 5.5km by the Helmholtz-Zentrum Gesthacht, Germany (Groll et al., 2013) using the same wind input data. All simulations were carried out at a mean water level and the presence of sea-ice was ignored in the SWAN wave model domain. Two bathymetric data sets with a spatial resolution of approx. 2km for the coarse model and with a higher resolution of approx. 1km for the fine model were used from Seifert et al. (2001).

Compared with observations the SWAN model is able to account for the average wave climate along the German Baltic Sea Coast (Schlamkow and Fröhle, 2009). Regarding the significant wave heights (H_{m0}) and mean wave directions (Θ_m) a good agreement was found. In contrast the mean wave periods (T_{m02}) are systematically underestimated by the model, hence an empirical correlation between observed wave heights and periods was used for the calculation of the mean wave periods, Eq. [1].

$$T_{m02} = 1.11 * H_{m0} + 2.5s \qquad [1]$$

The future changes of the wave climate in the Western Baltic Sea on the basis of the wave and climate model runs have been analysed in previous studies (for more information see Dreier et al., 2014; 2013).

Comparisons of the 30year averages of the wave conditions between the future and the past show that the changes of the average wave conditions can be directly linked to the changes of the average wind conditions. From the results of the regional climate model we found that the 30year averages of the wind velocity 10m above ground can increase between +2% and +4% and that the 30year averages of the mean wind direction can change between 1° and 11° towards more westerly directions to the end of the 21st century (2071-2100) when compared to the values of the reference period (1971-2000).

Regarding the changes of the average wave conditions it was found that increases of the annual and seasonal 30year averages of the significant wave heights are predominant at coastal stretches which are exposed to westerly winds. The bandwidth of the changes of both annual and seasonal averages of the significant wave heights for the two future scenarios 2050 (2021-2100) and 2100 (2071-2100) ranges between -2% and +10% when compared to the values of the reference period (1971-2000). Another notable fact is that the averages of the mean wave direction can change within the range of 3° to 7° towards more westerly wave directions.

At locations which are sheltered against westerly winds (like e.g. the Bays of Lübeck, Kiel and Eckernförde and the East Coasts of the Isles of Fehmarn, Rügen and Usedom) the trend of the changes of the significant wave heights is much unclear and the bandwidth of the changes ranges between -5% to +5%. Minor changes of the averages of mean wave direction within a range of 1° to 2° towards more easterly directions were found.

2.3 Analyses of Time Series of Sediment Transport Capacities

Hourly values of both directional and net transport capacities were simulated with GENESIS for each coastal section (cp. Table 1) and a spatial resolution of approx. 50m on the basis of the transient time series of wave parameters from 1960 to 2100 for each two realisations of the emission scenarios A1B and B1 (cp. Table 2).
After the compilation of the time series of the transport capacities different averaging methods are applied. Firstly, spatial averages of the transport capacities of all numerical grid cells within one coastal section have been calculated on an annual basis for each coastal section. Examples results of the calculated annual net transport capacity of the section A3_Warnemünde for the second realisation of the emission scenario A1B are shown in Figure 3.

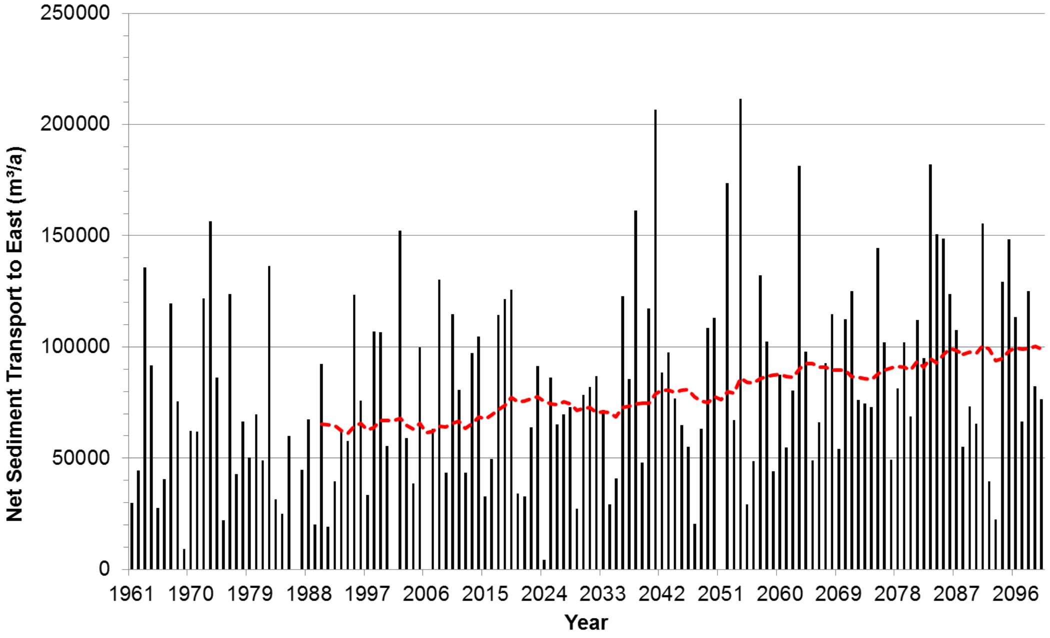

Figure 3. Annual Net Sediment Transport Capacity of the coastal section A3_Warnemünde for the second realisation of the emission scenario A1B (30year moving averages are indicated by a red dotted line).

Secondly, 30year moving averages are calculated from 1991 to 2100 for each coastal section and emission scenario run (cp. Figure 3, red dotted line). Finally, the relative changes of the future 30year averages between 2001-2100 of the net- and directional sediment transport rates and the 30year averages of the reference period 1971-2000 are analysed as with Eq. [2]. Example results of the relative changes of the sediment transport capacities are given in the next section of the paper.

$$\Delta Q_{mean,30yr} = \left(\frac{Q_{mean,30yr,n}}{Q_{mean,30yr,1971-2000}} - 1 \right) * 100\% \qquad [2]$$

where $n = 2001 \dots 2100$.

3. RESULTS AND DISCUSSION

The calculated annual averages of the net transport capacities of the coastal sections have been compared to previous assessments of the longshore sediment transport rates on the basis of wind fields of the Local Model (DWD) for the time period 2001-2005 (Jankowski and Schlamkow, 2011; Fröhle and Dimke, 2008). Due to the fact that the hourly wind velocities of the regional climate model Cosmo-CLM overestimate the observed values and that wind events from westerly directions are predominant also the projected sediment transport rates towards easterly directions are overestimated by a factor of two (e.g. noticed at the section A3_Warnemünde, with one of the highest net sediment transport rates along the German Baltic Sea coast). In contrast the magnitude of the sediment transport rates at sheltered areas against westerly winds can be underestimated by the factor of two or more (e.g. noticed at the section A28_Scharbeutz). Due to the bias of the projected wind velocities the relative changes of the sediment transport rates have been analysed rather than the absolute values.

Example results of the relative changes of the net- and directional sediment transport rates at the sections A3_Warnemünde and A31_Travemünde are given in Figure 4 left resp. right.

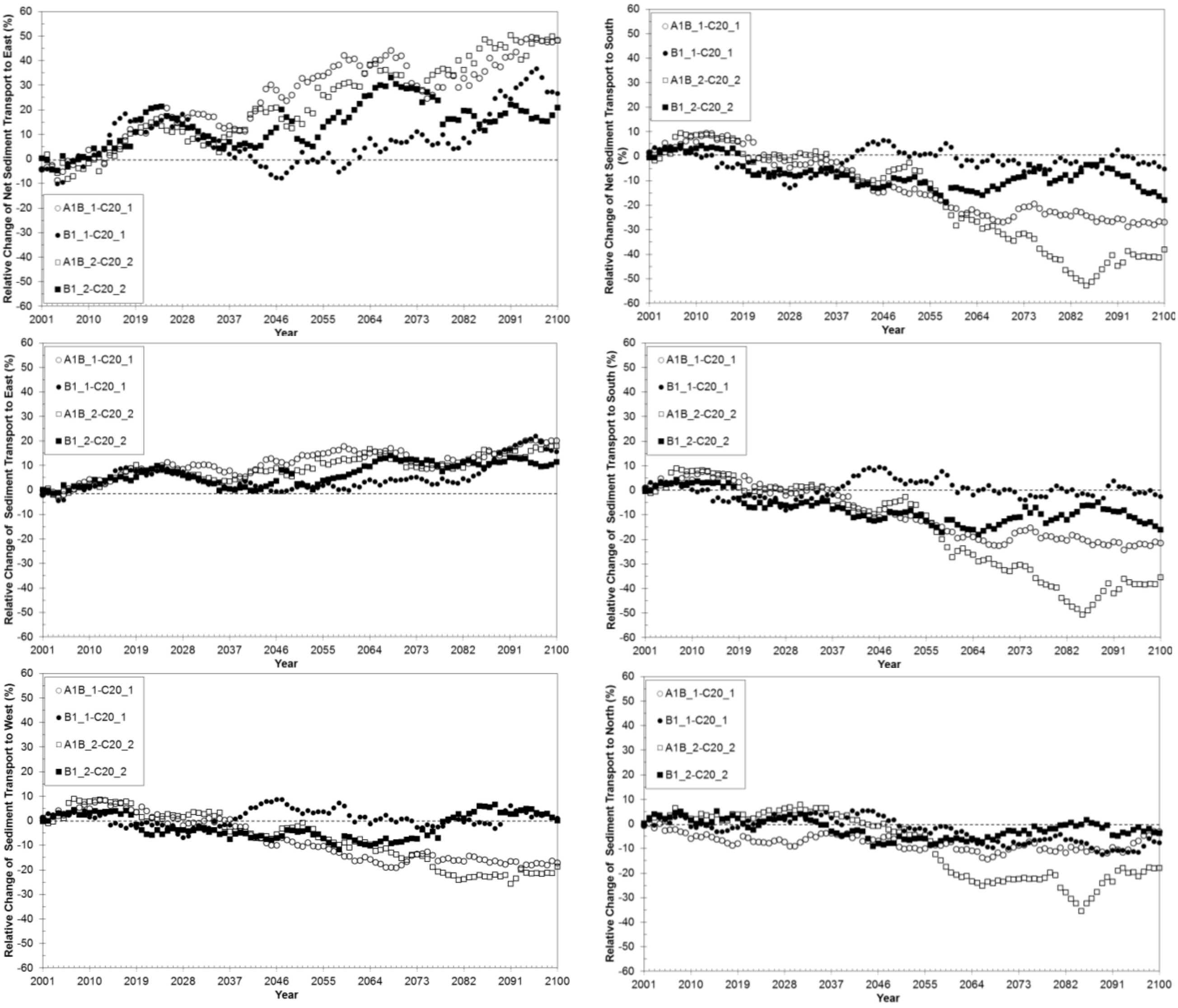

Figure 4. Changes of the net sediment (top) and directional transport rates (middle and bottom) of the coastal sections A3_Warnemünde (left) and A31_Travemünde (right) for the two realisations of the emission scenarios A1B and B1.

The results of the changes at the coastal sections are summarised in Table 3. Please note that Q_left resp. Q_right are referring to the directional sediment transport to the left resp. the right of the rotated reference (problem) coordinate system that is used in GENESIS. The nautical directions of the sediment transport rates are denoted in brackets.
The relative changes of the sediment transport rates are in general depending on the location, emission scenario run and the time of the comparison. Nevertheless a tendency towards higher net sediment transport rates was noted at coastal sections that are exposed to westerly wind directions (e.g. A3_Warnemünde and A4_Darss, cp. Table 2).

Table 3. Bandwidth of the relative changes of the sediment transport rates for the emission scenarios A1B and B1 between 2001 and 2100. Dominant increases resp. decreases of the net transport rates are highlighted in Red resp. Green. The transport directions are denoted in brackets.

	∆Q_left		∆Q_right		∆Q_net	
	Min[%]	**Max[%]**	**Min[%]**	**Max[%]**	**Min[%]**	**Max[%]**
A03_Warnemünde	-26 (W)	9 (W)	-4 (E)	22 (E)	-10 (E)	50 (E)
A04_Darss	-26 (SW)	15 (SW)	-1 (NE)	35 (NE)	-2 (NE)	47 (NE)
A26_Pelzerhaken	-1 (E)	22 (E)	-24 (W)	9 (W)	-130 (W)	32 (W)
A27_Mariashagen	-14 (NE)	16 (NE)	-35 (SW)	7 (SW)	-42 (SW)	9 (SW)
A28_Scharbeutz	-21 (NW)	9 (NW)	-27 (SE)	15 (SE)	-24 (SE)	10 (SE)
A30_Niendorf	-33 (W)	11 (W)	-12 (E)	12 (E)	-37 (W)	12 (W)
A31_Travemünde	-35 (N)	8 (N)	-51 (S)	9 (S)	-53 (S)	9 (S)

Moreover it became clear that the dominant increases of the net sediment transport rates directed to easterly directions are caused by the superposition of increases of the directional sediment transport rates directed towards east and decreases of the opposite directional sediment transport rates (cp. Table 3). Regarding the emission scenario B1 minor changes were noted whereas larger changes were found for the emission scenario A1B. The latter is in accordance with dominant changes of the average wave conditions for the emission scenario A1B, especially to the end of the 21st century (2071-2100).

In contrast the climate change signal at locations sheltered against westerly winds like e.g. the Bay of Lübeck (comprising the sections A26_Pelzerhaken, A27_Mariashagen, A28_Scharbeutz and A30_Niendorf) is in general weak. One reason for the weakness of the climate change signal might be the fact that the magnitudes of the transport rates are in general lower inside bays than compared with the open eastern coastal sections of the German Baltic Sea coast.

Another problem for the interpretation of the results might be the averaging process itself. Because the main direction of the net sediment transport can change along some of the coastal sections (e.g. within the sections A28_Scharbeutz and A30_Niendorf) the spatial averaging over the whole section might compensate local changes of the net sediment transport rates. Shorter sections of the coastline of approx. 500m maybe could lead to more representative results.

Moreover the direction of the net sediment transport rates can change for single years and for different emission scenarios. Figure 5 shows exemplarily the annual net sediment transport capacities of the section A30_Pelzerhaken and the first realisation of the emission scenario A1B.

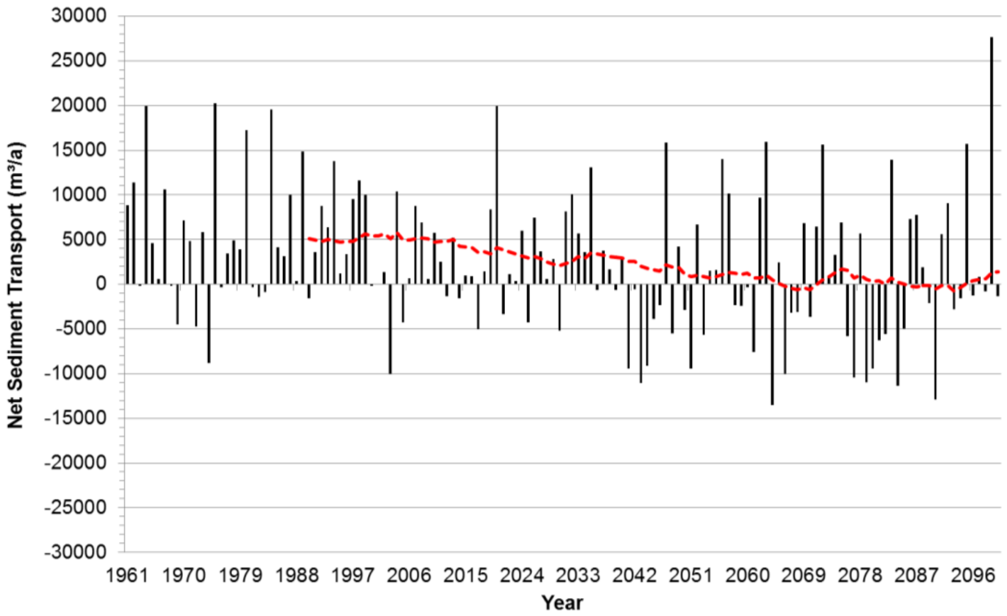

Figure 5. Annual Net Sediment Transport Capacity of the coastal section A30_Pelzerhaken for the first realisation of the emission scenario A1B (30year moving averages are indicated by a red dotted line).

The net sediment transport of the coastal section A30_Pelzerhaken is directed towards West for positive values resp. directed towards East for negative values. Annual directional transport rates of the same magnitude but opposite directions can compensate each other and result in very low averages of the net sediment transport rates. This is exemplarily shown in Figure 5 for the second half of the 21st century. Due to the fact that the net sediment transport rate is very low or nearby zero larger relative changes of the net sediment transport rate are being calculated (cp. Table 3).

4. CONCLUSIONS

In this study long-term time series of both directional and net sediment transport rates at selected sections of the German Baltic Sea coast have been calculated on the basis the regional climate model Cosmo-CLM, the wave model SWAN and the sediment transport model GENESIS for two of the IPCC greenhouse gas emission scenarios A1B and B1. The changes of the 30year averages of the transport capacities have been analysed from 2001 to 2100.

Future changes of the average wave conditions in the Baltic Sea area, especially for the emission scenario A1B, are noted like e.g. statistically significant changes of the frequency of occurrence of the significant wave heights and mean wave directions due to changes of the average wind conditions. Increases of the 30year averages of the significant wave heights up to +10% (0.5m) can occur at westerly wind exposed locations due to increases of the 30year averages of the wind velocities up to +4% and changes of the averages of the wind directions towards more westerly directions.

The changes of the wind and wave conditions can directly affect the potential longshore transport capacities. Remarkable increases of the net sediment transport capacities up to +50% to the end of the 21st century are possible at coastal stretches exposed to westerly wind directions. In contrast the net sediment transport capacities can decrease down to -50% at sheltered locations against westerly winds.

The results do not reflect the availability of sediments at a certain location but can be regarded as an indicator of possible long-term trends of the changes of the potential sediment transport induced by regional climate change. The changes of the sediment transport rates may intensify the accumulation of sediments at coastal (protection) structures that influence the longshore sediment transport or trap sediments such as harbours, offshore breakwaters, groins and navigational channels. Beside the effects on the functional design of the structures also the constructional design might be influenced too because the averages of net transport capacity do not reflect directional transport rates significantly larger than the average values. Therefore the changes of the annual directional transport rates have to take into consideration for the planning of coastal (protection) structures and to avoid negative impacts (erosion) at the constructions and the shoreline.

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