Separating annual, interannual and regional change in Sea Surface Temperature in the Northeastern Atlantic and Nordic Seas

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Key Points:

- Seasonal fluctuations in Nordic Seas and Northeastern Atlantic sea surface temperatures explains 90 % of the variability.
- Both summer maxima and winter minima are warming, with summer temperatures warming twice as fast (0.4 and 0.2 °C per decade).
- Other sources of variability include sea-ice melt and switches in large-scale oceanographic conditions in the Northeastern Atlantic.

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Abstract

Sea surface temperature (SST) in the Northeastern North Atlantic and Nordic Seas exhibits pronounced variability across seasonal to decadal time scales. These changes can be expected to be driven by a combination of altered local conditions, shifts in seasonality and large scale regional oceanographic change. Separating the contribution from each of these offers insight into how the region is changing. Here, we present the result of an analysis of weekly satellite derived SST data from 1979 to 2020. An empirical orthogonal function (EOF) analysis allows us to separate observed changes in SST into independent underlying timeseries. Each timeseries explains part of the variability in SST. EOF1 can be allocated with changes in seasonality and a long-term warming trend, with summer maxima warming with twice the rate (0.043 °C yr^{-1}) compared to winter minima (0.023 °C yr^{-1}). EOF2 is associated with the North Atlantic subpolar gyre and the North Atlantic Oscillation, affecting the Atlantic Water flow across the Greenland-Scotland Ridge, imposing a di-pole cooling/warming pattern. Local sea-ice melt along the southeast Greenland shelf is represented by EOF3, and finally the influx of warmer water with the North Icelandic Irminger Current is captured by EOF4. Each of these disaggregated signals differ considerably in their contribution to driving temporal and spatial trends in SST. The isolated signals offer a high-resolution long time series of valuable indicators of oceanographic change which will likely be reflected in biogeochemistry, plankton, fish, mammals, and seabirds in the region.

Plain Language Summary

Sea surface temperature (SST) can be measured by sensors mounted on satellites and this provides a dataset with exceptional regional and temporal coverage from 1979 to present. Here our focus is on examining oceanographic change in the Northeastern Atlantic and Nordic Seas, bordering Greenland, Iceland and Norway. We apply a data analysis technique that allows us to separate the variability in SST in the region into a series of underlying factors. With this we can resolve: how the seasonal winter minimum temperatures and summer maximum temperatures have been increasing; how conditions in the North Atlantic are driving changes in the region; how increased sea-ice melt is influencing SST; and finally trace the occurrence and impact of an abrupt inflow of warmer water northwards along the west coast of Iceland. Combined these

disaggregated factors may help explain changes in the distribution and structure of the marine ecosystem in the region.

1 Introduction

Sea surface temperature (SST) measured by satellites provides a unique time series with high temporal and geographical resolution unparalleled to many other essential ocean variables. Despite its limited penetration depth it can be used as a proxy for the ocean heat content of the mixed layer (Chen & Tung, 2018). As a result, variations in SST can be linked to changing positions of oceanographic fronts (Sutherland & Pickart, 2008; Raj et al., 2019), variability in upwelling (Lentz & Largier, 2006) or deep convection (de Jong & de Steur, 2016) and warming of surface waters as a result of climate change (Masson-Delmotte et al., 2019). Variations in SST can also indicate initiation of larger changes in regional marine ecosystems as oceanographic change can have a cascading impact on all trophic levels in ecosystems (Hátún et al., 2009).

The Northeastern Atlantic and Nordic Seas are characterized by distinctive domains in the average SST and its variability (Fig. 1 and 2). The shelf waters in the west are influenced by Polar Waters brought south from the Arctic Ocean with the East Greenland Current (EGC). SST is cold either due to its Arctic origin, or contribution from seasonal ice melt from both sea-ice and the Greenland ice sheet. Part of the southward flowing surface EGC deviates eastward, where it affects the surface waters in the Nordic Seas (Jeansson et al., 2017). Once past the Denmark Strait, the EGC is confined to the shallow, narrow region along the southeast Greenland coast. Further inshore, a low salinity southward flowing surface jet known as the East Greenland Coastal Current (EGCC) resides (Sutherland & Pickart, 2008; Bacon et al., 2014).

In the eastern part of the region surface waters are dominated by the comparatively warm and saline Atlantic Water (AW) flowing poleward with the North Atlantic Current (NAC). Part of this current continues northwards into the Norwegian Sea as the Norwegian Atlantic Current (NwAC) inducing a strong SST gradient across the Nordic Seas (Fig. 1) (Orvik and Niiler 2002). Some of the NwAC diverges into the Barents Sea, while the remainder continues north entering the Arctic Ocean via the West Spitsbergen Current (WSC) in the Fram Strait (Orvik and Niiler 2002). Here, about half of the flow recirculates turning west and merging with the EGC to

continue southwards as Return Atlantic Water (Bourke et al., 1988; Hatterman et al., 2016; Jeansson et al., 2017; Raj et al., 2019).

The region south of the Greenland-Scotland Ridge (GSR) is dominated by the cyclonic Subpolar Gyre (SPG). The NAC comprises the southern and eastern boundary currents of the gyre. As the NAC enters the Subpolar North Atlantic (SPNA) it separates into branches; one flows over the Rockall Plateau and the Rockall Trough between Iceland and Ireland, one enters the Iceland Basin and one recirculates southward to eventually re-join the subtropical gyre (STG) (Daniault et al., 2016). The Irminger Current (IC) separates from the northward flow in the Iceland Basin and turns westward towards east Greenland. South of the Denmark Strait, the IC bifurcates with a smaller portion flowing northwards through Denmark Strait and along the western and northern coast of Iceland as the North Icelandic Irminger Current (NIIC). The larger part turns south and flows along the east Greenland shelf break parallel to the EGC. Sharp oceanic fronts develop between the IC, EGC and EGCC (Hátún et al., 2005). A portion of this flow will remain in the Irminger Sea, as it recirculates near Cape Farewell, whilst another portion will round Cape Farewell to continue north along western Greenland.

In addition to advection of ocean currents, SST in the Northeastern Atlantic and Nordic Seas is strongly influenced by heat exchange with the atmosphere, sea-ice and associated melt water, and upward heat fluxes from deeper warm waters (Fuervik, 2000; Carvalho & Wang, 2020). Based on the HadISST datat set, Meredith et al., (2019) show a warming trend in the Northeastern Atlantic and Nordic Seas over the 1982-2017 period. Barton et al., 2018 and Asbjørnsen et al., (2020) also show recent SST increase in the northern Nordic Seas and Barents Sea. In contrast, the Irminger Sea experienced a decline in SST between 2007 and 2016 (Broome et al., 2020; Fig. 2), indicating a disconnect between the Northeastern Atlantic and Nordic Seas over this period. A linear regression analysis of SST over the 2007-2020 period clearly reflects these patterns in the region (Fig. 2). In the Greenland Sea, the warming trend can be up to 0.15 °C per year and appears to be persistent across the year. South of Iceland, significant cooling over the SPG is apparent. The observed cooling is largest in summer, with rates towards -0.15 °C per year (Fig. 2). Regions where no significant linear relationship is found (yellow patterns in Fig. 2) clearly reveal the frontal zones between water masses (Orvik and Niiler 2002), in particular boundaries of the EGC and EGCC towards the west and the propagation northwards

and subsequent dissipation of a front in the southeast of the region during the transition from winter to summer (Fig. 2).

Several mechanisms have been invoked to explain the observed trends in regional water temperatures. These include large scale atmospheric forcing such as the North Atlantic Oscillation (NAO), fluctuations in the SPG circulation, changing wind speeds, and variable sea-ice concentration (Furevik, 2000; Broome et al., 2020; Carvalho & Wang, 2020). The aim of this study is to carry out a holistic analysis of SST of the region by applying an Empirical Orthogonal Function (EOF) analysis also known as a Principle Component Analysis. SST is hypothesized to be responding to a combination of altered local conditions, potential shifts in seasonality and large scale regional oceanographic change, which will materialize as a linear combination of factors influencing surface water heat content. The analysis allows us to isolate the contribution of underlying independent (orthogonal) factors to the observed SST changes with no assumption on temporal or regional trends. Separating the contribution from each of these offers insight into how the region is changing and also offers factors which we propose can be linked to additional shifts in distribution and diversity of marine organisms, from phytoplankton up to marine mammals.

2 Materials and Methods

The region of interest expands between 48 °W and 9 °E, and 58 °N to 82 °N. Two Copernicus SST datasets with coverage of the region were used in the analysis (Table 1). The first was a near-real time data product derived across different satellite platforms called “Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA)”, developed by the Met Office. The product is identified as “SST_GLO_SST_L4_NRT_OBSERVATIONS_010_001” (Donlon et al., 2012; Good et al., 2020; Stark et al., 2007). It uses satellite data provided by the GHRSST framework (Group for High Resolution SST) and has global coverage on a 0.05° (approximately 6 km along the north-south axis in region of interest, and between 800 m and 3 km in the east-west direction) resolution grid and includes daily sea surface foundation temperature data (temperature of upper 10 m of the ocean, free of diurnal temperature variations), sea-ice cover and analysis error for the 2007-2020 period. In order to remove bias errors, the satellite observed SST has been compared with in-situ SST measurements (drifting buoys) and ENVISAT Advanced Along Track Scanning

Radiometer (AATSR) SST observations (Donlon et al., 2012). As a result, an uncertainty value (in Kelvin), is provided for each location at every time step. The high spatial resolution allows one to identify fine structures in the position of fronts (Fig. 2).

To extend the temporal coverage to 1979, the ERA5 reanalysis dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) and available via Copernicus Climate Change Service data portal was used (Hersbach et al., 2018). This dataset is derived from a combination of observational and model data to form a complete spatial and temporal series provided at 0.25° (approximately 27 km in the region of interest along the north-south axis, and between 4 km and 15 km) horizontal and hourly temporal resolution (Dee et al., 2014).

2.1 Data pre-processing and EOF analysis

In contrast to the linear regression analysis (Fig. 2), EOF analyses cannot be applied to data sets with missing data points. While interpolation with bordering (temporal and spatial) measurements can produce visually acceptable results, they do not actually aid the EOF analysis by providing additional information. In fact, this can potentially impair the separation of underlying features as signal noise and variability is averaged and combined. Missing data in the near real time (NT) dataset stems for the most part from the presence of sea-ice. Before EOF analysis, all data points with a sea-ice fraction greater than 25 % were discarded. These corresponded to data points already flagged with a high measurement error. An ice mask was then generated which excluded data from areas where there has been ice coverage. Due to the inclusion of models, the ERA5 dataset extrapolates below the sea-ice, offering the potential to include ice covered waters, thereby introducing a discrepancy in EOF results from the two datasets. The application of an identical ice mask to both datasets resulted in comparable EOFs (Fig. S1 to S4). As the ERA5 dataset has superior temporal coverage the EOF analysis presented from here onwards is based on the ERA5 reanalysis. The data was down-sampled to weekly averages and organized into a matrix with geographical location as columns and temporal series as rows. Before performing the EOF analysis the data was centered (mean subtraction) and

scaled (normalized to standard deviation) by location to ensure equal weighting of data from different regions.

With the EOF analysis, we separate SST variability in space and time into a number of orthogonal components each having a geographical loading and a temporal score. The product of the loadings map, score time series for a given component and the standard deviation map of the original data allows us to back-calculate the temperature variation represented by the component (i.e. the given components contribution to temperature anomaly).

2.2 Climate variables

To assess the potential driving forces of the temporal development in the EOFs, several climate indices were gathered. A SPG index based on multiple linear regression of the first and second modes of North Atlantic sea surface height variability was used as an indicator of the strength and shape of the subpolar gyre. The index was derived by Chafik in (2019) and gathered from the Bolin Center for Climate research: https://bolin.su.se/data/chafik-2019-3. The North Atlantic Oscillation (NAO) index is based on the atmospheric pressure difference between Iceland and the Azores and conditions in the study region can potentially be correlated to this as it influences North Atlantic temperature and precipitation patterns (Barnston & Livezey, 1987; Hurrell, 1995; van den Dool et al., 2000; W. Y. Chen & van den Dool, 2003). A monthly time series of the NAO index was obtained from NOAA.

3 Results

Almost 95 % of the observed variation in SST is explained by the first four components from the EOF analysis (Fig. 3). Systematic patterns in their geographic distribution and temporal signal indicate that they are linked to specific phenomena and offer confidence in the robustness of the result. The robustness of the derived EOF components was further confirmed by re-running the EOF decomposition on de-seasoned SST, which resulted in comparable components (Fig. S5). The largest portion (90 %) of the variability in the region can be attributed to seasonal warming and cooling. The EOF1 loading map is largely featureless (Fig. 3a) indicating that this component is of equal importance for the entire study area and likely driven by atmospheric forcing. The one exception is a narrow band along the edge of the sea-ice mask, where the

loading is slightly lower. A reconstruction of SST anomalies imposed by this component (Fig. 3b) shows a strong imprint of seasonality with variability around the mean of more than 6 °C. In order to assess if there has been a change in the timing and intensity of seasonal maxima and minima, the temperature anomaly for EOF1 was plotted by year and week (Fig. 4a). A regression analysis indicates that there has been no significant change in timing across the years (p-value >0.05), as would be expected. Also apparent is a positive linear trend in both the summer maximum (0.043 °C yr^{-1}) and winter minimum (0.024 °C yr^{-1}) SST (Fig. 4b). Note, that the rates provided on Fig. 4 were calculated specifically for the Irminger Sea location, but are very similar across the entire region as the EOF1 loadings are evenly distributed (Fig. 3a). These results show that SST increased with twice the rate in summers compared to winters over the course of 41 years.

The time series associated with EOF1 is also characterized by a shift towards higher temperatures in 2000 that persists through to the end of the time series (Fig. 4c). A Chow test was done to gauge whether the EOF1 time series is best described with a single linear regression model through the entire time series (Fig. 4b), or if the description of the time series significantly improves when using two regression models, one on either side of the identified shift. The Chow test concludes that the time series representation is significantly better when sectioned into two around August 2000 (Fig. 4c) (p-value < 0.01), thus confirming the existence and timing of the identified shift.

The second EOF explains approximately 2.6 % of the observed variation in SST and is opposite in sign pivoting north-south approximately at the latitude of Iceland. This spatial pattern has a high degree of similarity to the linear trends presented in Fig. 2. This gives confidence that the dipole nature of EOF2 is a real feature of SST variability in the Northeast Atlantic rather than an artefact introduced by the constraints of the EOF approach itself. The reconstructed SST anomalies from EOF2 show a contribution to SST variability of more than 2°C. The time series is characterized by three periods: i) a period from 1979 to 1995 where there are variable anomalies; ii) a period from 1995 to 2014 where temperature anomalies in the north are and remain persistently colder, and conversely persistently warmer in the south; and iii) a period from 2014 to 2020 where anomalies changed to be persistently warmer and cooler in the north and south respectively. These fluctuations hint at a possible linkage to regional climate indices

such as the SPG and NAO indices. A correlation analysis found relations between EOF2 scores and both the NAO (-0.41, p-value < 0.01) and the SPG (-0.67, p-value < 0.01) indices at five and four weeks lag respectively (Fig. 5). Lag times with the highest correlation were determined from cross-correlation analysis. It is clear that the segregations of the time series of EOF2 into three periods agrees with trends in the two indices (Fig. 5). In particular the middle period spanning from 1995 to 2014 where the NAO and SPG indices are persistently negative, and the final period where there is a systematic change to positive values (note both indices are plotted with inverted axes in Figure 5b and d).

Variability in SST within a narrow band spanning the length of the southeast Greenland shelf was captured by EOF3, which contributes 1.2 % of the total variation in SST (Fig. 3e). This band broadly corresponds to the area with low seasonality (EOF1, Fig. 3a), indicating that it has a more unique variability not directly related to the large-scale seasonal warming and cooling explained by EOF1. Fig. 3f indicates that these waters have experienced a systematic long-term warming across much of the time series, in particular from the late 1980s (approximately 1 °C increase over a 40 year period). Furthermore, reconstructed SST also indicates high frequency variability linked to seasonal trends (Fig. 6). The SST anomaly explained by EOF3 is lowest in summer months within the band of high loadings along the edge of the sea-ice mask (Fig. 6). An analysis of the timing of the summer minimum (similar to that done for EOF1) indicated that there has been no significant systematic shift over the time period. As can be seen in Fig. 6 the timing of the minimum is variable and ranges between late May and late June. Both the seasonal maxima and minima experience a comparable SST increase (e.g. 0.025 and 0.022 °C yr^{-1} respectively at 65 °N 30 °W) through the entire 41 year study period, indicating that the long-term trend is the same for both summer and winter. The intensity of this long-term trend, however, varies spatially as reflected in the EOF3 loading (Fig. 3f).

The fourth EOF is largely confined to the region along the Greenland-Faroe Islands ridge with greatest values northwest and southeast of Iceland (Fig. 3g). Fig. 3h shows the time series of the SST anomaly explained by EOF4 for two selected points, one near Denmark Strait and another in the Greenland Sea. From this, it is clear that EOF4 is focused on the changes occurring in Icelandic waters (red line in Fig. 3h). The time series is characterized by two frequencies: a high frequency variability which was found not to be linked to seasonality; and a

lower frequency change. The latter appeared to represent somewhat stable conditions before 2003, a positive excursion in SST up to 2 °C between 2003 and 2005 followed by a brief return, then a persistently positive SST anomaly from 2007 onwards (Fig. 3h). The 2007 shift is confirmed by a change point detection procedure similar to that done for EOF1. Comparison of this time series with measurements from the Icelandic monitoring program indicates that the warm SST anomaly in 2003 and 2004 captured in EOF4 corresponds well with observations as supported by a relatively high correlation coefficient ($R^2 = 0.47$, p-value = 0.02; Fig. 7).

4 Discussion

The decomposition of SST into its linear components has partitioned SST changes into that due to altered seasonality captured in EOF1 and EOF3 and that linked to variable oceanic advection captured in EOF2 and EOF4.

4.1 Seasonal control of SST

The seasonal warming and cooling of the ocean surface is the major determinant of SST variability in the SPNA and Nordic Seas. Although the timing of the seasonal maximum and minimum has not changed over the forty-year period considered here, the intensity of seasonal warming and cooling has (Fig. 3). Annually the region is a net source of heat to the atmosphere (Serreze et al., 2007). Cooling of surface waters from September to March exceeds the warming that occurs from April to August (Serreze et al., 2007). EOF1 indicates that winter SST has been rising at a rate of 0.024 °C per year and summer SST at a rate approximately twice that throughout the region. These warming rates are in good agreement with those reported for March (0.2°C per decade) and September (0.4 °C per decade) over the period 1982-2017 in Meredith et al. (2019). The findings reveal two changes that are occurring in the seasonal component of SST in the region. The fact that summer and winter temperatures are increasing suggests that there is a general increase in heat transport into the region. However, this does not explain why summer maxima are warming faster than winter minima. This could in turn be reflecting a decrease in the summer mixed layer depth. As SST increases the mixed layer depth can be expected to shoal,

assuming that the warming of surface water dominates the density change, rather than change at depth (Somavilla et al., 2017).

Strong seasonal variability is also evident in the annual build-up and melt of sea-ice. Summertime sea-ice melt along the east Greenland shelf absorbs considerable amounts of latent heat, and releases cold, fresh waters initially lowering summer SST in the western part of the Nordic Seas (Smedsrud et al, 2022). This is reflected in the high frequency signal captured in EOF3 (Fig. 6). This component thereby serves as a local, geographical correction to the seasonal pattern identified by EOF1. Since EOF3 mainly serves as a summertime correction, it should not be seen as an absolute summer cooling. It merely modifies the seasonal trend in EOF1 to represent a local delay/reduction of the summer heating along the ice front, possibly due to sea-ice meltwater or polar waters transported in the EGC. The general increase in SST along east Greenland observed in EOF3 (apparent as a baseline shift in Fig. 6) is comparable to that seen for winter SST in EOF1. The similarity of the interannual trends embedded in EOF1 and EOF3 suggests that these components have a common driver.

4.2 Regional connectivity

Although seasonal heating and cooling of the surface drives the majority of SST variability, advection of warm, saline AW into the Nordic Seas is responsible for imposing important regional differences. Since EOF1 represents seasonal variability, it is reasonable to assume EOFs 2 and 4 to be related to oceanic advection and interannual variability, which will be considered in the following. AW exchange between the SPNA and Nordic Seas is facilitated via three main inflow pathways: i) flow through the Faroe-Shetland Channel, ii) flow between Iceland and the Faroe Islands and iii) inflow with NIIC through Denmark Strait (Hansen and Østerhus, 2000; Østerhus et al., 2019). All three inflow pathways contribute to the substantial increase (21 TW) in ocean heat transport in 1998-2002 identified in Tsubouchi et al., (2021). The authors furthermore characterize this abrupt increase as a change-point similar to that reported for EOF1 in the current study (Fig. 4c & Fig. S2) suggesting that the identified 2000 shift in EOF1 represents increased oceanic heat transport across the GSR. As part of the variability in the inflow of warm waters is set upstream in the NAC, one can expect variability in the three inflows to be correlated and resolved as a single EOF. This is for the most part true, as seen for EOF2,

however the isolation of an additional contribution, more specific to the NIIC (EOF4), reveals a local component which is not directly correlated.

Although AW transport with the NIIC is the smallest of the three through-flows, it is the primary source of heat and nutrients to the north Iceland shelf (Fig. 1; Hansen and Østerhus, 2000). High variability due to translation of fronts is inherent to this area (Fig. 2e-h), and fluctuations in the temperature and volume of the AW inflow with the NIIC have been used to explain variable temperature and heat transport to the shelf (Jónsson and Valdimarsson, 2012; Zhao et al., 2018; Casanova-Masjoan et al., 2020). Based on mooring observations Jónsson and Valdimarsson (2012) captured an anomalously strong NIIC inflow event between 2003 and 2004, which concurs with the temperature excursion in the fourth component derived here (Fig. 7). Previous studies concerning the NIIC furthermore document a shift to persistently elevated temperatures after 2007 compared to conditions before the 2003 warm event (Zhao et al., 2018; Casanova-Masjoan et al., 2020). A similar shift was noted in EOF4 (Fig. 7), which supports our interpretation of EOF4 as representative of AW inflow with the NIIC.

East of Iceland, the NwAC carries heat and salt across the Iceland-Scotland ridge and into the Norwegian Sea. Consistent with numerous previous studies relating interannual variability in inflow properties and volume to large-scale wind forcing patterns (e.g. Sandø et al., 2012; Bringedal et al., 2018), we found a significant correlation (-0.41, p-value < 0.01) between NAO and EOF2 (Fig. 5d). Strengthened westerlies under positive NAO cause elevated heat loss and negative SST anomalies over the SPNA (Visbeck et al., 2003; Sarafanov 2009). Simultaneously, the intensified atmospheric circulation transports more warm, moist air northwards and increases AW inflow with the NwAC, invoking positive SST anomalies in the eastern Nordic Seas (Furevik, 2000; Dickson et al., 2000; Mikailova et al., 2021). As demonstrated by Deser et al., (2010), a dipole SST pattern between the SPNA and Nordic Seas consequently develops under positive NAO forcing. Whilst the correlation between NAO and EOF2 is significant, the robustness of this relationship is questionable as the strength of correlation is highly sensitive to the length of the smoothing window.

Other studies have attributed variable inflow properties to changes in the strength and shape of the SPG (e.g. Hátún et al., 2005; Lozier & Stewart, 2008; Kenigson & Timmermans,

2021). A strong correlation (-0.67, p-value < 0.01) with the SPG index suggests that SPG dynamics are indeed manifested in the development of regional SST patterns (Fig. 5). Shifts in the position of the subarctic front, commonly referred to as expansion/contraction of the SPG have been invoked to explain decadal temperature trends in the SPNA and variable composition of inflow across the GSR (Hátún et al., 2005; Desbruyères et al., 2021; Kenigson & Timmermans, 2021). Weak SPG circulation is associated with contraction of the SPG and expansion of the STG, effectively displacing the subarctic front northwestwards, and allowing for a wider passage for warm, saline subtropical waters to penetrate the eastern SPNA and flow into the Nordic Seas (Häkkinen et al., 2011). Conversely, during strong SPG circulation, subtropical waters are blocked by the now expanded SPG, rerouting the subtropical waters southwards (Häkkinen & Rhines, 2004). The Atlantic inflow to the Nordic Seas is in this case comprised of an increased ratio of cold, fresh SPNA source waters compared to STG waters. Accordingly, the SPG index and SST anomalies in the SPNA are inversely correlated in agreement with Hátún et al., (2005).

However, whilst the SPNA has been cooling since the mid 2000's in accordance with the expanded state of the SPG, the Nordic Seas have not (Fig. 2 and Fig. 5). A possible explanation for this apparent disconnect is that the SPNA cooling had simply not reached the Nordic Seas by 2014. According to Holliday et al., (2008) NAC anomalies are detectable in the southern Norwegian Sea approximately one year after crossing the Faroe-Shetland Channel, and appear south of Svalbard three years later. In another study, Kenigson and Timmermans (2021) suggest a lag of five years between the development of freshwater content anomalies in the SPNA and a measurable change in the Nordic Seas. It is therefore possible that the dipole fingerprint associated with EOF2 is the consequence of slow propagation and mixing time scales of temperature anomalies generated by changing states of the SPG. Broomé et al., (2020) offer an alternative explanation for the SPNA-Nordic Seas disconnect. The authors suggest that the connection between the SPNA and Nordic Seas is time varying as they show that correlation between temperature in the eastern Nordic Seas and SPNA is only significant along the subtropical AW pathway. Thus, the SPNA-Nordic Seas connection is strong under contracted

gyre conditions but not when the SPG is expanded. This notion highlights that SPNA and Nordic Seas exchanges across the GSR are not yet fully understood (Bringedal et al., 2018).

In contrast to the derived EOFs, the physical processes driving observed changes are not necessarily independent (orthogonal) of each other. Therefore, it is possible that both NAO and SPG associated changes are manifested in EOF2. Whilst we have only speculated the mechanism causing the dipole spatial pattern associated with EOF2, it is clear that AW inflow patterns are important drivers of SST variability in the SPNA and Nordic Seas.

The increased ocean heat transport as represented by the shift in EOF1 in 2000 and the de-seasoned EOF model (Fig. S2), the "switching" role of the SPG and increased AW inflow with the NIIC, collectively suggest an increase in the oceanic heat transport to the Nordic Seas over the 1979-2020 period. These findings are aligned with a suite of recent studies on the heat budget of the Nordic Seas recently reviewed by Smedsrud et al., (2022) and provide a separation of the response in SST into independent underlying factors. Increases in AW inflow in part contradict evidence for decreases in Atlantic meridional overturning circulation (AMOC) (e.g. Smeed et al., (2018)), which are based on deepwater moorings further south. This apparent disconnect between observations from the subtropics and Nordic Seas is also noted in Tsubouchi et al., (2021) and highlights the fact that linkages between the subtropics and higher latitudes are yet to be resolved.

5 Conclusions

Sea surface conditions are the result of the complex interplay between atmosphere and ocean. SST's are subjected to large scale atmospheric patterns (e.g. NAO), short term cycles (e.g. day/night cycles), intermediate term cycles (e.g. seasonal) cycles and long term cycles (e.g. strengthening and weakening of the AMOC). Our results show that EOF analysis is a robust method for disentangling both spatial and temporal patterns in SST, enabling us to attribute change to specific processes acting on various timescales and differing in geographic extents. This has implications for the predictability of SST conditions and their impacts in the Northeastern Atlantic and Nordic Seas. From the EOF analysis, we isolate a dominant seasonal signal revealing that summer maximum SST is increasing at about twice the rate of winter minima warming (EOF1), potentially reflecting a shallowing of the summer mixed layer depth.

Furthermore, the impact of NAO and the SPG on regional SST is isolated (EOF2). This is of major importance as it impacts the intrusion of warm AW into the Nordic Seas with consequence for climate and ecosystems in the region. More local effects on SST, such as the impact of sea-ice melt along the ice edge were also captured in the analysis (EOF3). Finally, EOF4 relates to variable AW heat transport onto the north Iceland shelf with the NIIC.

The influence of each of these independent SST components on regional SST trends varies considerably throughout the region and across the time period considered. Individually, the EOF components pose as high-resolution time series of oceanographic change that is likely also reflected in biogeochemistry, plankton, fish, mammals and seabirds in the region. We therefore suggest that some of EOF components presented here may provide useful proxies: EOF3 may be regarded as an indirect indicator of the impact of sea-ice melt, whereas EOF4 represents a proxy for influx of warm nutrient-rich AW to the north Iceland shelf.

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Open Research

The OSTIA and ERA5 datasets used in this paper are available from at: https://doi.org/10.48670/moi-00165 and https://doi.org/10.24381/cds.adbb2d47, respectively. CTD data from the Siglunes section and the first four EOF components derived are freely available at data.dtu.dk via DOI 10.11583/DTU.19316264.

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646 **Table 1.** SST datasets and their key characteristics used in this study.

Dataset type	Parameter	Coverage	Temporal resolution	Timespan in study	Spatial resolution
OSTIA near-real time	Foundation SST	Global	Daily	2007-2020	0.05°
	Sea-ice fraction	Gloabl	Daily	2007-2020	0.05°
	Analysis error	Global	Daily	2007-2020	0.05°
ERA5 Reanalysis	Foundation SST	Global	Hourly	1979-2020	0.25°
	Sea-ice fraction	Global	Hourly	1979-2020	0.25°

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648
649 **Figure Legends**

650 **Figure 1.** Average Sea Surface Temperature calculated from 2007-2020 daily values derived
651 from "Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA)", developed by the
652 Met Office (Table 1). Yellow contours indicate the 500 m isobath and red and grey arrows
653 indicate major warm and cold surface circulation features in the region, respectively. The
654 position of the Siglunes transect is denoted by the triangle on the north Iceland shelf.

655 **Figure 2.** Results of a linear regression across the OSTIA dataset from 2007-2020 segregated by
656 season: Winter (December to February); spring (March to May); summer (June to August) and
657 autumn (September to November). Top row shows the slope of the regression. Isolines indicate

the division between significant ($p<0.05$) and non-significant regression slopes. The bottom row presents maps of the p-value for the regressions.

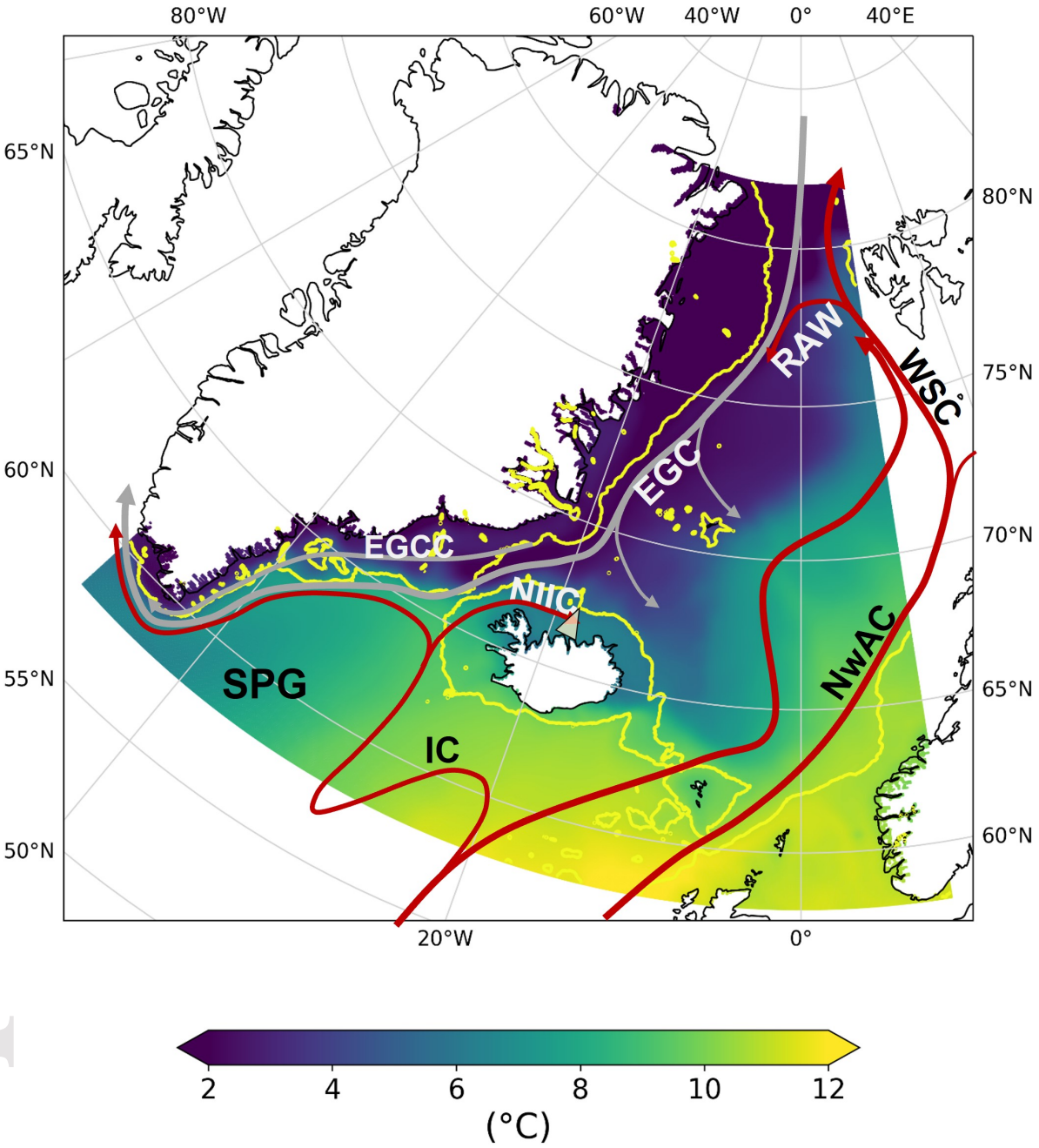
Figure 3. First four Empirical Orthogonal Functions derived from the analysis of the ERA5 SST dataset. The maps to the left indicate the geographical loadings and the plots on the right represent the contribution of each component to the SST anomaly for selected locations (red and black). The locations for the plotted SST anomalies are shown on each of the maps (red and black dot).

Figure 4. Analysis of temporal developments in the seasonality represented by EOF1. A) Hovmöller plot of the development of temperature anomaly assigned to EOF1 across the year and over the time series. Grey and yellow lines represent the timing of the summer maximum and winter minimum, respectively. B) Development of the annual summer maxima and winter minima across the time series. C) Analysis of de-seasoned scores revealing two distinct periods. Linear regression lines are presented for the period 1979-2000 (orange line) and the period 2000-2020 (green line).

Figure 5. Comparison of the time series of EOF2 with NAO and SPG. Cross-correlation analysis of EOF2 with NAO (A) and SPG (C) revealed a 4 and 5-week lag, respectively. Panels B and D compare EOF2 and the two indices. A 12 week rolling average with a cosine window is applied on both the EOF2 and the NAO and SPG time series. Both NAO and SPG were recalculated from monthly to weekly time series. The vertical lines in panels B and D (1995 and 2014) mark transition in the NAO and SPG indices.

Figure 6. Weekly mean seasonal SST anomalies explained by EOF3 in the Irminger Sea [31°W, 65°N, Fig. 3e red dot] averaged over 5 year intervals.

Figure 7. Normalized mean August temperature at the Siglunes transect (blue) and SST anomalies induced by EOF4 at the same location (red). Data from the Siglunes transect at approx. 67.75 °N, 18.83 °W (triangle on Fig. 1) collected by the Marine and Freshwater Research Institute were downloaded from SeaDataNet (https://cdi.seadatanet.org/search).



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