Contribution of atmospheric circulation to recent off-shore sea-level variations in the Baltic Sea and the North Sea

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Abstract. The main purpose of this study is to quantify the contribution of atmospheric factors to recent off-shore sea-level variability in the Baltic Sea and the North Sea on interannual time scales. For this purpose, we statistically analysed sea-level records from tide gauges and satellite altimetry and several climatic data sets covering the last century.

Previous studies had concluded that the North Atlantic Oscillation (NAO) is the main pattern of atmospheric variability affecting sea-level in the Baltic Sea and the North Sea in wintertime. ~~–~~However, we identify a different atmospheric circulation pattern that is more closely connected to sea-level variability than the NAO. This circulation pattern displays a link to sea-level that remains stable through the 20th century, in contrast to the much more variable link between sea-level and the NAO. We denote this atmospheric variability mode as the Baltic Sea and North Sea Oscillation (BANOS) index. The sea-level-pressure (SLP) BANOS pattern displays an SLP dipole with centres of action located over (5° W, 45° N) and (20° E, 70° N) and this is distinct from the standard NAO SLP pattern in wintertime. In summertime, the discrepancy between the SLP BANOS and NAO patterns becomes clearer, with centres of action of the former located over (30° E, 45° N) and (20° E, 60° N).

This index has a stronger connection to off-shore sea-level variability in the study area than the NAO in wintertime for the period 1993-2013, explaining locally up to 90% sea-level of the inter~~-~~annual sea-level variance in winter and up to 79% in summer. Sea-level in the eastern part of the Gulf of Finland is the most sensitive area to the BANOS-index in wintertime, whereas the Gulf of Riga is the most sensitive region in summertime. In the North Sea region, the maximum sea-level sensitivity to the BANOS pattern is located in the German Bight for both winter and summer seasons.

We investigated, and when possible quantified, the contribution of several physical mechanisms which may explain the link between the sea-level variability and the atmospheric pattern described by the BANOS-index. These mechanisms include the inverse barometer effect (IBE), fresh water balance, net energy surface flux and wind-induced water transport. We found that the most important mechanism~~s are~~ is the IBE in both wintertime and summertime. Assuming a complete equilibration of seasonal sea-level to the SLP gradients over this region,~~ at seasonal time scales~~ the IBE can explain up to 88% of the sea-level variability attributed to the BANOS-index in wintertime and 34% in summertime. The net energy flux at the surface is found to be an important factor for the variation of sea-level, explaining 35% of sea-level variance in wintertime and a very small amount in summer. The freshwater flux could only explain 27% of the variability in summertime and a negligible part

in winter. In contrast to the NAO, the direct wind forcing associated to the SLP BANOS pattern does not lead to transport of water from the North Sea into the Baltic Sea in wintertime.
Keywords: off-shore sea-level, atmospheric factors, the Baltic Sea, the North Sea, statistical analysis.

1 Introduction

Variations of regional sea-level can deviate substantially from the globally averaged sea-level (Church et al. 2013), due to the diversity of regional driving factors that may affect sea-level variations.

The Baltic Sea and its interconnection to the North Sea have been widely investigated for a better understanding of sea-level variability in this region (e.g. Yan et al. 2004; Novotny et al. 2006; Passaro et al. 2015). It is known that sea level variations in the Baltic Sea and the North Sea from interannual to multidecadal time scales are strongly driven by the atmospheric circulation, in particular by the North Atlantic Oscillation (NAO) (e.g. Andersson 2002; Hünicke and Zorita 2006; Dangendorf et al. 2012). The NAO is a mode of the large-scale atmospheric circulation in wintertime that dominates the atmospheric variability over Europe and the North Atlantic from interannual to decadal time scales (e.g. Hurrell 1995; Osborn et al. 1999; Hurrell et al. 2003; BACC II 2015).

The NAO represents the anticorrelation between sea-level-pressure (SLP) over the northern North Atlantic, centred over Iceland, and the subtropical high-pressure cell centred over Azores. The variations of the meridional SLP gradient are linked to the strength of the mean winter westerly winds over northern Europe and to the advection of oceanic air masses into this continent (Hurrell 1995; Slonosky et al. 2000, Hurrell et al. 2003). The temporal variations of the NAO can be described by the NAO-index, which can be constructed from the differences in two normalised SLP records, such as between Azores high and Icelandic low (Hurrell 1995; Jones et al. 1997). Normalisation is needed to filter the series being dominated by the larger variability of the northern station with respect to variability of the southern station (Hurrell et al. 2003).

The phases of the NAO have different influences on the climate of northern Europe. For instance, on the one hand, a positive phase of the NAO-index is associated with strong westerly winds transporting warm humid air masses eastward and resulting in mild winters over the northern Europe including the Baltic Sea (e.g. Hurrell 1995, Hurrell et al. 1997, Hurrell et al. 2003). A negative phase of the NAO-index describes~~d~~ weaker westerly winds or even westward advection of cold and dry Siberian air towards Europe (e.g. Hurrell 1995, Hurrell et al. 2003; Hagen and Feistel 2008).

In general, a positive (negative) phase of the NAO causes sea-level to rise (fall) in the Baltic Sea and the North Sea (e.g. Wakelin et al. 2003, Hünicke and Zorita 2008, Dangendorf et al. 2012, Hünicke et al. 2015). The NAO may directly impact on sea-level variations in the Baltic Sea and the North Sea in several ways.

The NAO-related westerly winds can transport water into the Baltic Sea from the North Sea basin through the transition zone (e.g. Kauker and Meier 2003; Ekman 2009). Another ~~possible~~ related mechanism is that NAO influences the temperature of northern Europe including the Baltic Sea. Variations in temperature can affect the sea-level due to thermal expansion of the water column (e.g. Hünicke and Zorita 2006; Dangendorf et al. 2012). A third possible mechanism involves the modifications of the surface water balance, which can affect the sea level-variability in a semi-enclosed sea like the Baltic Sea. For instance, a positive phase of the NAO may cause a positive fresh water balance resulting primarily from the higher precipitation within the Baltic Sea drainage basin (e.g. Hünicke and Zorita 2006; Hünicke et al. 2008; Lehmann et al. 2011). Th~~is effect~~ese mechanisms can not only change the total water volume of the Baltic Sea, but also the water density through changes in salinity.

~~Moreover~~Additionally, it is also reasonable to expect an influence of pressure differences on sea-level variability due to the NAO-related large-scale changes in the SLP field through the inverse barometer effect (e.g. Yan et al. 2004). There can be NAO-associated indirect factors such as snow melt, river run-off affecting the sea-level variations in this region as well.

Overall, these ~~connections~~ mechanisms make the NAO important in order to describe the effect of atmospheric forcing on sea-level variability, especially in wintertime (e.g. Jevrejeva et al. 2005; Ekman 2009; Stramska and Chudziak 2013).

However, it has ~~also~~ been found that the impact of the NAO on sea-level varies substantially across the Baltic Sea and the North Sea (e.g. Hünicke and Zorita 2006; Tsimplis and Shaw 2008). For example, (Yan et al. 2004) investigated~~ing~~ the relationship between the NAO and the sea-level around northern European coasts~~, Yan et al. (2004)~~ and reported that the NAO is positively correlated with sea-level variations on annual and longer time scales along the central and northern coasts of the Baltic Sea and the German Bight. They found that these positively correlated regions display higher sea-level~~s~~ under the stronger NAO phases, ~~which are clearer~~ more clearly so in wintertime, whereas ~~the~~ non-significant and even negative relationships to the NAO exist over the southern coast of the Baltic Sea and southwest England, respectively. They also concluded that the link between sea-level variations and the NAO is variable in time and has increased over both negatively and positively linked regions over the last decades. These findings are also ~~coherent~~ consistent with results of other studies such as Andersson (2002), Wakelin et al. (2003), Jevrejeva et al. (2005) and Hünicke and Zorita (2006). Furthermore, several studies including Andersson (2002)~~,~~ who focused on the Baltic Sea, and Dangendorf et al. (2014)~~,~~ who investigated the southeastern North Sea, reported that atmospheric variability that may be described by patterns different from the NAO may still explain part of the sea-level variability~~ that differs from the NAO~~. Some previous studies also showed that, on average, the NAO accounts for only one-third of total sea-level variability in the Baltic Sea on the interannual time scale (e.g. Kauker and Meier 2003; Jevrejeva et al. 2006).

Using the Stockholm tide gauge and the NAO-index time series, Andersson (2002) analysed the influence of atmospheric circulation on the Baltic Sea level. Her study indicated that interannual sea-level variations, particularly along the northern and eastern coasts, are highly modulated by the strong westerlies related to the NAO. In addition, she suggested that an atmospheric circulation index (the BAC-index) which can be constructed from the difference between normalised time series of the air pressure centres closer to the Baltic Sea entrance can describe the winter mean of Baltic Sea level variations better than the NAO. Related to this suggestion, Novotny et al. (2006) found a substantial correlation between air-pressure over the North Sea and interannual sea-level variations in the Baltic Sea. ~~They also showed that the interannual sea-level variations in the North Sea and the Baltic Sea are highly correlated to each other.~~

Concerning ~~different~~ other sorts of data sets including the satellite altimetry observations, there have been several studies focused on long-term (interannual and longer) sea-level variations in the Baltic Sea and its connection to~~with interrelation to~~ the North Sea. Stramska (2013) investigated off-shore and coastal sea-level variability in the Baltic Sea and the North Sea. Using the satellite altimetry observations, tide gauge records and meteorological data sets, she confirmed the high coherence of sea-level variability between the Baltic Sea and the North Sea. By exploring the sea-level variability in the Baltic Sea on interannual and decadal time scales, Xu et al. (2015) demonstrated that altimeter data have high correlations with tide gauge data in these regions, except in the Danish straits. They also showed that the basin-averaged altimetric Baltic Sea level exhibits strong correlation with the NAO-index in wintertime. Using Envisat altimetry data together with tide gauge observations in the Baltic Sea-North Sea transition zone covering the Danish straits, Passaro et al. (2015) concluded that coastal altimetry is able to capture the annual sea-level variations on a sub-basin scale.

Most of those previous studies addressed the link between coastal sea-level variability and atmospheric forcing, identifying the NAO as the most relevant atmospheric pattern for sea-level variability in the Baltic Sea. However, the link between the NAO and the Baltic Sea level is known to be unstable in time and quite heterogeneous in space. The correlation between sea-level records and the NAO calculated over gliding multidecadal windows in the 20th century displays periods in which this correlation is very high, of the order of 0.8 for some tide gauge records like in the most recent two decades, but also periods in which this correlation is as low as 0.3 and even may turn negative for some tide-gauges located in the southern Baltic Sea (e.g. Hünicke and Zorita 2006).

In this study, we revisit the link between the atmospheric circulation and sea-level variability in the Baltic Sea and the North Sea with the aim of ascertaining whether the NAO is indeed the most relevant pattern and of whether there may be other atmospheric patterns that display a stronger and more stable in time connection with sea-level variations in this region. This analysis leads us to describe a new index of atmospheric circulation that we denote the Baltic Sea and North Sea Oscillation (BANOS) index. We also analyse other meteorological fields, like surface energy fluxes, to investigate the physical mechanisms that may explain the connection between the BANOS pattern of atmospheric circulation and the Baltic Sea and North Sea sea-level~~s~~. The identified BANOS pattern bears some resemblance to another mode of atmospheric circulation that has been found to be connected to sea-level variations in Cuxhaven, at the German North Sea coast (Dangendorf et al. 2014). Whereas the mechanism for sea-level variations at this part of the North Sea are related to direct wind forcing, we find different physical mechanism to be responsible for the link to the Baltic Sea level variability.

As mentioned before, although the direct wind forcing has been assumed to be the main factor explaining this connection, there are other candidates that may also be involved. Since the link between the NAO and sea-level varies considerably in time, it is reasonable to assume that other physical mechanism may also contribute to sea-level variability.

The present analysis is not restricted to the coastal sea-level and makes use of satellite altimetry data to obtain a more complete picture of the link between atmospheric circulation and sea-level variability, using the most recent available altimetry data set~~, with~~ which is interpolated from along-track observations onto a 1/4°x1/4° cartesian resolution, over the Baltic Sea and North Sea region and extended to the North Atlantic in order to reveal possible large-scale effects on the off-shore sea-level variability.

A map showing the study area with an overview of some basins and subdivisions of the Baltic Sea and the North Sea is represented in Figure 1. More subdivisions can be defined in terms of focus and spatial scale of the study. Due to the scope of this study, we included some and labelled them in Figure 1.

Figure 1: The Study Area with sub-regions. 1-Bothnian Bay, 2-Bothnian Sea, 3-Gulf of Finland, 4-Baltic Proper, 5-Gulf of Riga, 6-Arkona Basin, 7-Danish Straits, 8-Kattegat, 9-Skagerrak, 10-North-eastern North Sea, 11-German Bight. The study area is also shown together with the tide gauge locations:Helsinki, Sassnitz, Warnemünde, Wismar, Travemünde, Smögen, Kungsholmsfort, Stockholm and Ratan (names are written in an order starting from far east station and follows clockwise rotation).

This study ~~is restricted to~~focuses on the winter (December-to-February) and summer (June-to-August) seasons.

This paper is organised as follows: Section 2 presents the data sets used in this study and the following section describes the applied statistical methods. Section 4 includes the main results of this study. In the ~~concluding~~ discussion and conclusions section, we assess the results.

2 Data Sets

The study uses primarily two different types of data sets. The first set consists of monthly means of sea-level observations obtained from satellite altimetry missions and tide gauges. ~~Although~~ We prescribed a minimum threshold of 75% data availability to include a particular time series in the analysis. However, we computed seasonal means of a tide gauge record if two months within one season were available. ~~the threshold of any computation involving tide gauge records was set at 75% availability of data for the considered period, seasonal means are calculated in case of availability of tide gauge records for two months.~~

The second set comprises climatic data including sea-level-pressure (SLP) observations and the NAO-index. The climatic data set also contains meteorological reanalysis data of precipitation, surface fluxes including short-wave and long-wave radiative fluxes, sensible and latent heat turbulent fluxes.

~~All data used in this study are derived from the monthly means for winter (December-January-February) and summer (June-July-August) seasons.~~In this study, we used seasonal mean values for winter and summer seasons. Those winter and summer mean values are computed from monthly means prior to the analysis. We analysed winter (December-January-February) and summer (June-July-August) seasons separately. Therefore, there was no need to remove the seasonal cycle for our analysis.

~~2.1 Sea Level Observations~~

~~2.1.1 Satellite Altimetry Observations (SLAs)~~

The satellite altimetry observations - Sea Level Anomalies (SLAs) - are retrieved from the delayed time multimission global gridded data products provided by the AVISO (www.aviso.altimetry.fr). We used the state-of-the-art satellite altimetry data ~~available~~ interpolated onto a 1/4°x1/4° cartesian grid resolution (DT2014 SLA) with 20-year mean reference period. More information about the data can be found in https://www.aviso.altimetry.fr/fileadmin/documents/data/duacs/Duacs2014.pdf. For our study, we considered winter and summer seasons, covering the period from December 1992 to August 2013 for the defined geographical window between (45° W - 30° E) longitudes, and (48° N - 70° N) latitudes.

~~2.1.2 Tide Gauge~~

Most of the tide gauge records representing monthly mean sea-level variations are provided by the Permanent Service for Mean Sea-Level (PSMSL - www.psmsl.org) (Woodworth and Player 2003). The largest part of the Stockholm tide gauge record was provided by Ekman (2003). Some parts of the Sassnitz, Travemünde, Warnemünde and Wismar tide gauge observations have been provided by Technische Universität Dresden. Overall, including the northeast boundary of the North Sea, nine tide gauges along the Baltic coasts were selected: Ratan, Helsinki, Stockholm, Smö~~o~~gen, Kungsholmsfort, Sassnitz, Travemünde, Wismar and Warnemünde. The selection was based on their geographical distribution and the record length of the tide gauges. The Smö~~o~~gen station has some missing values at the beginning of the analysis period; the other tide gauges provide complete records for the whole analysis period 1900-2013. The names of some stations listed in the PSMSL database like Smögen, Warnemünde and Travemünde are not totally correct.

~~2.2 Climatic Data~~

We considered four different data sets concerning climatic variables.

~~2.2.1 SLP Data~~

The sea-level-pressure (SLP) data are monthly means of 5°x5° gridded observations covering the Northern Hemisphere, from 1900 to 2013, provided by the National Centre for Atmospheric Research (https://climatedataguide.ucar.edu/climate-data/ncar-sea-level-pressure) (Hurrell et al. 2016a). The geographical domain of the data set used here is (70° W - 40° E) and (30° N - 90° N).

~~2.2.2 The NAO-index~~

The North Atlantic Oscillation (NAO) is a pattern of the large-scale pressure fields over the North Atlantic region. The time-varying intensity of this pattern can be summarised by the NAO-index. The NAO-index that we used was computed by Hurrell et al. (2016b) using the differences between normalized anomalies of two SLP stations: Lisbon, in Portugal and Reykjavik, in Iceland (https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based).~~.~~

~~2.2.3 Reanalysis Data: Surface Flux and Precipitation~~

~~In this study, w~~We used the National Center of Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) reanalysis data covering the period from 1949 to 2013 (Kalnay et al. 1996, Kistler et al. 2001) (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surfaceflux.html). The meteorological reanalysis assimilates different observations into a weather prediction model and produces as a complete gridded data set over the whole period.

This data set has ~~a~~ spatial resolution of a T62 Gaussian grid with non-regular 192x94 points covering the Earth's surface~~192x94 points with T62 Gaussian grid covering the Earth's surface~~ and is available as 4-times daily, daily and monthly values from 1948/01/01 to present. Here, we considered the monthly means of surface fluxes of net short-wave radiation, net long-wave radiation, net sensible, net latent heat fluxes and precipitation.

3 Methods

The present investigation is based on statistical analysis of sea-level and climatic data. The methods used in this study are widely known, but still summarised here for the sake of completeness.

We computed winter and summer means from December to February and from June to August monthly means, respectively. ~~Some m~~Moving correlations are computed over gliding 21-year periods for winter means and of summer means separately. The sea-level means and climate records are linearly de-trended prior to the related statistical analysis to filter out the effect of secular sea-level rise and the effect of land-crust movements that are not related to the atmospheric circulation. In particular, the Baltic Sea records display a clear long-term trend that is in part caused by the crust rebound after the last deglaciation (Glacial Isostatic Adjustment).

In addition, we estimated the sensitivity values of sea-level variations based on one unit change in the atmospheric circulation index by means of a linear regression analysis with the sea-level records as predictands and the atmospheric indices as predictors. The linear regression parameter of the regression analysis ~~The slope of the regression line~~ is denoted as the sensitivity of sea-level to changes in the intensity of the atmospheric patterns. We further used this method to explore the physical mechanism explaining the connection between indices of atmospheric circulation and sea-level in addition to the correlation analysis. This approach is used in different studies to have a better understanding of the statistical linkage between atmospheric condition and sea-level variation in this region (e.g. Wakelin et al. 2003; Dangendorf et al. 2012; Chen et al. 2014).

In this manuscript, the term "coherent" indicates only high degree of covariation and does not necessarily provide information about the relative variation of two variables.

4 Results

4.1 Comparison between satellite SLAs and tide gauges

We first examine how the satellite altimetry observations (SLAs) covary with the tide gauge records.~~the coherence of the satellite altimetry observations (SLAs) with the tide-gauge records.~~ For this examination, we selected the individual grids closest to each of the three tide gauges separately. ~~: Ratan, Stockholm and Wismar. The seasonal means of the sea-level observations had to be de-trended to filter out the impact of long-term climate signal and of land-crust movements on the sea-level observations. Therefore, we de-trended the 21-year window time series by using a linear regression.~~ The de-trended 21-year period time series for the period 1993-2013 are used to calculate the correlation coefficients displayed in Table 1.

Table 1: The correlations between individual satellite altimetry grids and the tide gauges for the period 1993-2013.

As the high correlations indicate, satellite altimeter observations are found to be coherent with the tide gauges. These results also indicate a substantial progress in satellite altimetry when we consider earlier the results from the study of Yan et al. (2004). In that study, for example, the correlation coefficient between closest SLA grid to Wismar and the Wismar tide gauge was ~0.50. This good agreement is likely due to the updating of geophysical corrections and usage of refined mapping parameters. Further information on the improvement of DT2014 SLA satellite altimeter data us provided by Pujol et al. (2016).

After testing the coherency of satellite altimetry observations with respect to the tide gauge records, we calculated the correlation coefficients between each of the nine tide gauges (Ratan, Stockholm, Helsinki, Smö~~o~~gen, Kungsholmsfort, Travemünde, Warnemünde, Wismar, Sassnitz) and all available SLA grid-cells. These correlation patterns show how the coastal sea-level variations at the tide gauges are linked to open sea-level variability. Figure 2 displays the obtained correlation patterns for the winter season.

Figure 2: The correlation patterns between the SLA grids and tide gauge records in wintertime (DJF) for the period 1993-2013. The value of correlation significance is ±0.43 at the 95% confidence level for this record length.

Figure 2 indicates that satellite altimetry time series are strongly correlated to tide gauges in the whole Baltic Sea and in large parts of the North Sea in wintertime over the period 1993-2013. Only the northern North Sea basin results in weak correlation values. The North Atlantic shows negative correlations to the Baltic Sea tide gauges. It should be noted that the seesaw pattern suggests negative and positive dipole relation between the North Atlantic Ocean and the Baltic Sea basin. Elsewhere, the correlation patterns are spatially homogeneous over the Baltic Sea and North Sea region. It should be noted that the relation between the SLA data and the tide gauge records becomes relatively weaker for the southern Baltic Sea stations (Travemünde, Wismar and Warnemünde). Considering only the North Sea, the correlations between tide gauges and SLA display an increasing pattern from west to east. The maximum correlation of these patterns is found in the German Bight (r=0.94).

The correlation patterns for the summer season are displayed in Figure 3.

Figure 3: The correlation patterns between the SLA grids and tide gauge records in summertime (JJA) for the period 1993-2013. The correlation coefficients are computed based on de-trended seasonal means between SLA grids and the tide gauge records. The value of correlation significance is ±0.43 at the 95% confidence level for this record length.

In general, the correlation patterns display a strong (max. r~0.92) link between the satellite altimetry and tide gauges over the whole Baltic Sea in summertime. Additionally, the patterns of correlations exhibit a quite uniform spatial distribution in this region. For example, when we consider the correlation patterns of the tide gauges Ratan, Stockholm, Helsinki and

Kungsholmsfort, the correlation is found to be the strongest over the Bothnian Sea, but it is slightly weaker in the northern Baltic proper and in the Bothnian Bay. This strong correlation pattern extends as far west as Skagerrak. In the North Sea, however, only the area between north-eastern North Sea and the German Bight displays high correlations for all tide gauges in summertime.

4.2 Relationships between the NAO-index and satellite SLAs

In this sub-section, we first correlated the SLAs obtained from the satellite altimeter observations with the NAO-index for the period 1993-2013. The correlation patterns of winter and summer seasons are displayed in Figure 4. To detect the possible large-scale impact on the off-shore sea-level variability in the Baltic Sea and the North Sea, we also included a part of the North Atlantic.

Figure 4: The correlation maps between the SLA grids and the NAO-index for the winter – means of DJF months - (~~up~~top) and summer – means of JJA months - (~~down~~bottom) seasons (1993-2013). The correlation coefficients are computed based on de-trended seasonal means between SLA grids and the NAO-index. The value of correlation significance is ±0.43 at the 95% confidence level for this record length. The areas indicating significant correlations are delineated with contour lines.

In wintertime, the correlation pattern between SLA grids and the NAO-index seems to be spatially uniform (r~0.71) over the entire Baltic Sea and the major part of the North Sea. In particular, the German Bight has a relatively stronger connection to the NAO than the rest of the North Sea. This agrees with previous studies (Wakelin et al. 2003, Woolf et al. 2003, Dangendorf et al. 2012, Chen et al. 2014, Xu et al. 2015, Sterlini et al. 2016). The transition zone between the Baltic Sea and the North Sea has a spatially heterogeneous correlation with the NAO-index, with a maximum correlation of 0.55 and a minimum of 0.01. The Baltic Sea displays a rather uniform correlation with the NAO-index and the maximum correlation occurs in the Bothnian Bay (r~0.76).

In summertime, there is almost no relation between the NAO-index and the SLAs in the Baltic Sea. Considering the North Sea, a part of the German Bight appears to be connected (r~0.60) to the NAO. However, the rest of the North Sea does not indicate a connection between sea-level and the NAO.

For this record length, the value of significance is ±0.43 at the 95% confidence level, under the usual assumptions of normally distributed and temporally uncorrelated variables. The significant correlation (r>0.6) between the NAO and the German Bight sea-level in summertime seems to contradict previous studies since they did not find a significant correlation between the NAO and the German Bight sea-level (e.g. Dangendorf et al. 2012). Additionally, it should be noted that tide gauge observations indicate a weak correlation to the NAO in~~at~~ the southern Baltic Sea in wintertime (e.g. Yan et al. 2004; Hünicke and Zorita 2006). The associated weak correlation between tide gauges in~~at~~ the southern Baltic Sea and the NAO in wintertime contradicts the results obtained by SLAs here as well. Since those associated studies used the different period of sea-level records, the reason for those contradictory results could be that the connections between the NAO and the southern Baltic sea-level variability in wintertime and between the NAO and a part of the German Bight in summertime may not be stationary over time.

As pointed out, the patterns of correlation between the tide gauges and the satellite altimetry fields indicate that the variations of sea-level in these regions are spatially quite uniform in both seasons (Figure 2 and Figure 3) on the interannual time scale. However, the NAO-index does not seem to be strongly connected to the SLA grids for the same period in summertime (Figure 4-bottom~~down~~).

4.3 Time evolution of the links between the NAO and the Baltic-North Sea levels

The results of the previous sub-sections show that, on the one hand, sea-level variations in the Baltic Sea and the North Sea tend to be spatially ~~coherent~~ well correlated over the whole area. On the other hand, the influence of the NAO on sea-level in these areas is, in contrast, spatially quite heterogeneous (i.e. ~~(~~Yan et. al. 2004; Hünicke and Zorita 2006). We also show that heterogeneity in the following figures. This apparent contradiction would put into ~~the~~ question that the NAO pattern is the major driver of sea-level variations in the Baltic and the North Seas. In this sub-section, we explore whether another pattern of atmospheric circulation, different from the NAO, can more strongly affect the sea-level variations over the entire Baltic Sea and the connection to the North Sea, in the winter and summer seasons. At this stage, we hypothesised that this large-scale factor is also atmospheric and investigated which patterns of atmospheric circulation might be more strongly related to sea-level variations on the interannual time scale than the NAO pattern. For this investigation, we first analysed the temporal stability of the statistical link between tide gauges and the NAO-index over the longer period 1900-2013.

The temporal stability of the correlation between the NAO and sea-level over the study area is examined based on the running correlations over 21-year windows between nine tide gauges and the NAO-index (not shown). The results indicate that there is a temporal variability in the strength of the connection between tide gauges and the NAO, as already found by previous studies, i.e. Andersson (2002), Yan et al. (2004) and Hünicke and Zorita (2006).

To identify which atmospheric pattern may be more closely connected to sea-level variability and at the same time display a stable link over time, we selected two representative stations (Stockholm and Warnemünde) from nine tide gauges and computed the 21-year moving correlations with the NAO over the years 1900 - 2013. The results are plotted in Figure 5.

Figure 5: The correlations of 21-year running windows between tide gauges (Stockholm-STO and Warnemünde-WAR) and the NAO-index for the winter (dashed line) and summer (~~pointed~~solid ~~-~~line) seasons. The value of correlation significance at the 95% level (two-tailed) is ±0.43 for this record length. The correlation coefficients are computed based on de-trended seasonal means between tide gauge records and atmospheric indices.

Figure 5 shows that the values of the 21-year running correlations are mostly non-significant in summertime. In wintertime, correlations between Stockholm and the NAO-index are weak or not significant until 1965. The Warnemünde station does not seem to be strongly connected to the NAO-index until 1998 in wintertime.

Given that the running correlations are not stable in time for both seasons over the period 1900-2013, it is hypothesised in this sub-section that the temporal instability of the link between stations and the NAO could indicate the existence of another atmospheric circulation pattern that both strongly affects sea-level variation and that differs from the traditional NAO pattern. Therefore, we further analysed the strength of the relation between the NAO and nine tide gauges by considering the periods in which the NAO had the strongest and the weakest connections to the sea-level variations. This analysis is also separately conducted for wintertime and summertime, respectively.

Figure 6 shows the correlation patterns between the NAO and nine tide gauges in 21-year windows in which these correlations were highest (1976-1996) and lowest (1950-1970) over the period 1900-2013 in wintertime.

Figure 6: The correlation maps between de-trended tide gauges and the de-trended NAO-index for the minimum (1950-1970) and the maximum (1976-1996) correlation periods in wintertime.

For the summer season, the 21-year period with the weakest connection between the NAO-index and tide gauges is 1924-1944, whereas the 21-year period with the strongest correlation is 1960-1980. The correlation maps derived from these two periods are shown in Figure 7.

Figure 7: The correlation maps between de-trended tide gauges and the de-trended NAO-index for the 1924-1944 and 1960-1980 periods when minimum and maximum correlations occur in summertime, respectively.

Figure 7 also illustrates that the difference in sea level-NAO correlation between both periods is spatially rather homogenous, i.e. correlations tend to be low in 1924-1944 for all tide gauges. ~~link between tide gauges and the NAO varies homogeneously in spatial domain over the whole area for both the strongest and weakest periods in summertime.~~

4.4 Definition of the BANOS-index

Given these results, the question arises as to whether the NAO is the atmospheric pattern most closely related to sea-level variability in the study area. Addressing that question, we decided to assess the correlation patterns between tide gauge records and SLP field based on the 21-year running windows for the period 1900-2013.

We carried out several analyses taking different periods into account.

First, we considered the period 1976-1996 (1950-1970), when the correlation between the NAO-index and the sea-level variability was maximum (minimum) in wintertime. The correlation pattern between SLP field and the Stockholm sea-level over this period is illustrated at the right (left) -panel of~~in~~ Figure 8.

Figure 8: ~~The correlation patterns between the Stockholm tide gauge and SLP grids for the period 1976-1996 in wintertime~~The correlation maps for the periods when the correlation between the NAO-index and sea-level variability were minimum (left) and maximum (right) in wintertime. The periods cover the years 1950-1970 (left) and 1976-1996 (right). The time series are de-trended prior to correlation calculations. The SLP grid cells that are selected to construct the BANOS-index are marked with squares.~~.~~

Although, ~~T~~the correlation pattern in Figure 8-right exhibits very similar pattern to the traditional NAO pattern,~~.~~

~~Second, we considered the 21-year period in which the correlation between sea-level variability in Stockholm and the NAO-index was minimum in wintertime. The correlation pattern between the SLP fields and the Stockholm sea-level for the related period, 1950-1970, is shown in Figure 9.~~

~~**Figure 9: The correlation pattern between the Stockholm tide gauge and SLP grids for the period 1950-1970 in wintertime.**~~

Figure 8-left~~9~~ displays an atmospheric pattern that differs from the typical NAO pattern. In particular, the implied direction and strength of geostrophic winds show discrepancies compared to the NAO pattern.

Since this pattern looks different from the typical NAO pattern, we constructed a new index that should reflect the SLP gradient along a different direction from what the NAO ~~denotes~~implies. First, two grid-cells with the maximum and minimum correlations to the Stockholm tide-gauge were identified. Second, from those grid-cells, the differences of the normalized SLP values were computed to construct a new circulation index that is in the following denoted as the BANOS-index. The geographical points of the SLP grids are (5° W, 45° N) and (20° E, 70° N) for wintertime. These two grid-cells are held fixed, and define the BANOS-index for the whole period 1900-2013.

The same steps are followed in order to construct the BANOS-index for the summer season. In this case, the correlation patterns with the SLP fields are calculated for the period 1924-1944 and 1960-1980 when the link between the NAO-index and the sea-level variations are weakest and strongest, respectively. The associated correlation maps are shown below in Figure 9~~10~~.

Figure 9~~10~~: The correlation patterns for the periods when the correlation between the NAO-index and sea-level variability were minimum (left) and maximum (right) in summertime. The periods ~~are~~ cover~~ing~~ the years 1924-1944 (left) and 1960-1980 (right). The time series are de-trended prior to correlation calculations. The SLP grid cells that are selected to construct the BANOS-index are marked with squares.

The correlation pattern obtained when the relation between stations and the NAO was weak, is different from the NAO pattern in summer. Based on the corresponding pattern, we also constructed the BANOS-index for summertime. For this construction, the geographical points of the SLP grid-cells were (30° E, 45° N) and (20° E, 60° N).

4.5 Comparison between the BANOS-index and the NAO-index

After constructing the BANOS-index, we compared it to the traditional NAO-index. For this comparison, we first assessed the direct relation between two indices for the winter and summer seasons for the entire period 1900-2013. The correlations between these two indices are 0.68 and -0.12 for winter and summer seasons, respectively. This indicates that the winter BANOS-index shares some similarities with the NAO-index in winter, but it is quite different from the NAO index in summertime. The time series of the indices are represented in Figure 10~~1~~.

Figure ~~11~~10: The time series of the BANOS-index and the NAO-index together with 21-year running means for the winter (top~~up~~) and summer (bottom~~down~~) seasons over the period 1900-2013.

In a next step, we investigated the link of the indices to the Stockholm and Warnemünde tide gauges from 1900 to 2013 and their stability over time. For this investigation, we used 21-year gliding windows in order to examine the connection between these stations and the two indices, also the indices are compared to each other. The time evolutions of the gliding correlations are displayed in Figure 11~~2~~.

Figure ~~12~~11: The correlations between selected tide-gauges and the BANOS and NAO indices ~~associated correlation values of variables~~ based on the de-trended 21-year running windows for the winter (top~~up~~) and summer (~~down~~bottom) seasons. Time series are de-trended in every 21-year period prior to the correlation computations. The value of correlation significance at the 95% level (two-tailed) is ±0.43 for this record length.

In wintertime, the BANOS-index is more strongly correlated with the Stockholm and Warnemünde stations than the NAO-index throughout the whole period. The correlations of 21-year moving windows between Stockholm and the BANOS-index are significant over the whole period 1900-2013 in wintertime. The highest correlation (r>0.94) between Stockholm and BANOS-index occurs during the satellite era (1993-2013). Considering the correlation between the BANOS-index and Warnemünde, it is shown that the strength of relation is significant with the exception of the period 1927-1937. The strongest correlation between the BANOS-index and Warnemünde (r~0.88) is obtained in the period 1991-2011.

This behaviour is in contrast with the gliding correlations between these two stations and the NAO. The gliding correlations between the NAO-index and two stations in winter start to increase from 1960 onwards. Notably, ~~most of the time~~the gliding correlations between the stations and the NAO-index resulted in weak or non-significant relations (r<0.43) most of the time over the period 1900-2013 in wintertime. In addition, the Cuxhaven station behaves similarly to Stockholm regarding its moving correlation to the both atmospheric indices.

In summertime, the running correlations between the BANOS-index and the sea-level variability in Stockholm indicate a stronger link than the one between the NAO-index and Stockholm over the whole period 1900-2013. The maximum correlation value between the BANOS-index and Stockholm (r=0.89) is calculated in the period 1928-1948. It should also be noted that the connection between Cuxhaven and BANOS-index is most of the time significantly correlated, but that was not the case for the NAO-index. The variability of the sea-level in Warnemünde is also strongly connected to the BANOS-index. The highest correlation between the BANOS-index and Warnemünde sea level (r>0.76) occurs during the period 1985-2005.

As in the case of wintertime, this strength of the relation between associated stations and the BANOS-index is in strong contrast with the link between the two stations and the NAO-index. Also, a negative trend is detected in the time series of running correlation between the NAO-index and the two stations starting from ~~the~~ year 1970 onwards in summertime. Overall, ~~this link between the stations and NAO is very weak in summertime.~~no significant correlation between the NAO and stations is estimated in summertime.

4.6 Influence of the BANOS pattern on off-shore sea-level variability

After assessing the time evolution of the link between the BANOS-index and the Stockholm and Warnemünde stations, we quantify the off-shore sea-level variability connected to the BANOS-index. The relation between satellite altimetry SLA grids from the AVISO product and the BANOS-index was analysed over the period 1993-2013. This analysis is carried out using correlation of de-trended time series for the winter and summer seasons. The correlation patterns for both seasons are shown in Figure 12~~3~~.

Figure ~~13~~12: The correlation patterns between the de-trended SLA grids and the de-trended BANOS-index for the winter (top~~up~~) and summer (~~down~~bottom) seasons over the period 1993-2013. The 95% significance level is ±0.43. The areas indicating significant correlations are delineated with contour lines.

In general, the connection between the BANOS-index and the off-shore sea-level variability is found to be strong over most of the study area for both winter and summer seasons, confirming the strong relationship between the BANOS-index and two tide gauges. In wintertime, the correlation patterns of the off-shore sea-level variability with the BANOS-index show that the strongest relation is located in the Baltic Proper and Gulf of Riga, with the value of r~0.95. The correlation pattern decreases (r~0.83) over the transition zone between the Baltic Sea and the North Sea. In the North Sea, the connection is strongest (r~0.93) in the German Bight area. The weakest relation occurs in the Skagerrak area, where correlation decreases to 0.28 (not significant).

Comparing the correlation maps showing the relation of SLA grids to both the BANOS-index and the NAO-index, it is seen that the BANOS-index is more closely connected to the off-shore sea-level variability than the NAO-index over the Baltic Sea and North Sea region.

In summertime, coastal and off-shore sea-level variations seem to be well connected to the BANOS-index, in contrast to the non-existent relation between the NAO-index and sea-level variability in the Baltic Sea and North Sea region, there is a spatially continuously increasing correlation from Skagerrak to Arkona Basin, ranging from -0.01 to 0.75. The maximum correlation value is detected in the central Baltic and in the eastern Baltic, reaching to 0.89. This means that the BANOS-related atmospheric circulation pattern explains up to 79% of the sea-level variance in the Baltic Sea in summertime. Referring to Figure 1, the associated sub-regions are the Baltic Proper, the Bothnian Sea and the Gulf of Finland. Considering the North Sea, the link between the BANOS-index and sea-level variability is found to be strongest in the eastern part of the North Sea, with a maximum correlation of up to r~0.63. Apart from this region, no substantial correlation is found in the North Sea in the summer season.

4.7 Sensitivity of satellite ~~SLAs~~ sea-level variations to the BANOS-index

Given not only the stable correlation in time between the BANOS-index and coastal sea-level variations, but also the high correlation between the BANOS-index and the satellite altimetry SLAs over the entire Baltic Sea and a part of the North Sea, we further quantify the linear response of off-shore sea-level variability to the BANOS-index. For this ~~aim~~purpose, the sensitivity of the sea-level to the BANOS-index is estimated from the linear regression parameter of the linear regression ~~slope of the regression line resulting from the regression analysis~~ where the BANOS index is the predictor and the sea-level at each grid-cell is the predictand. Before estimating the sensitivity of sea-level, we linearly de-trended the time series of the associated predictand and predictor, since the sea-level records contain the trend caused by global sea-level rise and crust movements which are not related to the variability of the atmospheric circulation.

The corresponding sensitivity values of the SLA grids are represented in Figure 13~~4~~.

Figure ~~14~~13: The sensitivity values of the SLAs to the BANOS-index for the winter (left) and summer (right) seasons over the period 1993-2013. Note the different ~~scales in~~intervals on the colour scales~~s~~.

In wintertime, the largest sensitivity of the SLA to the BANOS-index appears in the eastern part of Gulf of Finland, with values reaching to 92 mm per one unit (mm u^{-1}) (r>0.90) change in the BANOS-index. Another large sensitivity is detected in the northeast Bothnian Bay with the value of 81 mm u^{-1} (r=0.90). The sensitivity values are ranging from 77 mm u^{-1} to 80 mm u^{-1} (r=0.95) in the Gulf of Riga. Considering the North Sea region, the maximum sea-level sensitivity is calculated for the German Bight; 60 mm u^{-1} (r=0.93).

In summertime, the Gulf of Riga is found to be the most sensitive area with value of 31 mm u^{-1} (r=0.89). The eastern Gulf of Finland has a sensitivity reaching up to 29 mm u^{-1} (r=0.86). In the German Bight, we detected a value of 14 mm u^{-1} (r>0.48), where the sensitivity of the North Sea to the BANOS-index is the strongest during summer. Notably, Skagerrak was the least sensitive region to the BANOS-index in the winter (5 mm u^{-1}) and summer (-1 mm u^{-1}) seasons over the study area. Although the sensitivity values would change depending on the exact definition of the BANOS-index (for instance, whether or not the definition involved standardization to unit variance), the sensitivity parameters describe the relative sensitivity of associated sea-level in different locations with respect to other areas in the Baltic Sea and North Sea region.

4.8 Possible physical factors contributing to the sea-level variability

The aim of this sub-section is to investigate the physical mechanism(s) that may explain the link between the BANOS-index and sea-level in the Baltic Sea and North Sea region on the interannual time scale. For this purpose, we estimate the portion of the variances of sea-level that is statistically explained by different physical factors. We examined several plausible candidates, as explained in the following.

It is known that the SLP can substantially impact the sea-level variations by a direct response due to the inverse barometer effect (IBE). Also, the BANOS patterns suggest that the horizontal gradients in air pressure could influence the sea-level variations over the Baltic Sea and the North Sea. Net energy flux variations linked to the BANOS index can also affect sea-level variation. Additionally, the BANOS pattern may carry information about other mechanisms (i.e. variation in precipitation, evaporation) which may explain the contribution of the freshwater flux to the sea-level variability over the Baltic Sea and North Sea region. We also explore the effect of the wind on the off-shore water movement due to the Ekman transport.

4.8.1 The contribution of the inverse barometer effect (IBE)

One of centres of action of the BANOS patterns lies over the Baltic Sea, and therefore the influence of the IBE on sea-level variations seems to be a plausible factor which can explain the physical mechanism between the BANOS-index and sea-level on interannual time scales. By the investigation of IBE contribution, we assumed the presence of an infinite ocean without topographic limitation and complete equilibrium in the Baltic Sea and North Sea regions to the overlaying air pressure. This assumption implies that water is free to move responding to air-pressure gradients to reach hydrostatic equilibrium. This is a simplifying assumption that nevertheless allows to estimate an order of magnitude of the contribution of the BANOS-related IBE to sea-level variations. The BANOS pattern shows that lower air pressure over the Baltic Sea region and higher pressure around the Gulf of Biscay (over the area between Labrador Sea and Denmark Strait) in wintertime (summertime) are connected to higher sea-level in the Baltic Sea. Therefore, we first selected the geographical points by considering the BANOS patterns in order to estimate the impact of the pressure differences on the sea-level. For wintertime, the coordinates were (5° W, 50° N) - (20° E, 60° N) and for summertime they were (30° W, 65° N) - (20° E, 60° N). The choice of these points was dictated by the centres of action of the BANOS pattern constrained by the availability of sea-level data.

To test the possible influence of the IBE on sea-level, we initially took the differences of sea-level and of the SLP fields over the given geographical points for each season. Then, we implemented a linear regression over the period 1993-2013 where differences of sea-level variations were the predictand and differences of SLP fields were the predictor. The sea level sensitivity values are 18.1~~09~~ mm and of 7.0~~2~~ mm per 1 hPa change in the described SLP field differences for wintertime and for summertime, respectively.

In the~~a~~ next step, we investigated the sensitivity of the SLP differences per one unit change in the BANOS-index for the period 1900-2013. The linear regression between the BANOS-index (predictor) and the SLP differences (predictand) results in a sensitivity of 3.44 hPa and 1.39 hPa per one unit change in the BANOS-index in wintertime and in summertime, respectively. These results indicate a large contribution of the air pressure differences on the interannual variation in the sea-level over the selected points, estimated as of 62.2~~3~~ mm u^{-1} (3.44*~~x~~18.09) in wintertime and of 9.8~~76~~ mm u^{-1} (1.39*~~x~~7.02) in summertime per one unit change in the BANOS-index.

This means that assuming a complete equilibrium of sea-level to the SLP differences over this region, one unit increase in the BANOS-index would cause up to 62.2~~3~~ mm (9.8~~76~~ mm) rise in the sea-level during wintertime (summertime) due to the IBE in the Baltic Sea and the North Sea. More importantly, the correlation analysis between BANOS-index and differences in SLP fields suggests that 88% (34%) in wintertime (summertime) sea-level variance linked to the BANOS pattern can be accounted for by the IBE.

It can also be noted that the IBE related to the BANOS pattern on sea-level would cause constraining sea-level anomalies in the North Atlantic and in the Baltic Sea.

4.8.2 The contribution of net surface energy flux

Net surface energy flux (NEF), the total energy transfer through the Earth surface, is composed of radiative and turbulent fluxes. The radiative fluxes are composed of shortwave (SW) solar radiation reaching to the e~~E~~arth surface and long~~-~~wave (LW) emitted energy from the Earth surface. The turbulent fluxes are sensible heat (SH) and latent heat (LH) fluxes.

The NEF is the difference of associated fluxes between the energy absorbed by the Earth and the energy emitted from the surface of the Earth. Here, we simply re-expressed this relation by using following definition (Eq. 1).

$$\cancel{Q_{net}}NEF^{+\downarrow} = SW_{net} - (LW_{net}+SH_{net}+LH_{net}), \qquad (1)$$

~~Qnef~~ NEF is the net energy flux, defined here positive downward. SWnet is the net downward shortwave radiation, LWnet is the net upward longwave radiation, SHnet is net upward sensible heat flux and LHnet is the net upward latent heat flux. After computing the ~~Qnef~~ NEF for the winter and summer seasons over the period 1949 to 2013, we calculated the correlation values between individual heat flux in each grid-cell of the NCEP/NCAR meteorological analysis and the BANOS-index. The correlation patterns are illustrated in Figure 14~~5~~.

Figure ~~15~~14: The correlation patterns based on de-trended time series between the ~~Qnef~~ NEF(+↓) and the BANOS-index in wintertime (left) and summertime (right) over the period 1949-2013. For this record length, the 95% significance level is ±0.24. The areas indicating significant correlations are delineated with contour lines.

The correlation pattern indicates a strong connection between the NEF and the BANOS-index over the Baltic Sea and North Sea region in wintertime. This is consistent with the correlation pattern between the SLA grids and the BANOS-index for the winter season. However, in summertime the correlation pattern has negative values over the study area. This implies that the heat fluxes linked to the BANOS-index are not responsible for the sea-level variations over the Baltic Sea and North Sea region during summertime, although they can oppose the sea-level variations caused by other factors. Therefore, we only considered wintertime in order to estimate the contribution of the NEF variations to the connection between the BANOS-index and sea-level. For this computation, we took the spatial average of the NEF values considering the geographical window between the (0° - 30° E) longitudes and the (50° N - 72° N) latitudes.

The sensitivity value of the NEF to the BANOS-index is estimated as 3.28 (W m^{-2} u^{-1}) (r=0.59) in wintertime. This represents an average increase in energy (absorbed-minus-emitted) of ~~25,505,280~~2.5e7 (J~~W~~ m^{-2} yr^{-1}) per one unit change of the BANOS-index over one winter. This energy storage can be translated into an approximate estimation of sea level rise, assuming that the specific heat and thermal expansion of sea-water does not depend on water temperature, salinity or water pressure. Based on this rather strong assumption, we estimated the strength of the relation between sea-level variability linked to the BANOS-index and spatially averaged NEF. This analysis suggests that 35% of the BANOS-related sea-level variability in the Baltic Sea and North Sea region can be explained by the NEF contribution in wintertime. This estimation shows the order of magnitude of the net energy flux contribution to explain the linkage between the BANOS-index and sea level variability. Accordingly, the amount of relative thermal expansion of the water per one unit change in the BANOS-index could be computed as well. However, this computation would differ depending on the assumed average value of temperature and pressure through the water column. An estimation shows that 1 unit increase in the BANOS-index can cause 1 mm sea level rise due to the contribution of net energy flux. This estimation is independent of water depth under the assumption that the thermal expansion coefficients do not depend on temperature or pressure.

4.8.3 The contribution of freshwater flux

The BANOS patterns also suggest possible effects of freshwater flux on sea-level variability. The freshwater flux has two different components. One is precipitation (P) showing complex space-time pattern over the study area. The other is evaporation (E), associated with the net latent heat loss of the surface. The difference of these two factors (P-E) is defined as the freshwater flux.

Here, we used the latent heat flux from the NCEP/NCAR meteorological reanalysis in order to approximately compute the evaporation rate. The surface evaporation rate (E: mm s^{-1}) can be approximately computed by using Eq. 2.

$$E = \frac{Q_{lat}}{L_e \rho_W}, \qquad (2)$$

where Q_{lat} is the latent heat flux (W m^{-2}), L_e is the latent heat of water vaporization (2257 kJ~~j~~ kg^{-1}) and ρ_W is the freshwater density (1000 kg m^{-3}).

We then display the correlation patterns between the BANOS-index and the freshwater flux~~,~~ and between the BANOS-index and precipitation and evaporation separately in order to examine the possible impact of the freshwater flux on the sea-level variability linked to the BANOS pattern. The correlation patterns of the BANOS-index with precipitation, evaporation and freshwater flux are shown in Figure 15~~6~~.

Figure ~~16~~15: The correlation patterns of precipitation (top), evaporation (middle) and freshwater flux (bottom) to the BANOS-index in wintertime (left) and summertime (right) over the period 1949-2013. Time series are de-trended prior to the correlation computation. The 95% significance level is ±0.24. The areas indicating significant correlations are delineated with contour lines.

In summertime, the correlation patterns between the BANOS-index and precipitation and between the BANOS-index and freshwater flux display similar results, with the exception of the western part of the North Sea. In addition, correlation patterns between evaporation and the BANOS-index indicate that evaporation patterns appear to be partly connected to the BANOS-index over the Baltic Sea and North Sea region in the summer season. The results of these correlation patterns suggest that the effect of evaporation is opposite to the possible contribution of precipitation to the BANOS-driven sea-level variability in summertime. Thus, we further focused on the strength of the relation between freshwater flux (P-E) and BANOS-related sea-level variability in this region.

It should be noted that P-E does not cause sea-level to vary directly on the geographical points where they occur, but they have to be considered over the whole Baltic Sea catchment basin.

The corresponding correlation analysis between the freshwater flux averaged over the Baltic catchment basin and the BANOS-index indicates that 27% variance of the sea-level variability that was attributed to the BANOS-index in the Baltic Sea can be explained by freshwater flux variations. However, this contribution is very small for the North Sea.

In wintertime, the correlation patterns between the BANOS-index and the P-E vary from strongly negative in the ~~centre of the Baltic Sea region~~Baltic Proper to strongly positive into the eastern side - covering Gulf of Riga and Gulf of Finland - and the western side of the Baltic Sea centre, namely including the area Arkona basin, Danish straits, Kattegat and Skagerrak. However, considering the basin wide connection between the P-E and the BANOS-driven sea-level variability in the Baltic Sea and the North Sea, the effects of those factors on the sea-level variability seem to be negligible in wintertime.

Our results suggest that freshwater flux considerably contributes to the BANOS-driven sea-level variability only in the Baltic Sea region and only in summertime. In the light of this finding, we further investigated the relation between freshwater flux and the BANOS-index in order to see the spatial evolution of the freshwater flux based on the BANOS pattern of atmospheric circulation. Therefore, we estimate the sensitivity values of freshwater flux at reanalysis grid-cell per one unit change in the BANOS-index. The associated sensitivity patterns of the freshwater flux grids are shown in Figure 16~~7~~.

Figure ~~17~~16: The sensitivity patterns of the freshwater flux grids per unit change in the BANOS-index in wintertime (left) and summertime (right).

In the right panel of Figure 16~~7~~, the summer sensitivity pattern between freshwater flux and the BANOS-index shows that freshwater flux is relatively more sensitive over large parts of the Baltic Sea drainage basin with respect to the rest of whole study area. Figure 16~~7~~ also illustrates that the sensitivity of freshwater flux is largest over the eastern part of Baltic Sea drainage basin to one unit change in the BANOS-index throughout the summer season. An estimation considering the basin wide average of freshwater flux and the BANOS-index suggests that the sensitivity value of sea-level would reach ~~to ∼~~10 mm~~mm u^{-1}~~ per one unit change in the BANOS-index due to the freshwater flux effect in the Baltic Sea region over the summer season.~~ However, only a local strong sensitivity is found over the north of the North Sea drainage basin in wintertime.~~

4.8.4 The contribution of geostrophic wind forcing

Another plausible factor contributing to the linkage between the BANOS-index and sea-level variability in the Baltic Sea and North Sea region would be the BANOS-related wind~~ flows~~. In this sub-section, we aim at explaining the transport of water due to the wind forcing related to the BANOS pattern.

In wintertime~~ (Figure 8)~~, the geostrophic wind flow linked to the BANOS pattern (Figure 8-left) is slightly different to that indicated by the NAO pattern (Figure 8-right~~9~~). This may result in different responses to wind forcing in the Baltic Sea and North Sea region. Considering the area including north-eastern North Sea, Skagerrak and Kattegat (Figure 1) that slight modification in the wind direction suggests that the associated wind forcing cannot transport surface water from the North Sea into the Baltic Sea. This result is in contrast to the NAO-related wind forcing.

In summertime, the BANOS-related (Figure 9~~10~~-left) wind seems to generate similar direction of the water transport as the NAO pattern (Figure 9~~10~~-right) does over the transition zone. This indicates that the wind forcing mechanism in summertime can be similar ~~as in~~to the case of the NAO.

Figure 1~~7~~8 shows the estimated Ekman transport caused by the wind related to the BANOS pattern assuming that the Ekman layer is not interrupted by bathymetry~~ of shallow water.~~.

Figure ~~–~~17~~18~~: The vectors represent the direction of the Ekman transport caused by the SLP BANOS patterns, assuming a geostrophic wind ~~aproximation~~approximation and a complete ocean Ekman layer. The lengths of the vectors are proportional to the magnitude of the surface wind, and directed 90 degrees to the right of the surface wind. Upper (lower) panel shows the winter (summer) season Ekman transport vectors.

The vectors shown in Figure 17~~8~~ represent the ~~expected~~ estimated Ekman transports in the Baltic Sea and North Sea basins. For instance, concerning only the North Sea basin, if bathymetry ~~does~~ would not interrupt the Ekman spiral, Ekman transport ~~of the water which is~~ generated ~~from~~ by the BANOS-related ~~south-westerly~~north-easterly winds, ~~can move~~ would be directed in south-westward direction towards the ~~Norwegian,~~ German, Dutch and UK coastlines, in fact depleting sea-level in the Baltic Sea. For the wind forcing, to be relevant in explaining the link between the BANOS pattern and Baltic Sea level, the assumption of a complete Ekman spiral needs to be dropped, so that the transport could flow mote parallel to the surface wind. In that case, however, an atmospheric circulation pattern more efficiently driving higher Baltic Sea level would present a geostrophic wind anomalies more oriented in the west-east direction.

4.8.5 The contribution of open ocean sea-level variability

Coastal sea-level can also be affected by off-shore sea-level variations in the open ocean. For instance, under spatially uniform warming, sea-level at the coast will rise more than corresponding to its smaller expansion of its shallower water column due to the partial transfer of water mass from the open ocean caused by the stronger expansion of its deeper water column (see e.g. Grinsted et al. 2015). In the context of climate change scenarios, this effect have been estimated for the Baltic Sea as proximately an additional 10% sea-level rise at the coast. In our case, the estimation of this effect would entail the calculation of the effect of the BANOS pattern to temperature changes in the open ocean (North Atlantic) in addition to the expansion of the water column directly in the Baltic Sea. The observations needed for this calculation are not available for the whole 20th century, and ocean reanalysis cover only the last few decades, thus this calculation could only refer to a fraction of the analysis period. However, Figure 13 already indicates that this effect cannot be large for the interannual variability of sea-level in the Baltic Sea. The pattern showing the sensitivity of sea-level to variations of the BANOS pattern is constrained to the Baltic Sea and shows very small, even negative sea-level anomalies in the open ocean. Therefore, since sea-level in the open ocean is not higher for positive phases of the BANOS pattern, this transfer of water mass to the coastal areas and to the Baltic Sea cannot take place. This interpretation is also supported by Figure 14, which shows the correlation pattern between the BANOS index and net surface heat flux. The heat flux anomalies linked to the BANOS index are negative in large portion of the North Atlantic, albeit they are positive at the south of the British Channel.

5 Discussion and ~~C~~conclusions

We have identified an atmospheric circulation pattern that represents a more stable and stronger statistical connection to sea-level variations in the Baltic Sea than the better known NAO pattern. These results suggest that the BANOS pattern may represent a more effective forcing of sea-level by the atmospheric circulation. However, this result does not exclude the influence of other patterns of atmospheric circulation. Actually, the BANOS and the NAO patterns are statistically not independent and both describe a kind of SLP gradient, but with different orientation. Atmospheric variability that is described by the North Atlantic Oscillation also causes variations in the BANOS index. The relative importance of each mode of the atmospheric circulation for the Baltic Sea level variability may vary for different periods through the 20th century as it is clearly seen for the NAO. This influence depends on two factors. One is the link between the circulation pattern and the Baltic Sea level, the second factor is the amplitude of variations of the atmospheric index itself. Therefore, it is possible that for some periods in the past or in the future, the NAO may be more strongly correlated to sea-level than the BANOS index if, for instance, its amplitude of interannual variations becomes larger. However, regarding the long-term picture over the whole 20th century, our results indicate that influence of the BANOS pattern on the Baltic Sea level is on average stronger and more stable.

Here, it should be noted that the BANOS mode of atmospheric circulation shares some similarities with the atmospheric proxy that is suggested by Dangendorf et al. (2014). However, the SLP BANOS pattern indicates different atmospheric pattern than SLP pattern that they describe, especially in summertime. This difference also affects the role of the physical factors that explain the linkage between the BANOS-index and sea-level variability. For instance, we interpret that the BANOS mode of atmospheric circulation does not indicate a wind-driven surface water transport from the North Sea to the

Baltic Sea over the transition zone in wintertime. In addition, the correlation pattern between the BANOS-index and SLA grids indicates a large scale seesaw effect of BANOS SLP pattern on sea-level variability between the North Atlantic Ocean and the Baltic Sea region. This large-scale effect is also indicated by the correlation maps between SLA grid and tide gauges. As an interpretation of that seesaw picture effect, our study explains that the IBE plays a key role in explaining the linkage between the SLP BANOS pattern and sea-level variability. This effect was not discussed in the previous studies (e.g. Andersson 2002; Dangendorf et al. 2014)

~~We investigated and partly quantified the influence of the atmospheric circulation on sea-level variability in the Baltic Sea and North Sea region on interannual time scale.~~

The main conclusions that can be drawn from this study are summarized as follows:

~~of this study are as follows:~~

1) There exists another pattern of atmospheric circulation that is more strongly correlated to the Baltic Sea level variability. This link is also more stable in time and more homogeneous across space than the link between the NAO and sea-level.
2) The statistical analysis provides a ranking of the possible physical mechanisms that may explain the connection between the BANOS pattern and sea level. The main mechanism appears to be the Inverse Barometric effect. Additionally, in wintertime the surface heat flux anomalies also contribute to the link between the BANOS pattern of atmospheric circulation and sea-level, whereas in summer it is the freshwater flux anomalies.
3) The role of wind forcing and Ekman transport is also seasonally dependent. In wintertime, it appears to not to be an important factor, whereas in summertime it may also explain part of the connection between the BANOS pattern and the Baltic Sea level.

~~1) The correlation analysis between the satellite altimetry sea-level anomalies (SLAs) and nine tide gauges resulted in similar and spatially homogeneous patterns, indicating that sea-level tends to vary homogeneously at the coast and in the interior for both winter and summer seasons.~~

~~2) The correlations between the NAO-index and the two tide gauges (Stockholm and Warnemünde) over the 1900-2013 period are not stable in time in winter and most of the correlations between the NAO and tide gauges are not significant in the summer season. In addition, in contrast to the homogeneous (strong) correlation patterns between SLAs and nine co-located tide gauges, the correlation pattern between the NAO-index and SLAs is quite heterogeneous (relative weak) in summertime (wintertime). Overall, these findings suggest that another mechanism, possibly another pattern of the large-scale atmospheric variability different from the traditional NAO, is more responsible for the sea-level variations.~~

~~3) Further correlation analysis led us to identify a new pattern of atmospheric variability. From that pattern, we constructed a new atmospheric index (BANOS-index) displaying high and stable in time correlations to sea-level variability in both (up to r~0.95) winter and summer (up to r~0.89) seasons (in contrast to the NAO).~~

~~4) Sensitivity analysis between the SLA grid-cells and the BANOS-index indicated that the relatively most (least)~~

~~sensitive areas to BANOS-related atmospheric circulation are the Gulf of Finland (Skagerrak) in wintertime and the Gulf of Riga (Skagerrak) in summertime in the Baltic Sea and North Sea region. Considering only the North Sea, the most sensitive area is the German Bight in both seasons.~~

~~5) We investigated the physical mechanisms which likely contribute to the BANOS-related sea-level variations. This investigation resulted in the following findings:~~

~~- Inverse barometer effect (IBE) is the most important factor in wintertime and summertime. This effect would explain up to 88% (34%) of the BANOS linked sea-level variance in wintertime (summertime).~~

~~- We estimate that net energy surface flux can explain 35% of the BANOS-related sea-level variability in wintertime in the Baltic Sea and North Sea region. In summertime, there is no contribution from net energy surface flux to the linkage between the BANOS-index and sea-level variation in the Baltic Sea and North Sea region.~~

~~- The statistical analysis on the contribution of the freshwater flux suggests that, the spatially averaged freshwater flux over the Baltic Sea drainage basin accounts for 27% variance of the BANOS-related sea-level variability in summertime. However, the contribution of freshwater flux to the BANOS-driven sea-level variability is negligible in the Baltic Sea and the North Sea.~~

~~- In contrast to the NAO, the BANOS-driven wind flow does not seem to be involved in the transport of the North Sea water into the Baltic Sea in wintertime. However, in summertime, the wind flow associated with the BANOS pattern is similar to that implemented by the NAO in summertime.~~

6 Acknowledgements

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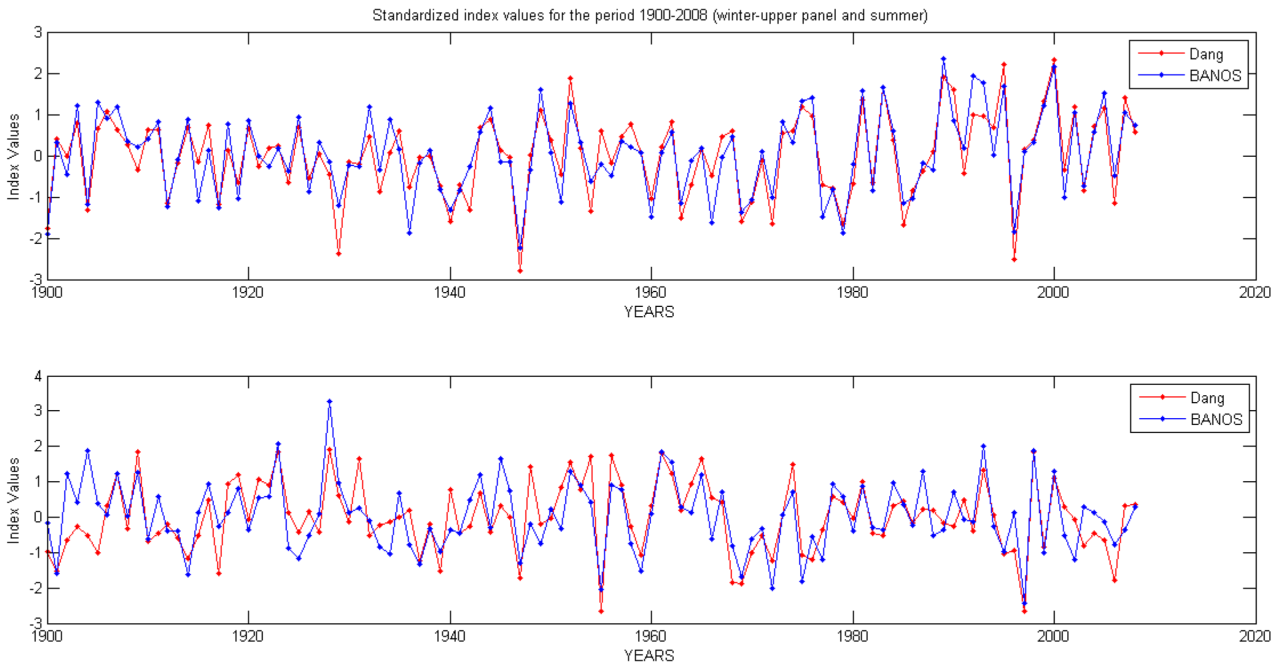
We thank the reviewer very much for reviewing our manuscript, for providing constructive criticism and useful suggestions. We respond to all comments below.

General comments

1.Dangendorf et al. 2013 found a very similar correlation pattern between sea level at the Cuxhaven tide gauge and atmospheric pressure. Furthermore, Dangendorf et al. 2014a derived an atmospheric proxy for sea level variability in the North Sea, based on the pressure difference from virtually the same areas to what has been presented here. Does the BANOS proxy represent a different pattern and does it perform better than this proxy? Otherwise, this study seems of limited use.

The BANOS mode of atmospheric circulation indicates different atmospheric pattern than SLP pattern that Dangendorf et al. 2014a suggest, especially in summertime. This difference also affects the role of the physical factors that explain the linkage between BANOS-index and sea-level variability. For example, in our interpretation, the BANOS mode does not indicate a wind-driven surface water transport from the North Sea to the Baltic Sea over the transition zone in wintertime. Furthermore, the correlation pattern (Figure 13-top) between the BANOS-index and SLA grids indicates a large scale seesaw effect of BANOS mode on sea-level variability between the North Atlantic and the Baltic Sea region. Our study explains that the Inverse Barometer Effect (IBE) plays a key role explaining the linkage between SLP BANOS pattern and sea-level variability. This effect was not discussed in the previous studies (i.e. Andersson 2002 and Dangendorf et al. 2014a).

To illustrate the covariability between those two indices (BANOS and Dangendorf et al.2014a proxy), we computed the correlation coefficients of de-trended time series between those two indices. For wintertime (summertime) the correlation is 0.89 (0.74) for the period 1900-2008. The standardized index time series (not de-trended) in the winter(upper panel) and summer seasons for the period 1900-2008 are shown below.



We have added an explanation of the difference between Dangendrof et al 2014a and this study in the introduction and discussed in the last section.

2.The results almost only show correlation patterns. These patterns can give insight, but it does not show the amplitude of the signals involved. Which fraction of the observed sea level variability can be explained by the atmospheric proxy? What about the fraction of explained variance (R-squared) as a measure of the BANOS model skill? Xu et al. 2015 show that the typical amplitude of variability differs widely within the Baltic (See their figures 3 and 4). Does the coherent NAO/BANOS-induced variability share a coherent basin-mean signal, only with regionally-varying amplitude? What is the standard deviation/RMS of the residual sea level after removing the NAO/BANOS signal?

In Figure 13, we show the correlation pattern between BANOS-index and SLAs for wintertime and summertime. Actually, those figures provide information about the fraction of sea-level variability that can be explained by the BANOS-index. For this computation, correlation coefficients should be squared. Additionally, we mention about the BANOS explained variance of sea-level in the different parts of the manuscript (i.e. “Abstract”, Page 1 Line 18-20).

To show the amplitude of the sea-level variability involved in the BANOS mode of atmospheric circulation, we computed the sea-level standard deviations from observations, from the sea-level explained by BANOS-index predictions and from the residuals. For the BANOS prediction, we applied a linear regression between BANOS (predictor) and satellite SLAs (predictand) for each SLA grid over the period 1993-2013. The residuals are deduced from that linear regression. The results are provided in the following figure (units: mm).

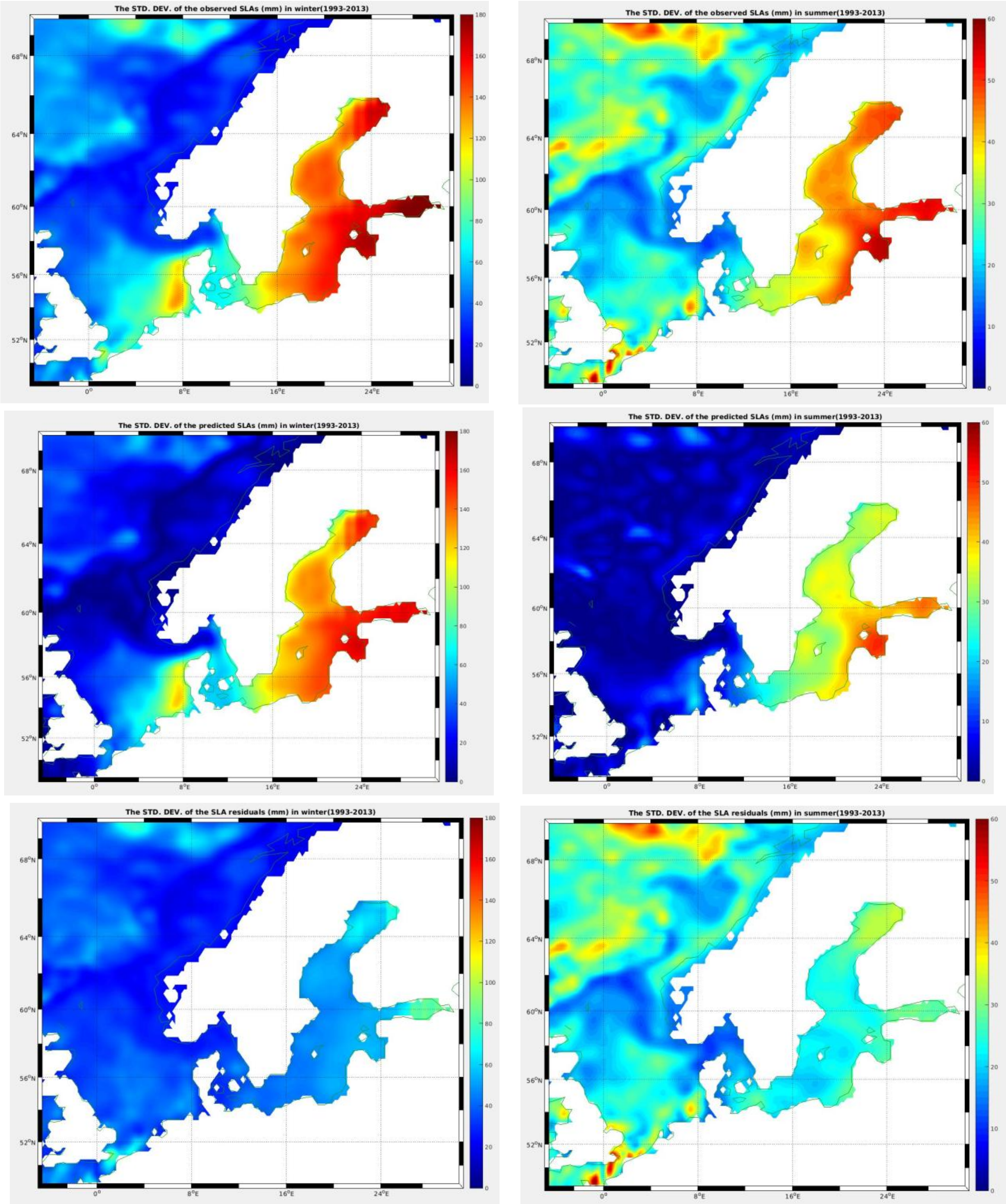


Figure shows the amplitude of sea-level variability from observations (top), BANOS predictions (middle) and the associated residuals (bottom) (Measured SLAi – BANOS predicted SLAi) for the winter (left panels) and summer (right panels) seasons for the period 1993-2013. In the figure, the scale is up to 180 (60) mm for the winter (summer) season.

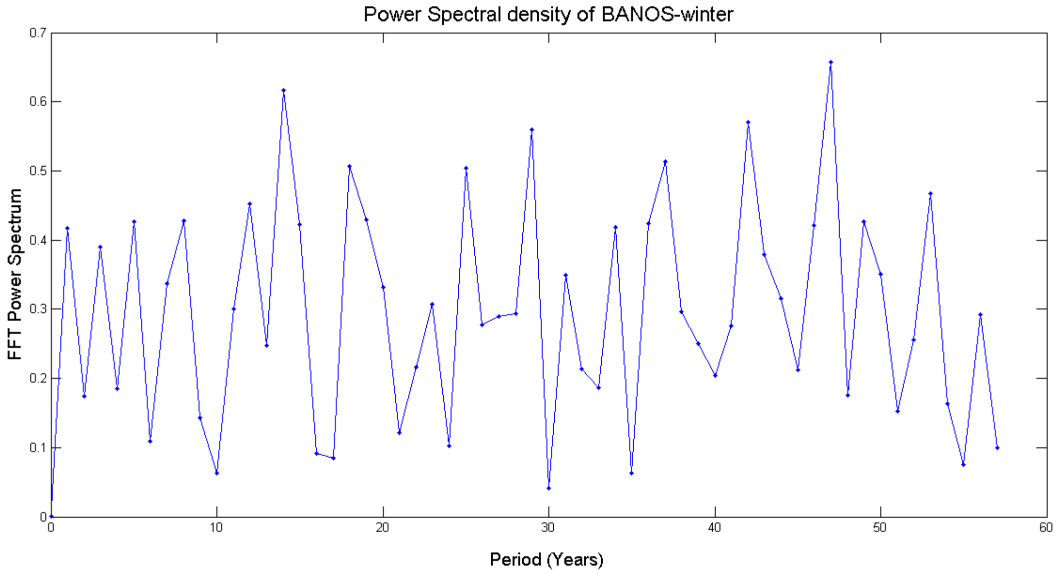
We note that observations and BANOS predictions depict consistent spatial distribution of the standard deviations, especially in wintertime. For wintertime, high sea-level standard deviations occur in Bothnian Bay, in Baltic proper, in the Gulf of Finland and in the Gulf of Riga. The residuals show relatively small and spatially homogeneous standard deviation (~50 mm) distribution in the Baltic Sea and the North Sea in wintertime. In summertime, the spatial distribution characteristics are also consistent. For summertime, the Gulf of Riga shows the highest standard deviation, which is also showed by the standard deviations explained by the BANOS index. Again in summertime, it could be said that residuals show small standard deviation values (>25 mm) and a homogeneous pattern in the Baltic Sea basin except for the Bothnian Bay and the southern part of the North Sea where the standard deviations differ.

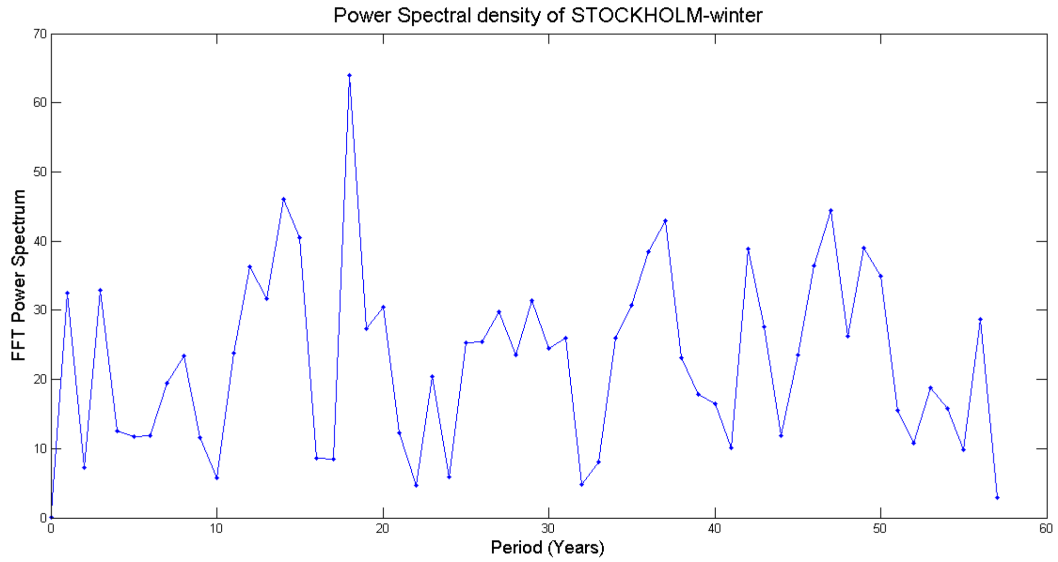
Overall, the results indicate that BANOS-induced atmospheric signal can explain a considerable amount of sea-level variability in the Baltic Sea and North Sea region. Especially in wintertime, the BANOS-index explains almost of all sea-level variations linked to the atmospheric circulation.

3.What are the typical time scales of the variability explained by the BANOS index? Are we explaining monthly variability, seasonal, annual or even longer variability? The abstract suggests 'interannual', which is sometimes repeated, but is not worked out. Since many processes act on different time scales, this classification is very necessary. For example, North Sea variability on decadal time scales is generally assumed to be driven by integrated longshore winds that cause coastally-trapped waves (See Calafat et al. 2012/2013, Dangendorf et al. 2014b and Frederikse et al. 2016), which has not much to do with NAO/BANOS-related effects. Does this signal affect the Baltic Sea? A tool that can be suitable to find the relevant timescales at which the correlations are largest is the wavelet toolbox from Aslak Grinsted (http://www.glaciology.net/wavelet-coherence). Furthermore, a plot that shows observed sea level and the fraction explained by the BANOS index could give more insight.

In this study, we analyse sea-level variability on interannual time scale. All time series involved in the analysis are winter means(December-January-February) and summer means (June-July-August), which are computed from monthly means.

Considering the analysis technique that Grinsted used, we applied a frequency domain analysis (Fourier Analysis) on the Stockholm sea-level and BANOS-index time series for winter seasonal means. The power spectrum of BANOS-index (upper panel) and of the Stockholm record in the following figures. Time series are detrended prior to the analysis and the analysis period was 1900-2013.





The time series show a white noise character, with no clear peaks in the spectrum.

In addition, several researchers using different techniques have examined the power spectra of the NAO indices. A spectral analysis on the NAO-index (Hurrell et al. 2003) indicates that the spectrum of winter mean NAO index is red, but there is no significant peak.

4.It's not clear to me how the time series are formed: do the authors use a mean value for each summer/winter (thus one value per year), or do they use the monthly data from the winter/summer months (thus multiple values per year)? How is the seasonal cycle treated?

For the whole analysis, we used seasonal mean value for each winter and summer. Those winter and summer mean values are computed from monthly means prior to the analysis. We analysed winter and summer separately. Thus, there is no need to remove the seasonal cycle.

We have made some clarification in the Data Sets section.

5.The region is unique due to the presence of many long tide gauge records. Why not use all of these records to show the capability of the BANOS index? Figure 6 and 7 suggest a non-uniform NAO response at different tide gauge locations. This analysis may also provide the much-needed insight into my points 2 and 3 above. Furthermore, the analysis of long-term records in the North Sea only seems to cover the German Bight, while many more tide gauges are available for most of its coastlines.

Keeping in mind that interannual sea-level variability in the Baltic Sea and the North Sea is spatially quite coherent (i.e. Stramska 2013), we used nine representative tide gauges assuming that they would be representative for sea-level variability on interannual time scale in this region.
The correlation pattern between BANOS-index and satellite SLAs indicates that only the eastern part of the North Sea(only German Bight) is connected to the BANOS mode of the atmospheric variability in wintertime(summertime). Since Dangendorf et al. (2013) considered the Cuxhaven record to analyse sea-level variability in the German Bight, we also carried out a statistical analysis considering the connection between the BANOS-index and the Cuxhaven station. That statistical analysis indicates that 64% of sea-level variance can be explained by the BANOS-index in wintertime for the period 1900-2008. The following table show the correlation coefficients among the BANOS-index, the Cuxhaven and Stockholm stations for the period 1900-2008.

Corr. Coeff. Winter (Summer)	Cuxhaven	Stockholm
BANOS	0.80(0.50)	0.84(0.72)
Cuxhaven	-	0.88 (0.67)

6.The inverted barometer effect (IBE) is and only is the static sea level response to air pressure anomalies, and therefore dictates a fixed regression coefficient of -1 cm/hPa. Therefore, the observed pressure correlations, for which a different regression coefficient is found are not only resulting from IBE.

The comment by the reviewer assumes that air pressure changes only at the location of the tide gauge. In the manuscript, we have clarified that the inverse barometer effect (IBE) should include the pressure gradients, since water should be transported from one point where pressure increases to another where pressure decreases. We assume the presence of an infinite ocean without topographic limitation and complete equilibrium in the Baltic Sea and North Sea region. For example, concerning the winter season, the increase in high SLP system over the North Atlantic (especially around Gulf of Biscay- Figure 9) pushes the water into region where the low-pressure decreases in the Baltic Sea and North Sea region.
We have rewritten that part of the text in order to make the explanation more clear than in the previous version.

7.The conditions for Ekman transport to develop are to my knowledge not satisfied, I'd guess, since the Baltic Sea is small and very shallow. For Ekman transport to develop, the dominating balance in the equations of motion is between wind stress and the Coriolis force. Since the Baltic Sea is both shallow and small, bottom friction will probably play a large role, and the basin size is probably smaller than the Rossby radius of deformation. Hence, I'm not convinced by the conclusions that follow from this analysis. Many other studies point at the large influence of local winds on sea level variability here. It may be worthwhile to investigate the wind effects using a barotropic ocean model. These models can explain a large fraction of the observed sea level variability of monthly-mean data, as shown by Xu et al. (2015).

In our study, Figure 18 shows the expected transport based on the assumption that wind-driven sea current is due to only a geostrophic wind approximation and a complete Ekman layer, which assumes that bathymetry does not interrupt the Ekman Layer.

However, knowing that transition area between the North Sea and the Baltic Sea is shallow, it is likely that bathymetry will interrupt the Ekman Layer, and that the water transport is more parallel to the geostrophic wind flow implied by the BANOS pattern.

We have updated the text in order to clarify our assumptions about the Ekman Layer.

8. In a paper by Chen et al [2014], the role of barotropic and baroclinic responses to the NAO in the North Sea are extensively discussed. One of their main arguments is that local density effects on a shallow shelf are small, but a horizontal pressure gradient that develops when a deep ocean column expands results in mass transport towards the shelf. How could we combine these results with your attribution process, which relies quite heavily on density effects (freshwater flux/heating)? Are in-situ temperature and salinity profiles available in the region to verify whether local density effects play a substantial role? Otherwise, regional ocean reanalysis products (some are available at http://marine.copernicus.eu) may provide estimates. From the observation of the anti-correlation between BANOS/NAO and open-ocean sea level, couldn't it be a wind-driven mass redistribution process? Over the last 15 years, you may have a look at what GRACE observations say about mass changes.

This is an extended comment that addresses several points. The reviewer is right that the expansion of the open ocean water column may affect coastal sea-level. This effect has been estimated for the North Sea in the context of future sea-level rise due to climate change by Grinsted et al., who estimate its possible contribution with about 10% of the total sea-level rise. It may be therefore not negligible but not totally significant. We discussed this possible contribution in the revised version by looking at the heat flux associated with the BANOS patterns.

Regarding the link between the NAO and sea-level variations in the North Atlantic (open-ocean), we feel that this is actually beyond the scope of our study that is restricted to the shelf seas.

We have added a subsection (4.8.5 Contribution of open ocean sea level variability) in order to assess and discuss the results by looking at the heat flux associated with the BANOS patterns.

In-line comments
Note that the page numbering re-starts every page. I use the PxLy notation, referring to page x line y.

Title and P1L6: This study mainly deals with the Baltic Sea, and only partially with the North Sea. I suggest: 'German Bight' instead of North Sea.

Here, we analysed the relation between atmospheric circulation and satellite SLAs including the whole North Sea. However, the results of our analysis show that German Bight is the most sensitive area in the North Sea to the BANOS mode of the atmospheric circulation. Therefore, the atmospheric mode that we identified mainly explains sea-level variability in the whole Baltic Sea and a part of the North Sea. At this point, we should mention that we considered the off-shore sea-level variability in the whole North Sea, but, only a part of the North Sea sea-level variability can be explained by BANOS mode of atmospheric circulation.
In addition, to quantify the contributing factors to the linkage between BANOS-index and sea-level variability, we made basin wide analysis in this region including the whole North Sea basin.
For those reasons, we prefer to keep it as 'North Sea'.

P4L15: References to Dangendorf et al. 2013/2014 should be discussed here, and further on, what do we learn from this paper that we do not know yet after reading these papers?

We now briefly discuss and further explain the novelty of this study with respect to the Dangendorf et al. studies at that part and in the discussion and conclusion section.

P5L3: For completeness, it's a good idea to add links to the web sites from which you've obtained the data.

We have added those links of the web sites.

P5L11: Do you derive season-means from monthly data? Or monthly data only over this period? What about spring and autumn?

We calculated seasonal means from the monthly data sets. The focus was on winter and summer seasons when the atmospheric anomalies are expected to be in the largest and the smallest phases.
We have clarified the text accordingly.

P5L13: Altimetry data does not have a ¼ by ¼ degree resolution: along-track observations are interpolated onto a grid which can have a higher resolution than the data from which it is composed. Note that observations are integrated over distances of about 100 km (See Le Traon et al 2001 or Pujol et al. 2014). Furthermore, observations deteriorate quickly close to land, and shallow-water tides may alias into lower frequencies. Hence, it it very tricky to separate smallscale features in shallow shelf seas. Tide gauges are generally more reliable in such areas. An alternative may be to use along-track altimetry observations, which do not suffer from problems related to interpolation. These are widely available from AVISO.

The reviewer is right that caution is needed when using satellite altimetry near the coast, but this is the reason why we also included a comparison between the tide-gauge records and the co-located altimetry pixels. We updated the explanation on the spatial resolution of the satellite altimetry data sets. We have also clarified the text for the spatial resolution of satellite altimetry data set.

P6L2: The word 'slope' here seems a bit misleading: you compute the regression coefficient between the atmospheric pattern and sea level. 'Slope' suggests a linear trend to me.

We do not use word *"slope"* in the mentioned line.

However, in P7L2 we had written *"The slope of the regression line is denoted as the sensitivity".* We changed it as *"The linear regression parameter of the regression analysis is denoted as the sensitivity".*

As well as P13L9 was *"is estimated from the slope of the regression line resulting from the regression analysis where the BANOS index".*

We have changed it as *"is estimated from the linear regression parameter of the linear regression where the BANOS-index…"*

P6L11: The NCEP/NCAR reanalysis 1 is not really state-of-the-art anymore. Furthermore, since you use this data set to derive heat fluxes and precipitation over sea, how good does this model perform for these quantities? I guess that this model does not directly assimilate heat flux and precipitation data, and that they are derived from wind and pressure data. It may be worthwhile to use something like MERRA or ERA-interim, in which flux observations derived from satellites are assimilated. An other alternative may be OAflux (http://oaflux.whoi.edu/)

We thank reviewer for this suggestion.

As a simple assessment test, we investigated the NCEP/NCAR net heat flux performance with respect to OAflux net heat flux. For this test, we considered field mean of a geographical area over the North Atlantic (a box covering 35° W - 15° W and 50° N-60° N) in the winter season(DJF) for the period 1984-2009. The correlation analysis on those time series indicates that NCEP/NCAR data set performs well. The correlation coefficient is 0.98.

Considering the MERRA and ERA-interim, the data sets are available from 1979 on, which is quite short in comparison to the NCEP/NCAR reanalysis data set. In this study, we analysed the contribution of atmospheric factors to the connection between BANOS mode of atmospheric circulation and sea-level. Therefore, once we established a statistical linkage between BANOS-index and sea-level variability, we could compute the strength of relation between atmospheric factors and BANOS-index by using the climatic variable as long as possible over the last century. Therefore, analysis period was not limited to satellite era. However, we can use products of MERRA and ERA-interim for the direct comparison between satellite SLAs and climatic variables in a future work.

P6L34: This statement seems easy to verify: what is the correlation over the common altimetry/TG period?

Probably there is a typo here - page 6 has only 28 lines. We could also not guess what could be the statement from the comment.

P7L10: Why only check for these three? If you use all available tide gauges in the region with a substantial amount of observations, you can generate a map with the correlations at each TG location. This will make much clearer whether altimetry observations do a good job, especially at the narrow straits (Kattegat/Skagerrak etc) and around islands.

Indeed, Figure 2 and Figure 3 provide information about the coherency of the satellite SLAs over this region as well. Since nine tide gauges have strong correlations to satellite SLAs on and around the closest point of their positions.

However, we computed additional correlation values between tide gauges and satellite altimetry over those areas.

P7L11: Could you make the followed procedure more clear? I don't fully understand how the data has been treated. I also wonder how you treated the seasonal cycle.

We have clarified the text based on the suggestion. Also please see our response to point 4.

P7L16: A correlation only does not show that signals are coherent: what about the fraction of explained variance, or a simple plot, in which both time series are compared?

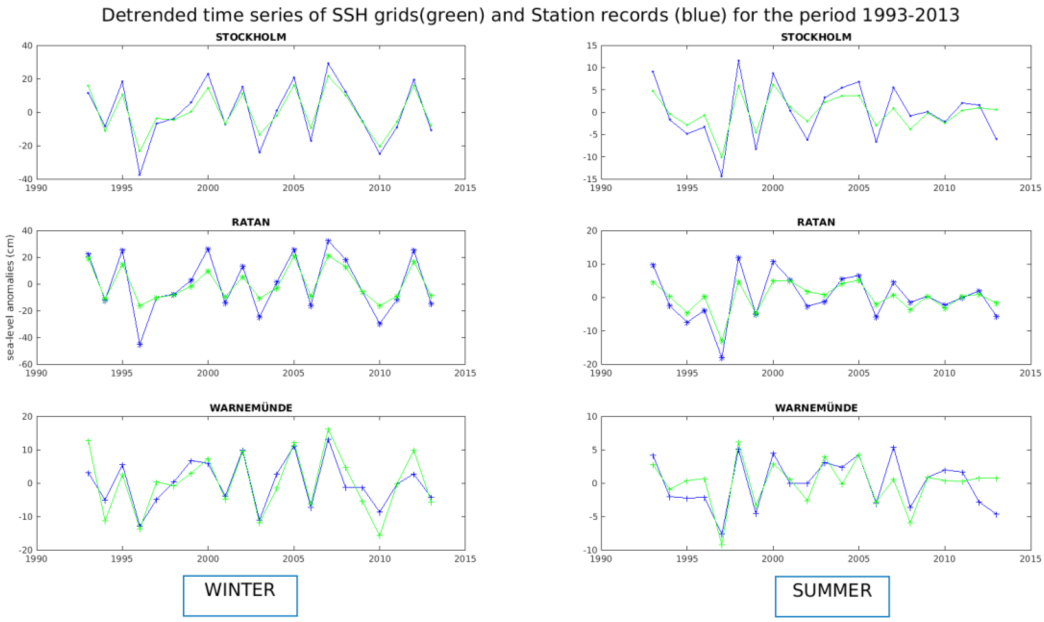
The reviewer probably means the variances themselves, since the fraction of explained variances are just the correlation squared.

The explained variances are:

	Winter	Summer
Ratan-SLA	0.90	0.83
Stockholm-SLA	0.94	0.85
Wismar-SLA	0.78	0.61

In the following figure, we show the detrended time series of tide gauges and satellite altimetry observations, which are from the closest points to each tide gauge. In each panel, the top figure is for Stockholm, middle is for Ratan and bottom is for Warnemünde, also left(right) column represents winter(summer) values.

It can be seen from the figures that, in general, the stations agree well with the satellite SLAs in wintertime, only the Warnemünde station has some discrepancies over the beginning and end of the considered period. In comparison to the wintertime, a relative discrepancy is found between all stations and satellite SLAs in summertime, especially in the relation between Warnemünde and satellite SLAs that discrepancy becomes clearer with respect to the wintertime. This discrepancy between satellite SLA and tide gauge in Warnemünde may occur due to the complex structure of the coast.



We have also explained what is meant with the term “coherent” in the Methods section.

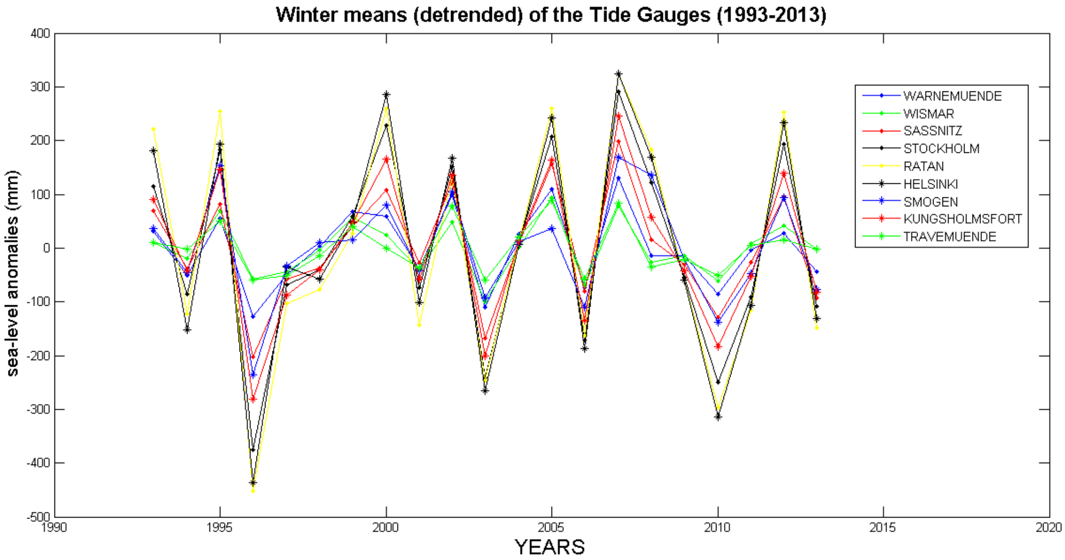
P7L17: Are you sure that you compare the same signals with Yan et al [2004] ? Same treatment of seasonal cycle/lowpass filters/detrending etc? Maybe this statement falls outside the scope of this manuscript.

In our study, we computed the winter means from monthly data sets, then detrended the data over the considered period prior to the correlation analysis. Since we analyse data sets in winter and summer separately on interannual time scale, we did not need to remove the seasonal cycle.

As far as we understand, Yan et al. 2004 also made correlation analysis with detrended time series based on interannual time scale (in Table II). Therefore, we think that a comparison between our results (our Table I) and Yan et al. 2004 (their Table II) is possible concerning those correlation coefficients.

P7L24: From this correlation pattern I’d assume that the tide gauge records have a high mutual correlation. Could you show the time series of all tide gauges in one plot to verify this?

The following figure shows the time series of associated tide gauges over the period 1993-2013. (time series represent detrended winter means (DJF) of tide gauges)



P7L28: This is an interesting finding and may give some hints about the underlying processes!

The seesaw pattern that suggests negative and positive dipole relation between North Atlantic and Baltic Sea basin wide sea-level variability also brought us to test the contribution of inverse barometer effect (IBE) to the linkage between sea-level and BANOS-mode of the atmospheric circulation. As a result, we found that major driver of the connection between sea-level and the BANOS-index was IBE.

We clarified the text in the introduction section based on this comment of reviewer.

P8L28: How do you define 'significant'?

We have added the significance threshold of the correlation coefficient for that record length.

P9L3: Add here very explicitly about which time scales you are discussing.

We have changed the sentence. New version: *"As pointed out, the patterns of correlation between the tide gauges and the satellite altimetry fields indicate that the variations of sea-level in these regions are spatially quite uniform in both seasons (Figure 2 and Figure 3) on the interannual time scale"*

P9L7: 'tend to be spatially coherent': again, the large amplitude variations over the region do not support this statement.

We removed this statement. Additionally, we would like to point out that the term *"coherent"* is sometimes used instead of the term *"strong correlation"* and that it does not necessarily provide information about the amount of the relative variation of two variables.

P9L8: 'the influence of NAO is spatially quite heterogeneous': where do you show this?

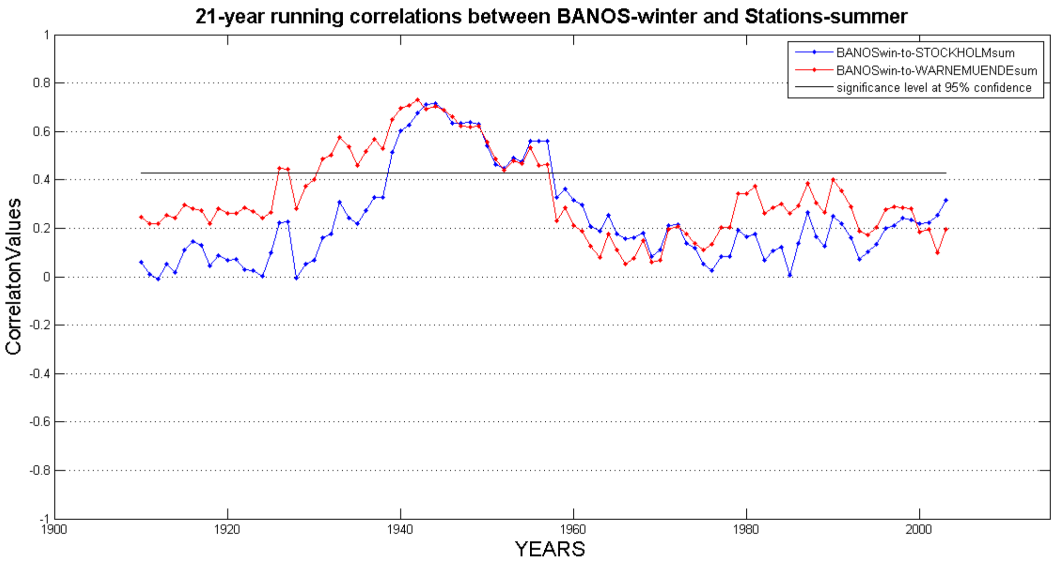
It has been documented in the literature (i.e. Yan et al. 2004, Hünicke and Zorita 2006, BACC Book II 2015) and we also show in Figure 5 and Figure 6. We made clarification in the manuscript about this statement.

P9L26: These findings contradict with the conclusion that Baltic sea level is coherent, as the difference in the found correlations is rather large, which would not be the case if the signals at both tide gauges were coherent.

Here, we wanted to exactly highlight this point. Whereas the sea-level variability seems spatially coherent, in the sense that the tide-gauges are relatively highly correlated, the correlations with the NAO are not. This implies that there may be another large-scale effect rather than the NAO which is driving the sea-level variability over the whole Baltic Sea basin. That rationale was also the background to look for another atmospheric pattern that is strongly connected to the Baltic Sea level variability and that differs from the NAO pattern.

P10L19: The correlation patterns seem to be almost the same as already found by Dangendorf et al, 2014a. Following the argumentation, this makes sense, as sea level variability in the Southeastern North Sea, used by Dangendorf et al, and the Baltic sea is coherent and thus has a common driver. Can't we just suffice by saying: "The atmospheric proxy, developed by Dangendorf et al. [2014] does not only work as a proxy for the S.E. North Sea, but also for the Baltic Sea."? Or is the new BANOS index doing significantly better? The only difference between Dangendorf et al and BANOS seems to me the Eastward shift in summer for the BANOS index. However the summer correlations are substantially less convincing than in winter, as I observe in figure 10. Especially the right panel in fig. 10. How does the model perform when you stick to the winter definition, even for summer?

To statistically test the performance of the winter BANOS-index for the summer sea-level variability, we computed the 21-year running correlation values between winter BANOS and summer stations (Stockholm and Warnemünde).



Based on the result of this analysis, we can say that winter BANOS does not perform well to explain the summer sea-level variability. For the rest of this comment, please see our response to point 1.

P11L11: It seems that there are some decadal features that are shared between NAO and BANOS. Here, a wavelet analysis, as described above, may be more insightful.

Please see our response to point 3.

P12L8: Isn't this negative trend just a symptom of the non-stationary correlation? Something similar happened between 1905-1935.

The reviewer is right. The correlation between the NAO and sea-level is not stationary, and this is one of the motivations of the study - namely to find an atmospheric pattern that yields more stationary correlations. The reason why the strength of the relation between sea-level and the NAO-index has decreased from 1970 onwards is not known yet. One possible reason is that the variability of the BANOS pattern becomes stronger so that the sea-level records deviate more strongly from the NAO. But this explanation would then prompt the question of as to why does the BANOS pattern become more energetic. We feel that an explanation for this behaviour lies rather in a study of the atmospheric dynamics and lies beyond the scope of this study

P12L9: I'd say: "No significant link between NAO and Baltic sea level in summertime"

We have added a statement to the text.

P12L11 and the following section: Like the NAO, you find a strong anti-correlation between North Atlantic sea level and the BANOS index. That's an interesting finding in my opinion.

Please see our response to P7L28. We have also added some comments to the manuscript in the Introduction section.

P13L5 and the following sections: Here you show the spatially heterogeneous senitivity, again pointing at a spatially varying sea level signal. Which fraction of the variability is explained?

Please see our response to point 2.

P13L9: Avoid the word 'slope' here. Maybe insert a short equation:
*dSLA = a*BANOS with a in [mm/BANOS]*

Please see our response to P6L2.

P13L12: It may well be the case that next to BANOS, more effects are at play here, that are not necessarily linear.

It may be the case. Indeed, a quantitative separation of the different contributions to sea-level variations and the estimation of their possible non-linear interaction can only be done by numerical experiments with a realistic Baltic Sea&North Sea ocean model, which should be analyzed in future studies. In this study, we established a statistical linear connection between natural variations and sea-level variability by assuming that established connection will stay same when we go backward or forward in time.

P14L4: Why is that suggested? Horizontal pressure gradients will result in a sea level gradient due to the IB effect, and generate geostrophic winds. Do you mean that wind effects play a role?

Please see our response to point 6.

P14L18: As stated in the introduction: The IBE effect is the static response to pressure effects with a sensitivity of 10 mm/hPa. Since, static equilibrium is generally reached on timescales in the order of days, deviations from this static effect imply that some other effects are at play here. That's not so strange, as close to coastal areas, winds play a large role. To separate these effects, a barotropic ocean model can bring more clarity.

We tried to explain our approach in our response to point 6. We have clarified how we handle with the inverse barometer effect (IBE) in the manuscript.

P15 equation 1: I'd suppose that the rate of change in steric sea level correlates with the heat flux and not the sea level itself. i.e. dSL/dt ~ Q_net instead of SL ~ Q_net. What if you integrate Q_net before computing any correlation?

The reviewer is right, but, we actually did integrate the heat flux over the whole season, so that the variable that we use to correlate with the seasonal sea-level is the total amount of heat that goes into the ocean (or leaves the ocean) over one season

P15L24: This number is rather large, I suspect it's incorrect.

This number is computed from the sensitivity of net energy flux to one unit change in the BANOS-index. Sensitivity value is 3.28 $J/m^2.s$. This means one unit increase in the BANOS-index causes 3.28 J/m^2 per second over the winter. To compute the sensitivity of net energy flux to the BANOS-index over one winter, we multiplied the 3.28 with 60*60*24*90, which is equal to that number. That amount of heat distributed over the upper 50 meters in the water column would rise the water temperature by about 0.1 K, so it is not clear to us what the reviewer means. We have checked this number. It is correct.

P15L25 and below: How did you compute this? If I'd compute the thermal heating that result of the afore mentioned number, the whole Baltic sea would evaporate rather quickly. Are there insitu T/S observations, or SST observations that can confirm the large impact of density changes induced by local heat fluxes? I'd guess that on a shallow shelf, the effect of density changes is rather limited. Furthermore, if so much water evaporates or rains into the basin, doesn't the resulting sea level *change lead to transport with the open ocean?*

Please see our response to P15 equation.

P16L11 and beyond: Like with energy fluxes, isn't it expected that sea level varies according to the integral of the total freshwater flux?:
dSL/dt ~ E
Furthermore, do you suppose that the total mass in the Baltic Sea is affected, or that the effects are caused by changes in the salinity?

We actually use the water flux integrated over the whole season.

P16L25: The correlation pattern does not tell much about what causes what. I'd say that the precipitation/evaporation pattern changes and sea level changes are both caused by the BANOS-related pressure changes. Therefore, they show mutual correlation. But that does not show that the P-E flux causes sea level changes! Hence, the conclusions reached from P16L32 onward are not really justified in my opinion without further proofs.

The reviewer is right that the statistical analysis is not proof of causal relationships. The statistical analysis is rather an estimation of the possible contribution of the fresh water flux and is to be understood as an analysis of plausibility.

P17L7: Do you mean 'geostrophic wind flow' here?

Yes, we mean geostrophic wind flow. We changed the text accordingly.

P17L8: I don't understand what you mean here: why can't the BANOS-induced wind forcing transport surface water between both basins? Although for different regions, many studies point at the large impact of local wind variations on monthly and interannual sea level, including Sterlini et al. 2016, Dangendorf et al. 2013, 2014a, 2014b, and many more. Does the same happen in the Baltic Sea? Figure 3a in Dangendorf et al, 2014a clearly suggest a wind set-up effect.

In wintertime, the SLP BANOS pattern attributed geostrophic wind flow does not indicate westerly winds over the transition zone. It rather implies south-westerly wind, which can cause strong water accumulation towards west Norwegian coast and German Bight. Hence, we can speculate that water accumulation (coastal downwelling) can cause water transport from German Bight and west Norwegian coast towards the Baltic Sea.

P17L15: To my knowledge, as described above, both the local bathymetry and shallow water, as well as the presence of coasts render the Ekman transport assumption invalid. The width of the basin is about 100 – 200 km, which is probably smaller than the Rossby radius of deformation. Especially around Skagerrak and Kattagat, the basin dimensions become very small. Hence, I would not trust results based on the Ekman transport assumption. Again, a wind-forced barotropic ocean model or a regional ocean reanalysis could bring more trustworthy results regarding changes in wind-induced transport and sea level variability.

In our discussion we provide an estimation of the potential contribution of Ekman pumping under 'perfect' conditions. We are aware that these conditions are not totally met, even less so in the shallow straights connecting the North and the Baltic Sea. However, our estimation is not focused on these areas. We wanted to estimate the transport that can be attributed to the large-scale BANOS pattern. In the end, the total water transport will be caused by a combination of the local wind forcing and the larger scale transport, which will also cause local pressure gradients along the narrow straights.

The reviewer is right that a quantitative estimation requires the use of a comprehensive ocean model, but our study is a statistical analysis of the available data.

P18L3: The impact of NAO/BANOS-related variability is the only atmospheric effect on sea level analysed in this study. There may be more atmospheric processes affecting sea level on interannual time scales.

We agree with the reviewer’s comment. It is also reason that we write “partly quantified”.

I’m afraid that most conclusions are not justified by the presented results:
• Conclusion #1: According to other studies, the amplitude of the interannual variability differs widely around the region and therefore, the variability is not coherent. Furthermore, in figure 14 you show that the spatial signal is far from coherent, as the sensitivity values differ by a factor 10 over the basin.

The comment by the reviewer is based on a different meaning of coherency. The reviewer uses this term when the records would show roughly the same amplitude of variability, whereas we use it to denote correlated behaviour in time.

We have clarified what is the meaning of ‘coherent’ in the Methods section.

• Conclusion #2: In figure 6, top I see a rather strong correlation between the NAO and the altimetry-derived sea level in wintertime, rather than weak!

We derive this conclusion from the 21-year running correlation values between the NAO and two tide gauges over the last century. The temporal variability of the link between the NAO and sea-level variability can sometimes show some strong correlation for an individual short term period, as it is happened over the satellite era.

• Conclusion #3: There are essentially two indices: summer-BANOS and winter-BANOS.

We have written the whole section from the scratch.

• Conclusion #4: The BANOS index only correlates with sea level variability in the German Bight, and not in the whole North Sea in summer.

Our conclusion #4 does not say something inconsistent to this comment.

• *Conclusion #5: Since the regression coefficient deviates from the static IB response, it's probably not only the IB effect that causes the pressure-sea level link. Furthermore, if the IB effect explains 88 % of sea level variability, and surface fluxes 35%, we explain more than 100 %. Again, you've only showed a correlation pattern and not what causes what. They also may have a common cause. How are these percentages derived? The conclusions regarding wind-driven variability depend on the Ekman transport approximation, which is probably not valid in this region.*

One of the complexities in identifying the physical mechanism of the sea-level variation is that there can be interrelations among the considered physical mechanisms. Hence, a possible overestimation may occur if some interdependent forcings (predictors) are included in the associated statistical model. This possibility can be partially excluded with the use of atmosphere indices that contain several effects and represent them in a single index (e.g. Sterlini et al. 2016). For example, the NAO, as a mode of atmospheric variability, can carry information about the wind, sea-level-pressure and surface heat fluxes. In this part of the study, describing relations between the effects of the related driving factors and sea-level variation based on atmospheric indices enables us to use those relations without making any further analysis such as multicollinearity test between drivers. Considering the explained variances of sea-level by the inverse barometer effect (IBE) and net energy flux (NEF), it seems that sea-level variance is overestimated due to the amount of explained variance in total. The first reason is that we assumed a complete equilibrium over the Baltic Sea and North Sea region for the IBE, which is in real not the case. Broadly speaking, we estimate a possible maximum contribution of the IBE to the BANOS attributed sea-level variability over the study area. The second reason is that the impact of the NEF is computed by taking the spatial average of the Baltic Sea and North Sea basins. The amount of thermal expansion of the water per one unit change in the BANOS-index would differ depending on the assumed average value of temperature, salinity and pressure through the water column (for this, please see our response to P15 equation).

Here, it should also be noted that a high correlation does not necessarily mean a strong direct physical connection between the conducted factor and sea-level variability. Therefore, the statistical analysis that we applied in this study investigates the potential of contributions of the considered physical factors to the sea-level variability. The quantitative attribution of the driving factors to the sea-level can only be described by numerical experiments with a realistic Baltic Sea and/or North Sea ocean model (e.g. Kauker and Meier 2003).

Figures,
1. In general, it may be a good idea to avoid the 'rainbow' color scale for correlations. A good summary of which color maps are suitable can be found here:

https://betterfigures.org/2015/06/23/picking-a-colour-scale-for-scientific-graphics/ I'd suggest to use a 'diverging' color scale. It looks like you use GMT for the plots, for which many good diverging color palettes can be found here:
http://soliton.vm.bytemark.co.uk/pub/cpt-city/jjg/cbcont/div/index.html

We used "MATLAB" software for all plots. We have tried to enhance the colour scale.

2. It may also be a good idea to contour areas with significant correlations

Contour lines delineating the significant correlations are now added to the figures (Figs. 4, 12, 14, 15).

3. Some figure captions can be expanded to describe the followed procedure. For example figure 4: "The correlation pattern between de-trended sea level during the winter months(DJFM) and the de-trended NAO index over the same months. The correlation has been computed between January 1993 and December 2014" or something similar. This will allow easier reproduction of your results.

We have expanded captions to the figures.

Figure 1: Maybe add the locations of the tide gauges

We have added the locations of the tide gauges.

Figure 10: On the left, some data seems to be missing

To compute the correlation coefficients, we prescribed a threshold of 75% data availability for the considered period.

For the Figure illustration, we replotted figure by excluding the threshold.

REFERENCES (in addition to reviewer's references)

Andersson 2002, *Influence of Long-Term Regional and Large-Scale Atmospheric Circulation on the Baltic Sea Level*. Tellus A 54 (1): 76–88.

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Kauker and Meier 2003, *Modeling Decadal Variability of the Baltic Sea: . Reconstructing Atmospheric Surface Data for the Period 1902– 1998*. Journal of Geophysical Research 108 (C8): 3267.

Hurrell, J. , Y. Kushnir, G.r Otterson, and M. Visbec. 2003 . *"An Overview of the North Atlantic Oscillation."* The North Atlantic Oscillation: Climatic Significance and Environmental Impact 134: 263. doi:10.1029/GM134.

Hünicke and Zorita 2006, *Influence of Temperature and Precipitation on Decadal Baltic Sea Level Variations in the 20th Century.* Tellus A 58 (1): 141–53.

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We thank the reviewer very much for reviewing our manuscript, for providing constructive criticism and useful suggestions. We respond to all comments below.

Specific Comments
A major part of the paper is the presentation and discussion of how much better the BANOS-index correlates to sea level changes in the Baltic Sea than the NAO-index. It would be helpful to the reader to discuss the BANOS-index with respect to other slp indices that have been used for the Baltic Sea. For example the BAC index in Andersson, 2002 or the BSI in Lehmann et al, 2002. How much different are those indices from the BANOS-index? Would the slp gradient over the transition zone between North Sea and Baltic Sea be different between BANOS and BAC or BANOS and BSI?

To answer the questions raised by the Reviewer, we initially contacted Andersson in order to obtain the time series of the BAC-index, but unfortunately we were informed that time series is not available any more. Therefore, we cannot make a statistical comparison between the BANOS-index and the BAC-index. Also, the BAC-index is constructed with a different method than the other indices (BSI-index, NAO-index and BANOS-index).

We also contacted Lehmann, he kindly shared the time series of the BSI-index with us. The BSI-index time series starts in 1948. Therefore, we made a correlation analysis between the BANOS-index and the BSI-index for the period 1948-2013. The time series are detrended prior to the correlation analysis. The results are shown in the following table.

Corr. Coef. (period 1948-2013)	Winter	Summer
BANOS - BSI	0.91	0.64
NAO- BSI	0.72	0.19
BANOS-NAO(corr. in the manuscript)	0.68	-0.12

Briefly, this correlation analysis indicates that the indices, BANOS and BSI, may share some similarities in wintertime, but the strength of the relation between those indices becomes much weaker in summertime. Moreover, the correlation between NAO and BSI indices seems very weak in summer, although it is statistically significant. On the other hand, there is neither a significant nor a positive relation between NAO and BANOS indices detected in summertime.

We should additionally mention that Lehmann et al. (2002) constructed the BSI index only from the analysis of winter months. They defined the BSI-index as the difference of normalised SLP anomalies at the positions of (53°N30', 14°E30') and (59°N30', 10°E30') by considering the period 1979-1998. This shows that they selected different SLP fields than we selected for the winter BANOS-index. Moreover, they concluded that a positive BSI pattern is linked to westerly winds over the Skagerrak and Kattegat, whereas in the winter BANOS-index the orientation of the winds is rather north-westerly. Regarding the BANOS-pattern related sea-level variability; we interpreted a large impact of the inverse barometer effect (IBE), which transports water from the North Atlantic towards the North Sea and the Baltic Sea. In addition, Lehmann et al. (2002) is more focused on monthly and weekly variation of the Baltic Sea level variability. Our study analyses sea-level variability on the interannual time scale.

We should also note that similar question was raised by the Reviewer 1. The reviewer suggested a comparison between Dangendorf et al. (2014) * atmospheric proxy and the BANOS-index. Please also see our response to the first point of Reviewer 1's revisions.

We have added an explanation of the difference between Dangendrof et al 2014a and this study in the introduction and the last sections.

*Dangendrof et al. (2014), A new atmospheric proxy for sea level variability in the southeastern North Sea: observations and future ensemble projections, Climate Dynamics, 43:447.

Is the BANOS-index usable without a gridded slp field? Can it be inferred from station data (e.g. Stockholm - Odessa), like the NAO-index and would it show good correlation the one derived from gridded data?

The station-based NAO-index is computed from the differences between two normalized SLP fields. Here, we used the same method. What the reviewer asks is whether it is possible to construct a BANOS-index from station data. It could be possible, but individual station pressure records can be affected by local effects - small-scale and transient meteorological factors - unrelated to the large-scale mode of atmospheric circulation. This problem is also addressed by Hurrell et al. via:

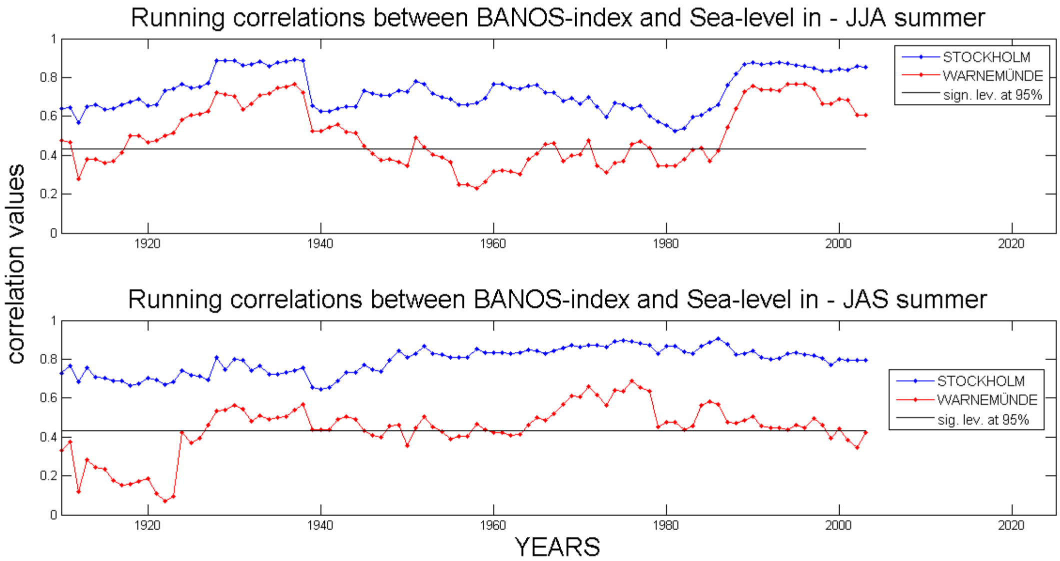
https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based

Since we have the gridded SLP fields for the period of analysis, we prefer to use those data that have also been profusely used in other studies.

How sensitive are the results and the conclusions for summer when the summer was defined as the months JAS? Baltic Sea sea level in summer show little variation during these three months (e.g. Hünicke and Zorita, 2008, Meier et al., 2004). The month of June usually lies between the spring minimum and the summer values. What is the reason to choose June, July and August as the summer season?

Some authors have used other months to compute summer means. The idea by selecting those months (JJA) as summer months were that the smallest variance of sea-level occurs in those months over the last two centuries (i.e. Andersson , 2002- Figure 3).

To measure the robustness of the BANOS-index based on the method suggested by the Reviewer, we computed the 21-year running correlations of JAS mean summer variations between BANOS-index and sea-level. We also include the 21-year running correlations between BANOS-index and sea-level for the JJA summer season. Results are shown in the following figure.



The figure indicates that the Stockholm sea-level variability can be well represented by the BANOS-index for the summer of the JAS months. For the JAS summer, those correlation values - for BANOS-index and Stockholm sea-level- indicate a steady relation over time and are always higher than 0.65 over the 20st century. We should note that the relation between BANOS-index and Stockholm for the JAS summer is even stronger and more stable in time than the relation between the BANOS-index and Stockholm for the JJA summer. However, Warnemünde is weakly connected to the BANOS-index for the JAS summer over the last century.

The title of the paper suggests the investigation of North Sea and Baltic Sea sea levels. In the derivation and evaluation of the BANOS-index only Baltic Sea sea levels are taken into account. From Figures 4 and 13 one would expect that the correlation of winter mean sea levels in the North Sea improve over the NAO correlations. For summer at least in the eastern part of the North Sea. Please consider to show one or two tide gauges from the North Sea in Figure 12, or add a figure like Figure 12 for two North Sea tide gauges.

We have added the results of Cuxhaven tide gauge to the Figure.

Please, also see the following table for the correlation coefficients among the BANOS-index, the Cuxhaven (settled on the coast of German Bight) and Stockholm stations for the period 1900-2008.

Corr. Coeff. Winter (Summer)	Cuxhaven	Stockholm
BANOS	0.80(0.50)	0.84(0.72)
Cuxhaven	-	0.88 (0.67)

In the abstract it is said that the wind associated with the slp pattern of the BANOS-index does not lead to transport of water into the Baltic Sea. The analysis in Section 4.8.4 is a good idea, but since the return flows along the coasts and at depth are not taken into account, the statement might not hold up to a more thorough investigation.

In the abstract, we consider the case that the geostrophic wind linked to the SLP BANOS pattern does not suggest a westerly wind over the transition zone between the North Sea and Baltic Sea in wintertime. Therefore, the geostrophic wind would not push surface water from the North Sea into the Baltic Sea over the transition zone, where the bathymetry is expected to interrupt Ekman Layer. It rather plays a role in accumulating water (downwelling) towards the west coast of Norwegian Trench and German Bight.

However, the geostrophic wind linked to the SLP BANOS pattern suggests a possible transport of surface water from the North Sea into the Baltic Sea in summertime, since BANOS related geostophic wind is expected to be westerly over the transition zone, as in the case of the NAO pattern.

In our study, we did not consider the return of the water flow.

I would like to see the correlation coefficients for all of the nine stations in Table 1. Future studies might benefit from that information and for the present study the information might help with the interpretation of Figures 2 and 3.

We have included the correlation coefficients for all stations in Table 1.

Good correlations between altimetry and tide gauge data is said to indicate progress in satellite altimetry. Could the source of the improvement over earlier comparisons be specified? It is probably not the altimeter instruments themselves that have progressed so much. Information on the geoid? New algorithms? Amount of data?

Primarily, updating the geophysical corrections and usage of refined mapping parameters should be the reasons improving the correlation between altimetry and tide gauge data.

We should also indicate that main improvement of DT2014 SLA data set is achieved by changing the reference period of the SLA products to a new altimeter reference period. This reference period takes the advantage of the 20 years observations and optimizes the reduction of along-track random noise, which was largely involved in the physical signal of the previous version DT2010. For the further information, we suggest the paper of Pujol et al. (2016) - http://www.ocean-sci.net/12/1067/2016/os-12-1067-2016.pdf .

The core of improvement from their study: *"Numerous innovative changes have been introduced at each step of an extensively revised data processing protocol. The use of a new 20-year altimeter reference period in place of the previous 7-year reference significantly changes the sea level anomaly (SLA) patterns and thus has a strong user impact. The use of up-to-date altimeter* *standards and geophysical corrections, reduced smoothing of the along-track data, and refined mapping parameters, including spatial and temporal correlation-scale refinement and measurement errors, all contribute to an improved high-quality DT2014 SLA data set"*

We have added an explanation of the improvement of the SLAs in the subsection 4.1.

In Section 4.8.1 yet another index is introduced as the slp differences between two geographical locations that differ from the ones introduced in Section 4.4. Would you please explain why there is a need to introduce different locations where to measure slp to get at the IBE contribution? Why Denmark Strait and not Labrador Sea for the summer for example? But more importantly why not stick to the definition (5W, 45N) - (20E, 70N) for winter and (30E, 45N) - (20E, 60N) for summer?

We needed geographical points where sea-level data were available in order to estimate the sensitivity of BANOS attributed sea-level to the IBE. Therefore, the points that we selected were the optimum ones according to winter-summer BANOS patterns and sea-level data availability.

We have clarified the text in that section.

In Section 4.8.2 please indicate in the text whether the whole water column was heated or just the mixed layer (down to what depth?) to absorb the energy.

The estimated explained variance (35%) shows the potential of net energy flux contribution to explain the linkage between the BANOS-index and sea-level variability. Here, we assume that the thermal expansion coefficients do not vary with temperature or pressure. It is, therefore, a first order estimation.

Under those assumptions, we estimate that 1 unit increase in the BANOS-index can cause 1 mm sea-level rise due to the contribution of net energy flux. This estimation is independent of water depth under the stated assumption that the thermal expansion coefficients are temperature and pressure independent.

Section 4.8.4 discusses an interesting point but the argumentation stops halfway through. How is the Ekman transport different in the transition zone between North Sea and Baltic Sea for NAO- or BANOS-index related patterns? And what are the consequences for the sea-level in the Baltic Sea?

We have clarified the text according to suggestions.

In Section 4.8.4 it is argued that during summer BANOS and NAO related wind forcing (slp gradients) could be similar. I thought the main reason to introduce the BANOS index was the liberty to define an index separately for winter and summer, so that missing correlation for summer sea-level variability in the Baltic Sea could be explained. This section would benefit from a rewrite, I suppose.

We have updated the text for clarification.

The Conclusions (page 18, line 28-29) mention that there is no contribution of NEF in summer. Section 4.8.2 states that summer has not been included in the analysis, because of negative *correlations. Please reformulate the sentence in the conclusions, page 18, line 28-29.*

We have re-written the whole conclusion section.

For the last part of the Conclusions (page 19, line 2-4) the evidence is missing. See also the comments above on Section 4.8.4 and the Abstract.

We have rewritten the whole conclusion section.

The conclusion might benefit from a restructuring. The itemized list could be shortened to contain the keywords only as a summary of a continuous text around it.

We have rewritten the whole conclusion section.

Technical Corrections
page 1, line 7: interannual time scales.
We have changed this accordingly.

page 2, line 24: NAO-index describes weaker
We have changed this accordingly.

page 3, line 19: Andersson (2002) who focused on
We have changed this accordingly.

page 3, line 20: Dangendorf et al. (2014) who investigated the
We have changed this accordingly.

page 3, line 20-21: investigated the North Sea, reported that atmospheric variability that differs from the NAO may still explain part of the sea-level variability.
We have changed this accordingly.

page 3, line 32: different sorts of data sets
We have changed this accordingly.

page 4, line 32: This study focuses on the winter
We have changed this accordingly.

page 5, line 1: this study and the following section
We have changed this accordingly.

page 5, line 5-7: Although the threshold of any computation involving tide gauge records was set at 75% availability of data for the considered period, seasonal means are calculated in case of availability of tide gauge records for two months. [I am not sure whether I understand it the way the authors mean it. Could this information be written a little more clearly?]

We have clarified the text accordingly.

Here we would like to mention that for the analysis period like 21-year running correlations, we prescribed a threshold of 75% data availability. However, we computed seasonal means if two months were available (means 66.6% availability of data set to compute seasonal mean).

page 5, line 23: the northeastern boundary of [If Smögen is meant by the northeastern boundary of the North Sea I recommend to call it Skagerrak.]
Here we write the names of tide gauges. When we mention about the region we write Skagerrak (i.e. Figure 1).

page 6, line 14: and produces a complete gridded data set

We have changed this accordingly.

page 6, line 16: resolution of a T62 Gaussian grid [Or mention the resolution in deg or km]

Reanalysis data set has no regular grid. We have changed it as the following.

Old version : "*This data set has a spatial resolution of 192x94 points with T62 Gaussian grid covering the Earth's surface*"
New version: "*This data set has spatial resolution of a T62 Gaussian grid with non-regular 192x94 points covering the Earth's surface*"

page 7, line 9: examine the correlation of the satellite [see below]

Old version:"*We first examine the coherence of the satellite altimetry observations with the tide gauge records.*"
New version: "*We first examine how the satellite altimetry observations covary with the tide gauge records.*"

page 7, line 11-13: The seasonal means ... linear regression. [This has been said in the methods section. It could be scratched.]
We have removed that part from the text.

page 8, line 30, 32 in the southern Baltic Sea
We have changed this accordingly.

page 9, line 5: Figure 4-lower [see also comment below]
We have changed this accordingly.

page 9, line 28: does seem to be strongly connected to the NAO-index from 1998 in wintertime. OR does not seem to be strongly connected to the NAO-index until 1998 in wintertime.

We have corrected the text. Here, the correct version should be: *"does <u>not</u> seem to be strongly connected to the NAO-index until 1998 in wintertime"*

page 9, line 30: could indicate the existence of
We have changed this accordingly.

page 10, line 30: from what the NAO implies.
We have changed this accordingly.

page 11, line 33: most of the time the gliding
We have changed this accordingly.

page 13, line 31: region on the interannual time scale. OR region on interannual time scales.
We have corrected the text.

*page 14, line 27: (3.44*18.09) OR (3.44 ncdot 18.09) AND (1.39*7.02)*
We have changed this accordingly.

page 15, line 3: radiation reaching the earth surface and longwave (LW) emitted
We have changed this accordingly.

page 15, line 9: [SH and LH do not correspond to the naming in the equation.]
We have changed this accordingly.

page 15, line 18: estimated as 3.28 W m-2 u-1)
We have changed this accordingly.

page 15, line 24: of 25,505,280 (W m-2) per one unit [How much change is that? It might be easier to grasp by using something like 2.5 10 ˆ7 (W m-2)]

We have modified the numerical expression following the suggestion of reviewer:

2.5e7 (J m-2 yr-1)

For the technical question, please see our response to previous question: "In Section 4.8.2 please indicate in the text whether the whole water column was heated or just the mixed layer (down to what depth?) to absorb the energy. "

page 15, line 24: of 25,505,280 (W m-2) per one unit [Should the units be (J/winterm-2) instead of (J/s m-2)?]

We have written it as 2.5e7 (J/m-2 yr-1)

page 16, line 9: (2257 kJ kg-1)
We have changed this accordingly.

page 16, line 16-17: [During summer the western North Sea is not similar in precipitation and freshwater flux.]

Old version: *"In summertime, the correlation patterns between the BANOS-index and precipitation and the between the BANOS-index and freshwater flux display similar results"*

New version: *"In summertime, the correlation patterns between the BANOS-index and precipitation and the between the BANOS-index and freshwater flux display similar results other than the western part of the North Sea"*

page 16, line 29: [It would be more concise to use the regions defined in Figure 1 when describing the correlation pattern.]
We have updated the text based on the suggestion.

page 17, line 2: of sea-level would reach 10 mm per one unit
We have changed this accordingly.

page 17, line 3: [Either remove the last sentence or explain why the high correlation in the north eastern part of the North Sea drainage basin (incl. Norway) does not contribute to North Sea sea level variability.]
We have removed the last sentence.

page 17, line 14: be similar to the case of the NAO.
We have changed this accordingly.

page 17, line 15: assuming that the Ekman layer
We have changed this accordingly.

page 17, line 16: interrupted by bathymetry.
We have changed this accordingly.

page 17, line 21: if bathymetry would not interrupt
We have changed this accordingly.

page 17, line 22: is generated by the BANOS-related north-easterly winds
We have changed this accordingly.

page 18. line 1: [The Norwegian coastline is in the north-eastward direction. That contradicts the previous argumentation.]
Old version: *"...towards the Norwegian, German, Dutch and UK coastlines"*
New version: *"…towards the German, Dutch and UK coastlines"*

page 18, line 4: on interannual time scales. OR on the interannual time scale.
We have changed it as *"on the interannual time scale"*

page 18, line 15: is more important for the
We have changed this accordingly.

page 18, line 32: [The last sentence seems to contradict what has been said in the first sentence (line 30-32). Would you please specify which contributions of the freshwater flux are negligible.
Old version: *"... is negligible in the Baltic Sea and the North Sea"*
New version: *"... is negligible in the Baltic Sea and the North Sea in wintertime"*

page 19, line 4: to that related to the NAO in
We have changed this accordingly.

caption Figure 14: Note the different intervals on the color scales.
We have changed this accordingly.

Readability: The readability of Section 2 could be improved by omitting the sub-subsections.

We have deleted the subheadings in Section 2.

Figure captions: I’d recommend to change the naming of the positions in the plots from down to lower/bottom and from up to upper/top.
We have changed this accordingly.

Coherency or correlation (page 7, line 9ff): Did you really look at correlations on different time scales or is "coherence" used here as a synonym for correlation? The expression coherence or coherency appears more often later on. It would be helpful to specify what is meant by coherency or perhaps just use correlation.

In the manuscript we use the term coherency in the general sense and not in the statistically related sense. We have explained what is the meaning of “coherent” in the Methods section.

Station Smogen (page 5, line 24ff): It appears in some places in the text, it should be Smögen.

Sea level data is provided by PSMSL (www.psmsl.org). In their webpage, the name of station is written as “Smogen”. We used the correct name and indicated that the name in the PSMSL is not totally correct.

Caption Figure 5: for the winter (solid line) and summer (dotted line) seasons.
We have changed this accordingly.

Figure 8-9: These two figures could be combined in the same way Figure 10 was done.
We have changed this accordingly.

Figure 10: Why is the northern half of the figure blank? If possible, the figure should be redone. It avoids unnecessary doubts.

To compute the correlation coefficients, we put the threshold for data availability to 75% for the considered period.
We have replotted figure by removing the data availability threshold for the illustration of the Figure.

Figures 8-10: The reader might appreciate the eye be guided with a mark on the plots, where the BANOS-index is defined.

We have changed it accordingly.

Figure 11: It is hard to see similarities and even more so difference between the two indices. An additional running mean could improve the figures. Red-blue bar plots like they are used for the display of the NAO-index might be an option.

We have renewed the illustration of the Figure.

Caption Figure 18: It is not clear which index or which season is displayed in the upper and lower panel of Figure 18. Also, for the sake of completeness it would be good to indicate the units and a reference vector.

Since these representative vectors are constructed from correlation gradients, they are unitless. We have partly rewritten the caption to clarify the winter and summer seasons.

Sub-sub-section 4.8.2: It would be clearer to use one name only for the net energy flux. Either Qnef or NEF. Also, in the text the "net"- and "nef"-part of names like SWnet should be a subscript. Or maybe drop the "net" altogether in the whole section.

We now use NEF instead of Qnef for the whole section.

Sub-section 4.8: In my opinion it would suffice to indicate the sensitivities with one digit after the floating point.
We have changed this accordingly.