Mechanisms of sea-level variability in the Baltic Sea region for the period 1850-2100

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“Freedom from the desire for an answer is essential to the understanding of a problem“

Jiddu Krishnamurti

Dedicated to any child in the world…

…including my little Elliot Miro.

Abstract

The present work focuses on the analysis of the long-term (from interannual to multidecadal) sea-level variability in the Baltic Sea and its connection straights to the North Sea, as well as on the driving factors that are responsible for this variability. More specifically, this study aims at answering the following research questions: 1. What is the contribution of atmospheric circulation to the recent sea-level variability in the Baltic Sea and North Sea region on interannual time scale? 2. Apart from the effect of atmospheric circulation, is there any other underlying factor(s) that modulates decadal sea-level trends in the Baltic Sea? 3. How strongly can a changing atmospheric circulation influence the future Baltic Sea level trends under the RCP8.5 scenario over the 21st century?

This study is mainly based on the statistical analysis of different data sets including sea-level from tide gauges, sea-surface height reconstructions and satellite altimetry. Additionally, climate records starting in 1900, including gridded observations, meteorological reanalysis and finally the outputs of climate simulations with global climate models for the recent and future climate over the period 1850-2100 have been used.

The main purpose of the first part is to explore, and when possible to quantify, the contribution of atmospheric circulation to sea-level variability in the Baltic Sea and North Sea region on the interannual time scale. Although previous studies had found that the North Atlantic Oscillation (NAO), an important mode of atmospheric variability in the North Atlantic and Europe, has strong influence on the Baltic Sea level variations, this thesis found that actually it is another atmospheric pattern that displays stronger correlations with the Baltic Sea level, which are also more stable over time and space than the correlations between the Baltic Sea level and the NAO. The physical mechanisms that explain the link between the Baltic Sea level and this new atmospheric index are different in winter and summer. Although the inverse barometer effect contributes to this link in the winter and summer seasons, freshwater flux is connected to the link only in summer and net heat flux only in

winter. In summertime, the wind forcing that is attributed to the new atmospheric pattern may play an important role possibly due to the Ekman transport of water from the North Sea into the Baltic Sea, as in the case of the NAO.

The second research question is motivated by the need to better understand the factors that have modulated the decadal sea-level trends in the past, with the aim of providing a better range of sea-level predictions for the next few decades. This part of the thesis investigates the possible factors that modulate the Baltic Sea level decadal trends and that do not originate from the direct effect of atmospheric circulation. The main conclusion is that, for each season, the precipitation over the Baltic Sea drainage basin in the previous season is an important factor that influences those decadal sea-level trends.

The third part of this study aims at estimating the influence of long-term changes in atmospheric circulation due to the anthropogenic climate change on the future Baltic Sea level rise. The analysis is based on simulations of state-of-the-art global climate models driven under the high-end greenhouse gas emission scenario for the 21st century. After estimating the sensitivity of the Baltic Sea level to the modes of the atmospheric circulation using observations, the contribution of these atmospheric modes to the Baltic Sea level trends is estimated from the projected atmospheric modes over the 21st century. The main result of this part is that atmosphere-driven sea-level rise in the Baltic Sea will remain relatively small, and that internal climatic variability dominates those atmospheric-driven trends.

Zusammenfassung

Die vorliegende Arbeit konzentriert sich auf die Analyse der langfristigen Meeresspiegelschwankungen (von interannuellen bis zu mehreren Dekaden) in der Ostsee und deren Verbindung mit der Nordsee, sowie auf die antreibenden Faktoren, die für diese Variabilität verantwortlich sind. Folgende Forschungsfragen sollen beantwortet werden: 1. Welchen Einfluss hat die atmosphärische Zirkulation auf die jüngsten Meeresspiegelschwankungen auf einer mehrjährigen Zeitskala? 2. Gibt es, abgesehen von der Wirkung der atmosphärischen Zirkulation, noch andere Faktoren, die dekadische Trends in der Ostsee modulieren? 3. Wie stark kann eine sich verändernde atmosphärische Zirkulation den Meeresspiegelanstieg der Ostsee gemäß dem RCP8.5-Szenario im 21. Jahrhundert beeinflussen?

Die vorliegende Studie basiert hauptsächlich auf der statistischen Analyse verschiedener Datensätze einschließlich Meeresspiegel von Wasserstandsdaten, Meeresoberflächenhöhenrekonstruktionen und Satellitenaltimetrie. Zusätzlich wurden Klimaaufzeichnungen ab 1900, einschließlich gegitterter Beobachtungen, meteorologischer Reanalyse sowie die Ergebnisse von Klimasimulationen mit globalen Klimamodellen für das rezente und künftige Klima im Zeitraum 1850-2100 untersucht.

Das Hauptanliegen des ersten Teils der Arbeit besteht darin, den Einfluss der atmosphärischen Zirkulation auf die Meeresspiegelschwankungen in der Ostsee und Nordseeregion auf einer interannuellen Zeitskala zu ermitteln und nach Möglichkeit zu quantifizieren. Bisherige Studien hatten festgestellt, dass die Nordatlantische Oszillation (NAO), ein wichtiger Modus der atmosphärischen Variabilität im Nordatlantik und in Europa, einen starken Einfluss auf die Meeresspiegelschwankungen in der Ostsee hat. Die vorliegende Arbeit konnte zeigen, dass tatsächlich ein anderes atmosphärisches Muster stärker mit den Meeresspiegelschwankungen im Ostseeraum korreliert, und dass diese Korrelationen zeitlich und räumlich stabiler sind als jene zwischen der Ostsee und der NAO. Die physikalischen Mechanismen, die den Zusammenhang zwischen den Meeresspiegelschwankungen im Ostseeraum und diesem neuen atmosphärischen

Index erklären, weisen jahreszeitlich unterschiedliche Ausprägungen auf. Hierbei spielt der invers barometrische Effekt sowohl in der Winter- als auch in der Sommersaison eine bedeutsame Rolle. Im Gegensatz dazu kommt dem Frischwasserzufluss nur im Sommer eine tragende Rolle zu, während der Netto-Wärmefluss nur im Winter bedeutsam ist. Im Sommer kann der Windstress, der dem neuen atmosphärischen Muster zugeschrieben wird, eine wichtige Rolle spielen, weil dadurch ein möglicher Ekman-Transport von Wasser aus der Nordsee in die Ostsee, wie im Fall der NAO, stattfindet.

Die zweite Forschungsfrage wird geleitet von der Notwendigkeit eines besseren Verständnisses jener Faktoren, die die dekadischen Meeresspiegeltrends in der Vergangenheit moduliert haben und verfolgt dabei das Ziel, bessere Meeresspiegelprognosen für die nächsten Jahrzehnte bereitzustellen. Untersucht werden mögliche Faktoren, die die dekadischen Trends des Ostseeraums modulieren und nicht von der direkten Auswirkung der atmosphärischen Zirkulation herrühren. Es konnte gezeigt werden, dass sowohl im Sommer als auch im Winter der Niederschlag der jeweils vergangenen Jahreszeit über dem Einzugsgebiet der Ostsee eine wichtige Einflussgröße auf diese dekadischen Meeresspiegelschwankungen darstellt.

Der dritte Teil dieser Studie zielt darauf ab, den Einfluss von langfristigen Veränderungen in der atmosphärischen Zirkulation aufgrund des anthropogenen Klimawandels auf den künftigen Anstieg der Ostsee abzuschätzen. Die Analyse bezieht sich auf Simulationen mit aktuellen globalen Klimamodellen, die unter dem High-End-Treibhausgas-Emissionsszenario für das 21. Jahrhundert angetrieben werden. Nach der Abschätzung der Sensitivitäten des Meeresspiegels gegenüber des Zustandes der atmosphärischen Zirkulation mittels Beobachtungen, wurde in einem zweiten Schritt der Beitrag dieser atmosphärischen Zustände zu den Ostsee-Tendenzen durch die projizierten atmosphärischen Muster über das 21. Jahrhundert abgeschätzt. Das wichtigste Ergebnis dieses Teils der Arbeit ist, dass der durch die Atmosphäre angetriebene Meeresspiegelanstieg in der Ostsee relativ gering ausfällt und dass die interne Klimavariabilität die von der Atmosphäre geprägten Trends dominiert.

Contents

1 Introduction

1.1 Motivation

Recent studies suggest that global mean sea level (GMSL) has risen with a rate of 1.7 ± 0.2 mm/year over the last century and present-day GMSL rise has reached a rate of 3.2 ± 0.4 mm/year, which is an important impact of climate change (Nerem et al. 2010, Church and White 2011). However, the increase in sea-level has been spatially heterogeneous, with complex spatial patterns. Regional sea-level rise has shown and will continue to show rates substantially different from the global average (Church et al. 2013). For instance, 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/year, whereas immediately further south in the mid-latitude North Atlantic, the sea-level trends have been negative, of the order of -5 mm/year. In the Pacific Ocean, similar contrasts can be also observed. In the Tropical Western Pacific, sea-level trends may attain a value of 15 mm/year, whereas in the mid-latitude Eastern Pacific the trends are negative, of the order of -5 mm/year (e.g. Church et al. 2010).

Considering the future regional sea-level changes, the investigations indicate that natural climate variability will likely dominate the regional sea-level changes over the next few decades through dynamical changes. However, it is also likely that towards the end of the 21st century, regional sea-level rise will be dominated by non-natural processes, such as the expansion of ocean water masses. By the end of the 21st century, it is very likely that sea-level will be higher than today over about 95% of the ocean area. Most of the regions that will experience a sea-level sink are located near former and current glaciers and ice sheets (Church et al. 2013).

Since coastal regions have been strongly affected by intensive urbanisation due to the sharply increased population and hence have received a large amount of economic investments over the last century, the estimation of future of the sea-level rise becomes an important factor for the decision makers and inhabitants of those regions (e.g. Brooks et al. 2006). This estimation is especially important along the coastal regions where inhabitants are highly dependent on the sea conditions, such as the Baltic Sea, which is located in densely populated northern Europe. Furthermore, the investigation of future sea-level rise in the Baltic Sea is of high scientific interest due to the possible large impacts of future global climate change on regional scale (e.g. Meier et al. 2004; Hünicke 2010; Meier et al. 2011; Grinsted et al. 2015).

There have been large numbers of studies focusing on understanding and describing the drivers of the Baltic Sea level variability. These drivers may be dynamic and static. Dynamical factors are, for instance, the effect of wind or oceanic currents. An example of static drivers is the glacial isostatic adjustment (GIA). It is also known that the regional factors impact the Baltic sea-level variations differently depending on the time scale and locations in the Baltic Sea (e.g. Novotny et al. 2006; Hünicke et al. 2008; Ekman 2009; Richter et al. 2011). Hence, the Baltic Sea level variability should be analysed in order to gain a comprehensive knowledge about its driving effects and characteristics.

The knowledge about the characteristics and the drivers of the long-term sea-level variations is not completely established in the Baltic Sea. This is because sea-level in the Baltic Sea is modulated by global fingerprints, regional dynamic and static effects. The coastlines of the Baltic Sea, as an inland sea, are also complex. In addition, the connection to the open sea, the North Sea, occurs only through shallow and narrow Danish straits. However, the role of dynamical factors arising from that connection in variability of sea-level in the Baltic Sea is not completely understood (e.g. Leppäranta and Myrberg 2009, Omstedt et al. 2014, BACC II 2015).

Unless otherwise specified, the term ‘sea-level’ is here used for the term ‘mean sea-level’ indicating that short term effects of tides and storm surges are filtered out from sea-level time series.

1.2 Causes for sea-level changes: from global to regional scale

Change in global mean sea level (GMSL) is an important indicator of climate change since it integrates all the factors that give rise to a radiative imbalance of the planet (e.g. Church et al. 2010). It is reported that GMSL rise has recently increased from a few centimetres per century over recent millennia to a few tens of centimetres per century in recent decades. This sharp increase can be attributed to anthropogenic climate change (Milne et al. 2009). The main contributors to contemporary GMSL change are the thermal expansion of the ocean, melting of glaciers and ice sheets, and water exchange between land and ocean (e.g. Church et al. 2011). These three factors explain 90% of the observed GMSL rise for the period 1971-2010 (Church, Monselesan, et al. 2013). A broad range of climate sensitive processes within ocean, atmosphere, land, ice and hydrological cycle will very likely continue to impact on sea level change from global to regional scales in the near future covering next centuries (e.g. Cazenave and Remy 2011; Jevrejeva et al. 2012; Grinsted et al. 2015; Carson et al. 2016).

Related changes in sea level on regional scale, it is known that the patterns of sea level rise show significant regional variations (Church et al. 2013). Figure 1.1 displays an example of regional sea level trends estimated from annual means of satellite altimeter observations (http://www.aviso.oceanobs.com) for the period 1993-2014.

The trend values show substantial regional variations, with some regions having experienced more than five times the GMSL (~3 mm/year) rise since 1993. The results of previous studies imply that most of the observed change in regional sea level is due to contribution of steric components of ocean (e.g. Köhl et al. 2007; Wunsch et al. 2007; Köhl and Stammer 2008; Song and Colberg 2011).

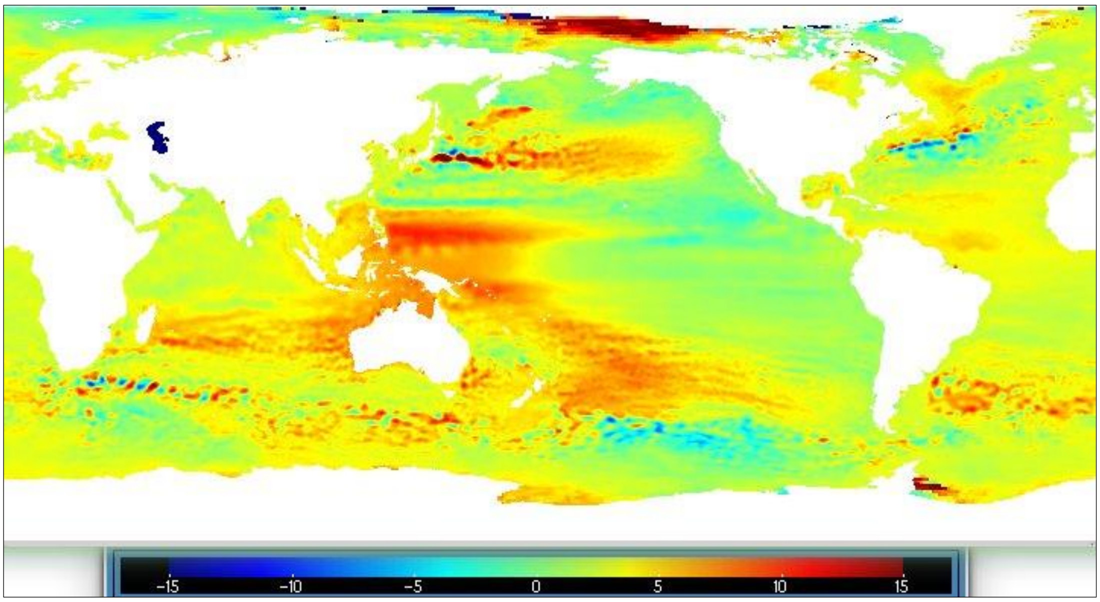


Figure 1.1: The spatial distribution of regional sea level rise (mm/year). The trend values of satellite altimetry observations are computed from annual means over the period 1993-2014. Range of longitude: 0.125 to 359.875 degrees east, range of latitude: -89.875 to 89.875 degrees north.

At regional scales, sea-level change can occur owing to sum of global, regional and local processes. As mentioned before, GMSL is mainly affected by thermal expansion of the ocean (thermosteric effect), melting of landlocked ice (glacier, ice sheet) and land water storage. The additional processes causing regional sea level changes can be divided into two parts: dynamic and static effects. Dynamic mean sea level changes occur due to changes in the circulations of atmosphere and ocean. The ocean currents can cause substantial sea-level variability owing to redistribution of mass, heat and freshwater from interannual to decadal time scales.

Moreover, wind forcing drives changes in the eustatic (massive) and steric (volumetric) sea level heights through atmosphere-ocean interaction processes. For instance, sea level can vary considerably as a result of wind stress forcing at different time scales and by different ways of its responses to the wind forcing. The short term variations in sea-level are not the focus of this study and therefore they are left out of consideration here. However, it should be at least mentioned that wind produces waves which influence the short term sea-level variations with periods on the order of seconds. On the longer term, from hours to decadal time scales, sea-level can be modulated by the wind stress forcing through Ekman transport, Ekman pumping/suction and direct effect of wind stress on the sea surface. Ekman transport in the upper layers of the ocean is a consequence of wind forcing, the Coriolis force and friction between the ocean layers. It causes net water transport directed 90° to the right (in the Northern Hemisphere) with respect to the wind direction, assuming that Ekman spiral is not interrupted by the bathymetry or coastal geometry. (e.g. Colling 2005). Secondly, related to Ekman processes, wind stress forcing causes Ekman pumping/suction (downwelling/upwelling). Upwelling/downwelling regions can be classified into two different types, open ocean upwelling/downwelling and coastal upwelling/downwelling. Persistent upwelling/downwelling causes water divergence/convergence, hence, valleys/hills in the open ocean areas. In coastal upwelling/downwelling regions, the alongshore winds cause the upward/downward transport of water from deeper/surface layer to surface/deeper layer by the off-shore/on-shore transport of water directed perpendicular to the wind stress forcing. Third, the direct effect of wind stress on the sea surface occurs in the case of interruption of the Ekman spiral due to the bathymetry of ocean floor. In that case, the direction of water transport varies according to the strength of wind stress and bathymetry (e.g. Pugh and Woodworth 2014).

In addition to the wind driven ocean currents (Ekman transport) and tidal currents which occur due to gravitational interaction of Earth, Moon and Sun, buoyancy (heat and freshwater) fluxes can cause ocean circulation. The term buoyancy describes the horizontal gradient in the density of water masses. It may be caused by the exchange of heat and freshwater between the atmosphere and ocean, altering the density of a water column. For instance, cooling of the ocean or evaporation (saltier ocean) makes the ocean denser; removing the buoyancy of the water. This can drive near-surface currents as well as cause formation, spreading and upwelling of deep waters. These processes cause internal changes of water masses by altering the temperature and salinity components, which are known as thermosteric and halosteric effects on sea-level, respectively (e.g. Rahmstorf 2006, Church et al. 2010). On the one hand, the thermosteric changes are not globally uniform and significantly contribute to the global mean sea level rise. On the other hand, the effect of halosteric changes on global mean sea level is negligible. However, those changes can remarkably influence sea-level at regional scale (e.g. Antonov et al. 2002, Ishii et al. 2006). For example, the halosteric contribution to sea-level variability almost counteracts the thermosteric contribution to the sea-level rise in the Labrador Sea. Since density changes can also be affected by the wind, a simple attribution of density changes to buoyancy forcing (i.e. thermohaline circulation) is not possible (Church et al. 2013).

These dynamical changes in regional mean sea level are closely related with the modes of atmospheric circulation such as El Nino/Southern Oscillation (ENSO), North Atlantic Oscillation (NAO). In particular, an atmospheric index which can be simply constructed based on the pattern of the associated mode of atmospheric circulation can carry information about atmospheric factors such as wind, pressure and heat fluxes and presence of ocean currents through the its connection with variations of sea-surface-temperature. These factors can be plausible candidates to explain variations of sea-level in a region on different time scales (e.g. Yan et al. 2004, Köhl and Stammer 2008, Milne et al. 2009, Church et al. 2010, Cazenave and Remy 2011, Stammer et al. 2013; Dangendorf et al. 2014).

In addition to the dynamic processes, static processes can also cause changes in regional mean sea-level. Static sea level changes are associated with the stress of the external isostatic (un)load. One static effect is the inverse barometer effect (IBE) due to variations in atmospheric pressure over a point on the ocean. Another static factor is the glacial isostatic adjustment (GIA) due to mass redistribution on the Earth crust. The consequences of this mass redistribution can alter the vertical land motion, ocean floor, gravity field and also affect the rotation of the earth. In addition, there can be some small-scale processes (tectonic, coastal) influencing sea level changes locally (e.g. Lambeck 1988; Wunsch and Stammer 1997; Milne and Mitrovica 1998; Church et al. 2010; Tamisiea and Mitrovica 2011; Stammer et al. 2013).

Figure 1.2 presents a view of the processes influencing regional sea level.

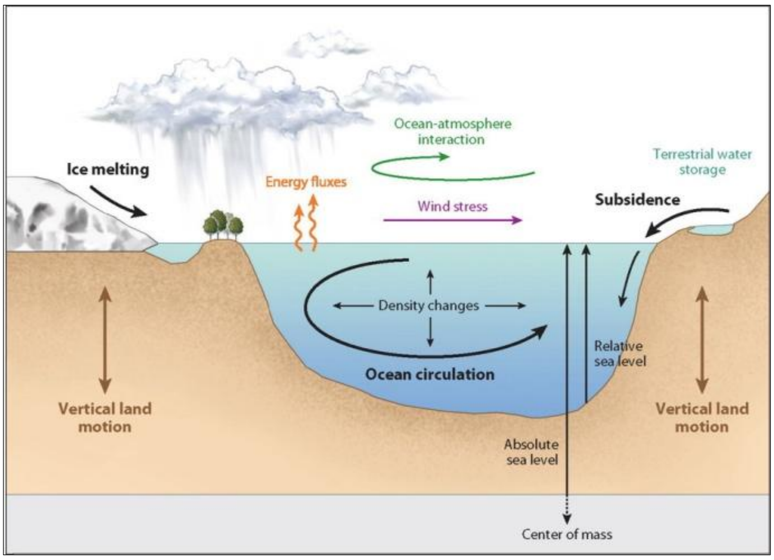


Figure 1.2: The processes that cause regional sea level variations (adapted from Stammer et al. 2013).

Overall, several processes alter the sea surface height and sea floor. The impacts of those alterations result in complex spatial patterns of sea level variations on regional scales.

1.3 The Baltic Sea and its connection to the North Sea

The Baltic Sea is a semi enclosed basin, located in densely populated northeast Europe, and connected to the North Sea only through the transition zone. Therefore, the Baltic Sea mass is brackish, with mean salinity about 7%, which is one-fifth of mean salinity of the oceans. The permanent salinity stratification limits vertical convection, hence, restricts oxygenation of deep water masses. The salinity field displays a continuous decrease from the North Sea boundary to freshwater in estuaries. The lowest salinity is measured in the surface waters of the northern Bothnian Bay and the eastern side of Gulf of Finland (e.g. Leppäranta and Myrberg 2009, BACC II 2015). It should be noted that there is an increase of the sea surface height from the North Sea into the Baltic Sea, the height difference between the inner part of the Gulf of Bothnia and the open Skagerrak reaching 35-40 cm. It occurs mainly due to the considerable difference in salinity (Ekman and Mäkinen 1996).

Figure 1.3 shows the Baltic Sea region including its drainage basin (from Leppäranta and Myrberg 2009).

Figure 1.3: The Baltic Sea region with its drainage basin (from Leppäranta and Myrberg 2009).

The Baltic Sea and its connection to the North Sea are exposed to climatic impacts. In addition to the fingerprints of global effects - i.e. melting of Greenland ice sheet (e.g. Grinsted et al. 2015), changes in the Baltic Sea level depend on several individual factors, which are mainly the components of dynamic and static processes (e.g. Andersson 2002; Kauker and Meier 2003; Hünicke and Zorita 2006; Ekman 2007; Hammarklint 2009; Madsen 2011; Richter et al. 2011). In particular, considering dynamic effects, the Baltic Sea is strongly influenced by the atmosphere in the eastern

North Atlantic and by the freshwater fluxes in its basin. The long-term variations show that the Baltic Sea sea-level responses are highly sensitive to changes in regional climatic drivers– i.e. wind, air pressure, air temperature, solar radiation, precipitation and river inflow (e.g. Moeller and Hansen 1994; Leppäranta and Myrberg 2009). The atmospheric drivers are directly related to the climate modes of atmospheric circulation such as the North Atlantic Oscillation (NAO) (e.g. Jevrejeva et al. 2005), which is the dominant mode of the atmospheric circulation over the North Atlantic in wintertime. The positive (negative) phase of the NAO indicates that the Azores high and Icelandic low became more intense (weaker), which leads to stronger (weaker) westerlies than the normal westerly flow. A positive (negative) phase of the NAO causes warm (cold) and wet (dry) winters in the Baltic Sea and North Sea region. The NAO shows substantial seasonal and interannual variability (e.g. Hurrell 1995; BACC II Author Team 2015). Concerning the linkage between the NAO and sea-level variations, it is known that the NAO is one of the important factors driving sea-level variations in the Baltic Sea, especially from interannual to decadal time scales and in wintertime. However, long-term sea-level variations in the Baltic Sea cannot be accounted for by only the contribution of the NAO (e.g. Andersson 2002). The strength of the relation between the NAO and the Baltic Sea level is spatially very heterogeneous (e.g. Hünicke and Zorita 2006). Sea-level variations at the southern Baltic Sea seem to be only weakly connected to the NAO even in wintertime, comparing to the rest of the Baltic Sea region (e.g. Yan et al. 2004, Hünicke et al. 2008, Leppäranta and Myrberg 2009, Omstedt et al. 2014, BACC II 2015). Overall, the NAO explains only 32% of sea-level variance in the Baltic Sea at interannual time scales (Kauker and Meier 2003). This indicates the need of the consideration of other modes of atmospheric variation or even the whole sea-level-pressure (SLP) field over the North Atlantic including Western Europe. Related to this, Heyen et al. (1996) implemented such an analysis in the Baltic Sea region for the winter season. They found a strong connection between anomalies of large-scale SLP and patterns of the Baltic Sea level variability in wintertime.

Other atmospheric factors like temperature and precipitation considerably affect sea-level as well. For example, Hünicke et al. (2008) investigated the influence of atmospheric factors such as SLP, temperature and precipitation on sea-level variability and found that decadal sea-level variations are well explained by SLP variations in the central and eastern Baltic Sea, but, area-averaged precipitation explains sea-level variations better in the southern Baltic Sea in wintertime. Furthermore, several analyses have considered the relation between atmospheric factors, not directly related to the NAO, and sea-level variations (e.g. Andersson 2002; Omstedt et al. 2004; Novotny et al. 2006).

Using the Stockholm station records and the NAO-index time series, Andersson (2002) investigated the effect of atmospheric circulation on the Baltic Sea level. On the one hand, her investigation indicated that interannual sea-level variations, particularly along the northern and eastern coasts, are highly modulated by the strong westerly winds related to the NAO. On the other hand, she suggested that an atmospheric circulation 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.

More recently, concerning different sorts of data sets including 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 the North Sea. Stramska (2013) investigated off-shore and coastal sea-level variability in the Baltic Sea and the North Sea. Using 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 winter NAO-index. 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. Overall, on the one hand, a substantial relation between the Baltic Sea and the North Sea level variations has been detected on the interannual time scale. On the other hand, a comprehensive analysis on sea-level variability over the whole Baltic Sea region has been made possible through the commission of the state-of-the-art satellite altimetry observations provided by AVISO since 2014, whereas the role of the atmospheric circulation in sea-level variability over the interior and coastal areas of the Baltic Sea region and the related atmospheric factors contributing to this link is not well established yet.

Moreover, previous studies have shown that the sea-level records display relatively large variations of decadal trends (e.g. 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/year (to a large extent caused by the GIA that occurs at millennial timescales, as briefly explained below). However, the trends of the Warnemünde sea-level record calculated over 30-year windows may vary between -0.5 mm/year to 2.5 mm/year. 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 trend deviations that should be understood and taken into account on decadal and longer time scales. However, the possible connections between natural variations and decadal sea-level trend variations in the Baltic Sea are not identified yet.

Furthermore, the existence of natural forcing in the decadal sea-level trends also suggests that modifications in the modes of atmospheric circulation are important driving factors to understand the possible sea-level rise for the near future in the Baltic Sea. Hence, the rationale is that climate-induced change in the modes of atmospheric circulation could modify sea level rise in the Baltic Sea. So far, there are only few studies focused on the impact of future circulation changes on sea-level in the Baltic Sea area (e.g. Hünicke 2010, BACC II 2015).

In addition to the dynamic processes, static processes also remarkably influence sea-level in the Baltic Sea. As a result of changes in the orbital configuration of the Earth's rotation, the formed glaciers in Fennoscandia began to recede since the last glacial maximum about 21,000 years ago (e.g. Peltier 2004). The consequence of this melting process is currently the glacial isostatic adjustment (GIA), which causes a geographically varying vertical land motion in the Baltic Sea basin (e.g. Ekman 1996; Richter et al. 2011). The largest vertical uplift rate attains 10 mm/year, which occurs close to the former centre of glaciations around the Gulf of Bothnia. Land subsidence is found in the southern part of the Baltic Sea with a rate of 1 mm/year due to the crustal response of land along the edge of deglaciation area (e.g. Lidberg et al. 2007; Rosentau et al. 2007). Figure 1.4 shows the present vertical land motion rates from the analysis of a regional Global Positioning System (GPS) network (from Richter et al. 2011).

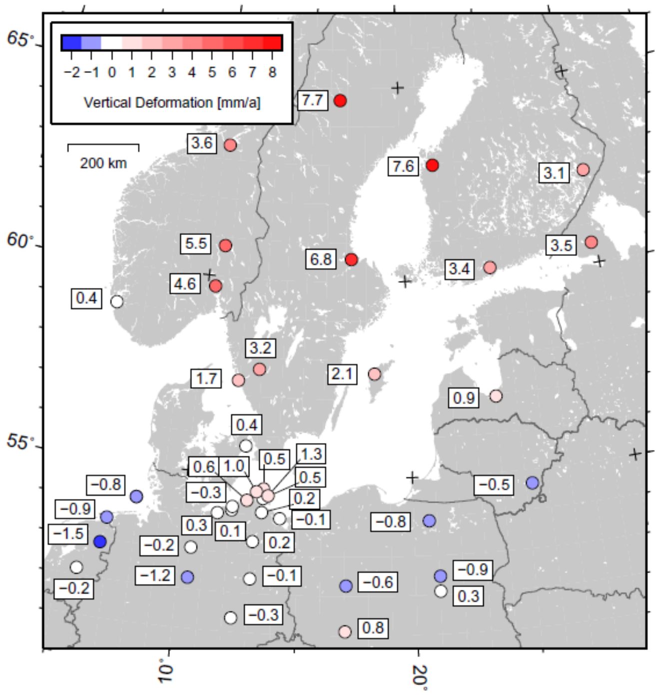


Figure 1.4: The rates of vertical land motion over the Baltic Sea region based on the analysis of a regional GPS network (from Richter et al. 2011).

The vertical land crustal motion affects both relative (tide gauge) and absolute (satellite altimetry) sea level observations. On the one hand, the observations of every individual tide gauge provide information about the sea-level variability with respect to a local reference point on the land. Therefore, the vertical land motion directly affects tide gauge readings, which measure relative sea level variability. The effects of vertical land motion on relative sea level measurements can be determined by analysing the long term-trends of the tide gauge records together with the GPS measurements (e.g. Richter et al. 2011). On the other hand, satellite altimetry observations rely on definition of sea surface height relative to a geocentric reference frame such as the reference ellipsoid. However, the GIA induced vertical land motion causes long-term sea-level trends in the satellite altimetry observations as well, since the ocean floor is falling relative to the centre of the reference frame of the satellite altimeter due to GIA (e.g. Peltier 2001, Huang 2013).

To sum up, much consideration has been devoted to improve the understanding of sea-level variability in the Baltic Sea. However, the connection between drivers and sea-level variability is not completely understood for this region. For instance, the reason for the spatial and temporal heterogeneity of the link between the Baltic Sea level and sea-level-pressure, including the NAO, remains unexplained. So far the knowledge about the role of atmospheric circulation in off-shore and coastal sea-level variability in the Baltic Sea region is not fully established yet. Therefore, drivers of sea-level variability that can be attributed to effects of atmospheric variability should be comprehensively analysed. In addition, the natural variations that may potentially cause large variations in decadal sea-level trends of the Baltic Sea have not been estimated. It is still not known whether the mechanisms that have been claimed to account for the interannual variations of sea-level are also responsible for the variability of decadal sea-level trends in the Baltic Sea. Furthermore, given the continuous remarkable deviations of regional sea-level trends from GMSL rise, studies devoted to close the gap of knowledge about the influence of atmospheric circulation on the near future sea-level rise in the Baltic Sea are needed.

1.4 Thesis Objective

The objective of this thesis is to have a better understanding of the connection between atmospheric drivers and sea-level variability in the Baltic Sea region. Accordingly, this thesis investigates the effect of atmospheric forcing on off-shore and coastal sea-level variations on the interannual time scale and on the variability of decadal sea-level trends in the Baltic Sea. It then estimates the possible range of the near-future Baltic Sea level rise that can be attributed to the changes in atmospheric circulation.

This study is framed by the research area of 'Integrated Climate System Analysis and Prediction' (CliSAP) research cluster (www.clisap.de). The research areas of CliSAP primarily consist of climate change and its impacts including three main parts (A) Climate Dynamics and Variability, (B) Climate Manifestations and Impacts, (C) Climate Change and Social Dynamics. The research area ‘Climate Dynamics and Variability’ focuses on the natural sciences. More specifically, it is settled for the investigations on (A1) climate variability and predictability, (A2) climate processes and feedbacks and (A3) climate sensitivity and sea level.

The objective of this study belongs to the ‘Climate Sensitivity and Sea Level’ research topic. In detail, ‘Climate Sensitivity and Sea Level’ research topic was established to work on four different subtopics: (A3-i) Mechanisms and sources of regional sea level change and variability, (A3-ii) natural and anthropogenic modes of sea level variability and change, (A3-iii) influence of the cryosphere on the ocean circulation and associated sea level changes, (A3-iv) the North and Baltic Sea, small islands and vulnerable regions. The content of this Ph.D. study intersects the A3-i, -ii and –iv subtopics. These subtopics have a general aim of identifying the relation between mean sea-level variability and climatic factors by using statistical methods and numerical models with special focus over the North Atlantic as well as the Baltic Sea and North Sea region. As a part of that special focus, the characteristics and driving-factors of long-term mean sea-level variability and change in the Baltic Sea and its connection to the North Sea have been statistically analysed here. In particular, the following research questions are investigated in this thesis:

- the relationship between coastal and off-shore sea-level in the Baltic Sea and North Sea region on interannual time scale
- the impacts of physical factors on atmosphere-driven off-shore sea-level variations in the Baltic Sea and North Sea region on interannual time scale
- investigation of possible underlying (apart from the effect of atmospheric circulation) effect contributing to decadal sea-level trend variability in the Baltic Sea
- the influence of decadal climatic variability (i.e. North Atlantic Oscillation, sea-level-pressure, temperature, precipitation) on the Baltic Sea level
- Projections of the atmosphere-driven Baltic Sea level trend under the RCP8.5 scenario over the 21st century

Based on the conducted research interests, the thesis is focused on addressing the following research questions in three different parts:

Part 1

- What are the spatial and seasonal (winter, summer) characteristics of off-shore sea-level variability of the Baltic Sea and North Sea region on interannual time scale?
- Is there an atmospheric pattern driving sea-level variations coherently and steadily over time?
- If there is one, what are the physical mechanisms explaining the connection between sea-level and the associated mode of atmospheric circulation?

Part 2

- What are the spatial and seasonal characteristics of decadal sea-level trends of the Baltic Sea?
- Apart from the effect of the atmospheric circulation, is there any other underlying factor(s) in decadal sea-level trends of the Baltic Sea?
- Are the decadal sea-level trends connected to the Atlantic Multidecadal Oscillation (AMO) index?

Part 3

- How well do the climate models simulate present-day climatology of the SLP over the Baltic Sea and North Sea region?
- Is Baltic Sea level rise expected to occur due to changes in atmospheric circulation under the RCP8.5 scenario over the 21st century?
- What is the influence of internal climatic variability of the CMIP5 models on the atmosphere-driven Baltic Sea level trends over the 21st century?
- Are the relevant modes of atmospheric variability affected by large-scale air temperature on multidecadal time scale?

Following this structure, the thesis is framed with this introductory chapter and a chapter including a summary and discussions of the main results. The body of this thesis is composed of three main chapters that essentially follow the outline of the parts just described. These chapters have already been prepared for the peer reviewed journals. Therefore, every chapter is independently formed from others and has its individual introduction, data, methods and conclusions sections. A brief summary on these main chapters is given below.

Chapter 2

In this part of thesis, the main subject is to investigate and when possible quantify, the contribution of the atmospheric factors to the link between modes of the atmospheric circulation and off-shore sea-level variability in the Baltic Sea and the North Sea on interannual time scale. The state-of-the-art satellite altimetry observations together with tide gauge records are used as sea level data for the investigation. Moreover, the influence of the climatic factors is analysed to describe the off-shore sea-level-anomaly (SLA) variations by using atmospheric indices (i.e. NAO), energy fluxes and SLP and precipitation fields. The main conclusion is that the effects of inverse barometer, net energy flux and freshwater flux substantially explain the sea-level variability in the Baltic Sea and North Sea region on interannual time scale.

Chapter 3

This chapter focuses on explaining the mechanisms of variability of decadal sea-level trends by analysing sea-level and climatic data for the whole Baltic Sea basin over the last century. To analyse the relation between sea-level observations and atmospheric forcing in each season, we use sea-level data sets; tide gauge and Sea Surface Height Anomalies (SSHA), and climatic data sets including the North Atlantic Oscillation (NAO) Index, the Atlantic Multidecadal Oscillation (AMO) Index, sea-level-pressure (SLP), near-surface air temperature and precipitation fields. The results of this study show that precipitation has a lagged effect on decadal sea-level trend variations when the effect of the atmospheric circulation is previously removed.

Chapter 4

This chapter aims at estimating the contribution of possible future trends in the atmospheric circulation to the Baltic Sea level trends over the 21^{st} century. For this aim, this particular study uses tide gauge observations, atmospheric indices which are constructed both from SLP observations and the SLP outputs of climate simulations, and air-surface temperature outputs of climate simulations. These outputs of climate models are simulations of the Coupled Model Intercomparison Project Phase 5 (CMIP5) driven by the Representative Concentration Pathways 8.5 W/m^2 (RCP8.5) scenario. Overall, the results suggest that atmosphere-driven Baltic Sea level trend will likely remain small over the 21^{st} century and that internal climatic variability dominates the trends of associated atmospheric patterns.

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

The main purpose of this chapter is to quantify the contribution of atmospheric factors to off-shore sea-level variability in the Baltic Sea and the North Sea on interannual time scales during the 20^{th} century. For this purpose, statistical analysis applied 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 20^{th} 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.

This chapter further investigates 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. The physical mechanisms that explain the link between the Baltic Sea level and this new atmospheric index are different in winter and summer. The main conclusion is that, although the inverse barometer effect contributes to this link in the winter and summer seasons, freshwater flux is connected to the link only in summer and net heat flux only in winter. In summertime, the wind forcing that is attributed to the new atmospheric pattern may play an important role because of driving a possible Ekman transport of water from the North Sea into the Baltic Sea, as in the case of the NAO.

2.1 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; B. 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 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 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; BACC II 2015). The NAO may directly impact on sea-level variations in the Baltic Sea and 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 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). This effect can not only change the total water volume of the Baltic Sea, but also the water density through changes in salinity. Moreover, 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 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, investigating the relationship between the NAO and the sea-level around northern European coasts, Yan et al. (2004) 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-levels under the stronger NAO phases, which are clearer in wintertime, whereas non-significant and 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 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 North Sea, reported that atmospheric variability that differs from the NAO may still explain part of the sea-level variability. 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 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 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 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-levels. 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 1/4°x1/4° 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 2.1. 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 2.1.

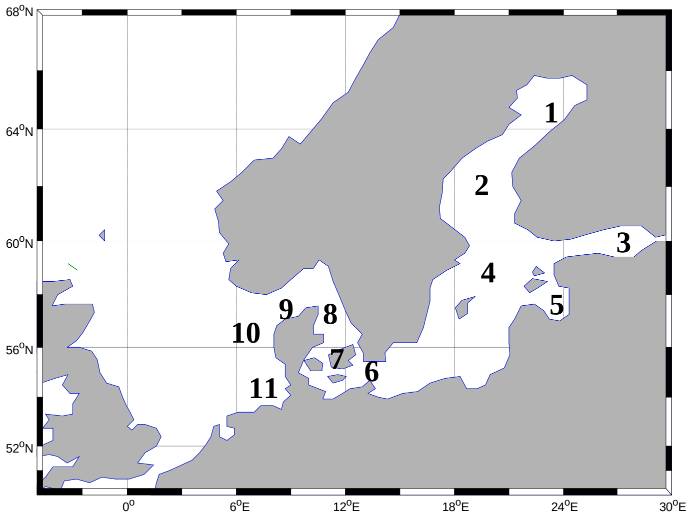


Figure 2.1: The Study Area with sub-regions. 1-Bothnian Bay, 2-Bothnian Sea, 3-Gulf of Finland, 4-Baltic Proper, 5-Gulf of Riga, 6-Arkona Basin, 7-Danish Straits, 8-Kattegat, 9-Skagerrak, 10-North-eastern North Sea, 11-German Bight.

This study 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 section, we assess the results.

2.2 Data Sets

The study uses primarily two different types of data sets. The first set consists of sea-level observations obtained from satellite altimetry missions and tide gauges. 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.

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.

2.2.1 Sea Level Observations

2.2.1.1 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 on a 1/4°x1/4° cartesian grid resolution with 20-year mean reference period. 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.

2.2.1.2 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) (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 northeastern boundary of the North Sea, nine tide gauges along the Baltic coasts were selected: Ratan, Helsinki, Stockholm, Smogen, Kungsholmsfort, Sassnitz, Travemünde, Wismar and Warnemünde. The selection was based on their geographical distribution and the record length of the tide gauges. The Smogen 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.

2.2.2 Climatic Data

We considered four different data sets concerning climatic variables.

2.2.2.1 SLP data

The 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 (Hurrell et al. 2016a). The geographical domain of the data set used here is (70° W - 40° E) and (30° N - 90° N).

2.2.2.2 The NAO-index

The 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.

2.2.2.3 Reanalysis data: Surface Flux and Precipitation

In this study, 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). The meteorological reanalysis assimilates different observations into a weather prediction model and produces a complete gridded data set over the whole period.

This data set has a spatial resolution of 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.

2.3 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 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 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).

2.4 Results

2.4.1 Comparison between satellite SLAs and tide gauges

We first examine 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 2.1.

Table 2.1: The correlations between individual satellite altimetry grids and the tide gauges for the period 1993-2013.

	Winter	Summer
Ratan	0.95	0.91
Stockholm	0.97	0.92
Wismar	0.89	0.78

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.

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, Smogen, 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 2.2 displays the obtained correlation patterns for the winter season.

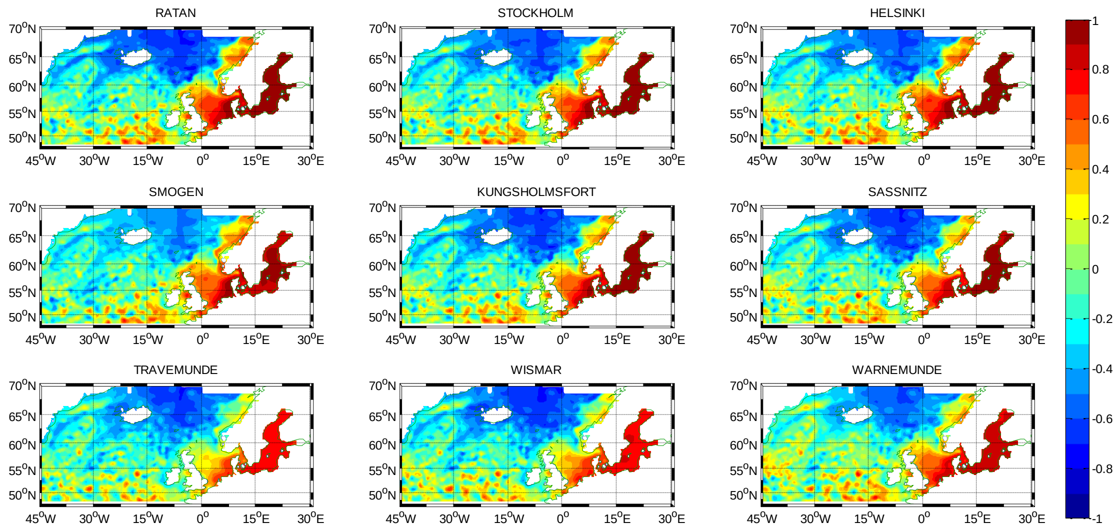


Figure 2.2: The correlation patterns between the SLA grids and tide gauge records in wintertime for the period 1993-2013.

Figure 2.2 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. 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 2.3.

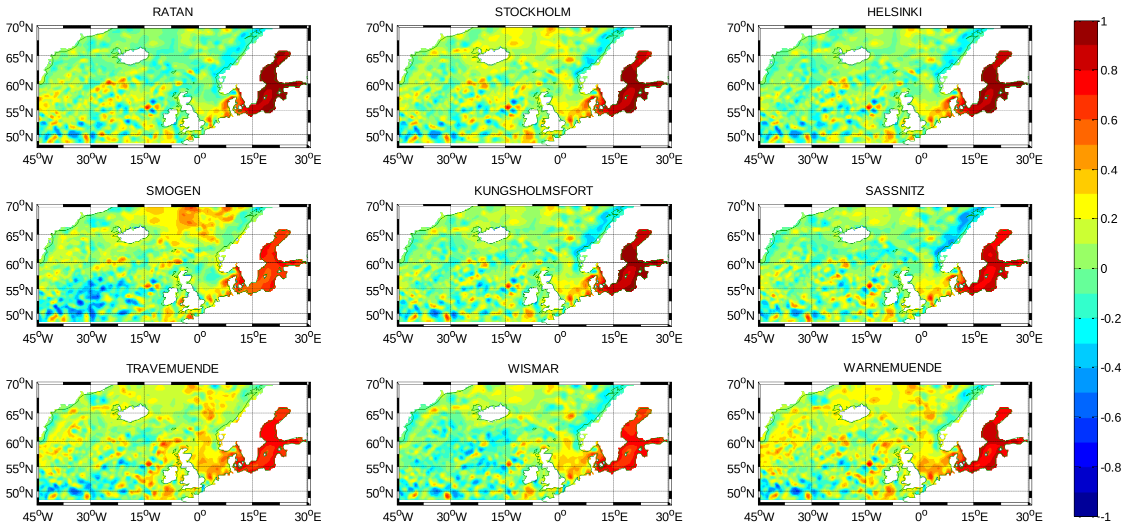


Figure 2.3: The correlation patterns between the SLA grids and tide gauge records in summertime for the period 1993-2013.

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.

2.4.2 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 2.4. 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.

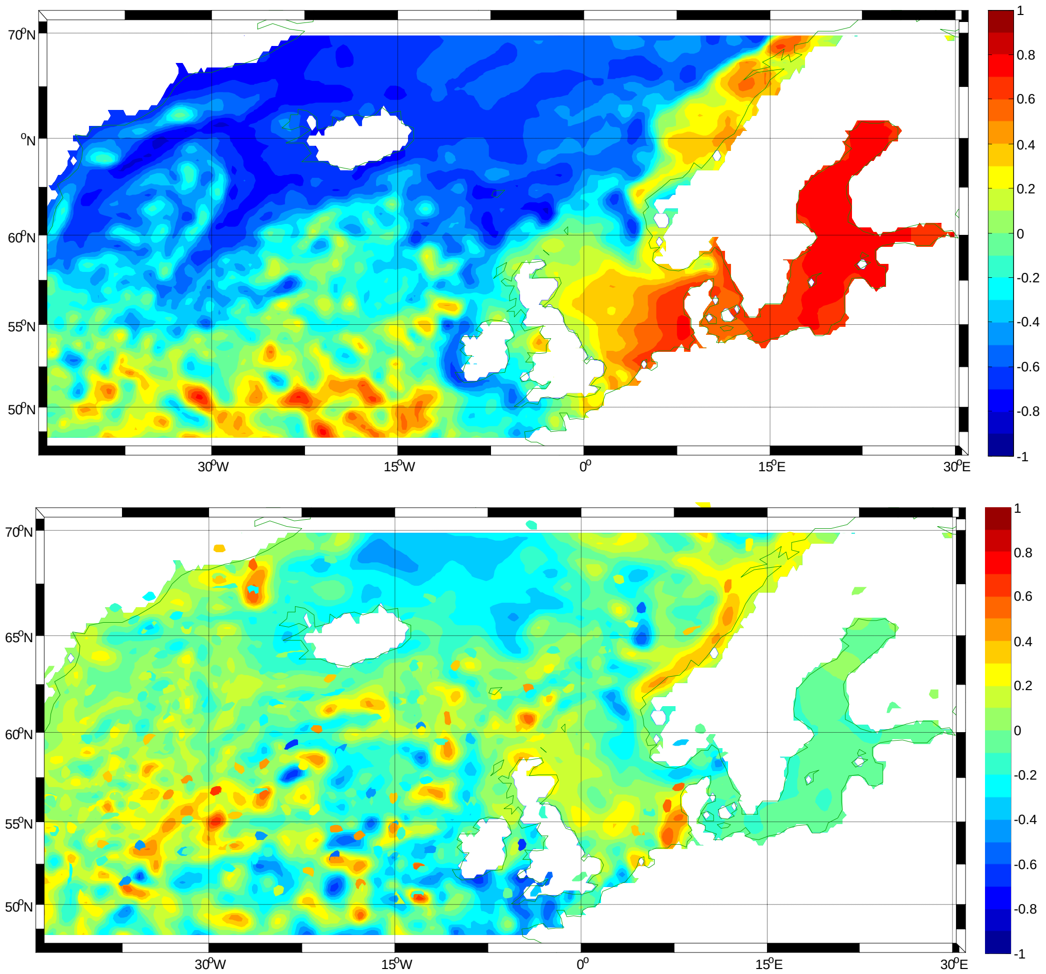


Figure 2.4: The correlation maps between the SLA grids and the NAO-index for the winter (top) and summer (bottom) seasons (1993-2013).

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.

The significant correlation 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 the southern Baltic Sea in wintertime (e.g. Yan et al. 2004; Hünicke and Zorita 2006). The associated weak correlation between tide gauges 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 2.2 and Figure 2.3). However, the NAO-index does not seem to be strongly connected to the SLA grids for the same period in summertime (Figure 2.4-lower).

2.4.3 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 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. 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 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 2.5.

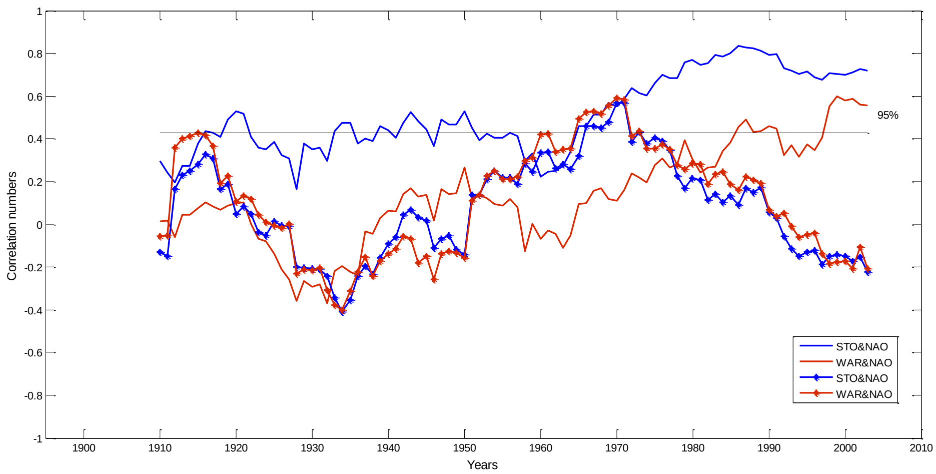


Figure 2.5: The correlations of 21-year running windows between tide gauges (Stockholm-STO and Warnemünde-WAR) and the NAO-index for the winter (solid-line) and summer(dotted-line) seasons. The value of correlation significance at the 95% level (two-tailed) is ±0.43 for this length

Figure 2.5 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 2.6 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.

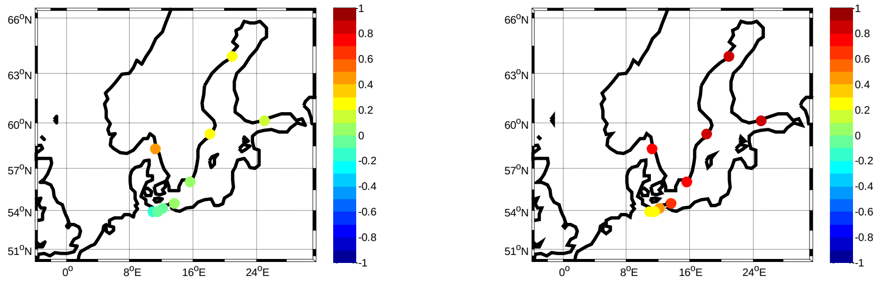


Figure 2.6: The correlation maps between tide gauges and the NAO-index for the minimum (1950-1970) and the maximum (1976-1996) correlation periods in wintertime.

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 2.7.

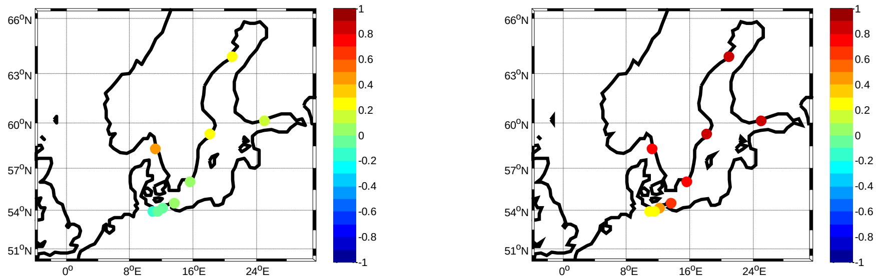


Figure 2.7: The correlation maps between tide gauges and the NAO-index for the 1924-1944 and 1960-1980 periods when minimum and maximum correlations occur in summertime, respectively.

Figure 2.7 also illustrates that the 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.

2.4.4 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, when the correlation between the NAO-index and the sea-level variability was maximum in wintertime. The correlation pattern between SLP field and the Stockholm sea-level over this period is illustrated in Figure 2.8.

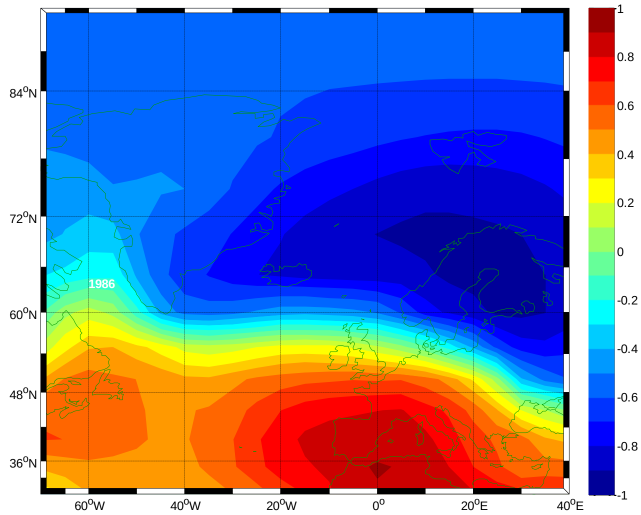


Figure 2.8: The correlation patterns between the Stockholm tide gauge and SLP grids for the period 1976-1996 in wintertime.

The correlation pattern in Figure 2.8 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 2.9.

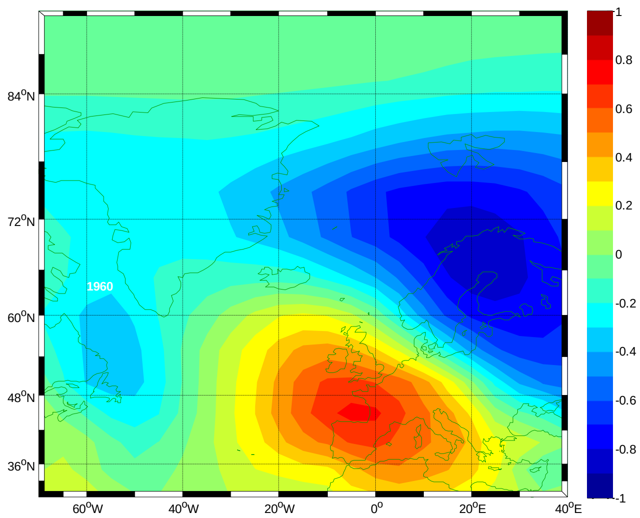


Figure 2.9: The correlation pattern between the Stockholm tide gauge and SLP grids for the period 1950-1970 in wintertime.

Figure 2.9 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 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 2.10.

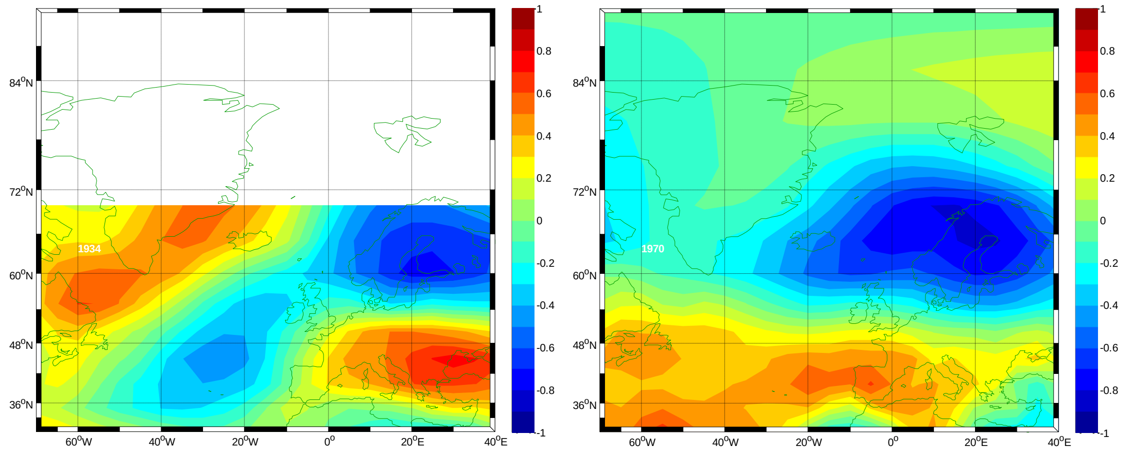


Figure 2.10: The correlation patterns for the periods when the correlation between the NAO-index and sea-level variability were minimum (left) and maximum (right) in summertime. The periods are covering the years 1924-1944 (left) and 1960-1980 (right).

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).

2.4.5 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 2.11.

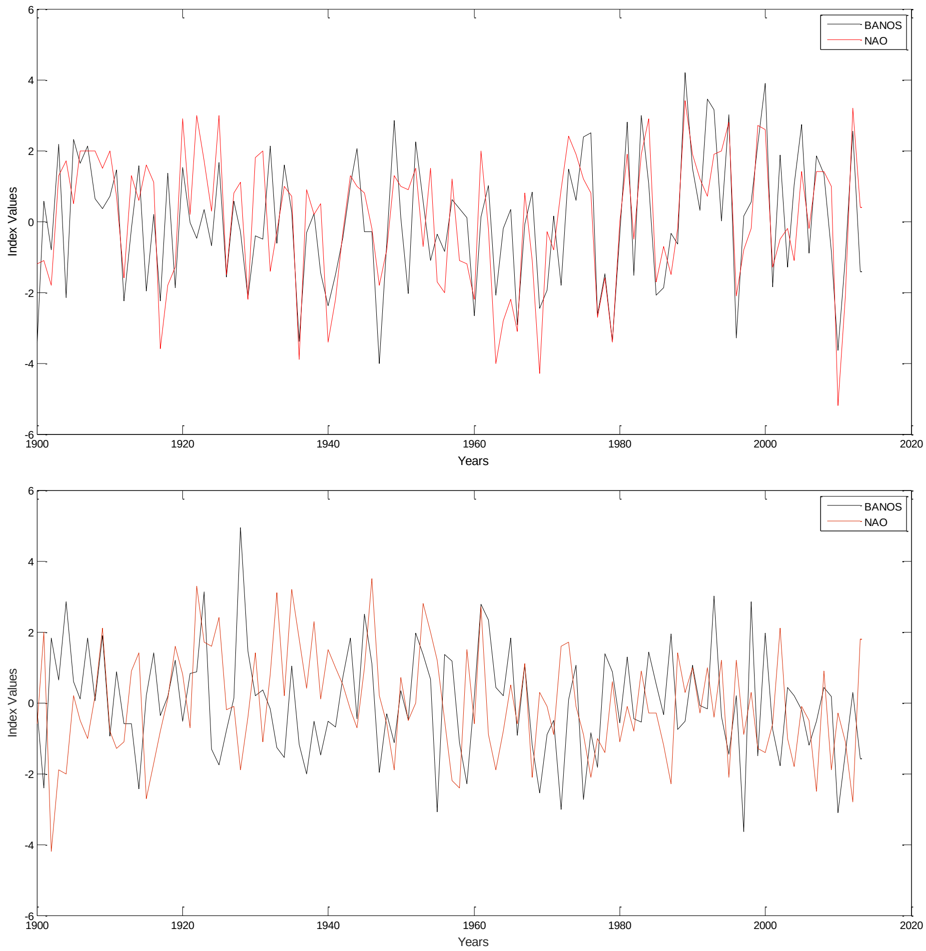
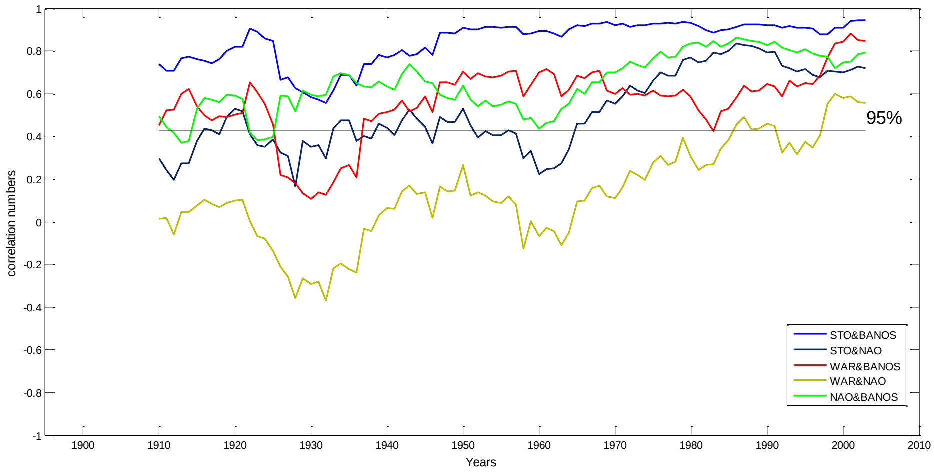


Figure 2.11: The time series of the BANOS-index and the NAO-index for the winter (up) and summer (down) seasons over the period 1900-2013.

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 2.12.



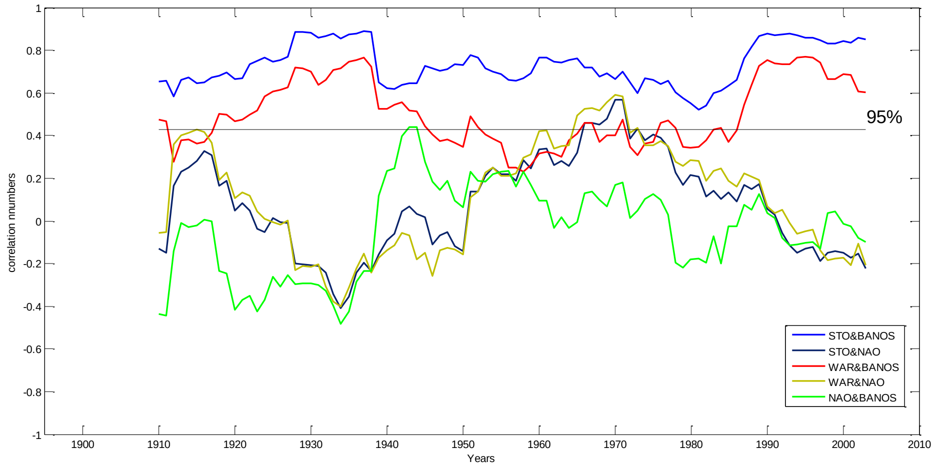


Figure 2.12: The associated correlation values of variables based on the 21-year running windows for the winter (up) and summer (down) seasons. Time series are de-trended in every 21-year period. The value of correlation significance at the 95% level (two-tailed) is ±0.43 for this length.

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 gliding correlations between the stations and the NAO-index resulted in weak or non-significant relations (r<0.43) over the period 1900-2013 in wintertime.

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. 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 in summertime. Overall, this link between the stations and NAO is very weak in summertime.

2.4.6 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 2.13.

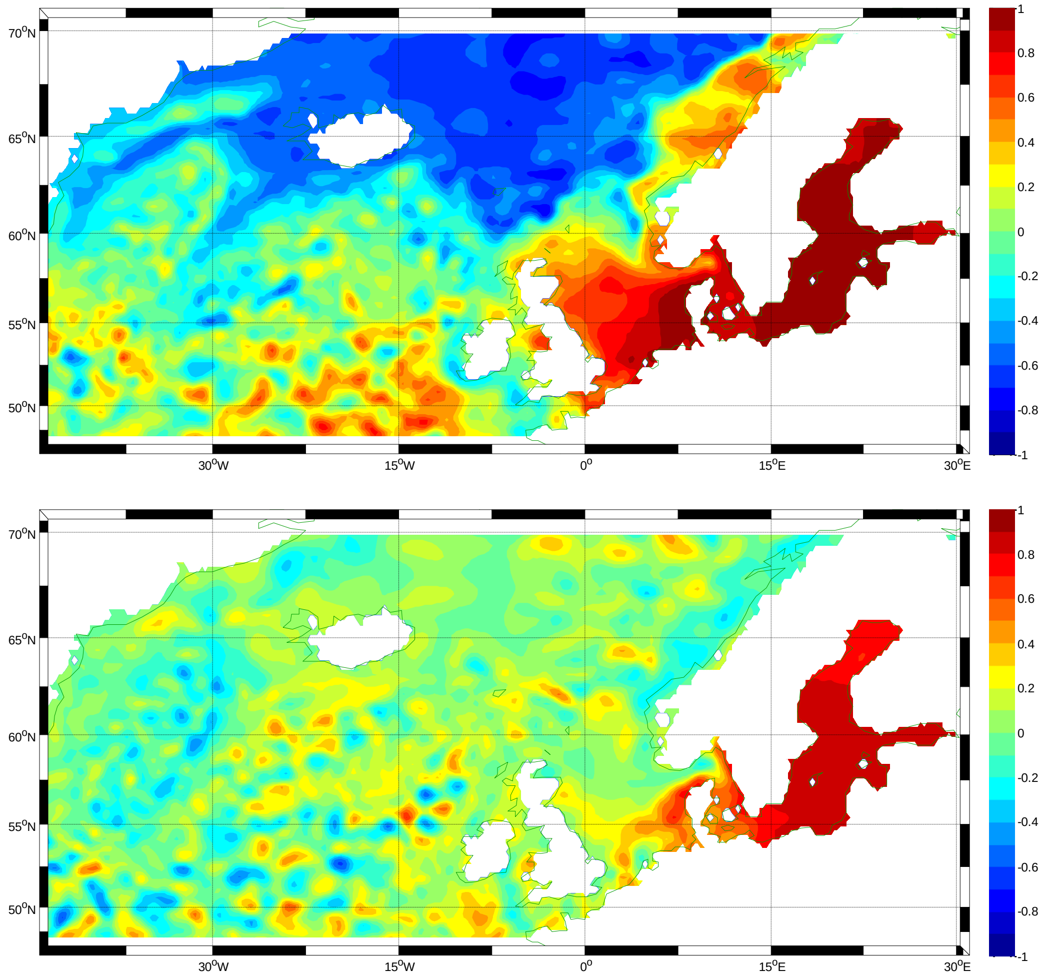


Figure 2.13: The correlation patterns between the SLA grids and the BANOS-index for the winter (up) and summer (down) seasons over the period 1993-2013.

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 2.1, 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.

2.4.7 Sensitivity of satellite SLAs 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, the sensitivity of the sea-level to the BANOS-index is estimated from the 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 2.14.

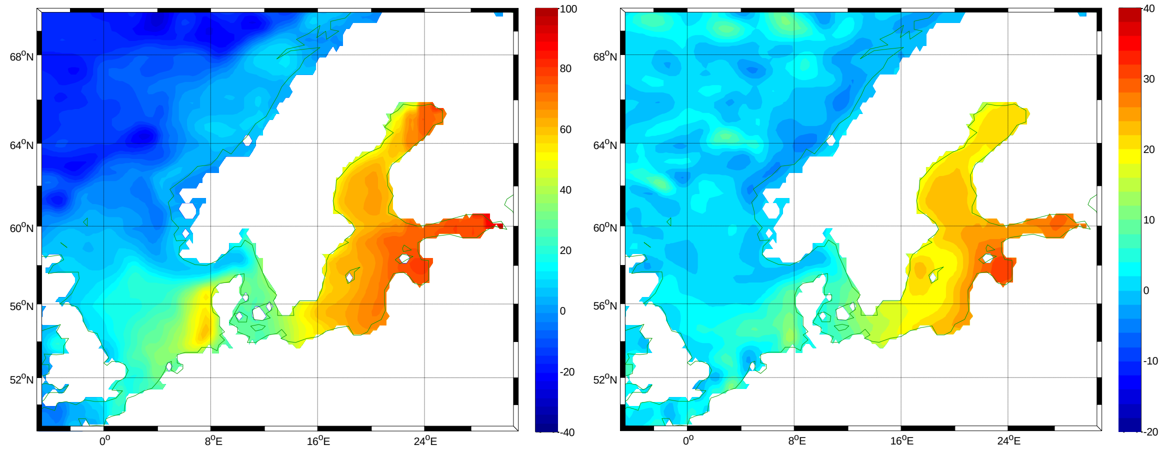


Figure 2.14: The sensitivity values of the SLAs to the BANOS-index for the winter (left) and summer (right) seasons over the period 1993-2013. Note the different scales in the colours.

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.

2.4.8 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.

2.4.8.1 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 scale. 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).

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 18.09 mm and of 7.02 mm per 1 hPa change in the described SLP field differences for wintertime and for summertime, respectively.

In 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 62.23 mm u^{-1} (3.44*18.09) in wintertime and of 9.76 mm u^{-1} (1.39*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 62.23 mm (9.76 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.

2.4.8.2 The contribution of net energy flux

Net 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 the Earth 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 (Equation 2.1).

$$Q_{nef}+^{\downarrow} = SW_{net} - (LW_{net}+SH_{net}+LH_{net}) \qquad (2.1)$$

Qnef is the net energy flux, defined here positive downward. SWnet is the net downward shortwave radiation, LWnet is the net upward longwave radiation, SH is net upward sensible heat flux and LH is the net upward latent heat flux. After computing the Qnef 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 2.15.

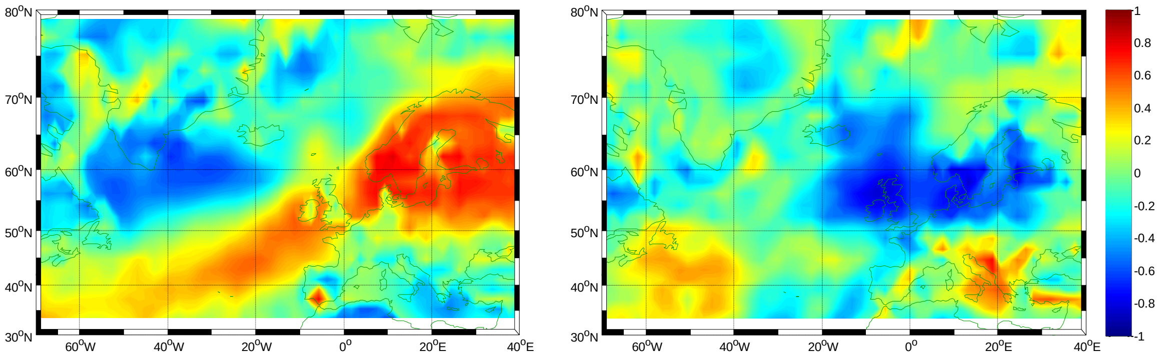


Figure 2.15: The correlation patterns between the Qnef (+↓) and the BANOS-index in wintertime (left) and summertime (right) over the period 1949-2013.

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}) (r=0.59) in wintertime. This represents an average increase in energy (absorbedminus-emitted) of 2.5e7 (J/winter m^{-2}) 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. 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.

2.4.8.3 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 Equation 2.2.

$$E = \frac{Q_{lat}}{L_e \rho_W} \qquad (2.2)$$

where Q_{lat} is the latent heat flux (W m^{-2}), L_e is the latent heat of water vaporization (2257 kj 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 2.16.

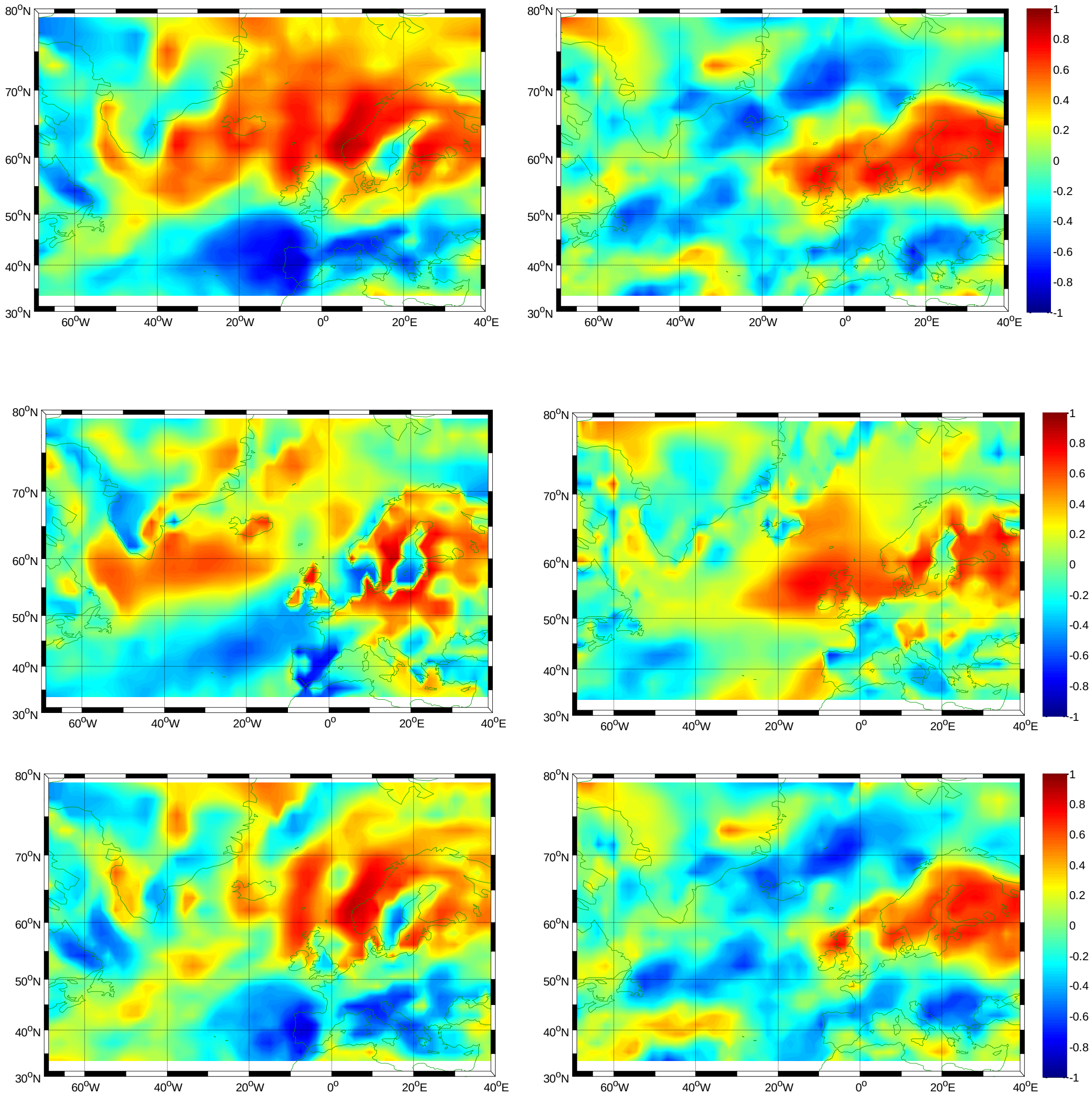


Figure 2.16: The correlation patterns of precipitation (top), evaporation (middle) and freshwater flux (bottom) to the BANOS-index in wintertime (left) and summertime (right) over the period 1949-2013.

In summertime, the correlation patterns between the BANOS-index and precipitation and between the BANOS-index and freshwater flux display similar results except for the western 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 to strongly positive into the eastern side and western side of the Baltic Sea centre. 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 2.17.

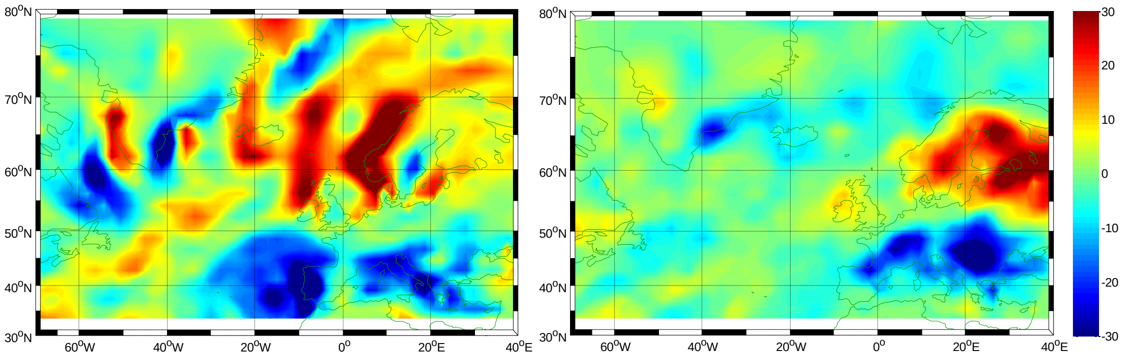


Figure 2.17: The sensitivity patterns of the freshwater flux grids per unit change in the BANOS-index in wintertime (left) and summertime (right).

In the right panel of Figure 2.17, 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 2.17 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 ~10 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.

2.4.8.4 The contribution of 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 2.8), the wind flow linked to the BANOS pattern is slightly different to that indicated by the NAO pattern (Figure 2.9). 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 2.1) 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 2.10-left) wind seems to generate similar direction of the water transport as the NAO pattern (Figure 2.10-right) does over the transition zone. This indicates that the wind forcing mechanism in summertime can be similar to the case of the NAO.

Figure 2.18 shows the Ekman transport caused by the wind related to the BANOS pattern assuming that the Ekman layer is not interrupted by bathymetry of shallow water.

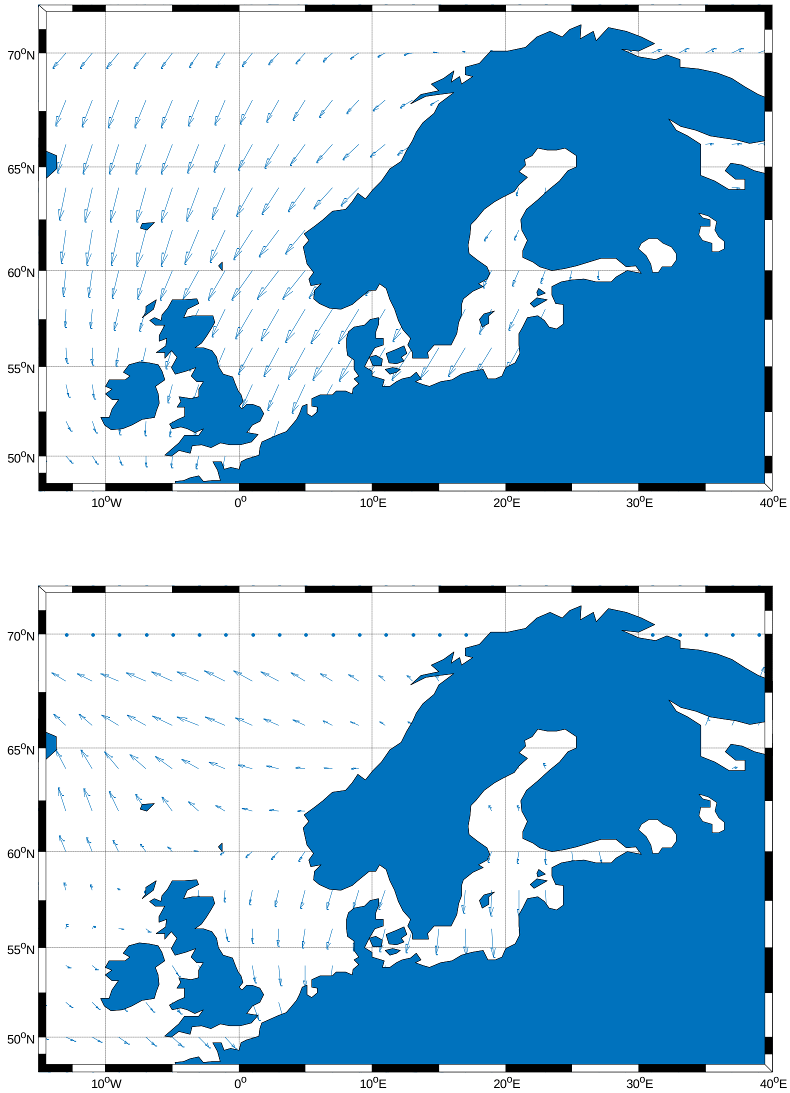


Figure 2.18: The representatives of the Ekman transport vectors are generated from correlation gradients of the BANOS patterns in wintertime (upper) and summertime (lower). Assuming that Ekman spiral is not interrupted by the topography.

The vectors shown in Figure 2.18 represent the expected Ekman transports in the Baltic Sea and North Sea basins. For instance, concerning only the North Sea basin, if bathymetry does not interrupt the Ekman spiral, Ekman transport of the water which is generated by the BANOS-related south-westerly winds, can move in south-westward direction towards the German, Dutch and UK coastlines.

2.5 Conclusions

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 scales. The main conclusions of this study are as follows:

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 wintertime.

   - 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.

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

The centennial trends are likely determined by climate change and centennial vertical land movements. However, coastal sea-level trends in the Baltic Sea display decadal-scale deviations around a centennial trend. This chapter investigates 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 underlying factors, apart from the effect of atmospheric circulation, on decadal sea-level trend anomalies.

For this analysis, tide gauge records, sea surface height reconstructions and climatic data sets have been used. Decadal trends of climatic data sets are statistically linked to decadal trends of sea-level data sets. The analysis indicates that atmospheric forcing is a driving factor on decadal sea-level trends, however, its effect is geographically heterogeneous.

To identify the influence of the large-scale oceanic forcing on the Baltic Sea level trends, we also filter out the signature of atmospheric variability on the Baltic Sea level by a multivariate linear regression model. Based on the residuals of this regression model, we found an indication of a common underlying factor leading decadal sea-level trends into similar direction in the whole Baltic Sea region. The main results of this study show that precipitation has a lagged effect on decadal sea-level trend variations from which the signature of atmospheric effect is removed.

3.1 Introduction

Global mean sea-level trend has risen over the 20th century with an approximate rate of 1.7 mm/year, with higher rates of about 3.2 mm/year measured by satellite altimetry over the past 30 years (Nerem et al. 2010; Church and White 2011). 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/year, whereas immediately further south in the mid-latitude North Atlantic, the sea-level trends may become negative, of the order of -5 mm/year. In the Pacific Ocean, similar contrasts can be also observed. In the Tropical Western Pacific, these trends may attain a value of 15 mm/year, whereas in the mid-latitude Eastern Pacific the trends are negative, of the order of -5 mm/year. 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 (Milne et al. 2009; Cazenave and Llovel 2010; Carson et al. 2016).

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.

The Baltic Sea is a unique basin of the Earth oceans. It is one of the largest brackish water with 415,000 km^2 surface area and volume of 21,700 km^3 and connected to the North Atlantic Ocean only through the narrow and shallow Danish Straits. The Baltic Sea is strongly modulated by large scale atmospheric circulation, hydrological processes in the catchment area and by the limited water exchange due to its narrow connection to the North Sea (e.g. Leppäranta and Myrberg 2009).

The Baltic Sea provides some of the longest tide-gauge records in the world, some of them covering almost the last 200 years. Previous studies have shown that the sea-level records display relatively large variations of decadal trends (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/year (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/year to 2.5 mm/year. 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 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 focus on the interannual variations of sea-level, we statistically analyse sea-level and climate decadal trends. The analysis is accomplished 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.

So far, most studies about sea-level variability in the Baltic Sea have focused on understanding its variability at interannual and decadal time-scales. 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).

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) 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. As their main conclusion, they suggested that sea-level variations are influenced by different factors in winter and summer seasons. Hünicke et al. (2008) identified that, on the one hand, sea-level variations at central and eastern Baltic Sea are well described by the SLP alone, but that area-averaged precipitation significantly modulates the decadal sea-level variations in the southern Baltic.

Beyond the atmospheric forcing on Baltic Sea level, we also explore other possible mechanism that may responsible for the decadal variability of Baltic Sea sea-level trends. The most obvious contributor is variations of the sea-level in the North Atlantic and the North Sea. 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 forcing 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 forcing.

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 and the Atlantic Multidecadal Oscillation (AMO).

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.

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. As an advantage of carrying out the analysis on gliding trends, we are able to compare trend anomalies deduced from absolute (SSHA) and relative (tide gauge) sea-level as well as climatic time series without any further process.

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/year. However, the trend of vertical land movement is around of -1 mm/year at the south coast of Baltic Sea (Ekman 1996, Peltier 2004, Lidberg et al. 2010, Richter et al. 2011). Because of focusing on climate-induced sea-level variability in the Baltic Sea region, we need to remove the GIA effect from sea-level time series.

Since the GIA-induced trend of the Baltic Sea level is not varied even for a few centuries period, the GIA does not cause an anomaly in the sea-level for 11-year gliding trends. Therefore, as one of the lateral outcomes of the gliding trend method, we filter out the GIA effect from tide gauge time series by using decadal trend anomalies which are not modulated by the GIA-affected signal.

Our research objectives can be summarised in the following questions: (1) How do the long-term trend relations alter seasonally and spatially between sea-level and climatic factors? (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 the 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.

3.2 Data

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

3.2.1 Sea Level Data

3.2.1.1 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 3.1.

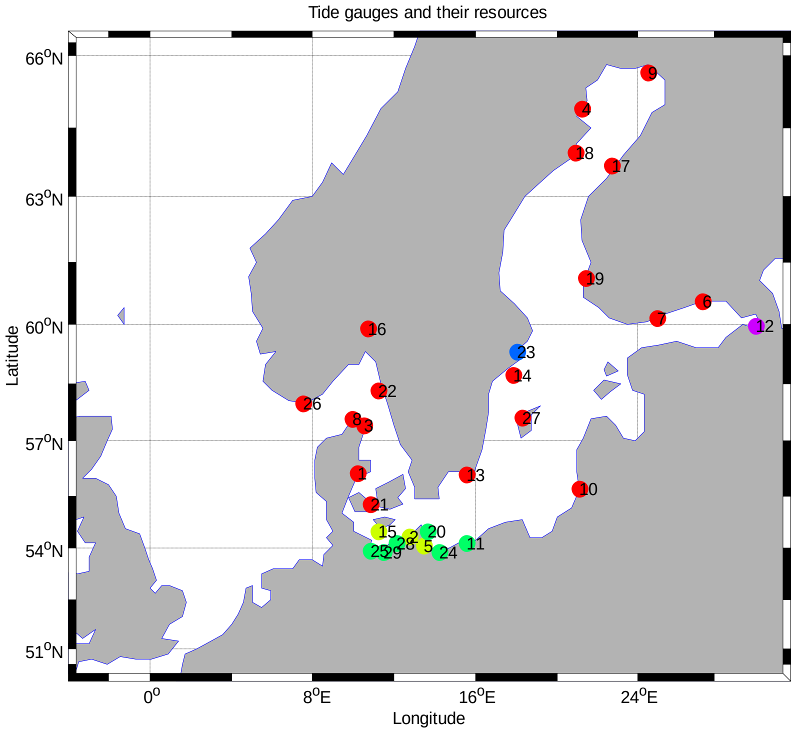


Figure 3.1: Tide gauges with their sources: 1-Aarhus, Barth, Frederikshavn, Furuogrund, 5-Greifswald, Hamina, Helsinki, Hirtshals, Kemi, 10-Klaipeda, Kolobrzeg, Kronstadt, Kungsholmsfort, Landsort, 15-Marienleuchte, Oslo, Pietarsaari, Ratan, Rauma, 20-Sassnitz, Slipshavn, Smogen, Stockholm, Swinoujscie, 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 random data gaps. To cope with this, 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 3.2.

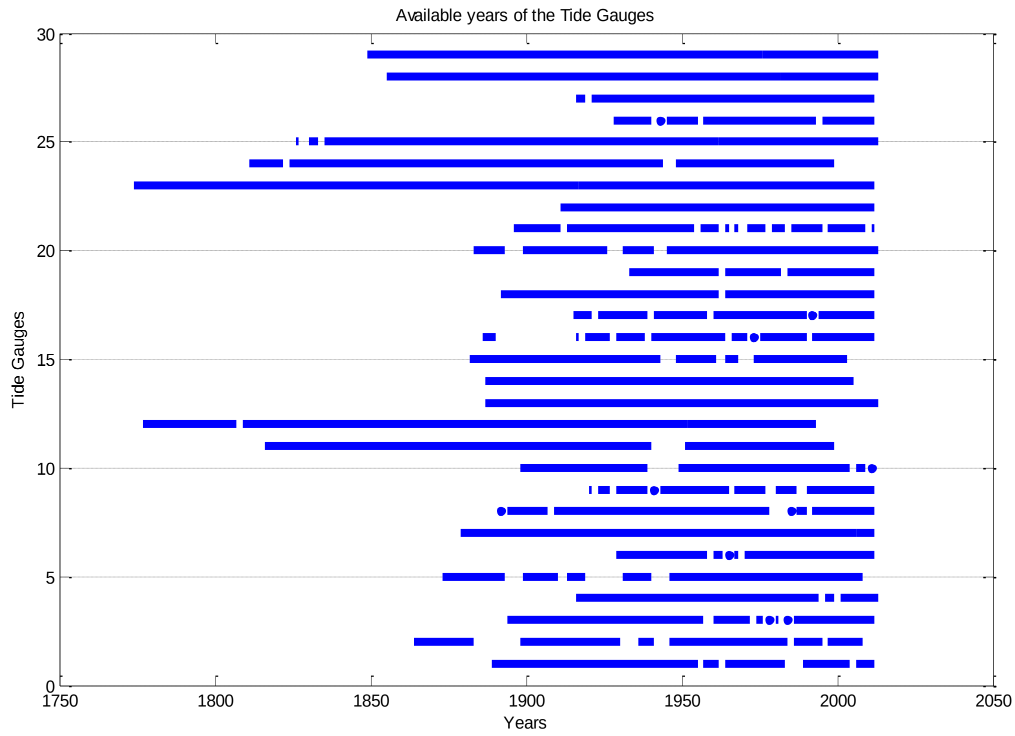


Figure 3.2: Time coverage of the tide gauge observations. Numbers on the y-axis refer to the station number defined in Figure 3.1.

3.2.1.2 Sea Surface Height Anomaly (SSHA)

Together with the tide gauge observations, we used SSHA time series which are reconstructions of tide gauges and satellite altimetry observations 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).

3.2.2 Climatic Data Sets

3.2.2.1 North Atlantic Oscillation (NAO) Index

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

3.2.2.2 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.

3.2.2.3 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 in this study the domain between 70°W-40°E and 30°N-90°N.

3.2.2.4 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 until present and covering the area of 60°W – 40°E and 32°N – 70°N (Morice et al. 2012).

3.2.2.5 Precipitation

We used two different precipitation data sets. One was the gridded 0.5°X0.5° monthly means, from 1901 to 2012 and cover 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 obtained by the National Centers 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.

3.3 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 3.1.

$$y_i = \beta t_i + \beta_0 \qquad (3.1)$$

The y_i denotes the observed value of sea-level, t_i is the ith time step, β is the trend of sea-level with respect to time and β_0 is the y-axis intercept. For the linear regression analyses, we used least square estimation minimizing the sum of squared residuals.

As 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 3.2.

$$Y(t) = ß_0 + \sum_{i=1}^{5} ß_i \, PCSLP_i(t) + e_j(t) \qquad (3.2)$$

Herein, $PCSLP_i(t)$ are the time series of the i^{th} SLP-trend principal component and $ß_i$ are the regression coefficients of the leading principal component vectors. Y is the time series of gliding 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.

3.4 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 3.3 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.

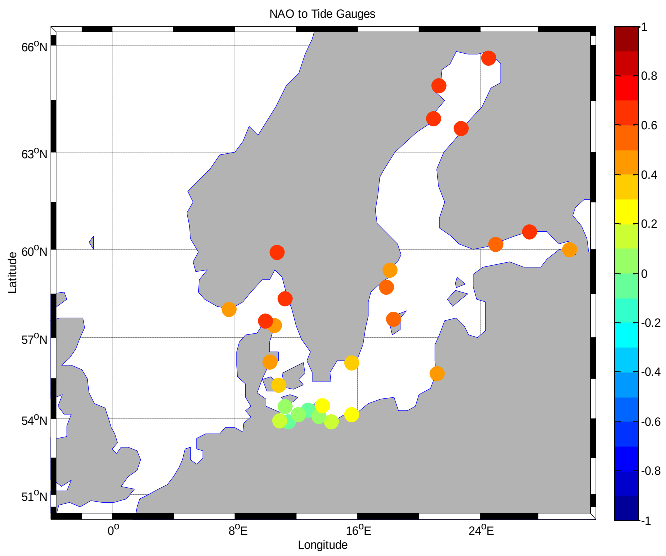


Figure 3.3: Correlations of gliding trends between the NAO-index and 29 tide gauges for wintertime (1900-2012).

The correlation pattern in Figure 3.3 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 54° latitude 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 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 the 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 of the Baltic proper and of the south coast of the Baltic Sea for further analysis, and 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 3.4.

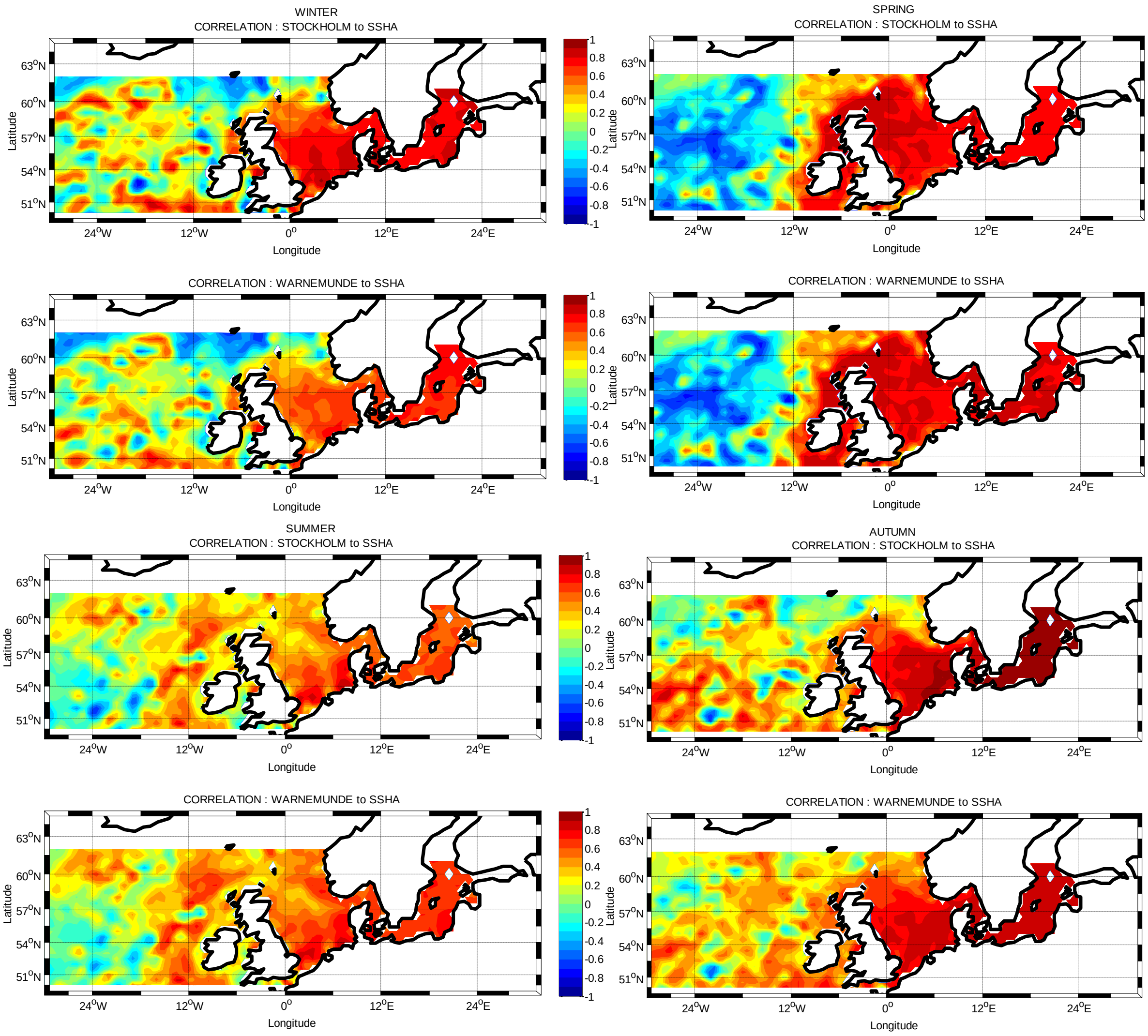


Figure 3.4: Correlations of decadal gliding trends between selected (Stockholm and Warnemünde) tide gauges and SSHA grids for all seasons.

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 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 a 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. We then implemented a multivariate regression model, using those principal vectors as predictors, and decadal sea-level trends of the tide gauges as predictands. 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.

Afterwards, we computed 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 3.5 represents the correlation patterns between the two selected tide gauges and the other seven tide gauges, for both the decadal trends and the residuals resulting from filtering the effect of the SLP trends.

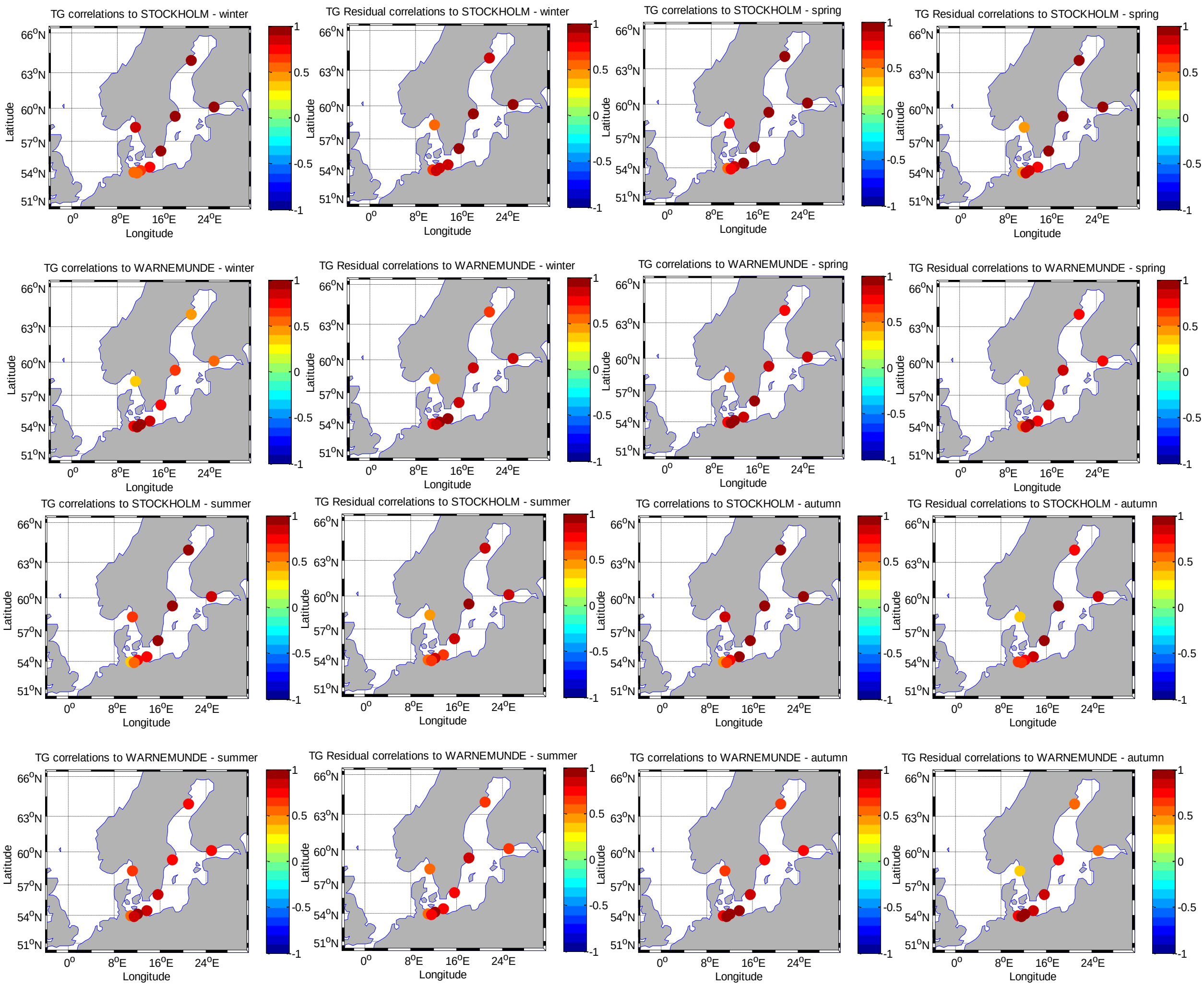


Figure 3.5: Correlation values between sea-level in two representative tide gauges (Stockholm and Warnemünde) and the rest of the tide gauges; left, using the decadal trends, right after removing the effect of SLP trends in all tide gauge records.

Figure 3.5 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 investigation are represented in the Figures 3.6 and 3.7, respectively.

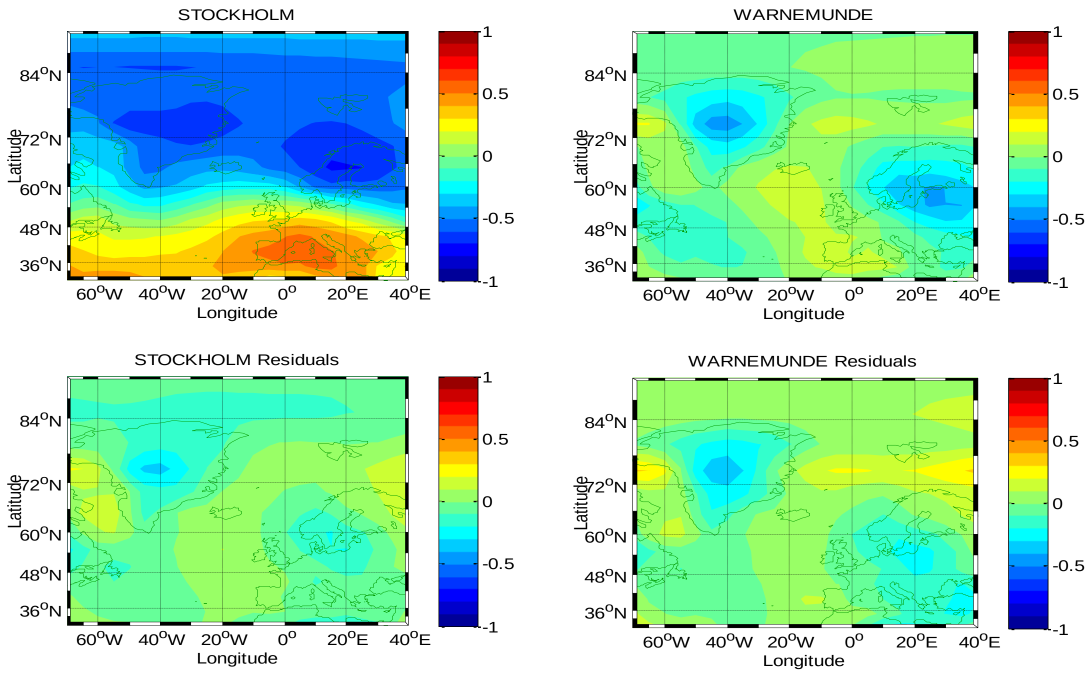


Figure 3.6: The correlation patterns between SLP fields and selected tide gauges. Maps at the top row are the correlation patterns from Stockholm and Warnemünde with atmospheric signal and the bottom row without atmospheric signal.

In Figure 3.6, the two maps in the upper row show the correlation patterns between decadal trends of the tide gauges and 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 3.7.

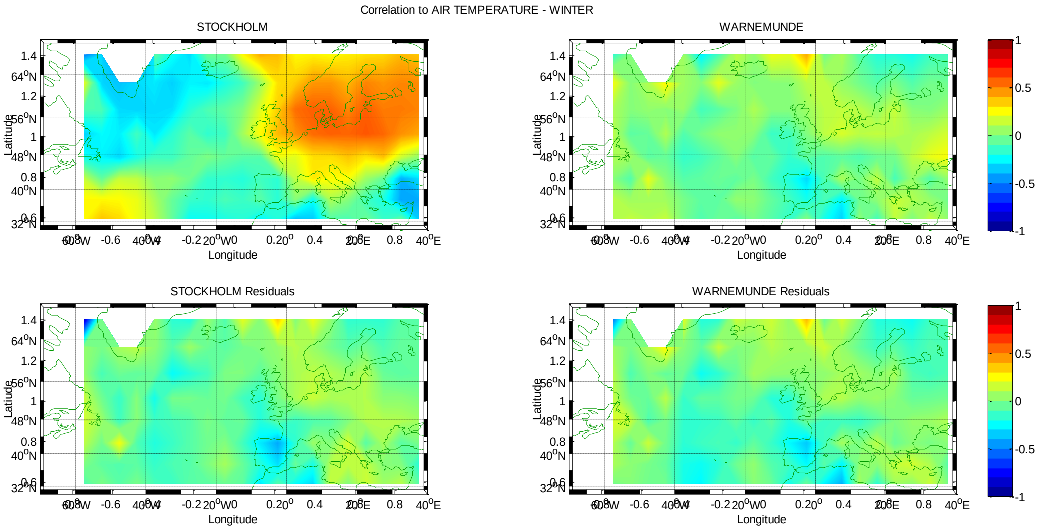


Figure 3.7: The correlation patterns between air temperature and selected tide gauges for winter. The two maps at the top row are the patterns of 11-year gliding trends from Stockholm and Warnemünde involved in atmospheric signal.

The Figures 3.6 and 3.7 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.

In summary, the results suggest that SLP (and therefore 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 3.8. 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 trend residuals.

To investigate a possible underlying effect causing variability in the sea-level trend residuals, we investigated the correlations between the previous season precipitation and the following season tide gauge residuals for all seasons. The results are represented in Figure 3.8.

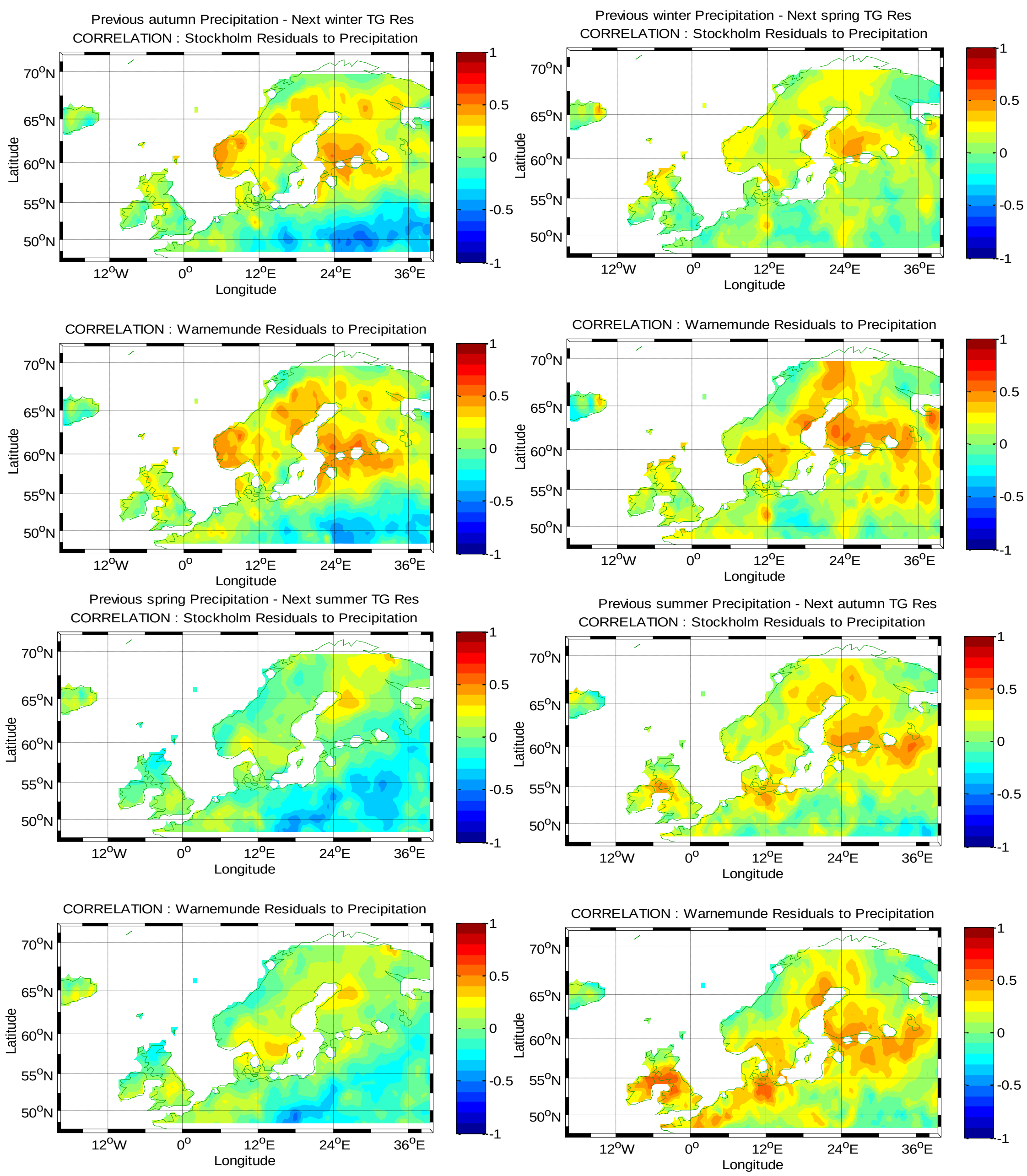


Figure 3.8: The correlation patterns between decadal sea-level trends and the area averaged CRU precipitation trends in the previous season for the period 1901-2012 over the Baltic Sea catchment area.

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 3.9.

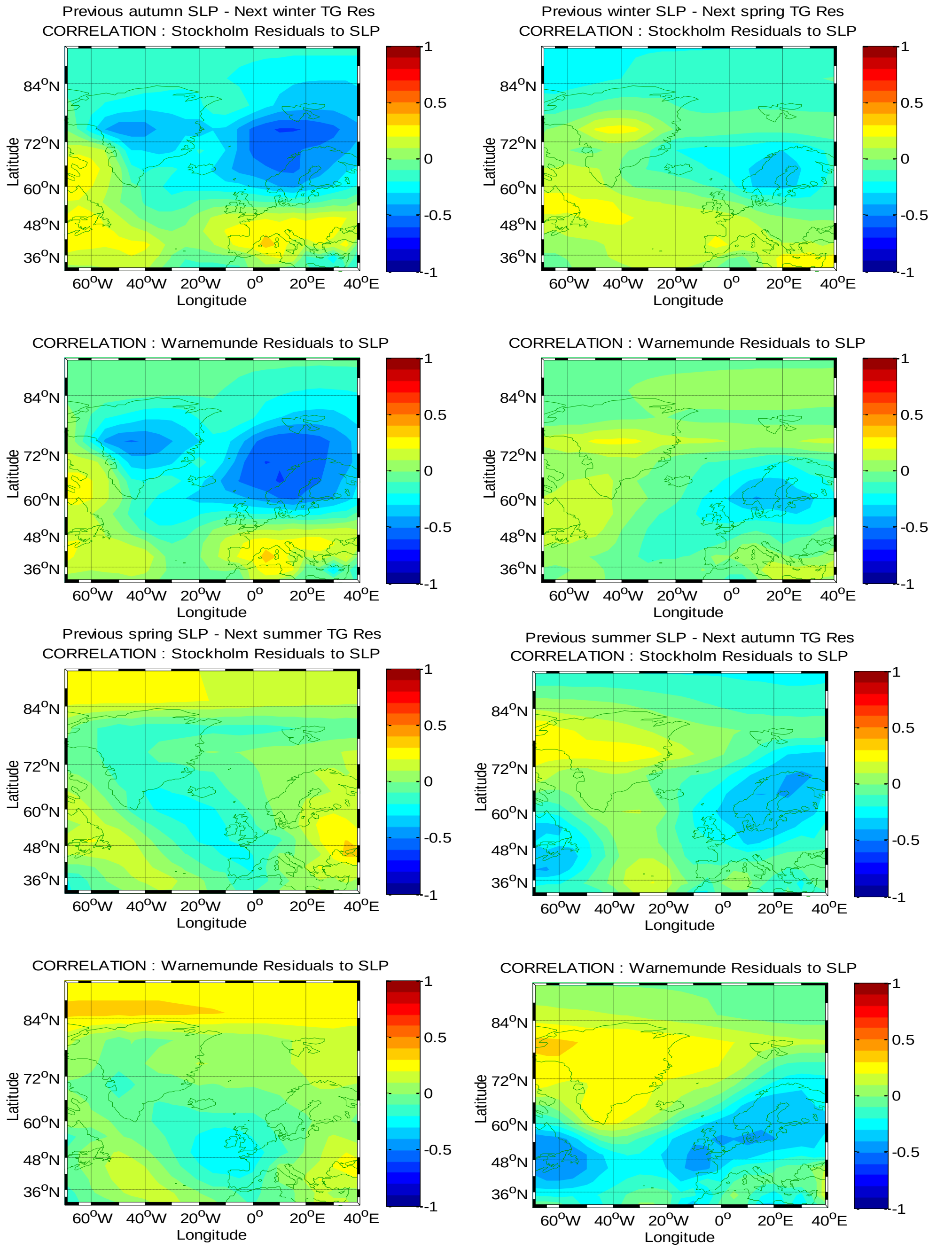


Figure 3.9: The correlation patterns of gliding trends on previous season factor (SLP) and following seasons tide gauge residuals.

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 precipitation 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 resolution. Besides, the time 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 3.1 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 3.1: 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

Table 3.1 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 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 only the results 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 3.10.

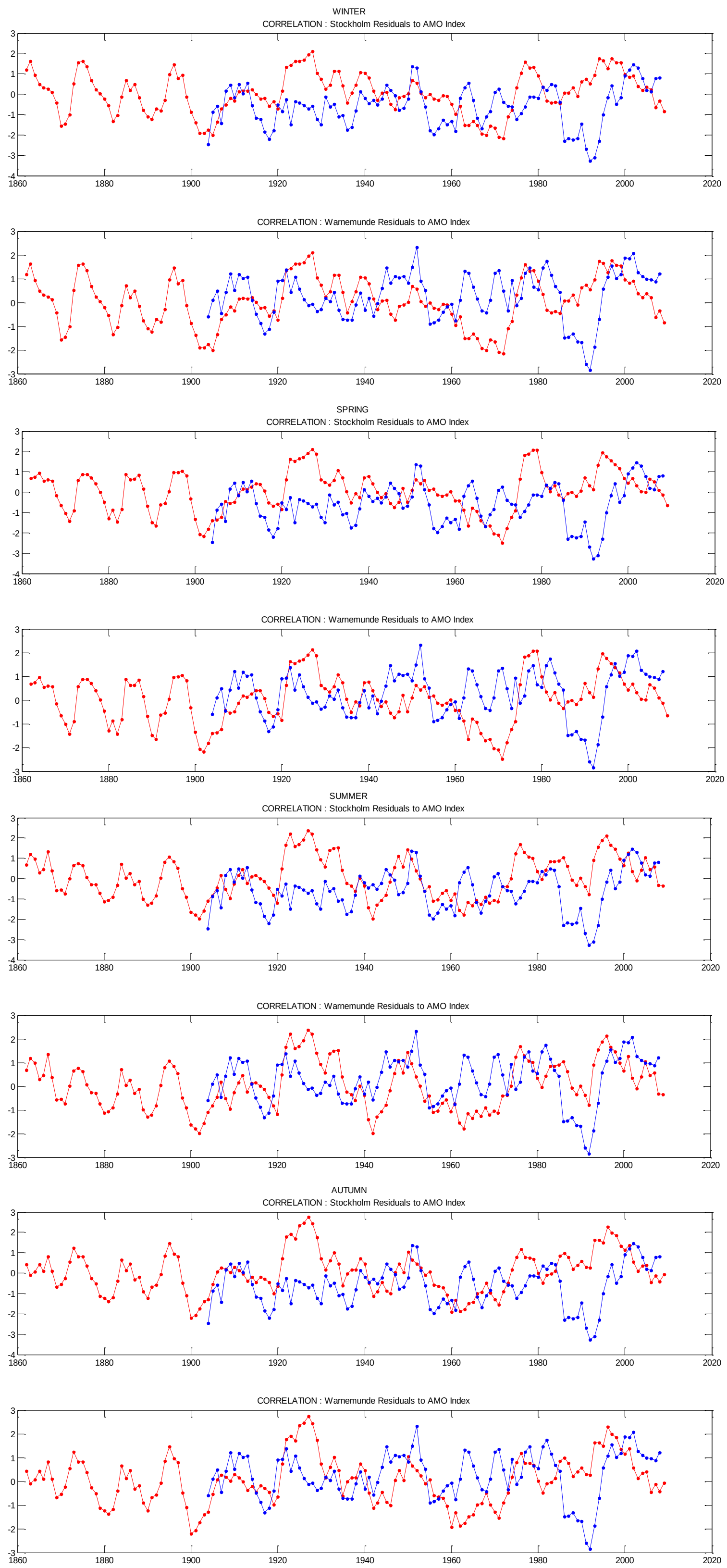


Figure 3.10: The gliding trend time series of the AMO-index(red) and tide gauge residuals (blue) (x-axis: years, y-axis: trend values).

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.

3.5 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 occurs 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.

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 AMO to sea-level trend residuals in the Baltic Sea in any of the four seasons.

4 Projections of the atmosphere-driven Baltic Sea level rise under the RCP8.5 scenario over the 21st century

Large-scale changes in the pressure field, the wind field, heat fluxes and freshwater fluxes can impact sea-level variation depending on the time scale and the region. These changes can also affect long-term sea-level rise along with the rise of water temperatures and melting of land-locked ice.

In Chapter 2, a strong and stable in time connection between an individual mode of the atmospheric circulation and sea-level variability in the Baltic Sea and North Sea region is established. The present chapter uses this stable relationship derived from observations and the future changes in atmospheric circulation simulated by global models to estimate a portion of future sea-level rise in the Baltic Sea over the 21st century.

In particular, the influence of atmospheric circulation on future Baltic Sea level rise under a high-end scenario of greenhouse gas emissions for the period 2006-2100 is estimated. To construct the associated atmospheric index, the sea-level-pressure (SLP) outputs from eight different climate models participating in the phase 5 of the Coupled Model Intercomparison Project (CMIP5) are used. After establishing a linear connection between the atmospheric index and sea-level variability, the Baltic Sea level rise is predicted based on the projected time series of atmosphere index over the 21st century. The results indicate that, although the influence of internal climatic variability is expected to be large, contribution of the atmospheric circulation to sea-level rise will remain relatively small in the Baltic Sea.

4.1 Introduction

Global warming causes global mean sea level to rise mainly due to thermal expansion of the water and melting of land-locked ice. However, regional sea level trends vary with different spatial patterns (Church et al. 2013). Thus, estimating the sea level variability in some regions requires studies focusing on revealing the impact of the regional driving factors on the sea level variability (e.g. Stammer et al. 2013; Slangen et al. 2014; Carson et al. 2016). It is also established that the projected regional sea level rise will depend on the region and the time scale. For instance, Grinsted et al. (2015) explored sea level rise projections in Northern Europe including the Baltic Sea under the Representative Concentration Pathway 8.5 (RCP8.5) scenario. Considering the regional fingerprints of some major sea level components of the global sea level budget like ocean thermal expansion, melting/dynamics of glaciers, ice loss from the Greenland and Antarctic ice sheets and changes in land water storage, their best estimation of relative sea-level at Stockholm over the 21st century under the RCP8.5 scenario is 0.25 m. However, 21st century projections of global mean sea level rise for the RCP8.5 scenario are in the range between 0.52 and 0.98 m (Church et al. 2013). Besides, it is known that the most important factors causing sea level variations in the Baltic Sea from interannual to decadal time scale are connected to variability of atmospheric circulation (e.g. Yan et al. 2004, Jevrejeva et al. 2005, Hünicke and Zorita 2006).

Therefore, modifications in the atmospheric conditions are important driving factors to understand the possible sea-level rise for the near future, especially in the regions like the Baltic Sea where variability of sea level is quite sensitive to the atmosphere driven boundary conditions such as wind, air pressure, air temperature and freshwater flux (e.g. Moeller and Hansen 1994; Leppäranta and Myrberg 2009). Hence, climate-induced change in the modes of atmospheric circulation could modify sea level rise in the Baltic Sea. However, there are only few studies focused on the effect of future circulation changes on sea-level in the Baltic Sea area (BACC II 2015).

Hünicke (2010) analysed the contribution of the sea-level-pressure (SLP) and precipitation to the future sea level changes in the Baltic Sea. Using SLP and precipitation outputs of five different IPCC SRES climate model simulations driven by the A2 scenario, she projected the contribution of these two atmospheric factors on sea-level rise through the 21st century for wintertime based on the established link, derived from observations, between those two atmospheric factors and sea-level. The findings of this study suggested that albeit SLP outputs of three climate models cause statistically significant sea-level rise in the central and eastern Baltic Sea, all analysed models indicate that precipitation will cause significant sea-level trends in the southern Baltic Sea.

Considering that possible modifications in atmospheric modes such as North Atlantic Oscillation (NAO) which can influence the climate in Northern Europe, especially in winter, Cattiaux and Cassou (2013) revisited the potential effect of warming trends due to the increase in greenhouse gas (GHG) emissions on modes of the atmospheric circulation. They compared the trends in the 21st century in the NAO as simulated in the third phase of the Coupled Model Intercomparison Project (CMIP3) A2 scenario with the fifth phase of the Coupled Model Intercomparison Project (CMIP5) RCP8.5 scenario. They found that, although the CMIP3 simulations indicate positive trends in the NAO, no trend is indicated by the CMIP5 simulations. The conclusions of Cattiaux and Cassou (2013) are important to understand and verify the possible projections of the atmosphere-driven sea-level variability in the Baltic Sea region.

Since the modes of the atmospheric variations like North Atlantic Oscillation (NAO) can carry information about large scale changes in the pressure field, wind field, heat fluxes and freshwater fluxes, there are several studies which investigated the link between the NAO and sea-level variability in the Baltic Sea (e.g. Andersson 2002; Hünicke and Zorita 2006). Two main conclusions on that linkage are that NAO has a heterogeneous effect on sea-level variability in spatial domain and this linkage is also not stable in time. More recently, using different contributors like meteorological effects on sea-level trends along the Finnish coast, Johansson et al. (2014) projected the sea-level rise based on the CMIP3 simulations. Investigating the connections of the NAO-index and the zonal component of the geostrophic wind to the interannual sea-level variability, they found that sea-level variability can be explained by 37-46% by the NAO-index, but zonal geostrophic wind explains 84-89% of the variance of sea-level. Based on this connection between zonal geostrophic wind and sea-level variability, they estimated a long-term mean sea-level in the Finnish coast driven by changes in the atmospheric circulation ranging from a 4 cm sink to a 19 cm rise by 2100. This study also proves that the NAO-index may not capture some small scale atmospheric effects which drive the interannual variability of the Baltic Sea level.

Confirming these conclusions, we further investigated the linkage between atmospheric circulation and sea-level variability (Chapter 2). The investigation showed us that there is another mode of atmospheric circulation which is more strongly and steadily over time connected to sea-level variability in the Baltic Sea and the North Sea. In addition, the linkage between that atmospheric pattern and sea-level variability is homogenous in space in the Baltic Sea. We denote this atmospheric variability mode as the Baltic Sea and North Sea Oscillation (BANOS) index which is constructed from the difference of two normalized SLP 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 this study, we estimate the influence of atmospheric circulation in future Baltic Sea level rise under the RCP8.5 scenario over the 21st century. For this estimation, we use SLP outputs of eight CMIP5 models, the BANOS-index and the NAO-index, and sea level records of the Stockholm and Warnemünde tide gauges in wintertime. In addition, it is suggested that large-scale sea-surface-temperature (SST) variations may play a role in modulating the modes of atmospheric circulation in the North Atlantic, in particular the NAO (e.g. Czaja et al. 2003, Rodwell 2003). It is therefore possible that a mode of atmospheric variability in the North Atlantic can be slowly directed by the multidecadal evolution of the SST (e.g. Greatbatch 2000). Based on this perspective, we investigated the connection in the multidecadal trends between the atmospheric indices and the extended North Atlantic/Europe region air temperature. A possible connection between those variables would suggest the existence of future global warming signal in the related modes of atmospheric circulation by BANOS and NAO.

Accordingly, this study has five main parts: The comparison of the CMIP5 model skills, predicting atmosphere-driven Baltic Sea level trend under the RCP8.5 scenario over the 21st century, testing the prediction skill by using the Brier Skill Score method, investigating the influence of internal climatic variability on the associated sea-level trends and exploring the connection between the modes of the atmospheric circulation and the large-scale air temperature.

We first intended to test the skill of the CMIP5 models to simulate the present climatology. Therefore, as the first research question of this study, we analyse how well the CMIP5 models simulate present-day climatology of the SLP over the Baltic Sea and North Sea region. In a second step, we established a linear link between atmospheric indices (NAO and BANOS) and sea-level the Stockholm and Warnemünde tide gauges using observations. Based on that linear connection, we were interested in the skill of associated statistical model. Therefore, we tested whether the statistical model is good enough to present the connection between modes of the atmospheric circulation and sea-level variability. Using the established connection, we further investigate whether a Baltic Sea level rise is expected to occur due to changes in the atmospheric circulation under the RCP8.5 scenario over the 21st century.

An additional goal was to quantify the variability of the simulated atmospheric trends that are due to the internal climate variability, and not to the external forcing, allowing us to infer a significance of the estimated long-term trends. This is achieved by taking three different ensemble members of eight CMIP5 models into account. Therefore, we selected the CMIP5 models which provide ensemble of simulations with at least three ensemble members. These models are CanESM2, CCSM4, CSIRO-Mk3.6.0, FIO-ESM, HadGEM2-ES, IPSL-CM5A-LR, MIROC5, MPI-ESM_LR (Taylor et al. 2012). In the last step, we explored whether the relevant modes of atmospheric circulation are affected by large-scale air temperature on multidecadal time scale. The possible effect would prove the impact of large-scale air temperature on that atmosphere driven sea-level variability in the Baltic Sea.

This study is restricted to the winter season and structured as follows: Data section explains the data used in this study. The next section outlines the methods that we apply to analyse the data sets. The results and conclusions are presented in the sections 4 and 5, respectively.

4.2 Data

Winter (December-to-February) means of following data sets were used in this study.

4.2.1 Sea Level Observations

Winter means of the Stockholm and Warnemünde tide gauges are used to estimate the sensitivity of the Baltic Sea level to the NAO-index and BANOS-index. These stations are representative stations which are located in the central and southern parts of the Baltic Sea. The observations are provided by Permanent Service for Mean Sea Level (Holgate et al. 2013) and Ekman (2003) long-term sea level records.

4.2.2 Climatic Data

4.2.2.1 NAO-index

The 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 monthly time series of NAO-index that we used was computed by Hurrell et al. (2016a) using the differences between normalized anomalies of two sea-level-pressure stations; Lisbon, Portugal and Reykjavik, Iceland.

4.2.2.2 SLP data

There are three types of SLP data used in this study.

First, to construct the BANOS-index, we used the SLP data which is 5°x5° gridded Northern Hemisphere monthly means, from 1900 to 2013, provided by the National Centre for Atmospheric Research (NCAR;Hurrell et al. 2016b). This construction was carried out as the difference between normalized SLP fields over the geographical points (5°W, 45°N) and (20°E, 70°N). These two grid-cells are fixed, and define the BANOS-index for the period 1900-2013.

Second, we used the SLP outputs from eight different CMIP5 models (Taylor et al. 2012) to project the variability of two atmospheric indices, BANOS and NAO, over the 21st century. Three realizations (r1i1p1, r2i1p1, r3i1p1) for each model were used in this study under the boundary condition of the RCP8.5 scenario. The detailed information on the CMIP5 models is given in Table 4.1.

Table 4.1: The list of the selected CMIP5 models with individual grid resolution. At this stage, here, the models are ranked based on the alphabetical order.

Model Name	Institute ID	Atmospheric Grid	
		Latitude	Longitude
CanESM2	CCCMA	2.7906	2.8125
CCSM4	NCAR	0.9424	1.2500
CSIRO-Mk3.6.0	CSIRO-QCCCE	1.8653	1.8750
FIO-ESM	FIO	2.7906	2.8125
HadGEM2-ES	MOHC	1.2500	1.8750
IPSL-CM5A-LR	IPSL	1.8947	3.7500
MIROC5	MIROC	1.4008	1.4063
MPI-ESM-LR	MPI-M	1.8653	1.8750

The SLP outputs of those models were used in order to project the modes of the atmospheric variations under the RCP8.5 scenario. RCP 8.5 was developed using the MESSAGE model and the Integrated Assessment Framework by the International Institute for Applied Systems Analysis (IIASA), explained in Riahi et al. (2007). The RCP8.5 scenario is a concentration pathway with the highest defined rates of GHG emissions. This scenario consists of assumptions that there will be high population and relatively slow income growth with modest rates of technological change and energy intensity improvements. In the long term, this will lead to high energy demand and GHG emissions in absence of climate change policies. Like the other RCPs, the RCP8.5 is named based on the radiative forcing value in the year 2100 relative to pre-industrial value, + 8.5 W/m^2, (Riahi et al. 2011). Since it is assumed that reader is familiar with the climate scenarios, we did not intend to inform reader on the RCP8.5 scenario in detail.

Third, we compared the 30-year SLP means of historical runs of eight CMIP5 models outputs with SLP reanalysis data provided by National Centers for Environmental Prediction (NCEP)/ National Center for Atmospheric Research (NCAR) (Kalnay et al. 1996). The goal of this comparison was to assess the model performance in simulating the SLP climatology. For this comparison, we selected the period 1971-2000 which is a standard reference period in climatology in order to characterize present normal climate conditions over a certain area. This comparison requires same grid structure with the same resolution, we interpolated all SLP grids of each model onto the regular NCEP 2.5° x 2.5° grid by using bilinear interpolation prior to assessment of the climate models. The selected region covers the geographical area between (20°W – 37.5° E) longitudes and (47.5° N – 70° N) latitudes.

4.2.2.3 Surface Air Temperature

We used the surface air temperature outputs of those CMIP5 models covering the extended North Atlantic region (Area limits: 90°E to 50°W and 20°N to 80°N). The aim was to examine the possible effect of the large-scale temperature variations on the mode of atmospheric circulation on the decadal time scale (Taylor et al. 2012).

4.3 Methods

Concerning the methods that we used in this study, this section can be divided into three parts.

4.3.1 Method for model assessment

We first evaluate the skill of the considered CMIP5 climate models in simulating the present-day SLP climatology. For this evaluation, we computed the similarity of the spatial SLP means, their root-mean-square (RMS) differences and their respective spatial standard deviations of the SLP fields of the reanalysis and of the chosen CMIP5 climate models. To represent the results, we use Taylor diagram (Taylor 2001) graphically summarizing the similarity of the climate models with respect to reference data set. Based on those computed relative values, we compare the CMIP5 models for the projections of atmosphere-driven sea level trends in order to evaluate the model performances. For this comparison, we carry out three different computations:

$$\sigma_r^2 = \frac{1}{N}\sum_{n=1}^{N}(r_n - \bar{r})^2 \tag{4.1a}$$

$$\sigma_f^2 = \frac{1}{N}\sum_{n=1}^{N}\left(f - \bar{f}\right)^2 \tag{4.1b}$$

$$R = \frac{\frac{1}{N}\sum_{n=1}^{N}(f_n - \bar{f})(r_n - \bar{r})}{\sigma_f \sigma_r} \tag{4.2}$$

$$E'^2 = \frac{1}{N}\sum_{n=1}^{N}\left[(f_n - \bar{f}) - (r_n - \bar{r})\right]^2 \tag{4.3}$$

where r is a reference field, f is a test field, R is the correlation coefficient, E′ is centred root-mean-square (RMS) difference, and standard deviations of reference field and of test field computed through (Eq. 4.1a) and (Eq. 4.1b), respectively. The overall mean of a field is marked with an overbar.

Essentially a Taylor diagram quantifies characteristics of the statistical relationship between two fields in terms of their centred root mean square difference, their correlation and standard deviations. Here, one field (reanalysis data) should be chosen as the reference field and the other field (model simulation) is the test field.

Note that prior to the CMIP5 model assessments, we interpolated all SLP grids of each model onto the regular NCEP 2.5 x 2.5° grids using bilinear interpolation.

4.3.2 Method for establishing linkage between atmospheric circulation and sea level

The second part was to establish the linkage between the modes of the atmospheric circulation and sea level variability. At this part, we initially calculate the correlation of the sea-level records and the atmospheric indices on the interannual time scale. Later, we use a linear regression by considering the atmospheric indices as the predictors and sea level observations as the predictands. The estimated regression coefficient represents the sensitivity of sea level to the specified mode of atmospheric circulation. After establishing the connection between sea level and atmospheric indices, we estimated the trends of atmospheric indices by taking the difference between two normalized SLP fields (space-fixed, defined in previous section) of eight different CMIP5 models for the period 2006-2100. Then, by assuming that the link between modes of atmospheric circulation and sea level will remain unchanged over the 21st century, we estimated the trends of the Baltic Sea level together with associated uncertainty values at the 95% confidence level.

In addition, the skill of the regression is evaluated by using the Brier Skill Score (BSS) method which is also known as Reduction of Error (von Storch and Zwiers 1999). The BSS can be defined as in the following (Equation 4.4).

$$BSS = 1 - \frac{\sum_t^N (p(t) - o(t))^2}{\sum_t^N (o(t))^2} \qquad (4.4)$$

The p(t) and o(t) values are the differences between predicted (observed) values at time t and the individual means in the calibration period. The sum covers the validation (1900-1959) and calibration (1960-2013) periods. One advantage of using the BSS is that it considers the changes in the means between validation and calibration period. The BSS values can range between 1 (perfect prediction) and -∞ which indicates a skill worse than climatology.

4.3.3 Method for examining the possible effect of large-scale temperature variation on the mode of atmospheric circulation

The third part of this study was to understand whether large-scale temperature variation over the North Atlantic region impacts the mode of atmospheric circulation which is constructed from space fixed points as the BANOS-index. For this purpose, we first computed the 21-year gliding trends of surface air temperature and the BANOS-index for the period 1850-2100, by using the historical runs (covering the period 1850-2005) and RCP8.5 runs for the period 2006-2100. Then, we tested the co-variation of 21-year gliding trends between surface air temperature and the BANOS-index.

4.4 Results

4.4.1 Assessment of the CMIP5 Models

To assess the skill of the eight CMIP5 climate models in simulating the present-day winter SLP pattern, we compared the SLP fields of one simulation (r1i1p1) yielded from CMIP5 with reanalysis SLP fields in the extended Northern European region for the period 1971-2000. The Taylor diagram is used to represent the model performances based on the relative RMS error, standard deviation of SLP simulations with respect to SLP reanalysis winter means. The spatial correlations of SLP fields between the CMIP5 model outputs and reanalysis data sets are also illustrated in the Taylor diagram. The results are displayed in Figure 4.1.

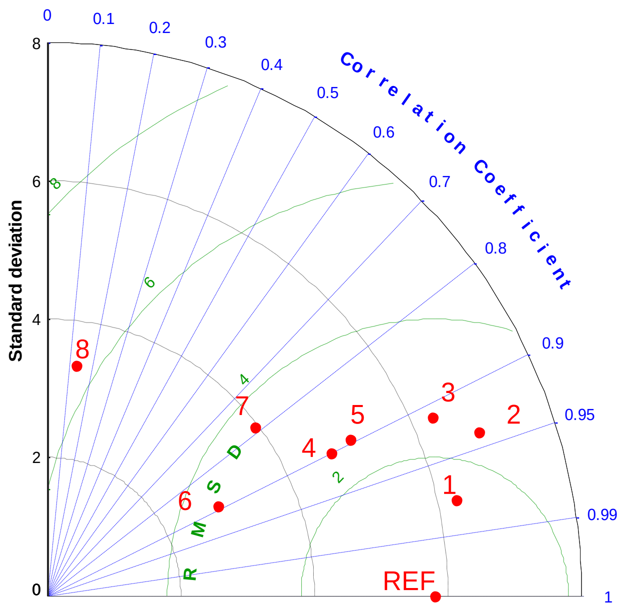


Figure 4.1: Taylor Diagram displaying the statistical comparison of 30-year SLP means considering the relative differences of eight CMIP5 models ((1) MOHC: HadGEM2ES, (2) NCAR: CCSM4, (3) CCCMA: CanESM2, (4) MPI-M: MPI-ESM-LR, (5) FIO: FIO-ESM, (6) MIROC: MIROC5, (7) IPSL: IPSL-CM5A-LR, (8) CSIRO-QCCCE: CSIRO-Mk3.6.0) with respect to SLP reanalysis values (REF). Models are ranked and numbered based on their relative performances. The SLP means were selected over the geographical area covering the Baltic Sea basin.

Figure 4.1 is the Taylor diagram representing the relative skill of eight CMIP5 models with respect to reference data set, in this case the reanalysis. Based on the equations which are given in the method section, statistics for those eight models were calculated, and a ranking assigned to each model reflecting its performance. The centred RMS between model and reference is proportional to the distance to the point on x-axis marked as “REF”. The green arcs represent the relative RMS values. The standard deviation of a model is proportional to the radial distance from the origin. Correlation zones are separated by blue lines and become greater towards the x-axis.

In a Taylor diagram, a point, which agrees best with the reference field, should be closest to the point marked “REF”. Keeping that in mind, we evaluate the model performances in terms of relative statistical similarities between reference and model results based on the correlation, RMS difference and standard deviations. On average, most of the CMIP5 models are found to reasonably well represent the reanalysis SLP fields. The best performing model is HadGEM2-ES from Met Office Hadley Centre (MOHC) according to all criteria. Six CMIP5 models are found to be highly coherent ($r>0.89$) with respect to reference field.

In some cases, the models are performing relatively better or worse depending on other criteria. For example, the model FIO-ESM performs slightly better than the model MPI-ESM-LR if we only consider the relative standard deviations. However, the other statistical indicators, centered RMS difference and correlation, imply that MPI-ESM-LR is performing better than FIO-ESM. We also encountered this case when we compared the performance of the CCSM4 and CanESM2 models. Here, in this kind of cases, our key criterion for ranking the model performance was based on a high correlation and a relative RMS error between the involved model and reference field.

It should be also noted that although the model MIROC5 performs better than the models IPSL-CM5A-LR and CSIRO-Mk3.6.0, these models are closer to the standard deviation arc of the reference point than MIROC5.

4.4.2 Relation between atmosphere indices and sea-level variability

The relation between atmosphere indices and sea level is described by two statistical indicators. First, we computed the correlation coefficients between the atmosphere indices (BANOS and NAO) and the tide gauges (Stockholm and Warnemünde) in order to quantify the strength of the relationship. For this computation, we used winter means of the concerned time series over the period 1900-2013 on the interannual time scale. The results are represented in Table 4.2.

Table 4.2: The correlation coefficients between atmospheric indices and tide gauges over the period 1900-2013 for wintertime. Notably, time series are de-trended prior to the correlation computation. * The correlation between the NAO-index and the Warnemünde station is not-significant at the two-sided 95% confidence level.

	Correlation	
Index/Station	**Stockholm**	**Warnemünde**
BANOS	0.85	0.55
NAO	0.55	0.17 *

Here, we detect that the BANOS-index accounts for the sea level variance better than the NAO-index for both stations. Considering the relation between the BANOS-index and the stations, the explained variance of sea-level reaches up to 72%. Moreover, while the correlation between the NAO-index and the Warnemünde station is non-significant, the correlation between the BANOS-index and the Warnemünde station is quite stronger and also significant.

Second, we estimated the sensitivity of each station with respect to both atmospheric indices. Assuming that sea level is a linear function of an atmospheric index, we established a linear connection between sea level and the selected atmospheric index. This connection relies on a linear regression where sea level is the predictand and the atmospheric index is the predictor. The sensitivity of the sea level to the associated index is quantified from the slope of the regression line. For this regression, we took the period 1960-2013 as the calibration period. The sensitivity values of the stations are given in Table 4.3.

Table 4.3: The sensitivity values of sea level are estimated per one unit change in the associated index. For the estimation, we implemented a linear regression where sea level is predictand and atmospheric index is predictor. Time series are de-trended prior to the sensitivity computation.

	Sensitivity of Stations ($mm\ u^{-1}$)	
Index/Station	**Stockholm**	**Warnemünde**
BANOS	73	23
NAO	54	11

The results indicate that the Baltic Sea level is more dependent and sensitive to a change in the BANOS-index than to a change in the NAO-index. Concerning the calibration period, the BANOS-index driven sea level trend in Stockholm results in an increase of 10.1 cm. For the same period, the Warnemünde station shows 3.3 cm sea level rise due to the trend in the BANOS-index.

After quantifying the relation between the Baltic Sea level and the selected atmospheric indices through the linear regression, we predicted the contribution of the atmospheric circulation in the variations of Stockholm and Warnemünde sea level over the period 1900-2013. For this calculation, we excluded the long-term trend which is due to the secular sea-level rise and land crust movements. Then, by considering the Brier Skill Score (BSS) values, we measured the skill of the linear regressions. The 31-year running means of predicted and observed sea-levels and the BSS values are shown in Figure 4.2.

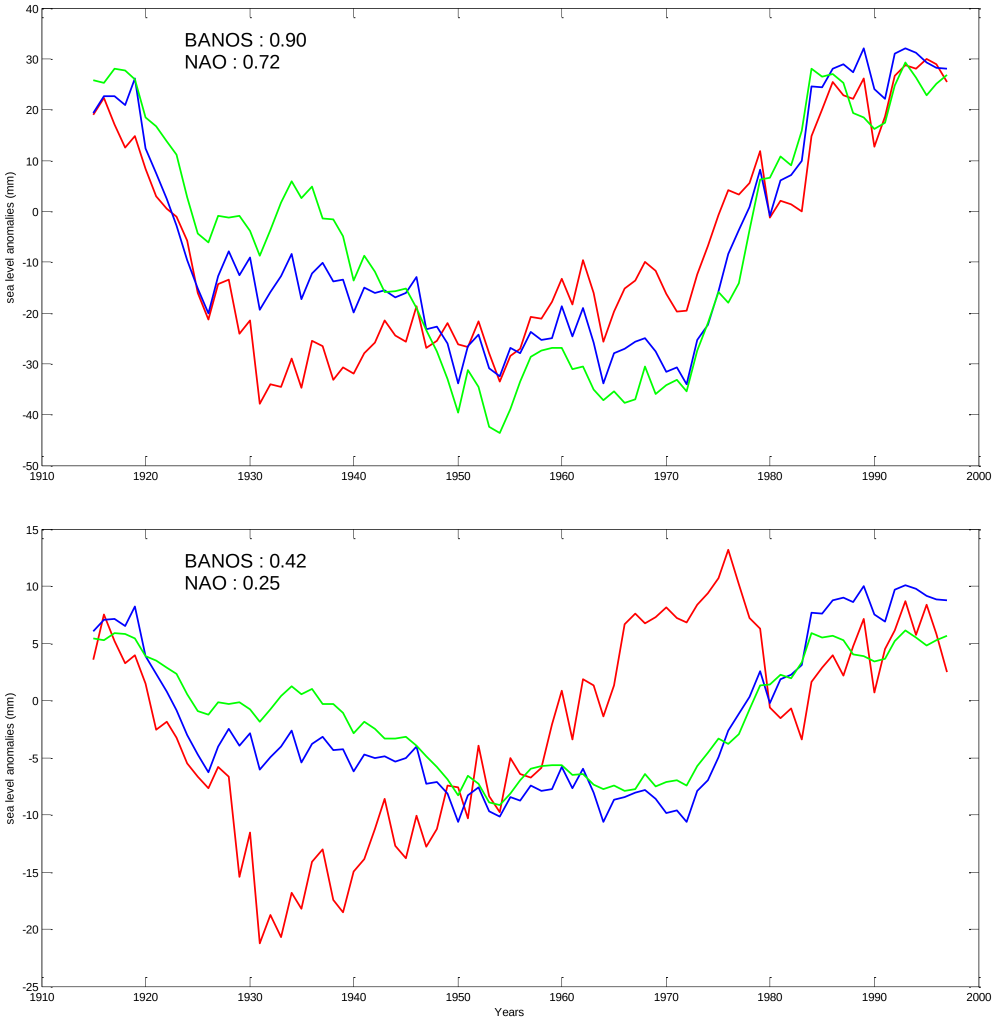


Figure 4.2: The 31-year running means of predicted (blue; the BANOS-index predicted, green; the NAO-index predicted) and observed (red) sea levels of the Stockholm and Warnemünde stations (upper panel is for Stockholm) together with the BSS values in the 31-year mean smoothed time series. Note the different y-axis scales.

Figure 4.2 shows the time evolution of predicted and observed sea level time series based on the 31-year time scale. The numbers in the figure indicate the BSS values. On the one hand, a value of zero means that the value of the mean (climatology) in the calibration period is the prediction value. On the other hand, negative values indicate a worse skill than the simple climatological mean. This means that the best linear connection between atmosphere indices and the sea-level variability in the Baltic Sea is captured by the connection between the BANOS-index and the Stockholm tide gauge. The linear regression involving the relation between the NAO and Warnemünde sea-level has a skill slightly better than the climatology.

4.4.3 Projections of the atmosphere indices

Using the SLP outputs simulated by the CMIP5 climate models under the RCP8.5 scenario, we projected the changes in the atmospheric indices over the 21st century. The projections are computed from the difference of two normalized SLP fields. The computation is explained in the introduction section. The projected variations of the BANOS and NAO indices are represented in Figure 4.3 below.

Figure 4.3: Projections of the atmospheric index (BANOS and NAO) variations. First eight CMIP5 models from top show the BANOS-index projections, the last eight CMIP5 models show the NAO-index projections. The models are ranked based on their performances.

Figure 4.3 represents the projections of two atmospheric indices based on the SLP outputs of eight CMIP5 models driven by the RCP8.5 scenario. For each climate model, three realizations were considered, each started from different initial conditions. The realizations are red (r1i1p1), green (r2i1p1) and blue (r3i1p1) coloured. The long-term trends of the indices in each simulation are computed by using a linear regression.

4.4.4 Trends of sea-level in the Baltic Sea

In this sub-section, the sea level trends that can be attributed to the trends in the atmospheric indices are estimated for the period 2006-2100. The Stockholm and Warnemünde sea level variations have different sensitivity to the atmospheric modes. As it is shown above, the sensitivity of the Stockholm sea level is 73 mm per one unit change in the BANOS-index and 54 mm to the NAO-index. Based on these sensitivity values, the sea level trends of Stockholm (central Baltic) and Warnemünde (southern Baltic) are estimated using the projected trends of the atmospheric indices over the 21st century. The associated sea level trend values (for Stockholm) for three different realizations of each CMIP5 model are given in Table 4.4.

Table 4.4: Atmosphere driven sea level trends (Stockholm) with associated standard errors based on the BANOS and NAO indices over the period 2006-2100. The significant trends (at the 95% confidence level) are marked (*).

Model	Realization	Trend±1 SE (mm/year)	
		BANOS	NAO
HadGEM2-ES	r1i1p1	0.13±0.40	-0.36±0.30
	r2i1p1	0.48±0.38	0.11±0.31
	r3i1p1	-0.26±0.38	-0.20±0.31
CCSM4	r1i1p1	**1.17±0.40***	0.57±0.29
	r2i1p1	0.06±0.40	-0.27±0.28
	r3i1p1	**0.86±0.38***	0.20±0.29
CanESM2	r1i1p1	0.30±0.42	-0.12±0.32
	r2i1p1	-0.27±0.41	**-0.66±0.29***
	r3i1p1	0.21±0.42	-0.29±0.30
MPI-ESM-LR	r1i1p1	-0.25±0.41	-0.10±0.30
	r2i1p1	0.38±0.38	**0.73±0.29***
	r3i1p1	0.65±0.38	0.59±0.30
FIO-ESM	r1i1p1	**1.06±0.37***	0.46±0.26
	r2i1p1	**0.89±0.38***	0.51±0.28
	r3i1p1	0.31±0.39	-0.03±0.29
MIROC5	r1i1p1	-0.18±0.40	-0.05±0.29
	r2i1p1	-0.13±0.40	-0.13±0.31
	r3i1p1	-0.31±0.37	-0.52±0.29
IPSL-CM5A-LR	r1i1p1	**1.04±0.37***	**0.71±0.27***
	r2i1p1	-0.11±0.37	-0.07±0.28
	r3i1p1	-0.16±0.40	-0.07±0.30
CSIRO-Mk3.6.0	r1i1p1	0.59±0.38	0.27±0.31
	r2i1p1	**0.91±0.38***	**0.73±0.29***
	r3i1p1	**1.31±0.39***	**0.61±0.30***

Table 4.4 shows that most of the models do not imply a significant trend at the 95% confidence level. Moreover, some realizations belonging to the same model resulted in sea level trends of opposite sign in the Baltic Sea.

The trend values given in Table 4.4 are only for the Stockholm station, the Warnemünde sea level trends can be computed from this table, since the estimated contribution of the atmospheric indices to the trends in Warnemünde are proportional to those estimated for Stockholm. In the case of the BANOS-index, this proportionality constant is 0.32. In the case of the NAO, it is 0.20.

4.4.5 The effect of the large-scale temperature multidecadal variability on the modes of atmospheric circulation

Finally, we investigated the possible effect of the temperature on the modes of atmospheric circulation BANOS and NAO for the period 1850-2100. The rationale for this calculation is to ascertain whether the possible trends in the BANOS and NAO indices may be caused by the general rise of temperatures, and therefore, their trends could also be ascribed to anthropogenic radiative forcing. This statistical attribution would be derived from a correlation between the low-frequency variability of the atmospheric indices and that of the mean temperature in the North Atlantic/European region. Therefore, the possible correlations between the atmospheric indices and spatially averaged large-scale mean temperature should reflect the influence of temperature on the atmospheric circulation.

For this investigation, we tested correlations of 21-year window gliding trends between spatially averaged temperature over the North Atlantic region and the BANOS-index. The correlation values consisting of 21-year gliding trends between the BANOS-index and spatially averaged air temperature time series are shown in Table 4.5.

Table 4.5: Correlations of 21-year gliding trends between spatial mean of surface air temperature and the BANOS-index are shown for the period 1850-2100. The value of two-sided 95% significance level is 0.12 for this record length. The significant correlation coefficients are marked (*).

Model	**Correlations of 21-year Gliding Trends**		
	r1i1p1	**r2i1p1**	**r3i1p1**
HadGEM2-ES	-0.12	**0.18***	0.04
CCSM4	**-0.14***	-0.07	-0.08
CanESM2	0.05	-0.12	**-0.16***
MPI-ESM-LR	**0.13***	-0.05	-0.07
FIO-ESM	0.01	-0.09	-0.03
MIROC5	**-0.25***	**-0.26***	**-0.24***
IPSL-CM5A-LR	0.12	-0.03	0.10
CSIRO-Mk3.6.0	-0.05	**0.20***	**0.30***

The correlation values are derived from three different realizations with each of the CMIP5 models. As it can be seen in Table 4.5, the correlations are close to zero and almost all of them not-significant (r>0.12) at the 95% significance level. In addition, some climate models indicated positive and negative correlation coefficients in different members of the ensemble. As well as the results, which are gained from the correlations of 21-year gliding trends between the NAO-index and spatially averaged surface air temperature, did not indicate any connection (not shown). Overall, there is no long-term relation between surface air temperature and the modes of atmospheric circulation detected.

4.5 Conclusions

This study investigates the influence of atmospheric circulation on the future Baltic Sea level rise under the RCP8.5 scenario over the 21st century for wintertime. This investigation aims at describing the range of possible trends in the Baltic Sea level due to the trends in modes of the atmospheric circulation. Main conclusions that can be drawn from this study are:

- Most of the models simulate the SLP climatology reasonably well, although some models (HadGEM2-ES, CCSM4, CanESM2, MPI-ESM-LR and FIO-ESM) show more realistic simulations in terms of the root-mean-square error and spatial correlation than the models MIROC5, IPSL-CM5A-LR and CSIRO-Mk3.6.0.
- Sea-level variations in Stockholm and Warnemünde are better explained by the BANOS-index by the NAO-index. The correlations of winter means between atmospheric indices, BANOS and NAO, and tide gauges are measured as 0.85 and 0.55 for Stockholm, and 0.55 and 0.17 for Warnemünde over the period 1900-2013, respectively. In addition, the test on the skill of the statistical model that we used in this study shows that long-term sea-level variability can be well represented by establishing a linear connection between the BANOS-index and the Stockholm tide gauge. Concerning that relation, the Brier Skill Score (BSS) attained a value of 0.90 for the 31-year smoothed time series.

Although this connection is sharply reduced in the southern Baltic, the BSS still indicates a considerable linkage reaching up to 0.42.

- The projected contributions of atmospheric circulation to sea-level rise did not show a clear picture. More specifically, some models - even simulations within the same ensemble - displayed opposite trends. On the one hand, this implies that the influence of internal climatic variability of the CMIP5 models on the atmosphere-driven Baltic Sea level trends is large. On the other hand, it is likely that atmosphere-driven sea-level rise in the Baltic Sea will remain relatively small through the 21st century.
- Correlations of 21-year window gliding trends between spatially averaged surface temperature over the North Atlantic and the BANOS-index did not imply any long-term relation of multidecadal trends between atmospheric condition and large-scale mean temperature for the period 1850-2100. This let us conclude that the mode of atmospheric circulation that has a strong connection to the Baltic Sea level is not influenced by modifications of large-scale surface air-temperature on multidecadal time scale, as in the case of the NAO.

5 Summary and Discussion

This thesis investigated the influence of the atmospheric circulation on mean sea-level variability and change in the Baltic Sea and the areas connecting it to the North Sea from interannual to decadal time scales. The period for the analysis spans from the middle of 19th century to the end of the 21st century. The investigation can be divided into three parts according to the individual focuses and overall the observational, reanalysis and model simulation data sets have been used in this investigation. The summary of the individual parts and the possible arguments on the analyses are outlined in the following.

In the first part of this study, in Chapter 2, the aim was to explore and when possible quantify, the contribution of atmospheric circulation to the recent off-shore sea-level variability in the Baltic Sea and North Sea region on interannual time scale. For this analysis, we used sea-level observations; satellite altimetry and tide gauge, and several climatic variables.

In this part of the study, the main question was:

What is the contribution of the atmospheric circulation to the recent sea-level variability in the Baltic Sea and North Sea region on interannual time scale?

There are three main atmospheric factors contributing to the link between a mode of atmospheric circulation and sea-level variability in the Baltic Sea and North Sea region on interannual time scale. The identified driving factors are the inverse barometer effect in both seasons, the net-energy flux in wintertime and the freshwater flux in summertime. In addition, BANOS pattern related wind flow indicates a possible Ekman transport flowing from the North Sea into the Baltic Sea only in summertime. Notably, the associated mode of atmospheric circulation is constructed as a single atmospheric index which has a coherent and stable in time connection to the sea-level variability in this region.

Although high correlations between satellite altimetry sea-level anomalies (SLAs) and the NAO-index are detected over the entire Baltic Sea and the eastern part of the North Sea in wintertime, no link between sea-level and the NAO is found in this region during summertime. However, the correlation analysis between the 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 the winter and summer seasons. This contrasts with the correlation pattern between the NAO-index and SLA grids, particularly for the summer season.

The relationship between the NAO-index and two tide gauges (Stockholm and Warnemünde) based on 21-year gliding windows over the period 1900-2013 indicated an increase in the correlations starting from the year 1960 in wintertime. This implied that the connection between the NAO and sea-level variability is not stationary in time. In summer, the particular analysis examining this relationship also showed that most of the correlations between the NAO-index and tide gauges are not significant ($r<0.43$). In the light of those findings, we hypothesised that the NAO-index is not the main pattern driving sea-level variability in the Baltic Sea and the North Sea. We found a related, but distinct, pattern of atmospheric circulation that displays higher correlations to sea-level variability in these regions. Based on the associated large-scale atmospheric circulation pattern, we constructed a new index that we denote the Baltic Sea and North Sea Oscillation (BANOS) index. The correlation analysis between the two indices and the representative tide gauges indicate that the connection between sea-level and BANOS-index is stable in time, in contrast to the NAO-index.

The results showed that the sea-level in the eastern Gulf of Finland is the most sensitive in wintertime. The north-eastern Bothnian Bay and the Gulf of Riga are other prominent areas. In the North Sea, the German Bight has the largest sensitivity in wintertime. In summertime, the sensitivity values considerably decrease with respect to the wintertime (i.e. sea-level sensitivity reduces from max. 92 mm in wintertime to max. 31 mm in summertime per one unit change in the BANOS-index). The sea-level in the Gulf of Riga has the largest sensitivity over the whole Baltic Sea and North Sea region. The greatest sensitivity in the North Sea is estimated in the German Bight for the summer season as well.

The study further investigated the physical mechanism contributing to the linkage between the BANOS-index and sea-level. For this particular investigation, we examined the strength of relations between the BANOS-index linked sea-level and several physical factors like sea-level-pressure (SLP), surface heat flux. As long as a strong link between those variables is captured, we estimated the sensitivity of sea-level with respect to the associated physical factor.

Assessing the atmospheric patterns of the BANOS-index, we initially examined the contribution of the inverse barometer effect (IBE). The statistical analysis on the possible contribution of the SLP difference due to the IBE between the Baltic Sea and Gulf of Biscay in wintertime and between the Baltic Sea and over the area between Labrador Sea and Denmark Strait for summertime to the BANOS-index attributed sea-level is applied. This effect would explain 88% (34%) in wintertime (summertime) sea-level variance linked to the BANOS-index. The contribution of the IBE explains the largest part of the BANOS-index attributed sea level variation. However, these sensitivity and explained variance values cannot be expected to occur uniformly over the whole region, because the effect of IBE on the sea-level would slightly differ from place to place in this region.

The statistical analysis on the contribution of the freshwater flux suggests that, on the one hand, the Baltic Sea and North Sea sea-levels do not seem to be connected to the modifications in freshwater flux in wintertime. On the other hand, in summertime, the effect of freshwater flux explains 27% of the variance of the Baltic Sea level.

Considering the contribution of net heat flux (NHF) to explain the linkage between the BANOS-index and SLAs, we found that the NHF can account for 35% of the atmosphere-driven sea-level variability in this region in wintertime. In summertime, there is no contribution detected from NHF to the connection between the BANOS-index and sea-level variation in the Baltic Sea and North Sea region. Also, 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 may contribute to sea-level variability, as in the case of NAO.

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.

Whereas considering the explained variances of sea-level by the inverse barometer effect (IBE) and net heat flux (NHF), 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 reality not the case. In other words, the IBE influences the sea-level variations directly at the geographical points that we selected. The second reason is that the impact of the NHF is computed by taking the spatial average of the Baltic Sea and North Sea basins. It should be kept in mind that the NHF can explain up to 35% of the sea-level variance over this region. Accordingly, the amount of relative thermal expansion of 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.

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

In addition, the role of the Ekman transport is considered to explain the wind-driven ocean mass transport primarily for the transition zone area between the North Sea and the Baltic Sea in the winter and summer seasons. The effect of the wind on sea-level variation depends on the several local factors including the wind direction, coastal geometry and bathymetry of the concerned areas. The influence of local winds in the Baltic Sea and the North Sea on sea-level variations is not investigated, because the study focuses on large-scale climatic drivers of the off-shore sea-level variations over the Baltic Sea and North Sea region. Here, ‘large-scale climatic driver’ term refers to atmospheric or atmosphere-related effects that cover an area larger than Baltic Sea and North Sea region, but still influences sea-level in this region. Nevertheless, there are some local effects of the wind on sea-level variations that we should at least briefly mention for the sake of completeness of the study.

For example, in wintertime, the pattern of the BANOS-index indicates that Ekman transport in the North Sea is generated from north-westerly winds. This drives the water into south-western direction, towards the east UK, German and Dutch coasts. In this situation, the coastlines imply a convergence of water (downwelling) due to mass accumulation. At this spatial scale, the correlation pattern between the BANOS-index and sea-level anomalies (SLAs) confirms the link that this response of SLAs to wind forcing seems to be extended also to the North Sea. Therefore, the geostrophic wind linked to the BANOS strongly influences sea-level in the North Sea. Since the NAO and BANOS patterns suggest similar Ekman transport of the ocean at this spatial scale, this result is in agreement with the previous studies (e.g. Sterlini et al. 2016, Dangendorf et al. 2014). In addition, bathymetry can explain part of the spatial correlation pattern between the BANOS-index and satellite altimetry SLAs. The correlation pattern decreases sharply over the region covering the west of the Skagerrak region and moving along the Norwegian coast (Norwegian Trench), where local water depth reaches 700 m. This decrease in the correlation pattern is also consistent with the study of Sterlini et al. 2016, which used the satellite altimetry observations (SLAs) over the North East Atlantic region. Notably, Ekman (2007) suggests that the redistribution of water masses by the wind in the Baltic Sea results in relative higher or lower sea levels at the eastern sides of the Baltic Sea with respect to the rest of the Baltic Sea. That suggestion is in accordance with our result on the sensitivity of sea-level to the BANOS-index. The corresponding sensitivity pattern shows that eastern parts of the Baltic Sea are the most sensitive areas to the atmospheric circulation.

In the second part of this study, in Chapter 3, the objective was to identify the large-scale effect(s), in addition to the influence of atmospheric circulation, modulating decadal sea-level trends in the Baltic Sea. In this analysis, seasonal means of relative sea-level observations, gridded sea-level reconstructions and climatic data including sea-level-pressure, near-surface air temperature and precipitation fields, and indices; North Atlantic Oscillation (NAO) and Atlantic Multidecadal Oscillation (AMO) were used to investigate the connection between sea-level trend variability and climatic variables.

Overall, this analysis provided an answer to the second question posed in the Abstract:

Apart from the effect of atmospheric circulation, is there any other underlying factor(s) that modulate decadal sea-level trends in the Baltic Sea?

Yes, there is a lagged effect of precipitation on the decadal sea-level trends in the Baltic Sea. This effect accounts for considerable parts of decadal sea-level trend variance independent of the atmospheric circulation in spring, summer, autumn and winter seasons through precipitation decadal trends during the winter, summer and autumn seasons.

In the first step, we investigated the interconnections between the decadal trends of sea-level in different regions of the Baltic Sea and their connections to the decadal trends of the NAO. The results showed that although the decadal trends are spatially very homogeneous, the tide gauges along the southern Baltic Sea have weak correlation to the NAO. To explain this apparently contradicting result, we tried to identify an underlying factor that is independent of the atmospheric circulation could explain the spatial homogeneity of the decadal trends. With this purpose, we statistically removed the signature of atmospheric variability from the decadal sea-level trends by using a multivariate linear regression in which the first five principal vectors of SLP fields were regressors, sea-level decadal trends were the predictand. An analysis of the residuals and other climate variables indicated that precipitation in the previous season influences the decadal sea-level trends in the Baltic Sea. No connection was detected between those residuals and the AMO-index. This implied that it is likely that underlying effect is not originated from the North Atlantic.

Since the Baltic Sea sea level variations are highly sensitive even to small changes in the boundary conditions such as river run-off (e.g. Moeller and Hansen 1994, Leppäranta and Myrberg 2009), one could argue that the link between the previous seasons precipitation and following season sea-level can be captured by analysing the contribution of river runoff to the Baltic Sea drainage basin. Here, it should be mentioned that the river discharges depend on various complex hydrological processes such as precipitation, infiltration and storage, but, the changes in run-offs can be explained mostly owing to precipitation (e.g. Kriauciuniene et al. 2012, BACC II Author Team 2015).

However, there are two important questions on the connection between precipitation and river run-off. One is that precipitation does not only simultaneously influence river runoff. Part of river runoff is delayed by snow and ice storage in the Baltic Sea drainage basin, thus, there is a delay between precipitation and freshwater input into the Baltic Sea. In wintertime, much of the precipitation freezes and is stored as snow in the drainage area, in particular, towards northern part of the basin. Therefore, run-offs in the northern area experience their lowest rates in the year before snow melts. Also, river runoff is affected by evaporation mainly in summer. The highest values of run-offs are measured in spring or early summer due to snowmelt. Moreover, those run-off values are usually reduced during summer owing to the strong evaporation and evaporation is normally larger than precipitation in the Baltic Sea (e.g. Kauker and Meier 2003; Hisdal et al. 2010; Kriauciuniene et al. 2011).

It should also be mentioned that the most important human impact on the Baltic Sea seems to be associated with the changes of river discharges in the Baltic Sea drainage basin (e.g. Moeller and Hansen 1994). A question that is important in this context is that most of the rivers in the Baltic Sea drainage basin have been increasingly regulated through the 20th century. It is also known that the Baltic Sea drainage basin comprises two main parts of the river discharge; one is that the northern boreal part that drains mainly into the Gulf of Bothnia, and the other is the south-eastern part that drains into the southern basins of the Baltic Sea (e.g. BACC II 2015). Since the boreal rivers entering the Gulf of Bothnia have a steeper catchment slope compared to the rivers discharging into the south-eastern catchment areas of the Baltic Sea, boreal rivers have a higher runoff (Kriauciuniene et al. 2011).

Overall, it is a challenging task to quantify the effect of precipitation on the variability of decadal sea-level trends in the Baltic Sea. However, the results of this particular study together with the knowledge about the Baltic Sea drainage basin indicate that further analysis on variability of river runoff is important to have a better understanding of the effects of both regional climate variability and anthropogenic activity on long-term sea-level variability in the Baltic Sea.

In the third part of this study, in Chapter 4, the influence of possible future trends in the atmospheric circulation on sea-level trends in the Baltic Sea over the 21st century is investigated. For this investigation, we used seasonal means of several observations, reanalysis SLP data and simulation outputs. The observables were relative sea-level records, SLP grids and atmospheric indices by the Baltic Sea and North Sea Oscillation (BANOS) index and the North Atlantic Oscillation (NAO) index. The simulated data were SLP and air-temperature fields, which were obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models.

This chapter is aimed at answering the third question addressed in the Abstract:

How strongly can influence of a changing atmospheric circulation on the future Baltic Sea sea-level trends under the RCP8.5 scenario over the 21st century?

Overall, the experiments of eight different CMIP5 models indicate that atmosphere-driven sea-level trend will remain relatively small in the Baltic Sea over the 21st century. However, the influence of the internal climatic variability of the CMIP5 models indicates a large impact on atmosphere-driven sea-level trends in the Baltic Sea.

As the initial step, we evaluated the skills of the CMIP5 models in simulating present-day climatology by analysing the spatial similarity between the simulated average SLP outputs and SLP reanalysis data. One of the main results of this particular analysis indicates that most of the models simulate the SLP climatology reasonably well, although some models (HadGEM2-ES, CCSM4, CanESM2, MPI-ESM-LR and FIO-ESM) show more realistic simulations in terms of the root-mean-square error and spatial correlation than the models MIROC5, IPSL-CM5A-LR and CSIRO-Mk3.6.0.

The link between sea level variations in two selected locations, Stockholm and Warnemünde, and two atmospheric indices (BANOS and NAO) is statistically analysed. At this step, the finding was that sea-level variations in Stockholm and Warnemünde are better explained by the BANOS-index than the NAO-index in wintertime. The correlations of winter means between atmospheric indices, BANOS and NAO respectively, and tide gauges are as 0.85 and 0.55 for Stockholm, and 0.55 and 0.17 for Warnemünde over the period 1900-2013.

Once we established a statistical link by means of a linear regression between sea-level variability and the modes of atmospheric circulations, the projected future evolution of the BANOS and NAO indices was estimated by using the SLP outputs of CMIP5 models under the Representative Concentration Pathway (RCP8.5) scenario for the period 2006-2100. Then, assuming that the link between atmospheric indices and sea-level will remain unchanged, we estimated the atmosphere-driven sea-level trends by using that established link for the Baltic Sea. The contributions of atmospheric forcing to sea-level suggest different directions of sea-level trends in the Baltic Sea over the 21st century, even for some simulations with the same model. Most of the corresponding sea-level trends were not-significant at the 95% confidence level. Therefore, it is very likely that these trends are just due to internal climate variability and not to the external forcing.

In addition, a possible effect of the temperature on the modes of atmospheric variability which may modulate sea-level is examined for the period 1850-2100. The motivation was to test whether slowly varying large-scale temperature variations would affect the SLP modes. For this examination, we calculated the correlations of the 21-year window gliding trends between spatially averaged temperature over the North Atlantic and the associated atmospheric indices. This particular analysis did not yield any long-term relation of multidecadal trends between the modes of atmospheric circulation and air temperature. Therefore, we concluded that the effect of large-scale temperature on these modes is very small in these climate simulations.

It can be argued that the approach that we used in this study is limited since the indices are constructed only by two special modes of the atmospheric circulation. Therefore, they may not reflect the considerable influence of atmospheric circulation on sea-level trend in the Baltic Sea. This would be supported by the argument that the other modes of the atmospheric variability can substantially influence sea-level in the Baltic Sea over the 21st century. Relating to this, Hünicke (2010) used the SLP fields in the European region in order to estimate the contribution of regional climate drivers to future winter sea-level changes for the central and eastern Baltic Sea. In that study, she applied a statistical downscaling approach to the five different global climate model simulations driven by SRES A2 scenario (Special Report on Emission Scenarios) on decadal time scale. She concluded that although there is a large spread of sea-level rise estimations, the contribution of SLP to sea-level changes indicates a positive trend in the central and eastern Baltic Sea.

There are two additional points that should be mentioned. The first one is that the simulated future trends in the NAO depend on the set of simulations analysed. The former ensemble of climate simulations belonging to the CMIP3 project indicates a clear intensification of the NAO under the emission scenario A2, whereas the CMIP5 ensemble of simulations driven by scenario RCP8.5 generally indicates weaker trends, also with a lower level of inter-mode agreement (Cattiaux and Cassou 2013). This means that if we had used the NAO-index constructed from the output of the CMIP3, the results would likely be similar to those obtained by Hünicke (2010).

The second and more crucial one is that, in our study, our primary index was the BANOS index which is a special index explaining the Baltic sea-level variability strongly and steadily over time (Chapter 2). For instance, the BANOS-index has a strong (significant) correlation to the Stockholm (Warnemünde) station with value of 0.85 (0.55) in wintertime. However, the results of Hünicke and Zorita (2006) illustrate that multivariate regression between leading components of the SLP fields covering North Atlantic-West European sector and sea-level imply weak (non-significant) connection to the Stockholm-r=0.48 (Warnemünde-r=0.11) station in wintertime. As mentioned above, they used 3-to-5 leading components of the SLP fields in order to estimate the SLP-driven sea-level variability in the Baltic Sea during winter. It can be the case that, the BANOS mode of the atmospheric circulation was not well captured in that study.

Overall, this enables us to conclude that this regional atmosphere-index can be used to estimate the atmosphere-driven sea-level rise in the Baltic Sea.

This question could be also ascertained by applying the same method as in Hünicke (2010) to estimate the future sea-level trends caused by changes in the atmospheric circulation, but applied the CMIP5 scenario simulations instead of the CMIP3 simulations.

Abbreviations

AVISO
: Archiving, Validation and Interpretation of Satellite Oceanographic data

BACC
: Assessment of Climate Change for the Baltic Sea Basin

BSS
: Brier Skill Score

CCCMA
: Canadian Centre for Climate Modeling and Analysis

CliSAP
: Integrated Climate System Analysis and Prediction

CMIP3
: Coupled Model Intercomparison Project Phase 3

CMIP5
: Coupled Model Intercomparison Project Phase 5

CRU
: Climatic Research Unit

CRUTEM4
: Climatic Research Unit Temperature 4

CSEOF
: Cyclostationary Empirical Orthogonal Function

CSIRO-QCCCE
: Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence

ENSO
: El Nino/Southern Oscillation

FIO
: The First Institute of Oceanography

GHG
: Greenhouse Gas

GIA
: Glacial Isostatic Adjustment

GMSL
: Global Mean Sea Level

GPS
: Global Positioning System

HadCRUT4
: Hadley Centre Climatic Research Unit Temperature 4

HadSST3
: Hadley Centre Sea Surface Temperature 3, 67

IIASA
: International Institute for Applied Systems Analysis, 90

IPCC
: Intergovernmental Panel on Climate Change

IPSL
: Institut Pierre-Simon Laplace

JPL
: Jet Propulsion Laboratory

LH
: Latent Heat

LW
: Long Wave

MIROC
: Atmosphere and Ocean Research Institute of the University of Tokyo, National Institute for Environmental Sciences and Japan Institute for Marine-Earth Science Technology

MOHC
: Met Office Hadley Centre

MPI-M
: Max-Planck Institute for Meteorology

NAO
: North Atlantic Oscillation

NCAR
: National Center for Atmospheric Research

NCEP
: National Center of Environmental Prediction

NEF
: Net Energy Flux

NHF
: Net Heat Flux

NOAA
: National Oceanic and Atmospheric

PCA
: Principal Component Analysis

PO.DAAC
: Physical Oceanography Distributed Active Archive Center

PSD
: Physical Sciences Division

PSMSL
: Permanent Service for Mean Sea Level

RCP
: Representative Concentration Pathway

SH
: Sensible Heat

SLAs
: Sea Level Anomalies

SRES
: Special Report on Emission Scenarios

SSHA
Sea Surface Height Anomaly
SST
Sea Surface Temperature
SW
Short Wave
TUD
Technical University of Dresden

List of Publications

This thesis is related to the following manuscripts:

- Karabil, S., Zorita, E. and Hünicke, B. (2017): Contribution of atmospheric circulation to recent off-shore sea-level variations in the Baltic Sea and North Sea. Earth System Dynamics, at the final stage to be submitted.

- Karabil, S., Zorita, E. and Hünicke, B. (2017): Mechanisms of variability of decadal sea-level trends in the Baltic Sea over the 20th century. Earth System Dynamics, at the final stage to be submitted.

- Karabil, S., Zorita, E. and Hünicke, B. (2017): Projections of the atmosphere-driven Baltic Sea level rise under the RCP8.5 scenario over the 21st century. Journal of Marine Science and Engineering, at the final stage to be submitted.

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List of Figures

List of Tables

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Eidesstattliche Versicherung

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertationsschrift selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

Declaration on Oath

I hereby declare, on oath, that I have written the present dissertation by my own and have not used other than the acknowledged resources and aids.

Unterschrift: ______________________________

Datum: 01.02.2017 ______________________________