LETTER

On the relationship between Scandinavian extreme precipitation days, atmospheric blocking and Red Sea coral oxygen isotopes

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Abstract

In the context of ongoing climate change towards a warmer world, it is important to gain insights into the frequency and intensity of weather and climate extreme events over longer periods of time prior to the start of instrumental observations. Reconstructions of their variability are usually hampered by the rareness of natural archives for the pre-instrumental period that document climate variability at a sub-seasonal resolution. A potential archive for extreme events are annually banded reef corals which incorporate isotopic proxies of temperature and hydrology into their carbonate skeletons at sub-seasonal resolution, grow for centuries, and overlap with the observational period. Here, we investigate the relationship between the frequency of heavy precipitation days in southwestern Scandinavia and colder conditions in the northern Red Sea during winter, as documented by a coral oxygen isotope record from the northernmost area of tropical reef growth in the European sector of the Northern Hemisphere. Statistical analysis of observational data reveals that cold conditions in the northern Red Sea are associated with an increased frequency of heavy precipitation in southwestern Scandinavia. From a synoptic-scale perspective, this teleconnection can be explained by winter atmospheric blocking over mid-latitude Europe, which is a large-scale pattern of atmospheric pressure that can be active for several days or weeks. We show that increased winter blocking activity in the European region is related to an increased frequency of extreme moisture transport by atmospheric rivers affecting southwestern Scandinavia, as well as to an increased meridional advection of cold continental air from the north towards the subtropical northern Red Sea. The coral-based Scandinavian heavy precipitation reconstruction shows strong decadal variations during the pre-instrumental period. Our results provide insights into the frequency of winter atmospheric blocking events and related daily precipitation extremes in the European region, as well as into the impact of mid-latitude climate extremes on coral reef ecosystems in the northern Red Sea, during the last centuries.

1. Introduction

A major focus of current climate research is the variability in extreme weather and climate events. This research direction has been motivated by the observed increase in the frequency and intensity of weather and climate extremes, such as heatwaves, heavy rainfall, and floods, during the last few decades. These extremes can have severe effects on society and ecosystems at a global scale. Part of the observed increase is associated with anthropogenic forcing (e.g. Mann et al. 2017). However, observational records are often too short to robustly assess the significance of these trends. Proxy records of climate variability derived from natural archives (e.g. sediments, trees, speleothems, corals, and clams) can be used to put observed trends of weather
and climate extremes during the last decades into a longer-term perspective, as they extend beyond the start of instrumental observations. Commonly, weather and climate extremes are observationally recorded and assessed on a daily time scale. However, natural archives that are able to document climate variability at seasonal, sub-seasonal, or even daily time scales are extremely rare.

One of these rare archives is provided by annually banded reef corals, which grow in the warm surface waters of the tropical oceans. Isotopic and geochemical proxies incorporated into their massive carbonate skeletons during growth can provide reconstructions of surface ocean conditions, such as temperature and hydrology, for centuries at subseasonal resolution (e.g. Gagan et al 2000, Lough 2010, Felis 2020). These coral proxy records are commonly interpreted in terms of tropical modes of climate variability, such as the El Niño-Southern Oscillation (ENSO) (e.g. Cobb et al 2013) or the Indian Ocean Dipole (e.g. Abram et al 2020). However, at some rare locations such as the northern Red Sea, where these corals grow at subtropical latitudes, coral proxy records have been shown to provide information on mid-latitude modes of climate variability, such as the Arctic/North Atlantic Oscillation (AO/NAO) (Rimbu et al 2001). In this study, we use a coral oxygen isotope record ($\delta^{18}$O) from Ras Umm Sidd in the northern Red Sea (Felis and Mudelsee 2000). The $\delta^{18}$O signal of this bimonthly resolved coral record that extends back to 1751 reflects a combination of temperature and hydrological changes near the sea surface; the latter in the arid northern Red Sea are driven primarily by evaporation (Felis et al 2000, 2018). The Ras Umm Sidd record is still one of the longest subseasonally resolved coral $\delta^{18}$O records from the Northern Hemisphere extratropics and has contributed to global-scale reconstructions of temperature across the oceans and continents for the last millennium (Abram et al 2016).

It has been previously shown that the winter time series (January–February) of this coral $\delta^{18}$O record captures information on the variability of temperature and precipitation over mid-latitude Europe as well as the impact of AO/NAO-like atmospheric variability and ENSO teleconnections over the Northern Hemisphere on eastern Mediterranean and Middle Eastern climate (Rimbu et al 2001, 2003, Felis and Rimbu 2010).

Motivated by the recent availability of instrumental datasets of weather and climate extremes (Dunn et al 2020) and a new winter coral $\delta^{18}$O time series derived from the Ras Umm Sidd record (Felis and Mudelsee 2019a), we investigate the relationship between this coral time series from the northern Red Sea and the frequency of extreme precipitation over Europe during winter (December–January–February, DJF). At a regional scale, we find that an increased frequency of heavy precipitation over southwestern Scandinavia is associated with colder conditions in the northern Red Sea, as documented in the coral $\delta^{18}$O record. From a synoptic-scale perspective, this teleconnection can be explained by taking into account the role of atmospheric blocking over Europe. Blocking patterns refer to a class of weather systems in mid- to high latitudes (e.g. Woolings et al 2018, Davini and D’Andrea 2020) which can disrupt the usual westerly flow of air masses for several days or even weeks and are therefore related to extreme weather at the regional scale. We find that an increase in blocking activity over Europe is related to an increased frequency of atmospheric rivers affecting southwestern Scandinavia, as well as to increased meridional advection of cold continental air from the north towards the northern Red Sea.

2. Data and methods

Here, we use the new, annually resolved winter coral $\delta^{18}$O record from Ras Umm Sidd in the northern Red Sea (Felis and Mudelsee 2019a, 2019b), located near the southern tip of the Sinai Peninsula (Egypt, $\sim$34° E, 28° N), covering the period from 1751 to 1995 (figure S1). This record was derived from the annual winter maxima of sub-seasonally analyzed coral $\delta^{18}$O values due to the better detectability of extreme events compared to the winter values (January–February) derived from the bimonthly interpolated coral $\delta^{18}$O time series used in previous studies (Rimbu et al 2001, 2003, Felis and Rimbu 2010). The coral $\delta^{18}$O record used in this study was shown to represent sea surface conditions (temperature and evaporation) in the northern Red Sea during late winter (Felis and Mudelsee 2019a). At this time, Red Sea deep water renewals usually occur (January through March), and each winter coral $\delta^{18}$O value comprises a time interval of $\sim$2 months (Felis et al 2000).

The R10mm extreme precipitation index describes the number of days in winter with a total daily precipitation amount higher than 10 mm (e.g. Zhang et al 2011). The links between the winter coral $\delta^{18}$O record and R10mm variability were studied for the period 1950–1995 as well as 1901–1995 using the R10mm data derived from the European gridded daily precipitation dataset abbreviated as E-OBS (e.g. Cornes et al 2018) and HADEX3 datasets (Dunn et al 2020), respectively. We also made use of fields of the frequency of very heavy precipitation days (R20mm) as well as the precipitation total due to moderate wet days (R75pTOT). The R20mm counts the number of days with daily precipitation higher than 20 mm while R75pTOT represents precipitation totals due to daily precipitation higher than the 75th local percentile of wet days precipitation for the period 1961–1990. Both R20mm and R75pTOT were derived from the E-OBS dataset.
dataset (e.g. Cornes et al 2018) and retrieved from the Copernicus Climate Change service webpage (https://surfobs.climate.copernicus.eu/dataaccess/access_eobs_indices.php). Further, we have used the University of Delaware monthly mean precipitation and air temperature datasets (Wilmott and Matsuura 2001) to derive the winter mean precipitation and temperature anomaly patterns associated with the coral δ¹⁸O record. Our analysis focused on the interannual to decadal time scales so that the linear trends were removed from the data prior to any statistical analysis. We note that by removing linear trends, the impact of recent global warming or other forcing responsible for long-term variability in our data is partially removed.

Daily specific humidity and horizontal wind fields from the 20CRv2c dataset (Compo et al 2011) were used to calculate the vertically integrated horizontal water vapor transport (IVT) for the period 1851–1995. Details of the methodology for IVT calculations can be found elsewhere (e.g. de Vries 2021). Strong horizontal water vapor transport, sometimes associated with atmospheric rivers, is often related to extreme precipitation over the Scandinavian region (e.g. Azad and Sorteberg 2017, Whan et al 2020). As a measure of extreme IVT, we defined the MIVT90p index as the number of days in a winter with the magnitude of the IVT higher than the 90th local percentile. This index was calculated for each grid point of the 20CRv2c model for all winters during the 1851–1995 period. Through composite analysis, we identified the extreme IVT frequency and related precipitation patterns associated with the coral δ¹⁸O record from the northern Red Sea during winter. A similar methodology was recently used to identify extreme meridional water vapor transport patterns associated with Greenland ice core δ¹⁸O records (Rimbu et al 2021).

The activity of atmospheric blocking is commonly monitored using various blocking indices, which are based on geopotential or potential vorticity gradient fields, anomalies with respect to a basic state or a threshold, or a mixture of these two approaches (Davini and D’Andrea 2020, and references therein). In this study, we applied the two-dimensional (2D) blocking indicator proposed by Scherrer et al (2006). A brief description of this blocking indicator is provided in this section. For each grid point within the 36° N–74° N latitudinal interval, the northern (GHGN) and southern (GHGS) gradients of the 500 hPa geopotential height (Z500) were calculated. A 16° latitudinal interval was used to calculate both GHGN and GHGS. Usually (e.g. Scherrer et al 2006) the grid points for which GHGS > 0 and GHGN < (−10 m/°lat) are considered to be blocked. Such conditions require an anomalous westerly (eastery) large-scale flow north (south) of the blocked grid point.

To minimize the problem of identifying some non-blocking circulations, like cut off lows, as blocked flows (Pinheiro et al 2019 and references therein), besides the two conditions mentioned above, we considered a grid point to be blocked if the Z500 daily anomaly at that grid-point is higher than 100 m. Instantaneous blocking, referred to here as blocking, was then measured as the percent of number of blocked days per winter. We did not apply temporal or spatial filtering to the instantaneous blocking. This is motivated by the fact that blocking variability patterns remain qualitatively the same if the aforementioned filtering is applied (e.g. Davini et al 2012, Davini and D’Andrea 2020).

The maps of blocking frequency were calculated for each winter of the 1851–1995 period using daily Z500 fields retrieved from the 20CRv2 reanalysis dataset (Compo et al 2011). The blocking frequency for winters for which the values of linear detrended and normalized coral δ¹⁸O values are higher (lower) than 0.5 (−0.5) are averaged. The differences between the average fields associated with high (>0.5) and low (< −0.5) coral δ¹⁸O winters are referred to here as composite maps. The local (grid-points) significance of the composites was calculated using several methods, including the normal-z statistic and the Student’s t-test (e.g. von Storch and Zwiers 1999). We found comparable results using each method, so that only results based on t-test statistics will be presented. As the autocorrelation functions of the time series used in the composite analysis, i.e. winter coral δ¹⁸O and blocking indices, is non-significant for time lags greater or equal to one, we considered the anomaly maps as independent when calculating local statistical significance.

The linear regression models and associated statistical errors were derived using various R packages (R Core Team 2021). Linear models and prediction intervals are based on lm() and predict() functions from the base R package stats (R Core Team 2021), assuming that the data follow normal distributions. The performance of the regression model is estimated using the leave-out-one cross-validation (LOOCV) functions from the R package caret (Kuhn 2022).

3. Results and discussion

3.1. Patterns of European heavy precipitation associated with Red Sea coral δ¹⁸O
The composite map of heavy precipitation days based on the R10mm index and the coral δ¹⁸O record from the northern Red Sea during winter shows large-scale spatial structures over the European-Mediterranean region (figure 1).

In general, positive anomalies are evident in northwestern Europe, whereas negative anomalies are observed in southern Europe and the Mediterranean. Pronounced regional anomalies emerge from this
pattern. Significant positive anomalies are observed in southwestern Scandinavia and northwestern Great Britain. Significant negative anomalies are observed along the western Iberian Peninsula and eastern coast of the Adriatic Sea (figure 1). Importantly, the results are independent of the choice of the instrumental dataset, as similar patterns emerge if other extreme precipitation indices are used, that is, R20mm and R75pTOT (figure S2). We note that the strongest anomalies are observed along the western rim of the European continent facing the Atlantic Ocean at ~60° N and ~40° N. In this study, we focus on the physical mechanisms responsible for the atmospheric teleconnection between the frequency of heavy precipitation in the prominent positive anomaly center of southwestern Scandinavia (~60° N) and the northern Red Sea surface ocean climate, as documented by the Ras Umm Sidd coral δ18O record (Felis and Mudelsee 2019a) during winter.

As a measure of the variability of extreme precipitation frequency in southwestern Scandinavia during winter, we define an index as the average of R10mm anomalies within the area 5° E–7.5° E; 58° N–62° N (figure 1, rectangle box). The time series of this index shows variations similar to the coral δ18O record during 1950–1995 winters (figure 2).

The correlation between these time series is +0.52 (significant at the 95% level). Both time series are significantly positively correlated with the North Atlantic Oscillation (NAO) index, which is consistent with the spatial anomaly pattern of an increased frequency of heavy precipitation over Norway (Azad and Sørteberg 2017) and colder/more arid conditions in the northern Red Sea (Rimbu et al. 2001, Felis and Rimbu 2010) during the positive phase of the NAO. We note relatively high values in both the winter coral δ18O record and the R10mm index for southwestern Scandinavia during the years 1993 and 1992 (figure 2), when several atmospheric rivers were recorded along the western coast of Norway (Azad and Sørteberg 2017). Further, atmospheric rivers recorded in Norway during the winters (DJF) of 1989, 1983, 1976, 1968, 1957, and 1956 (Azad and Sørteberg 2017) are all associated with above mean δ18O values in the coral record (figure 2). A strong link between extreme Norwegian precipitation and atmospheric rivers was identified also in model simulations (Wahn et al. 2020). Thus, our results suggest that the Ras Umm Sidd winter coral δ18O

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**Figure 1.** Composite map (high minus low) of the frequency of heavy precipitation days (R10mm) based on the coral δ18O record from the northern Red Sea (Felis and Mudelsee 2019a) for the 1950–1995 winters. The regions where anomalies are above the 90% significance level are dotted. Units: days. The black rectangle indicates the area used to calculate the southwestern Scandinavian extreme precipitation index, i.e. the average of R10mm anomalies within (5° E–7.5° E; 58° N–62° N), for comparison with the winter coral δ18O record. The black dot indicates the coral site at Ras Umm Sidd (RUS) (Sinai, Egypt).
record from the northern Red Sea (Felis and Mudelsee 2019a) could serve as a proxy for the frequency of atmospheric rivers landing on the western coast of Norway during winter.

A recent study (Zavadoff and Kirtman 2020) shows that atmospheric rivers landfalling over western Europe are associated with Rossby wave breaking (RWB) events in the Atlantic-European region. Importantly, RWB and atmospheric blocking are intimately related (e.g. Davini and D’Andrea 2020). Therefore, it is reasonable to hypothesize that atmospheric blocking plays a role in connecting the northern Red Sea temperature anomalies and frequency of extreme rainfall in Scandinavia during winter, as suggested by our data analysis presented in the next section.

3.2. The role of atmospheric blocking over Europe
The winter coral δ¹⁸O record from the northern Red Sea and the time series of extreme precipitation frequency in southwestern Scandinavia during winter are significantly positively correlated during the 1950–1995 period. To understand the physical mechanism behind this atmospheric teleconnection, we analyzed the atmospheric circulation and water vapor transport for a particular day when an atmospheric river event was recorded on the western coast of Norway (Azad and Sorteberg 2017), which is 3 January 1992 (figure 3).

In the winter of 1992, both the extreme precipitation index for southwestern Scandinavia and the coral δ¹⁸O record indicate values above their corresponding means (figure 2). The 500 hPa atmospheric circulation on 3 January 1992, shows a blocking-like circulation over Europe with strong westerlies over northern Great Britain and southern Scandinavia (figure 3(a)). Consistent with this circulation pattern, our defined blocking index indicates a large area with blocked grid points near the 500 hPa geopotential height (Z500) maximum (figure 3(a), purple closed contour).

This atmospheric circulation pattern is associated with enhanced moisture transport from the Atlantic Ocean to southwestern Scandinavia (figure 3(b), vectors). Heavy precipitation (>10 mm) is observed along the coast of southwestern Scandinavia (figure 3(b), shaded). This is consistent with previous works (Azad and Sorteberg 2017, Wahn et al 2020) showing that such enhanced water vapor transport events, which are sometimes associated with atmospheric rivers, can lead to heavy precipitation in the coastal areas of southwestern Scandinavia. However, we note that the occurrence of extreme precipitation in these areas is also dependent on orographic and upper-level atmospheric forcing (de Vries 2021). Importantly, this large-scale atmospheric circulation pattern over Europe during winter results in negative temperature anomalies in the eastern Mediterranean-Middle Eastern region, including the northernmost Red Sea, owing to the meridional advection of cold continental air from the north towards these areas (figure 3(a), shaded.
Figure 3. (a) The 500 hPa atmospheric circulation and surface negative air temperature anomalies and (b) the vertically integrated horizontal water vapor transport (IVT) and surface precipitation higher than 10 mm for 3 January 1992. In (a) contours indicate the 500 hPa geopotential height (Z500) (m) and vectors the 500 hPa horizontal wind (m s\(^{-1}\)). Areas with negative temperature anomalies (°C) are shaded. Grid points within closed contours (purple) are considered to be blocked, as defined by our atmospheric blocking index (see text). In (b) streamlines and vectors represent the direction and magnitude of IVT (kg ms\(^{-1}\)). Areas with precipitation higher than 10 mm are shaded. The black rectangle indicates the area used to calculate the southwestern Scandinavian extreme precipitation index (5° E–7.5° E; 58° N–62° N) for comparison with the winter coral δ\(^{18}\)O record. The black dot indicates the coral site at Ras Umm Sidd (Sinai, Egypt).

regions). The atmospheric circulation and moisture transport anomaly patterns associated with the winter coral δ\(^{18}\)O record (figure S3), which are based on winter mean data, also show that positive precipitation anomalies in southwestern Scandinavia are associated with enhanced moisture transport towards the region as well as cold conditions in the northern Red Sea. This suggests that an increased frequency of synoptic-scale circulation patterns like those represented in figure 3, are associated with a significant increase in the winter mean precipitation in southwestern Scandinavia as well as with a significant decrease in winter mean temperature in the northern Red Sea region.

The case study presented above suggests that atmospheric blocking over Europe during winter, as detected by our blocking indicator, is simultaneously related to heavy precipitation in southwestern Scandinavia and to colder conditions in the northern Red Sea. Thus, blocking circulation is a potential atmospheric circulation pattern that can explain the significant positive correlation between the frequency of heavy precipitation in southwestern Scandinavia and the coral δ\(^{18}\)O values in the northern Red Sea during winter (figure 2). Atmospheric circulation patterns classified as instantaneous blocking by our index are not restricted to classical blocking patterns, that is, omega block, dipole, or open ridges (e.g. Kautz et al 2022), but include a large family of circulation patterns satisfying the instantaneous blocking criteria. We conclude that
Figure 4. The composite maps (high minus low) of (a) the frequency of extreme IVT magnitude (MIVT90p, only values higher than one day are shown) and (b) the blocking frequency during winter, both based on the coral $\delta^{18}O$ record from the northern Red Sea (Felis and Mudelsee 2019a) for the 1950–1995 winters. The regions where anomalies are above the 90% significance level are dotted. Units: days and percentage of blocked days from the total number of winter days. The rectangle box indicates the area of the European blocking index (see text for definition). The black dot indicates the coral site at Ras Umm Sidd (Sinai, Egypt).

a high frequency of such types of atmospheric circulation patterns in a certain winter is associated with both an increased frequency of heavy rainfall in southwestern Scandinavia and colder conditions in the northern Red Sea, which are documented as higher values in the winter coral $\delta^{18}O$ record from Ras Umm Sidd.

We further investigate and verify the atmospheric teleconnection pattern that connects blocking over Europe, Scandinavian extreme rainfall, and northern Red Sea coral $\delta^{18}O$ during winter. Thus, we calculate composite maps for the frequency of extreme IVT days (MIVT90p) as well as for the blocking frequency in the North Atlantic region, both based on the winter coral $\delta^{18}O$ record (figure 4).

The composite maps reveal that anomalously high values of coral $\delta^{18}O$, that is, unusually cold conditions in the northern Red Sea, are associated with an increase in extreme moisture transport over northern Great Britain and southern Scandinavia (figure 4(a)), accompanied by an enhanced blocking frequency in the European Atlantic region (figure 4(b)). The blocking pattern associated with the winter coral $\delta^{18}O$ record remains qualitatively the same if both temporal and spatial filters are considered in the blocking detection method (figure S4). These results are consistent with the observation that winters with an increased frequency of extreme moisture transport events towards the coast of southwestern Scandinavia are characterized by a higher frequency of heavy precipitation (Azad and Sorteberg 2017), and with a significant positive correlation between the frequency of heavy precipitation in this area and the winter coral $\delta^{18}O$ record from the northern Red Sea (figure 2).

The region in southwestern Scandinavia used to define our precipitation index (figure 1) is located near the end of the North Atlantic extratropical cyclone tracks (e.g. Hodges et al 2011). Importantly, this region is
mountainous. Consequently, the horizontal advection of moisture within the warm sector of the extratropical cyclones (i.e. the warm conveyor belt) from the ocean towards the coast can result in precipitation that is locally enhanced by the steep topography. Furthermore, the configuration of the large-scale atmospheric circulation can contribute to the generation of heavy rainfall in this region. It has been shown that a combination of RWB, which influences the position of the upper-level jet, and intense moisture transport are associated with the majority of extreme precipitation events over mountainous regions along extratropical coasts (de Vries 2021).

To better assess and confirm the role of atmospheric blocking in explaining the link between the frequency of Scandinavian extreme precipitation and the coral $\delta^{18}O$ record during winter, we define a blocking index as the average instantaneous blocking frequency for all grid-points within ($10^\circ$ W–$30^\circ$ E; $40^\circ$ N–$55^\circ$ N). In this region the instantaneous blocking frequency is increased during cold conditions, i.e. high coral $\delta^{18}O$ values, in the northern Red Sea (figure 4(b), rectangle box). This index is significantly positively correlated with our R10mm (coral $\delta^{18}O$) at the level 0.81 (0.44) during the period 1950–1995. The correlation maps between this index and R10mm (figure S5(a)) and winter mean temperature (figure S5(b)) clearly show that during a winter with enhanced blocking frequency in this region an increased frequency of heavy precipitation days occur in western Scandinavia as well as anomalous cold conditions in the northern Red Sea.

To verify whether our derived winter anomaly patterns of atmospheric circulation and extreme precipitation are robust with respect to the investigated time interval, we performed a similar composite analysis for the periods 1901–1949 (figure S6) and 1851–1900 (figure S7). We find that the derived patterns are qualitatively the same, suggesting that the relationships between the frequency of heavy precipitation over southwestern Scandinavia, atmospheric blocking over Europe, and the coral $\delta^{18}O$ record from the northern Red Sea during winter were stable over the period of instrumental observations. This is supported also by the significant positive correlation between our blocking index and the coral $\delta^{18}O$ record during these periods (figure S1).

3.3. Variability during the pre-instrumental period

The results suggest that the winter coral $\delta^{18}O$ record from Ras Umm Sidd in the northern Red Sea (Felis and Mudelsee 2019a), which extends back to 1751 (figure S1) could be used as a predictor for the frequency of extreme precipitation in southwestern Scandinavia during winter. Thus, we performed a simple linear regression to test whether coral $\delta^{18}O$ can significantly predict our defined southwestern Scandinavian extreme precipitation index during the 1950–1995 period. The predictive model was $\text{EPI} = 78.71 + 26.04^* \delta^{18}O_{\text{coral}}$ where the extreme precipitation index (EPI) is measured in days and $\delta^{18}O_{\text{coral}}$ in ‰ (permil). We found that the model parameters are statistically significant ($F(1,44) = 15.52, p < 0.001$). The r-squared coefficient of the model estimates with LOOCV (Kuhn 2022) is 0.2 while the root mean square error is 7.2 and the absolute mean error is 5.8. Note that the LOOCV method provides a much less biased measure of parameters compared to using a single test. The correlation coefficient between the predicted and observed extreme precipitation indices is +0.52. This simple linear regression model was used to reconstruct a time series of the southwestern Scandinavian extreme precipitation index back to 1751.

For further verification of the reconstruction during the instrumental period, we calculated a similar index (figure S8) but based on a different instrumental dataset (HADEX3) that extends back to the year 1901 (Dunn et al. 2020). This index is significantly positively correlated with our predicted index ($r = + 0.45$, significant at the 95% level) for the 1950–1995 period. The correlation decreases to $r = + 0.34$ for the 1901–1949 period. Thus, we conclude that, in spite of the relatively low amount of explained variance when using unfiltered data, the winter coral $\delta^{18}O$ record from the northern Red Sea is a potentially useful predictor of the southwestern Scandinavian extreme precipitation index during the observational period.

We note that the reconstructed extreme precipitation index for southwestern Scandinavia during winter reveals a tendency towards more pronounced decadal variability prior to 1900 compared to the 20th century (figure 5).

The reconstruction further suggests more frequent extreme precipitation over southwestern Scandinavia during the $\sim$1790–1800 and $\sim$1820–1840 time intervals (figure 5). Furthermore, during $\sim$1800–1810, a decade of low values of extreme precipitation frequency is indicated (figure 5). In general, based on our atmospheric teleconnection patterns derived for the period of instrumental observations, more frequent blocking events over Europe during time intervals dominated by high values in the reconstructed extreme rainfall index for southwestern Scandinavia could be expected. However, we note that not the entire observed variability at decadal and longer time scales in the reconstructed index time series is related to changes in blocking frequency. The extreme precipitation in this region could also be the result of various potential forcing factors affecting the mid-latitude climate on these time scales.
Figure 5. The time series of the reconstructed southwestern Scandinavian extreme precipitation index (dots), defined as the average winter R10mm anomalies within (5° E–7.5° E; 58° N–62° N), for 1751–1995. The winter coral δ¹⁸O record from the Ras Umm Sidd (Sinai, Egypt) (Felis and Mudelsee 2019a) is used as a predictor for this index. The shaded area depicts the 90% prediction interval.

4. Conclusions

We provide a synoptic-scale perspective on the atmospheric teleconnection between the frequency of heavy precipitation days in southwestern Scandinavia and colder conditions in the northern Red Sea during winter, as documented by the winter coral δ¹⁸O record from Ras Umm Sidd (Felis and Mudelsee 2019a). This teleconnection can be explained by considering the role of winter atmospheric blocking in Europe. Our results indicate that an increase in blocking activity over Europe, which can disrupt the usual westerly flow of moisture-bearing air masses from the Atlantic Ocean for several days or even weeks, is related to an increased frequency of extreme moisture transport by atmospheric rivers, affecting southwestern Scandinavia, as well as to an increased meridional advection of cold continental air from the north towards the northern Red Sea. Consequently, winters characterized by enhanced blocking frequency over Europe are associated with a higher frequency of extreme precipitation days in southwestern Scandinavia and lower temperatures in the northern Red Sea. This explains, from a synoptic-scale perspective, the significant correlation between the frequency of heavy precipitation days in southwestern Scandinavia and the northern Red Sea coral δ¹⁸O anomalies during winter reported in this study. Our results are consistent with previous interpretations of the winter coral δ¹⁸O record in terms of AO/NAO-like atmospheric teleconnections (Rimbu et al 2001, Felis and Rimbu 2010), because during the positive phase of the AO/NAO the North Atlantic jet is shifted north increasing the probability of anticyclonic RWB and high-latitude atmospheric rivers (Zavadoff and Kirtman 2020) as well as atmospheric blocking over Europe.

The winter coral δ¹⁸O time series shows not only interannual but also decadal and multidecadal variations (figure S1). This suggests that the autocorrelation in the time series could become important for certain time periods or longer time scales. Therefore, complex statistical methods (e.g. Trenberth 1984) should be considered to better assess and confirm the statistical significance patterns presented in this study. Furthermore, a simple visual inspection of figure S1 reveals a possible link between the winter coral δ¹⁸O record and the Atlantic Multidecadal Oscillation (AMO), the dominant mode of multidecadal variability in the North Atlantic (e.g. Trenberth and Shea 2006).

A number of studies have examined the correlation between blocking events and some atmospheric climate variables and modes of variability, including the AMO (e.g. Wazneh et al 2021 and references therein). In our interpretation, the multidecadal variability in the winter coral δ¹⁸O record could be related to the AMO modulation of the blocking frequency over Europe during winter.

Global climate simulations using numerical models commonly show an underestimation of atmospheric blocking frequencies, and even coupled model intercomparison project models do not achieve the observed...
blocking frequency during winter in the European sector (Davini and D’Andrea 2020). Given the importance
of atmospheric blocking in the seasonal prediction systems of the European Centre for Medium-Range
Weather Forecasts (Davini et al 2021), we suggest that the winter coral δ18O record from the northern Red
Sea extending back to the year 1751 (Felis and Mudelsee 2019a), could be used as a complementary source of
information about the frequency of winter atmospheric blocking in the European sector on longer time
scales during the pre-instrumental period. As some climate models project a decrease in blocking activity
over Europe in a warmer future climate (e.g. Davini and D’Andrea 2020) we speculate that the coupling
between northern Red Sea temperatures and southwestern Scandinavian extreme rainfall during winter
could decrease in the future. However, this atmospheric teleconnection would probably remain significant,
as no dramatic changes in the position or intensity of blocking patterns over Europe have been projected,
even in the most pessimistic scenario (Davini and D’Andrea 2020).

Finally, we note that the northern Red Sea hosts some of the most productive and diverse shallow-water
coral reefs globally, which are considered as refugia from global warming and ocean acidification (Fine et al
2019). It is interesting that these coral reefs during the past centuries developed in concert with and were
affected by mid-latitude climate extremes such as winter atmospheric blocking over Europe. An increased
frequency of such blocking events during a specific winter, which usually occurs on time scales of days to
weeks, would result in ‘accumulated’ colder mean conditions in the northern Red Sea, as integrated in the
winter coral δ18O record from Ras Umm Sidd. Importantly, anomalously cold and dry winters in the
northern Red Sea can result in open-ocean deep convection (Felis and Mudelsee 2019a) triggering deep
vertical water mass mixing events that can have severe impacts on coral reefs in the area (Genin et al 1995,
Felis et al 1998). Given the projected decrease in winter atmospheric blocking activity in the European sector
(e.g. Davini and D’Andrea 2020), this negative effect of mid-latitude atmospheric blocking on northern Red
Sea coral reefs could be speculated to decrease in a warming climate, while the potential of these reefs as
refugia from global warming would probably be diminished because of a decreased occurrence of
anomalously colder winters in the region.

Data availability statement

The coral data for this paper, i.e. the new Ras Umm Sidd winter coral δ18O time series from the northern Red
Sea are available at https://doi.pangaea.de/10.1594/PANGAEA.900471 at the World Data Center PANGAEA.
The climate data used in this study are also openly available as follows:

- E-OBS extreme climate indices (https://surfobs.climate.copernicus.eu/dataaccess/access_eobs_indices.php),
- HADEX3 extreme climate indices (www.metoffice.gov.uk/hadobs/hadex3/),
- 20CRv2c reanalysis data (https://psl.noaa.gov/data/gridded/data.20thC_ReanV2c.html)
- University Delaware temperature and precipitation datasets (https://climatedataguide.ucar.edu/climate-
data/global-land-precipitation-and-temperature-willmott-matsuura-university-delaware)

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