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Mechanisms of variability of decadal sea-level trends in the Baltic Sea over the 20th century

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Abstract. Coastal sea-level trends in the Baltic Sea display decadal-scale variations around a centennial trend. These long-term centennial trends are likely determined by climate change and centennial vertical land movements. In this study, we analyse the spatial and temporal characteristics of the decadal trend variations and investigate the links between coastal sea-level trends and atmospheric forcing on decadal time scale. This investigation mainly focuses on the identification of the possible impact of an underlying factor, apart from the effect of atmospheric circulation, on decadal sea-level trend anomalies.

For this analysis, we use monthly means of long tide gauge records and gridded sea-surface-height (SSH) reconstructions. The SSH time series are constructed over the past 64 years and based on tide-gauge records and satellite altimetry. Climatic data sets are composed of the North Atlantic Oscillation (NAO) index, the Atlantic Multidecadal Oscillation (AMO) index, gridded sea-level-pressure (SLP), gridded near-surface air temperature and gridded precipitation fields.

The analysis indicates that atmospheric forcing is a driving factor of decadal sea-level trends. However, its effect is geographically heterogeneous. The Baltic Sea can be classified into two parts according to atmospheric impacts on decadal sea-level trends: one part consists of the northern and eastern regions of the Baltic Sea, where this impact is large. The other one covers the southern Baltic Sea area, with a smaller impact of the atmospheric circulation

To identify the influence of the large-scale factors other than the simultaneous effect of atmospheric circulation on the Baltic Sea level trends, we filter out the direct signature of atmospheric circulation on the Baltic Sea level by a multivariate linear regression model and analysed the residuals of this regression model. These residuals hint at a common underlying factor that coherently drives the decadal sea-level trends into the similar direction in the whole Baltic Sea region. We found that this underlying effect is partly a consequence of precipitation contribution to the Baltic Sea basin in the previous season.

The investigation on the relation between the AMO-index and sea-level trends implies that this detected underlying factor is not connected to oceanic forcing driven from the North Atlantic region.

Keywords: sea level, the Baltic Sea, decadal trend, statistical analysis.

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1 Introduction

Global mean sea-level trend has risen over the 20th century with an approximate rate of 1.7 mm yr^{-1}, with higher rates of about 3.2 mm yr^{-1} as measured by satellite altimetry over the past 30 years (Church and White 2011; Nerem et al. 2010). This rise is also projected to continue at high rates in the future due to the global warming. However, regional sea-level change has displayed and will likely continue to display clear deviations from the global sea-level average (Slangen et al. 2012; Church et al. 2013). As these authors pointed out, the sea-level trends estimated by satellite altimetry in the North Atlantic at high latitudes south of Greenland are of the order of 10 mm yr^{-1}, whereas immediately further south in the mid-latitude North Atlantic, the sea-level trends may become negative, of the order of -5 mm yr^{-1}. In the Pacific Ocean, similar contrasts can be also observed. In the Tropical Western Pacific, these trends may attain a value of 15 mm yr^{-1}, whereas in the mid-latitude Eastern Pacific the trends are negative, of the order of -5 mm yr^{-1}. These regional differences in observed and projected multidecadal regional sea-level trends are likely caused by spatially heterogeneous atmospheric forcing and ocean internal variability (e.g. Church et al. 2010). Since the regional trends can be sustained for several decades (Hu and Deser 2013), the understanding of the origin of these deviations is important for more accurate predictions of regional sea-level rise (Carson et al. 2016; Cazenave and Llovel 2010; Milne et al. 2009). This study contributes to the understanding of variations in the decadal sea-level trends in the Baltic Sea.

In the case of semi-enclosed seas like the Baltic Sea, the deviations of the sea-level trends from the global mean could potentially be large since they are exposed to additional forcings such as regional wind forcing and its interaction with the coastlines, the balance between precipitation and evaporation, and spill-over effects from the open ocean. Also, the regional oceanographic characteristics such as stratification due to regional temperature and salinity profiles may modulate the heat-uptake differently as in the open ocean.

Previous studies have shown that the sea-level records display relatively large variations of decadal trends in the Baltic Sea (Richter et al. 2011). For instance, the Warnemünde (southern Baltic) sea-level record displays an average long-term sea-level trend over the last 150 years of about 1.5 mm yr^{-1} (to a large extent caused by the Glacial Isostatic Adjustment that occurs at millennial timescales, as briefly explained later). However, the trends of the Warnemünde sea-level record calculated over 30-year windows may vary between -0.5 mm yr^{-1} to 2.5 mm yr^{-1}. Although the recent 30-year trends are high, the maximum 30-year trend so far was reached around year 1900. This indicates that natural variations can cause substantial deviations that should be understood and taken into account, especially for shorter term (multidecadal) future sea-level projections.

In this study, we analyse long-term sea-level and climate records with the aim of explaining the observed variability of the decadal and multidecadal sea-level trends in the Baltic Sea. We further investigate whether or not the same mechanisms that have been invoked to explain the interannual variations of Baltic sea-level are also responsible for the variability of the decadal sea-level trends.

For this purpose, and in contrast to most previous studies that focused on the interannual variations of sea-level, we statistically analyse sea-level and climate decadal trends. The analysis is carried out for each season separately. In this analysis, we characterize the spatial coherency of the variations of decadal trends across the Baltic Sea and try to identify the connection between the variations of decadal sea-level trends and the variations of climate trends.

A series of studies have shown that an important part of the interannual to decadal variations of sea-level in the semi enclosed Baltic Sea result from atmospheric forcing, mostly from the wind (e.g. Heyen et al. 1996, Andersson 2002, Kauker and Meier 2003, Chen and Omstedt 2005, Hünicke and Zorita 2006). Since the Baltic Sea is located in a region of predominantly westerly winds and its narrow physical connection to the North Sea and North Atlantic is also zonally oriented, the intensity of the westerly winds exerts a strong influence on the Baltic Sea level. The intensity of westerly winds in this region is well described in wintertime by the index of the North Atlantic Oscillation (NAO). Thus, many of the studies mentioned above have explored the statistical link between the NAO and the Baltic Sea level.

Although the NAO is an important factor modulating long-term (interannual to decadal) sea-level in the semi-enclosed Baltic Sea, its influence is not so strong in seasons other than winter. Additionally, the link between the NAO and the Baltic Sea level is spatially very heterogeneous even in wintertime, and has also displayed substantial decadal variations in the last two centuries (e.g. Andersson 2002, Jevrejeva et al. 2005, Hünicke et al. 2015).

By using air pressure, air temperature and precipitation observational time series for the winter and summer seasons, Hünicke and Zorita (2006) concluded that precipitation and air temperature together with the sea-level-pressure (SLP) -including NAO SLP pattern- significantly modulate the sea-level variability on decadal time scales. They also showed that the influence of precipitation and temperature has a stronger effect on sea-level variations in summer than in winter. They suggested that sea-level variations are influenced by different factors in winter and summer seasons. Hünicke et al. (2008) identified that sea-level variations at central and eastern Baltic Sea are well described by the SLP alone, but, that area-averaged precipitation may modulate the decadal sea-level variations in the southern Baltic.

Beyond the atmospheric forcing on the Baltic Sea level, we also explore other possible mechanism that may be responsible for the decadal variability of Baltic Sea sea-level trends. Since the signal of the atmospheric forcing on Baltic sea-level can be very strong for some locations, we also apply a somewhat novel strategy to better identify the possible influence of the slowly-varying North Atlantic and North Sea sea-level. For this purpose, we set up a statistical model that should capture the simultaneous link between atmospheric circulation and sea-level and then focus on the residuals of this statistical model, i.e. the part of variability of the sea-level that cannot be statistically explained by the simultaneous atmospheric circulation.

These atmospheric predictors in this statistical model are based on a Principal Component Analysis (PCA) of the SLP time series, retaining only the leading components that explain most of its variability. The residuals of this multivariate regression analysis provide decadal sea-level trends that are not directly linked to the atmospheric forcing. We analyse these residuals and their connections to other atmospheric factors like precipitation in previous seasons and other oceanic factors like sea-level in the North Atlantic Ocean in terms of the existence of the Atlantic Multidecadal Oscillation (AMO) in those residuals.

Besides, as another crucial factor inducing sea-level change in the Baltic Sea, the Glacial Isostatic Adjustment (GIA) – which is a consequence of the Scandinavian ice-sheet melting – leads to negative sea-level trends along the northern Baltic coast. The largest land uplift rates occur over the northern part of the Baltic Sea, and reach approximately 10 mm yr^{-1}. At the south coast of Baltic Sea the trend of vertical land movement is around of -1 mm yr^{-1} (Ekman 1996, Peltier 2004, Lidberg et al. 2010, Richter et al. 2011). Because of focusing on climate-induced sea-level trend variability in the Baltic Sea region, we had to remove GIA effect from sea-level time series. The gliding trends of all sea-level and climatic observational records; tide gauge and sea surface height anomalies (SSHA) for sea-level, and the AMO-index, the NAO-index, the SLP fields, near-surface air temperature, precipitation are computed over running 11-year windows. We had two crucial advantages by carrying out the analysis on decadal gliding trends. The one advantage is that the trends deduced from absolute (SSHA) and relative (tide gauge) can be compared without any further process. The latter advantage is that the GIA does not cause affect the calculation of the 11-year gliding trends since the GIA-induced trend of the Baltic Sea level does not presumably vary on time scales of one century,

In this study, new relative sea-level tide gauge data sets provided by the Technical University of Dresden which covers part of the Travemünde, Wismar, Warnemünde, Sassnitz, Swinoujscie, Kolobrzeg records and completely for the Marienleuchte, Barth and Greifswald records are used.

Our research objectives can be summarised in the following questions: (1) How do the long-term trend relationships between sea-level and climatic factors vary seasonally and spatially? (2) Apart from the effect of atmospheric circulation, is there any other underlying factor in decadal sea-level trends of the Baltic Sea? (3) Is there any signature of Atlantic Multidecadal Oscillation (AMO) on decadal sea-level trends in the Baltic Sea?

This study is organised as follows: The datasets and methodology are described in section 2 and 3, respectively. In section 4, we provide main outcomes of this study and compared the results. Section 5 presents several conclusions.

2 Data

We used the seasonal means of the following sea-level and climatic data sets.

2.1 Sea level data

2.1.1 Tide gauge

We obtained relative sea-level data from 29 tide gauges considering the availability and geographical distribution of stations along the Baltic Sea coast. The tide gauge data were provided from different sources (Bogdanov et al. 2000, Ekman 2003, (Holgate et al. 2013, Permanent Service for Mean Sea Level (PSMSL) 2016, Technical University of Dresden (TUD)). The tide gauges with data sources are illustrated in Figure 1.

Figure 1: Tide gauges with their sources: 1-Aarhus, Barth, Frederikshavn, Furuogrund, 5-Greifswald, Hamina, Helsinki, Hirtshals, Kemi, 10-Klaipeda, Kolobrzeg, Kronstadt, Kungsholmsfort, Landsort, 15-Marienleuchte, Oslo, Pietarsaari, Ratan, Rauma, 20-Sassnitz, Slipshavn, Smogen, Stockholm, Swinoujscie, 25-Travemünde, Tregde, Visby, Warnemünde, Wismar (stations are ordered alphabetically). (Red: PSMSL; Purple: Bogdanov et al.; Yellow: TUD; Green: PSMSL and TUD; Blue: Ekman and PSMSL).

The tide gauge time series contain data gaps. We computed the 11-year gliding trends only when 80% of time series (9 time steps) were available. The time coverage of the used tide gauge records is displayed in Figure 2.

Figure 2: Time coverage of the tide gauge observations. Numbers on the y-axis refer to the station number defined in Figure 1.

2.1.2 Sea surface height anomaly

Together with the tide gauge observations, we used SSHA time series which are reconstructions of sea-level based on statistical processing of tide gauges and satellite altimetry observations to achieve a longer temporal coverage than provided by the satellite data. This reconstruction spans the period covering the period from 1950 to 2008. To reconstruct sea-level fields, satellite altimetry derived cyclostationary empirical orthogonal functions are combined with tide gauge observations. The Cyclostationary Empirical Orthogonal Function (CSEOF) reconstructed sea-level data was obtained from Jet Propulsion Laboratory (JPL) Physical Oceanography Distributed Active Archive Center (PO.DAAC) and developed by the University of Colorado (Hamlington et al. 2011).

2.2 Climatic data sets

2.2.1 North Atlantic Oscillation (NAO) index

The NAO-index is derived from difference between the normalized sea-level-pressure (SLP) in Gibraltar and Reykjavik. The index covers the period from 1821 to 2012 (Jones et al. 1997).

2.2.2 Atlantic Multidecadal Oscillation (AMO) Index

The AMO-index is computed based on the area weighted average of sea-surface-temperature over the North Atlantic between 0° to 70° N (Enfield et al. 2001). The AMO-index used here was provided by National Oceanic and Atmospheric Administration/Physical Sciences Division (NOAA/PSD), covering the period 1856-2015.

2.2.3 Sea Level Pressure (SLP)

The SLP data are 5°x5° gridded Northern Hemisphere monthly means from 1899 to present and are provided by the National Centre for Atmospheric Research (NCAR; Trenberth and Paolino 1980). We used the domain between 70°W -40°E and 30°N - 90°N in this study.

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2.2.4 Near-surface Air Temperature

We used the combined HadCRUT4 land and marine surface temperature anomalies from CRUTEM4 and HadSST3 with 5°x5° gridded monthly means, starting in 1850 and continues until present and covering the area of 60°W – 40°E and 32°N – 70°N (Morice et al. 2012).

2.2.5 Precipitation

We used two different precipitation data sets. One was the gridded 0.5°X0.5° monthly means from 1901 to 2012 in the geographical window 20°W-40°E and 48°N-70°N, obtained from the Climatic Research Unit (CRU; Harris et al. 2014; Trenberth et al. 2014)

The second precipitation data set was monthly means from the meteorological reanalysis of the National Center for Environmental Protection/National Center for Atmospheric Research (NCEP/NCAR; Kalnay et al. 1996; Kistler et al. 2001). The reanalysis data set has a spatial resolution of 192x94 points with T62 Gaussian grid covering the area (88.542° N – 88.542° S) latitudes and (0° E – 358.125° E) longitudes over the Earth's surface. Here, we considered the period from 1948 to 2012 for the area covering the drainage basin of Baltic Sea.

3 Methodology

The tide gauge records contain the secular signal due to global climatic change and the postglacial land uplift, which cause a long-term trend in the sea-level observations. As it is mentioned in the introduction, our focus is the analysis of the variability of decadal sea-level trends.

After selecting the sea-level and climatic data sets with their time ranges, each season is treated separately. We computed the 11-year gliding trends for every season (Winter-DJF, Spring-MAM, Summer-JJA and Autumn-SON), requiring at least 80% availability of data for each single gliding trend computation. The gliding trend for each 11-year window is estimated through linear regression on time, as described by Equation (1).

$$y_i = \beta t_i + \beta_0, \quad (1)$$

The term y_i denotes the observed value of sea-level, t_i is the ith year within the 11-year window, β is the trend of sea-level with respect to time and β_0 is the y-axis intercept. We used least square estimation approach for the linear regression analyses.

In the following step, we first applied PCA to the SLP gliding trend time series to capture the leading five principal vectors of the SLP fields representing most of the variance of the SLP gliding trends. Afterwards, we conducted a multivariate linear regression analysis with the leading five principal components of the SLP trends as predictors and the tide gauge gliding trends as predictands.

A multiple linear regression model is defined in Equation (2).

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$$Y(t) = ß_0 + \sum_{i=1}^{5} ß_i \, PCSLP_i(t) + e_j(t), \quad (2)$$

Herein, $PCSLP_i(t)$ are the time series of the i^{th} SLP principal component and $ß_i$ are the regression coefficients of the leading principal component vectors. Y is the time series of gliding trend anomaly for each tide gauge. The error term, $e_j(t)$, is the vector of sea-level trend residuals which cannot be linearly described by the first five principal component vectors of the SLP trends. We used those residuals assuming that they contain the variability of sea-level trends not caused by the simultaneous atmospheric (SLP) forcing.

4 Results

The NAO is widely known as a major atmospheric factor modulating the sea-level in the Baltic Sea region on interannual time scales. To confirm that this link is also valid for the decadal trends, we show in Figure 3 the correlation pattern between the decadal trend of the NAO-index and the decadal trends of 29 tide gauges in the Baltic Sea in wintertime.

Figure 3: Correlations of gliding trends between the NAO-index and 29 tide gauges for wintertime (1900-2012).

The correlation pattern in Figure 3 shows that the link between the trends of the NAO and trends of tide gauges is very heterogeneous in space. Particularly, this correlation pattern indicates a strong variation from north to south of the Baltic Sea basin. This result is consistent with the findings of former studies on the interannual correlation between the NAO and tide gauges (e.g. Hünicke and Zorita 2006). The stations along the southern part of the Baltic Sea have weak linkage to the NAO, but, the effect of the NAO becomes stronger towards the north of the Baltic Sea.

We now investigate whether this spatially heterogeneous link between the NAO and the tide gauges in wintertime is also reflected in small correlations between the sea-level trends derived in the different areas of the Baltic Sea. The rationale behind this investigation is that if the NAO is major factor modulating the sea-level trends, these trends should also be only weakly related. For this purpose, we select one tide gauge from the central Baltic (Stockholm), and the other one (Warnemünde) as representative station of the south coast of the Baltic Sea and of the Baltic proper for further analysis. Then, we calculate the correlations between each of these two tide gauges and the trends derived from reconstructions (SSHA) including the satellite altimetry observations over the whole Baltic Sea. The correlation patterns are illustrated in Figure 4.

Figure 4: Correlations of decadal gliding trends between selected (Stockholm and Warnemünde) tide gauges and SSHA grids for all seasons.

Although the NAO has non-uniform linkages to the Baltic Sea region, the correlations between SSHA and each of the two representative stations seem to be very similar. This indicates that even though the tide gauges along the southern coast of the Baltic Sea have weak connections to the NAO, sea-level trends in the Stockholm and Warnemünde tide gauges are strongly correlated to each other and with decadal sea-level trends of SSHA reconstructions in the Baltic Sea. One

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explanation that we pursue further in this analysis is that another factor, independent of direct atmospheric forcing encapsulated by the NAO, is more strongly responsible for the spatial homogeneity of the sea-level decadal trends.

To identify this factor, we statistically filter the influence of the atmospheric forcing on the decadal sea-level trends. This is accomplished by the regression model with the leading five principal components of the SLP trends that explain 89%, 81%, 78% and 79% variance of the SLP trends for winter, spring, summer and autumn, respectively, as indicated in Equation (2). The residuals of the multivariate regression analysis for the tide gauges were used as new decadal trends which are presumably free of the direct atmospheric forcing.

We then compute the correlations between residuals of the two tide gauges (Stockholm and Warnemünde) and residuals of the rest of the nine tide gauges (Ratan, Stockholm, Helsinki, Smogen, Kungsholmsfort, Sassnitz, Travemünde, Wismar, Warnemünde) in the Baltic Sea. Figure 5 represents the correlation patterns between the two selected tide gauges and the other tide gauges, for both the decadal trends and the residuals resulting from filtering the effect of the SLP trends.

Figure 5: Correlation values between sea-level in two representative tide gauges (Stockholm and Warnemünde) and the rest of the tide gauges; left, using the decadal trends, right after removing the effect of SLP trends in all tide gauge records.

Figure 5 illustrates that the correlations between stations tend to become stronger after removing the atmospheric effect from the decadal sea-level trends. For example, before removing the atmospheric effect, the correlation between Warnemünde and Stockholm decadal trends was 0.72. However, it increased to 0.89 after removing the atmospheric signal from both stations.

To confirm that the atmospheric signal in decadal sea-level trend anomalies is significantly removed and to show, at the same time, that the similarity of the trend anomalies increases after this removal, we examined the relationships of two representative tide gauges with both the SLP field and the near-surface air temperature in wintertime. The results of this analysis are represented in the Figures 6 and 7, respectively.

Figure 6: The correlation patterns between SLP fields and selected tide gauges. Maps at the top row are the correlation patterns from Stockholm and Warnemünde with atmospheric signal.

In Figure 6, the two maps in the top row show the correlation patterns between decadal trends of the tide gauges and of the SLP field. We see that the stations Stockholm and Warnemünde are heterogeneously connected to the SLP field. However, the patterns regarding the correlations of decadal trend anomalies between SLP fields and residuals of sea-level trend anomalies (the two maps in the bottom row) indicate very similar variations of the Stockholm and Warnemünde tide gauges. In the next step, we replaced the SLP fields by the near-surface air temperature anomalies in order to display the correlation patterns between the two tide gauges and the air temperature. The results are illustrated in Figure 7.

Figure 7: The correlation patterns between air temperature and selected tide gauges for winter. The two maps at the top row are the patterns of 11-year gliding trends from Stockholm and Warnemünde involved in atmospheric signal.

The Figures 6 and 7 confirm that the atmospheric signal is removed from the decadal tide gauge trend anomalies. Moreover, it is shown that the correlation patterns of Stockholm and Warnemünde residuals are very similar in terms of their correlations to near-surface air temperature and to the SLP time series.

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In summary, the results suggest that SLP, and therefore mean seasonal wind, forcing has a spatially heterogeneous effect on different locations and this occurs for all four seasons. After removing the effect of the SLP from the tide gauge 11-year gliding trend time series, most of these correlations become more clear and stronger. This suggests that there is an underlying factor modulating sea-level trends uniformly through the whole Baltic Sea basin.

To explore the nature of this underlying effect causing a more uniform variability in the sea-level trend residuals, we investigated two possible physical mechanisms. One is the role of precipitation in the Baltic Sea catchment area. The other factor is the role of the low-frequency variability in the North Atlantic, as described by the Atlantic Multidecadal Oscillation (AMO)(Enfield et al. 2001)

The results concerning precipitation are represented in Figure 8. Since precipitation over the catchment area of the Baltic Sea would affect sea-level only after some lag, we investigated, for each season separately, the correlations between the previous season CRU precipitation data set and tide gauge residuals.

The results are represented in Figure 8.

Figure 8: The correlation patterns between decadal sea-level trends and the area averaged CRU precipitation trends in the previous season over the Baltic Sea catchment area for the period 1901-2012.

Since precipitation is strongly controlled by the atmospheric circulation, we also investigated the link between the sea-level trends and SLP trends in the previous season. The patterns are shown in Figure 9.

Figure 9: The correlation patterns of gliding trends on previous season factor (SLP) and following seasons tide gauge residuals.

The figures display that, in addition to the atmospheric forcing, there is a lagged contribution of precipitation to the decadal sea-level trends in the Baltic Sea. This contribution seems to be strong on the decadal sea-level trend variability, except for the spring season.

To further quantify the effect of the precipitation on the following season, we also used reanalysis precipitation data in addition to the CRU precipitation data. In contrast to the CRU precipitation data set covering only land, the reanalysis data covers both ocean and land, but with coarser spatial resolution. Besides, the temporal coverage of reanalysis precipitation data is shorter, starting from 1948. Considering the drainage basin of the Baltic Sea, the spatial means of two data sets are computed in order to examine the covariability between precipitation and sea-level residuals. Table 1 shows the results of correlation analysis between precipitation (both from CRU and NCEP/NCAR) and residuals of sea-level in terms of the decadal gliding trend variations.

Table 1: The correlations between decadal trends of between precipitation field means from CRU and NCEP/NCAR in the previous season and residuals of sea-level at the Stockholm and Warnemünde stations. Significance levels are r>0.26 and r>0.19 at the 95% confidence interval (two-sided) for the associated time series lengths, (1952-2007) and (1904-2007). The significant correlation coefficients are marked with (*) symbols.

Table 1 indicates that precipitation has a considerable lagged effect on decadal trends of sea-level variations, once the direct SLP forcing has been subtracted from the sea-level records. For instance, taking the results of both precipitation data sets

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into account, summer season precipitation implies relatively strong linkage to the residuals of sea-level decadal trend variations, reaching to r=0.56 in autumn.

Concerning the results only from precipitation of the reanalysis data set, it is shown that there are significant connections between winter precipitation and summer sea-level residuals, between summer precipitation and autumn sea-level residuals and between autumn precipitation and winter sea-level residuals for the selected two stations. However, the results of reanalysis precipitation time series do not imply a significant connection between spring precipitation and sea-level residuals in any season. The results derived using the CRU precipitation indicate that, on the one hand, winter precipitation affects decadal trends of sea-level in the spring, that summer precipitation contributes to sea-level decadal trends in autumn for both stations. Besides, autumn season precipitation seems to explain a part of variation of Warnemünde sea-level residuals in winter. On the other hand, precipitation decadal trends of spring season do not have a significant connection to the decadal trends of sea-level residuals.

To examine other possible large-scale factors on sea-level trends, we investigated the potential influence of the North Atlantic sea-surface temperature anomalies in the form of the AMO-index. The 11-year gliding trend anomalies of sea-level residuals and the trends of the AMO-index are represented in Figure 10.

Figure 10: The gliding trend time series of the AMO-index and tide gauge residuals (x-axis: years, y-axis: trend values).

This particular analysis suggests very weak relations between the AMO-index and residuals of sea-level trend anomalies. The strongest correlation in all seasons was 0.2. These results indicated that there is no significant contribution of the AMO related factor to decadal sea-level trend residuals in the Baltic Sea region.

5 Conclusions

We statistically investigated the variability of the decadal trends in the Baltic Sea over the period 1900-2012 and explored various physical factors that may explain this variability. The decadal trends of the Baltic Sea level are influenced by the SLP and therefore by the wind forcing, as in the case of interannual variations. However, this influence is spatially heterogeneous, with a stronger effect in the northern and a weaker one in the southern Baltic Sea. This contrasts with a rather homogeneous variation of the decadal sea-level trends in the Baltic Sea, which implies that SLP alone cannot be the sole factor that drives the variations of the decadal sea-level trends.

To identify this underlying factor, we explored the role of precipitation and of the Atlantic Multidecadal Oscillation (AMO). Precipitation in the previous season over the Baltic Sea catchment area seems to be a robust candidate to explain the variations of the decadal sea-level trends in the summer and autumn seasons, as well as partly in wintertime, but its role is much weaker in the spring season. The lagged effect of precipitation is rather homogeneous for all Baltic Sea tide gauges.

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Considering the weak correlations between the Atlantic Multidecadal Oscillation (AMO) index and sea-level decadal trends for all seasons, we found that there is no contribution of the oceanic forcing to sea-level trend residuals in the Baltic Sea in any of the four seasons.

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References

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

Bogdanov, V. I. et al. 2000. *Mean Monthly Series of Sea Level Observations (1777-1993) at the Kronstadt Gauge*.

Carson, M. et al. 2016. "Coastal Sea Level Changes, Observed and Projected during the 20th and 21st Century." *Climatic Change* 134(1–2):269–81.

Cazenave, A. and W. Llovel. 2010. "Contemporary Sea Level Rise." *Annual Review of Marine Science* 2:145–73.

Chen, D. and A. Omstedt. 2005. "Climate-Induced Variability of Sea Level in Stockholm: Influence of Air Temperature and Atmospheric Circulation." *Advances in Atmospheric Sciences* 22:655–64.

Church, J. A. et al. 2013. "Sea Level Change." *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* 1137–1216.

Church, J. A. and N. J. White. 2011. "Sea-Level Rise from the Late 19th to the Early 21st Century." *Surveys in Geophysics* 32(4–5):585–602.

Church, J. A., P. L. Woodworth, T. Aarup, and W. S. Wilson. 2010. *Understanding Sea-Level Rise and Variability*. Wiley-Blackwell.

Ekman, M. 1996. "A Consistent Map of the Postglacial Uplift of Fennoscandia." *Terra Nova* 8:158–65.

Ekman, M. 2003. "The World's Longest Sea Level Series and a Winter Oscillation Index for Northern Europe 1774-2000." *Small Publications in Historical Geophysics* 32.

Enfield, D. B., A. M. Mestas-nuñez, and P. J. Trimble. 2001. "The Atlantic Multidecadal Oscillation and Its Relationship to Rainfall and River Flows in the Continental U . S . A Research Article Resubmitted to Geophysical Research Letters." *Atlantic* 28(10):2077–80.

Hamlington, B. D., R. R. Leben, R. S. Nerem, W. Han, and K. Y. Kim. 2011. "Reconstructing Sea Level Using Cyclostationary Empirical Orthogonal Functions." *Journal of Geophysical Research: Oceans* 116(12):1–17.

Harris, I., P. D. Jones, T. J. Osborn, and D. H. Lister. 2014. "Updated High-Resolution Grids of Monthly Climatic Observations - the CRU TS3.10 Dataset." *International Journal of Climatology* 34(3):623–42.

Heyen, H., E. Zorita, and H. von Storch. 1996. "Statistical Downscaling of Monthly Mean North Atlantic Air-Pressure to Sea Level Anomalies in the Baltic Sea." *Tellus A* 48:312–23.

Holgate, S. J. et al. 2013. "New Data Systems and Products at the Permanent Service for Mean Sea Level." *Journal of Coastal Research* 29(3):493–504.

Hu, A. and C. Deser. 2013. "Uncertainty in Future Regional Sea Level Rise due to Internal Climate Variability." *Geophysical Research Letters* 40(11):2768–72.

Hünicke, B. et al. 2015. "Recent Change - Sea Level and Wind Waves." Pp. 155–85 in *Second Assessment of Climate Change for the Baltic Sea Basin*, edited by T. B. I. A. Team. Springer.

Hünicke, B., J. Luterbacher, A. Pauling, and E. Zorita. 2008. "Regional Differences in Winter Sea Level Variations in the Baltic Sea for the Past 200 Yr." *Tellus, Series A: Dynamic Meteorology and Oceanography* 60 A(2):384–93.

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

Jevrejeva, S., J. C. Moore, P. L. Woodworth, and A. Grinsted. 2005. "Influence of Large • scale Atmospheric Circulation on European Sea Level: Results Based on the Wavelet Transform Method." *Tellus* 57A:183–93.

Jones, P. D., T. Jonsson, and D. Wheeler. 1997. "Extension to the North Atlantic Oscillation Using Early Instrumental Pressure Observations from Gibraltar and South-West Iceland." *International Journal of Climatology* 17(13):1433–50.

Kalnay, E. et al. 1996. "The NCEP/NCAR 40-Year Reanalysis Project." *Bulletin of the American Meteorological Society* 77(3):437–71.

Kauker, F. and H. E. M. Meier. 2003. "Modeling Decadal Variability of the Baltic Sea: 1. Reconstructing Atmospheric Surface Data for the Period 1902–1998." *Journal of Geophysical Research* 108(C8):3267.

Kistler, R. et al. 2001. "The NCEP-NCAR 50 Year Reanalysis." *Bulletin of the American Meteorological Society* 82:247–67.

Lidberg, M., J. M. Johansson, H. G. Scherneck, and G. A. Milne. 2010. "Recent Results Based on Continuous GPS Observations of the GIA Process in Fennoscandia from BIFROST." *Journal of Geodynamics* 50(1):8–18.

Milne, G. A., W. R. Gehrels, C. W. Hughes, and M. E. Tamisiea. 2009. "Identifying the Causes of Sea-Level Change." *Nature Geoscience* 2(7):471–78.

Morice, C. P., J. J. Kennedy, N. A. Rayner, and P. D. Jones. 2012. "Quantifying Uncertainties in Global and Regional Temperature Change Using an Ensemble of Observational Estimates: The HadCRUT4 Data Set." *Journal of Geophysical Research* 117.

Nerem, R. S., D. P. Chambers, C. Choe, and G. T. Mitchum. 2010. "Estimating Mean Sea Level Change from the TOPEX and Jason Altimeter Missions." *Marine Geodesy* 33(sup1):435–46.

Peltier, W. R. 2004. "Global Glacial Isostasy and the Surface of the Ice-Age Earth: The ICE-5G (VM2) Model and GRACE." *Annual Review of Earth and Planetary Sciences* 32(1):111–49.

Richter, A., A. Groh, and R. Dietrich. 2011. "Geodetic Observation of Sea-Level Change and Crustal Deformation in the Baltic Sea Region." *Physics and Chemistry of the Earth* 53:43–53.

Slangen, A. B. A., C. A. Katsman, R. S. W. van de Wal, L. L. A. Vermeersen, and R. E. M. Riva. 2012. "Towards Regional Projections of Twenty-First Century Sea-Level Change Based on IPCC SRES Scenarios." *Climate Dynamics* 38(5–6):1191–1209.

Trenberth, K. E. et al. 2014. "Global Warming and Changes in Drought." *Nature Clim. Change* 4(1):17–22.

Trenberth, K. E. and D. A. Paolino. 1980. "The Northern Hemisphere Sea-Level Pressure Data Set: Trends, Errors and Discontinuities." *Monthly Weather Review* 108:855–72.

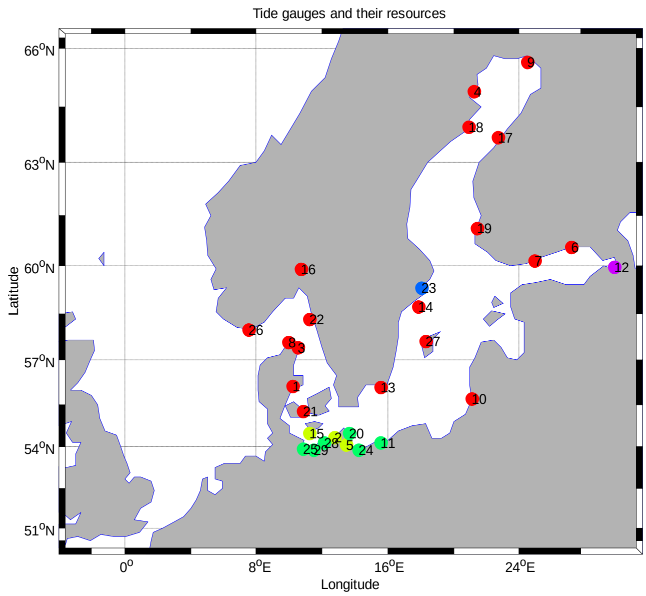

Figure 1: Tide gauges with their sources: 1-Aarhus, Barth, Frederikshavn, Furuogrund, 5-Greifswald, Hamina, Helsinki, Hirtshals, Kemi, 10-Klaipeda, Kolobrzeg, Kronstadt, Kungsholmsfort, Landsort, 15-Marienleuchte, Oslo, Pietarsaari, Ratan, Rauma, 20-Sassnitz, Slipshavn, Smogen, Stockholm, Swinoujscie, 25-Travemünde, Tregde, Visby, Warnemünde, Wismar (stations are ordered alphabetically). (Red: PSMSL; Purple: Bogdanov et al.; Yellow: TUD; Green: PSMSL and TUD; Blue: Ekman and PSMSL)

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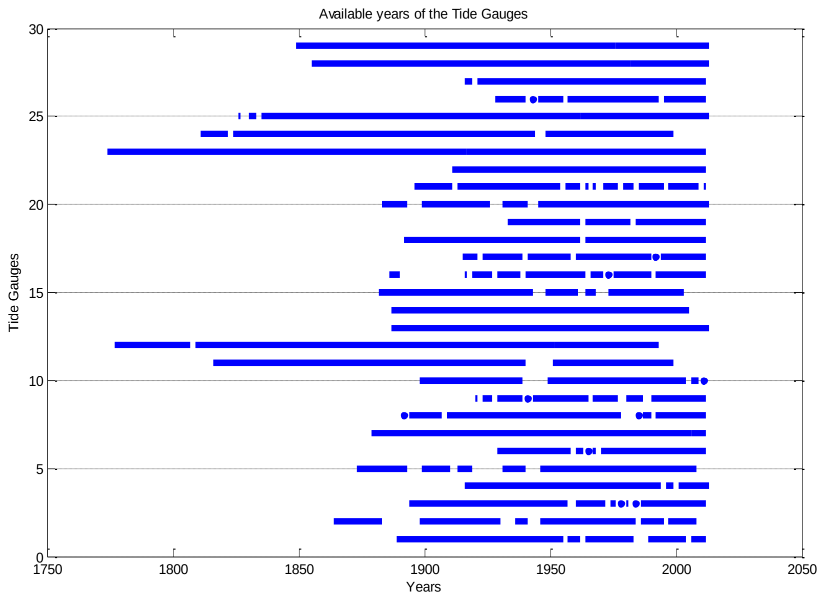

Figure 2: Time coverage of the tide gauge observations. Numbers on the y-axis refer to the station number defined in Figure 1.

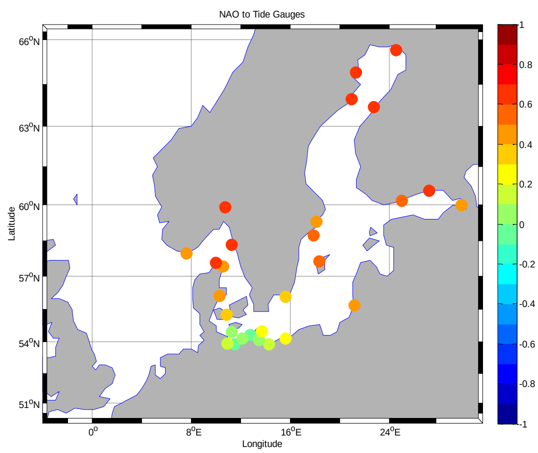

Figure 3: Correlations of gliding trends between the NAO-index and 29 tide gauges for wintertime (1900-2012).

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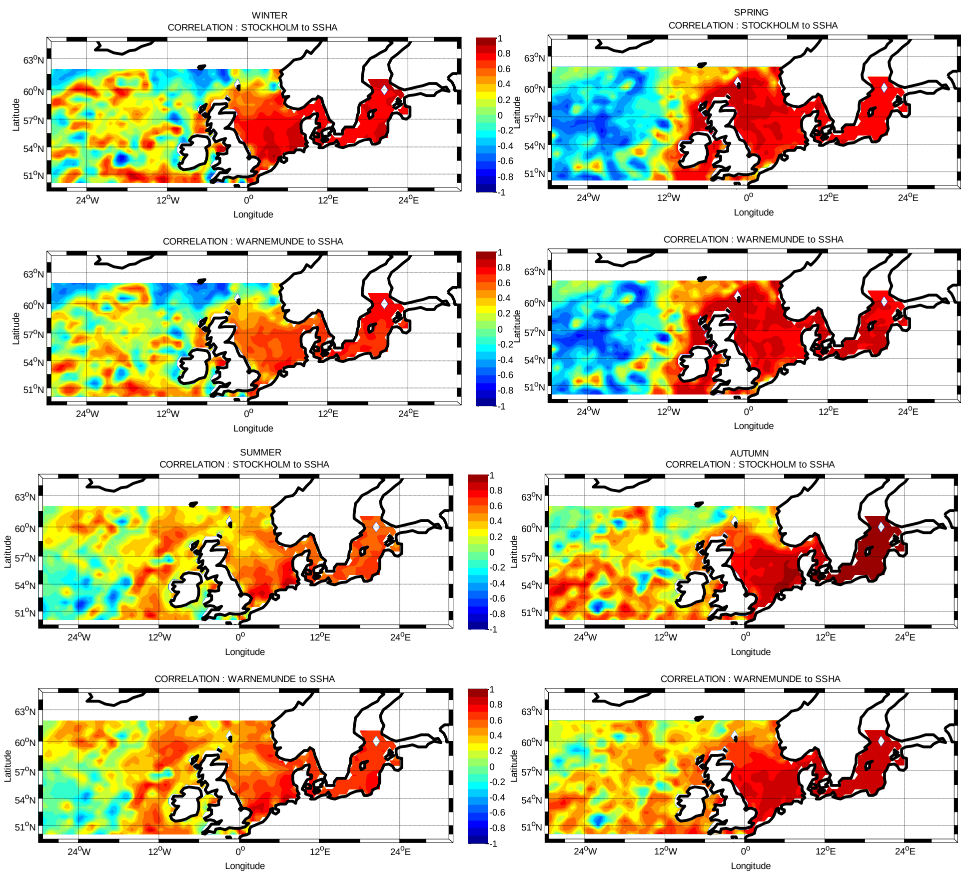

Figure 4: Correlations of decadal gliding trends between selected (Stockholm and Warnemünde) tide gauges and SSHA grids for all seasons.

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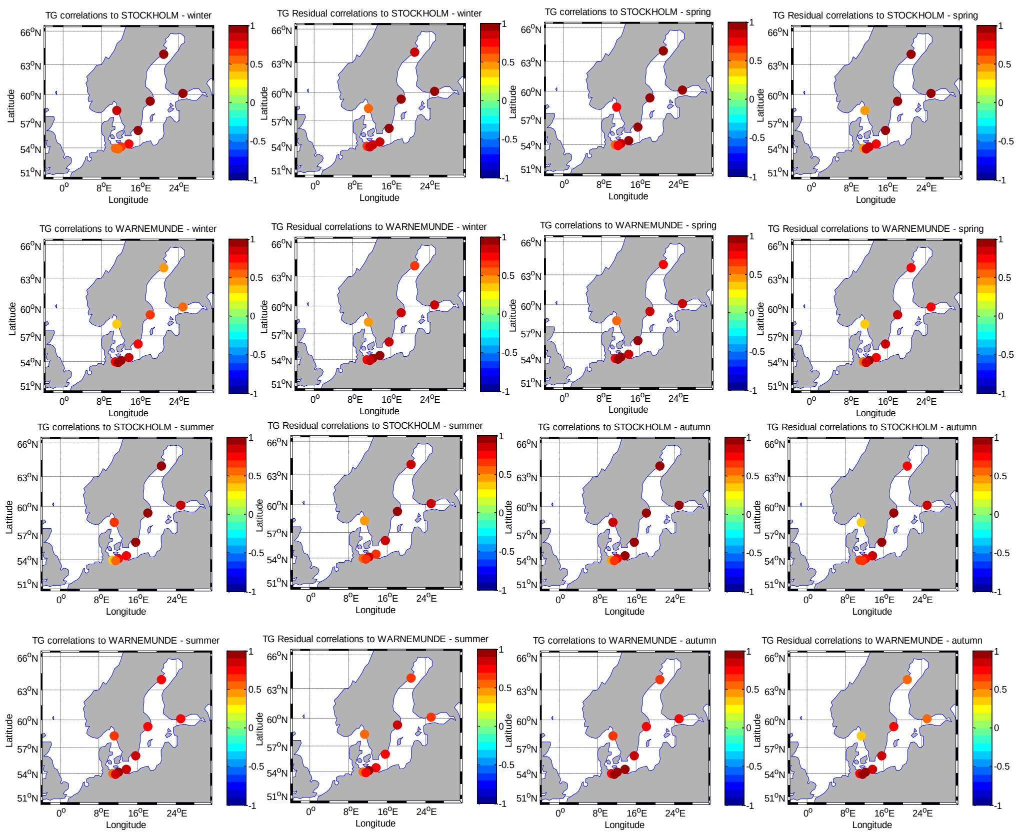

Figure 5: Correlation values between sea-level in two representative tide gauges (Stockholm and Warnemünde) and the rest of the tide gauges; left, using the decadal trends, right after removing the effect of SLP trends in all tide gauge records.

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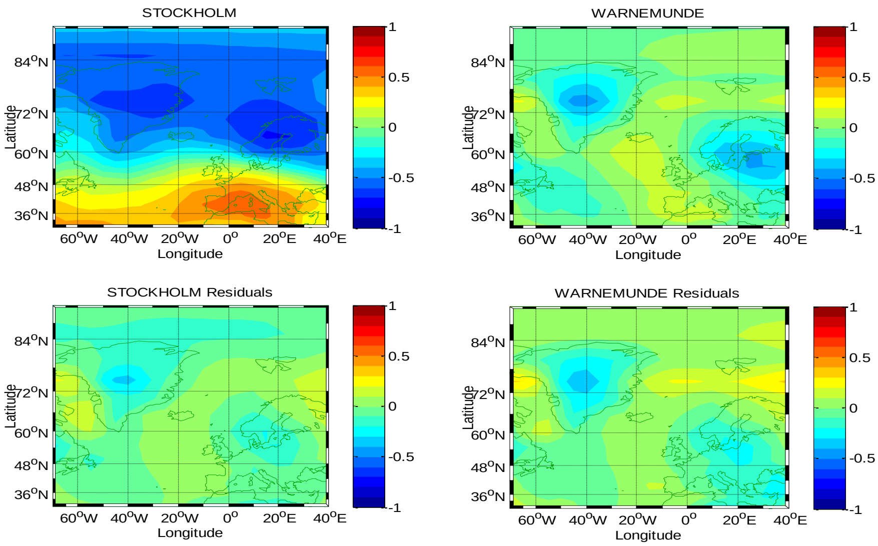

Figure 6: The correlation patterns between SLP fields and selected tide gauges. Maps at the top row are the correlation patterns from Stockholm and Warnemünde with atmospheric signal.

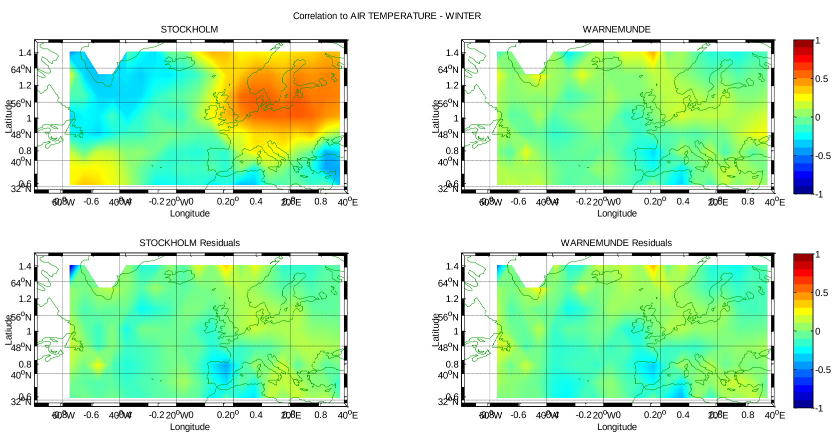

Figure 7: The correlation patterns between air temperature and selected tide gauges for winter. The two maps at the top row are the patterns of 11-year gliding trends from Stockholm and Warnemünde involved in atmospheric signal.

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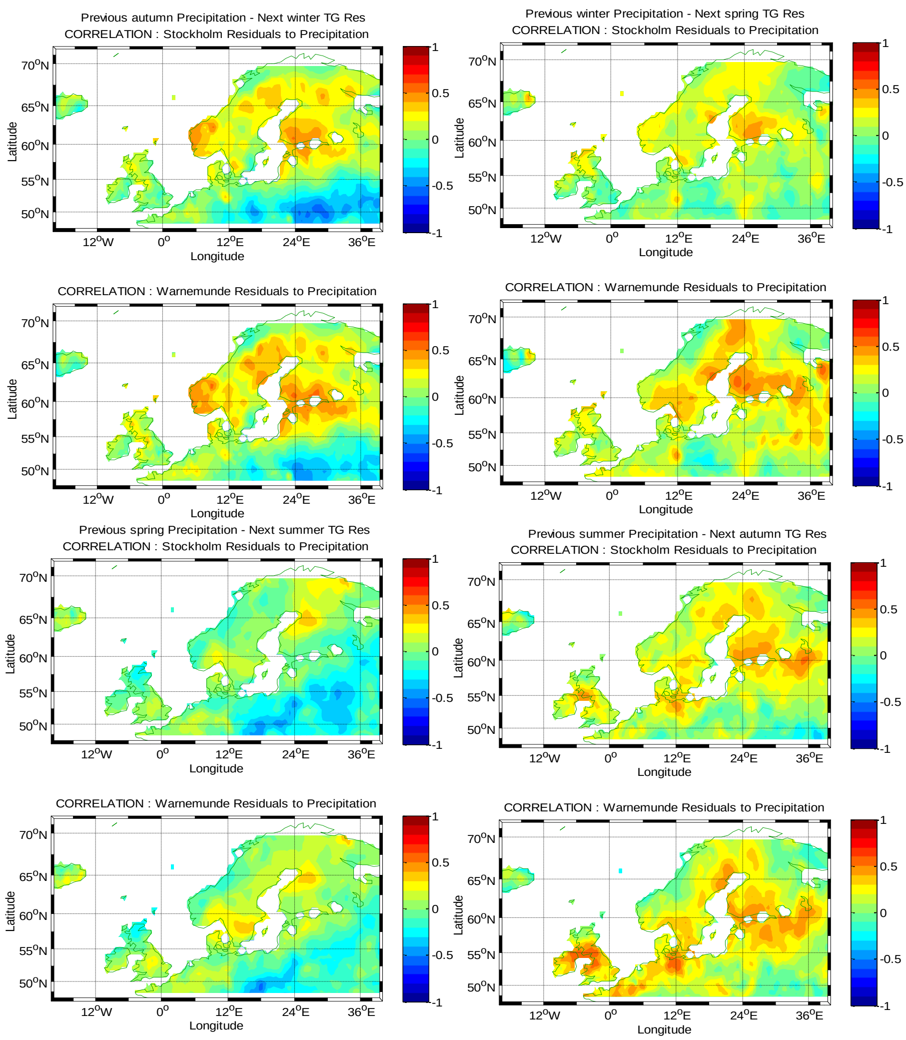

Figure 8: The correlation patterns between decadal sea-level trends and the area averaged CRU precipitation trends in the previous season over the Baltic Sea catchment area for the period 1901-2012.

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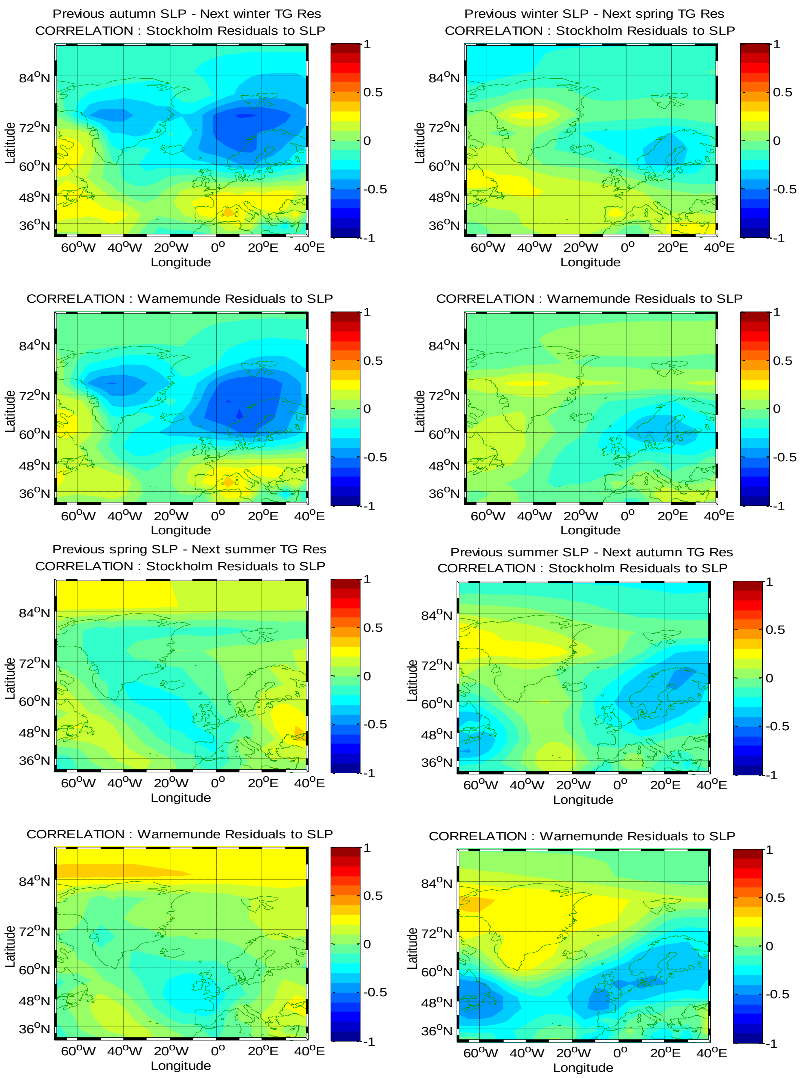

Figure 9: The correlation patterns of gliding trends on previous season factor (SLP) and following seasons tide gauge residuals.

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Table 1: The correlations between decadal trends of between precipitation field means from CRU and NCEP/NCAR in the previous season and residuals of sea-level at the Stockholm and Warnemünde stations. Significance levels are r>0.26 and r>0.19 at the 95% confidence interval (two-sided) for the associated time series lengths, (1952-2007) and (1904-2007). The significant correlation coefficients are marked with (*) symbols.

Precipitation Season	**Station**							
	Stockholm				**Warnemünde**			
Reanalysis / **CRU**	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn
Winter	0.14	0.11	0.48*	0.04	0.05	0.15	0.29*	0.21
	0.26*	0.36*	0.38*	0.02	0.21*	0.51 *	0.19	-0.01
Spring	-0.01	0.10	0.00	-0.06	-0.13	-0.03	0.10	-0.19
	-0.07	0.21*	-0.01	0.06	0.00	0.15	0.18	0.08
Summer	0.24	-0.02	0.42*	0.49*	0.34*	0.11	0.20	0.56*
	0.10	0.03	0.29*	0.49*	0.19	-0.03	0.14	0.52*
Autumn	0.32*	-0.41	-0.10	0.17	0.32*	-0.41	0.00	-0.12
	0.16	-0.17	-0.16	0.16	0.25*	-0.15	0.02	0.08

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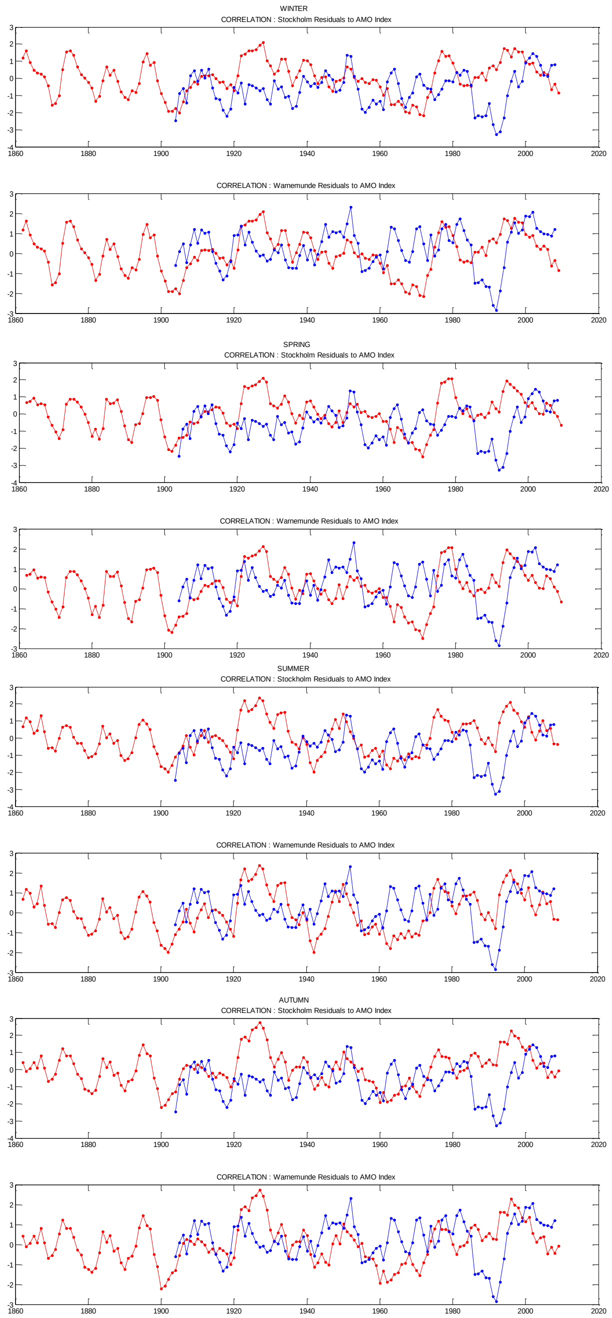

Figure 10: The gliding trend time series of the AMO-index and tide gauge residuals (x-axis: years, y-axis: trend values).