

Article

Spectral Analysis of Ocean Variability at Helgoland Roads, North Sea: A Time Series Study

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Abstract

The understanding of coastal ecosystems regarding variability and resilience under climatic and anthropogenic forcing is reliant upon long-term ecological records. We examined the Helgoland Roads time series (1968–2017), which includes temperature, salinity, nutrients (nitrate, phosphate), and biological parameters (diatoms and *Acartia* spp.). We applied autocorrelation, multi-taper spectral analysis, and wavelet and cross-wavelet transforms to identify dominant temporal patterns and scale-dependent interactions. Sea surface temperature shows consistent long-term warming, and subdecadal (2–3-year) and decadal (7–8-year) oscillations reflect coherent patterns with the North Atlantic Oscillation and Arctic Oscillation. Salinity varied in anti-phase to Elbe River discharge at 6–7-year scales, reflecting control of seasonal, riverine freshwater, and salinity scenarios. Nutrients, as declining long-term trends (particularly phosphate), are associated with seasonal to multi-year variability linked to episodic discharge events. Biological parameters had strong annual periodicities reflective of bloom cycles but also variability above the annual limit. Diatoms responded to climatic, nutrient, and biological responses at the 3–5-year scale associated with this ecological context, particularly nitrate and phosphate; *Acartia* (spp.) respond to temperature, salinity, and resource availability (diatoms), reflecting climate/nutrient/trophic linkages. This study indicates that Helgoland Roads is represented as a multi-scale, non-stationary system, in which climate variability, riverine input, and ecological linkages are cascaded down to physical and chemical processes that structure biological communities. Spectral methods reveal scale-dependent synchrony and highlight the risks of trophic mismatch under climate change, emphasizing the importance of sustained high-frequency monitoring.

Keywords: Helgoland Roads; spectral analysis; wavelet transform; nutrients diatoms; climate variability



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1. Introduction

Coastal and marine ecosystems, influenced by land and oceanic inputs, possess dynamic spatio-temporal variability in physico-chemical and biological properties. Assessing this variability is essential for understanding ecosystem responses to climatic oscillations, anthropogenic pressures, and natural cycles [1,2]. Long-term monitoring systems from around the world, like those of the Gulf of Maine [3], California Current [4], Tokyo Bay [5],

and Baltic Sea [6], have offered discovering multidecadal shifts in temperature, salinity, and nutrient dynamics. Datasets from these monitoring stations facilitated investigating long-term changes in coastal marine ecosystems due to large-scale atmospheric drivers like the Pacific Decadal Oscillation (PDO) and the North Atlantic Oscillation (NAO). Studies based on these datasets collectively underscore the importance of high frequency observations to determine ecological resilience to complex climate variability and/or anthropogenic force worldwide.

The Helgoland Roads (HR) time series, located in the southeastern North Sea, has been monitored continuously since 1962, making it one of the most extensive marine time series anywhere [7,8]. Situated within a narrow tidal channel between the islands of Helgoland and Düne, HR represents a transitional hydrographic zone influenced simultaneously by the open North Sea and the Elbe River plume. This dual influence of marine and terrestrial processes makes HR an ideal model system for assessing how coupled climatic and land-based forcings shape coastal ecosystem dynamics, mechanisms relevant to many estuarine and shelf-sea systems worldwide [9,10].

Despite having substantial research on coastal ecosystems, less is known about the persistence, periodicity, or coupling of physical/chemical/biological variability at multiple time scales. The HR dataset, which contains over fifty years of consistent daily data collection, offers a unique dataset to help disentangle this multi-scale variability, and the respective connections to climate and riverine drivers. A combination of autocorrelation, multi-taper spectral, and wavelet analysis will be employed to (i) assess dominant modes of variability across hydrographic and biological variables, (ii) quantify cross-scale coherence between environmental drivers and the biological responses, and (iii) situate any observed periodicities in a wider coastal and climatic context that might help in understanding how coastal systems respond to interacting marine, climatic, and anthropogenic drivers, insights that are transferable to other temperate shelf and estuarine environments globally.

2. Methods

2.1. Data Sources and Measurement History

This study is based on time series data (1968–2017) from HR station (Figure 1) maintained by the Alfred Wegener Institute (AWI) [7]. The dataset includes long-term physical variables (sea surface temperature [°C], salinity, Secchi depth [m]), chemical variables (nitrate NO_3^- and phosphate PO_4^{3-} [$\mu\text{mol L}^{-1}$]), and biological variables (total diatom abundance [cells L^{-1}] and *Acartia* spp. abundance [ind. m^{-3}]).

Instrumentation and analytical protocols at AWI have been adapted over the last several decades and regularly calibrated and standardized to maintain temporal consistency:

- Temperature and salinity were recorded using mercury thermometers and inductive salinometers until the early 1980s, when they were replaced by the now-aged CTD sensor and are routinely re-calibrated and re-verified for accuracy [11].
- Secchi depth was recorded consistently with a 30 cm white disk and under standardized conditions.
- Nutrients were analyzed by classical colorimetric techniques [12] and then were analyzed with automated continuous-flow analyzers (Bran + Luebbe and Skalar systems, from the 1990s). Data were homogenized by AWI's internal calibration protocols to ensure consistency, and quality assurance was provided under the ICES framework and PANGAEA [11,13].
- Phytoplankton and zooplankton samples were taken from 1 m depth, preserved in Lugol's iodine and identified microscopically with inter-operator calibration between operators to maintain taxonomic consistency [7,14].

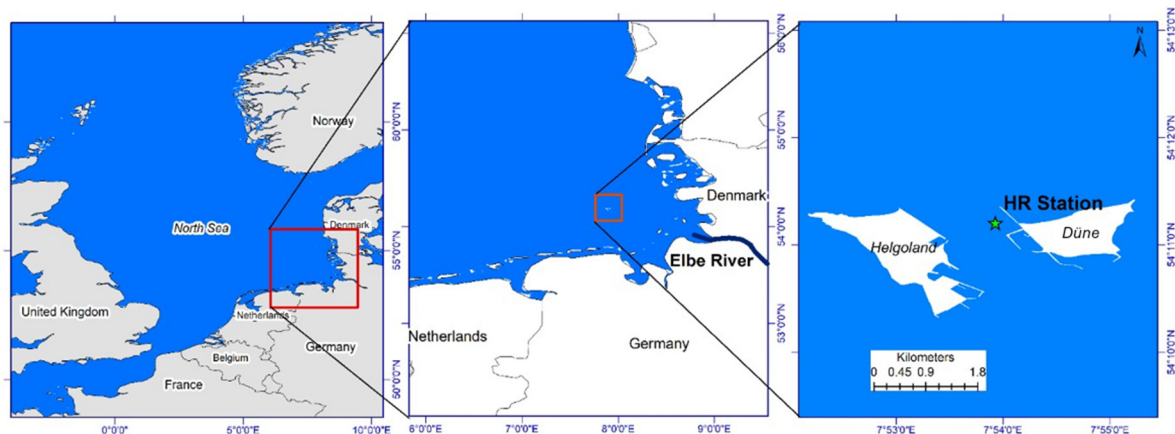


Figure 1. Geographical location of the study area (data used from www.marineregions.org). Left panel shows the map of the North Sea with a rectangular box indicating the location of the German Bight. Middle panel map shows a close-up of the German Bight with a rectangular box showing the position of Helgoland. Right panel map shows the location of Helgoland Roads Times Series Station between two islands, i.e., Helgoland and Düne.

Instrumental transitions involved overlapping calibration periods and statistical standardization to maintain continuity [11]. The error estimated from the changes in methods is $\pm 3\%$ for physical variables and $\pm 5\text{--}8\%$ for chemical and biological data, on a par with findings from other long-term North Sea observatories [13].

Monthly Elbe River discharge [15] and monthly North Atlantic Oscillation (NAO) [16] and Arctic Oscillation (AO) [17] indices were also added to depict terrestrial and atmospheric drivers.

2.2. Data Preprocessing and Harmonization

The daily data were compiled into monthly means to provide a comparison between variables and to identify long-range trends. While the averaging of data over time can mask short-term events, such as a single episode with high phytoplankton biomass, averaging allows for strong evaluation of variable interannual to interdecadal persistence.

To examine variability, temporal elimination of trends and seasonal signals was achieved by calculating monthly climatological means from long-term data (1968–2017) and removing these values from the raw series, then creating normalized anomalies. As shown in Figure 2, the normalized anomalies highlighted the more dominant low-frequency modes; specifically, only the normalized anomalies showed interannual to interdecadal periodicities in temperature.

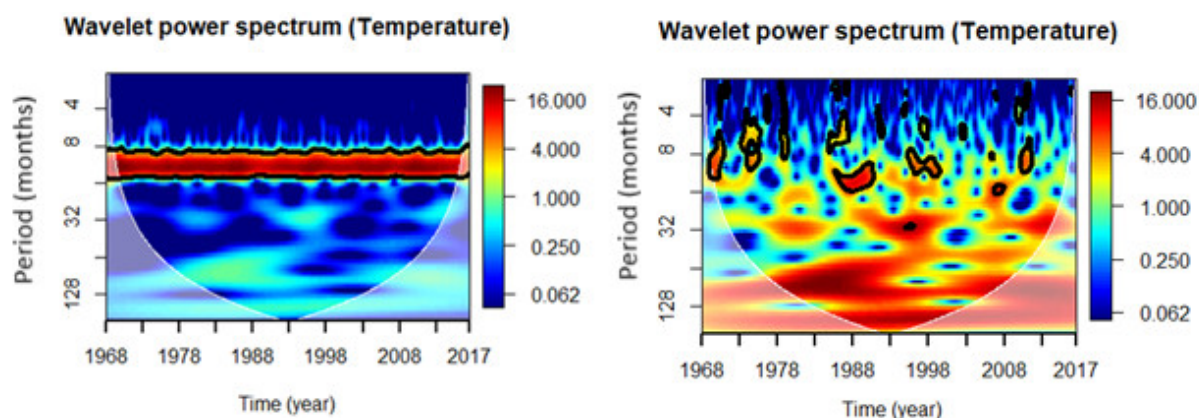


Figure 2. Wavelet power spectrum of temperature: for original time series data (left) and for normalized anomalies (right).

2.3. Analytical Procedures

2.3.1. Autocorrelation Analysis

Temporal significance was assessed using autocorrelation functions (ACF) for the 1968–2017 period and for subsequent 10-year intervals. Lag dependencies and other persistence patterns were evaluated for statistical significance with Bartlett-adjusted confidence limits.

2.3.2. Multi-Taper Spectral Analysis (MTM)

In identifying the dominant frequency, the multi-taper method (MTM) was implemented, which utilizes average orthogonal Slepian tapers to optimize spectral leak and variance, thus offering a stronger level of spectral stability than the traditional Fourier transform [13]. For the MTM, we used three orthogonal tapers and a time–bandwidth product equal to three, as per the recommendations for ecological time series data [13]. A first-order autoregressive (AR1) red-noise process was utilized as the background spectrum model, and peaks above the 95% significance threshold were deemed statistically significant. MTM analyses were carried out using PAST 4.17 [18], which has introduced adaptive weighting and estimating significance using the F-test, as detailed by [19].

2.3.3. Wavelet and Cross-Wavelet Analyses

For the analysis of non-stationary variability, the Continuous Wavelet Transform (CWT) method was employed using the complex Morlet wavelet, with the ability to localize dominant oscillations in time/frequency [20,21]. The Cross-Wavelet Transform (XWT) was applied to determine spectral power shared and phase relationships for paired variables, including the following:

- (i) SST vs. climate indices (NAO, AO);
- (ii) Salinity vs. Elbe River discharge;
- (iii) Nutrients vs. hydrographic variables;
- (iv) Biological vs. environmental drivers [22,23].

The statistical significance of the wavelet power spectra was evaluated using the default analytical approach implemented in the WaveletComp package version 1.1.453, which estimates confidence levels directly from the normalized variance of the time series. The cone of influence (COI) was used to delineate regions potentially affected by edge effects in the wavelet transform. All computations were performed in R using the WaveletComp package [21].

2.4. Methodological Limitations and Generalization

The analysis is based on data from a single high-frequency station, Helgoland Roads, that incorporates the interplay of marine and terrestrial forcings which are characteristic of many temperate shelf systems. Therefore, the temporal patterns and cross-scale linkages presented here provide insights that are relevant beyond Helgoland Roads and to other coastal systems influenced by riverine inputs, tidal mixing, and atmospheric influences [9,10].

3. Results

3.1. Temporal Variability

Physical, chemical, and biological normalized monthly anomalies (Figure 3) show both long-term patterns and short-term variations after the seasonal cycle was removed. Sea surface temperature (SST) indicates a continuous upward trend since approximately the mid-1980s, reflecting a persistent background warming in the German Bight. Regional warming has occurred within interannual fluctuations, such as distinct warm anomalies

(with reference to the mean climatological temperature in the region) observed during the early 1990s and again in the early 2000s. Likewise, salinity exhibits pronounced decadal variability, including freshening periods associated with enhanced riverine influence followed by recovery periods.

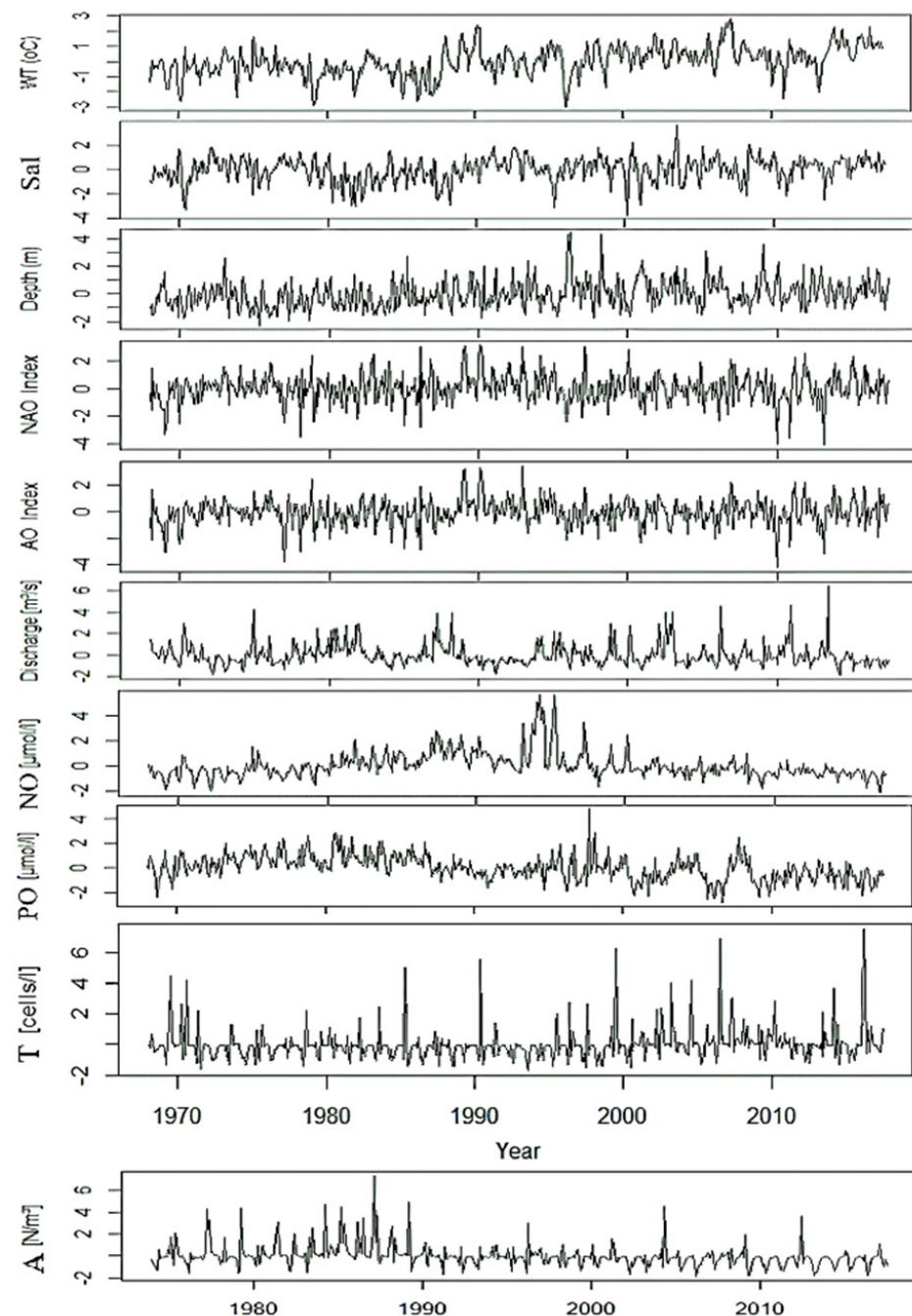


Figure 3. Normalized anomalies of the monthly time series of the variables (without seasonality).

Nutrient concentrations struggle to exhibit similar long-term trajectories. Nitrate anomalies show a progressive downward trajectory throughout the 1980s and after, representing reductions in anthropogenic loading and nutrient management in the Elbe catchment. Phosphate displays downward anomalies with episodic fluctuations, particularly during the 1970s and early 2000s.

Biological variables differ greatly in terms of temporal heterogeneity. Although diatom abundances do show episodic peaks, they are not in regular succession, indicating bloom events and more long-term variability. The episodic peaks are most pronounced during the late 1980s and mid-2010s, *Acartia* spp. also demonstrated marked fluctuations; the abundances were also notably high during the mid-1980s and late 1990s, and in the early 2010s, demonstrating population dynamics operate at seasonal and multi-year time scales.

The autocorrelation analysis of the anomalies for consecutive decades (Figure 4) shows differences in persistence across variables. SST and salinity anomalies retain significant autocorrelation over multiple lags for all time blocks, indicating physical forcing has very long memory. By contrast, nitrate and phosphate anomalies displayed weaker autocorrelations, with significance only observed for the shortest lags, which is indicative of rapid turnover and sensitivity to incoming resources. The biological time series stresses quite short persistence: total diatom and *Acartia* spp. anomalies were significantly autocorrelated only for lags of one year, consistent with the annual bloom and lifecycle of *Acartia*. Beyond this, autocorrelation dissipated rapidly, which illustrated dominance of short-term environmental variance over long-term memory.

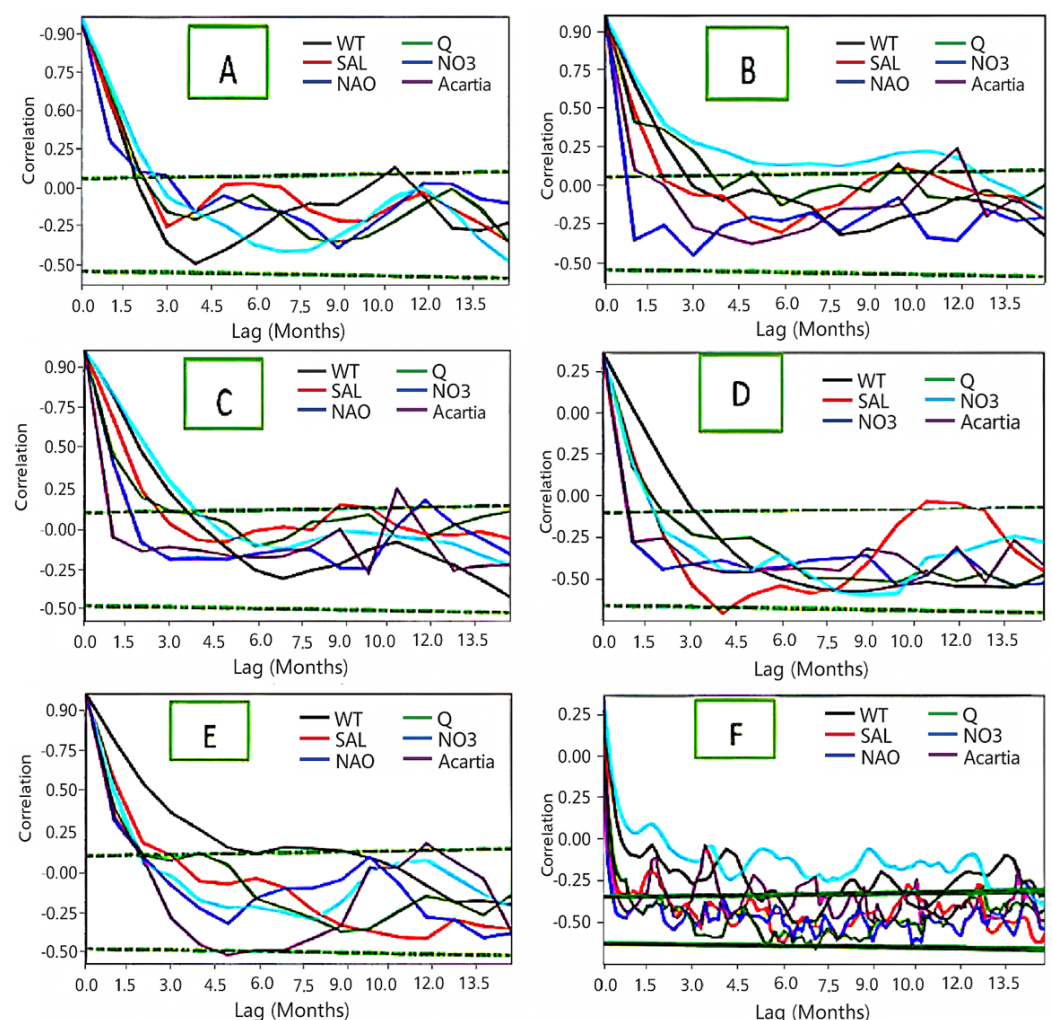


Figure 4. Autocorrelation of the time series anomalies for 10-year blocks from 1968 to 2017. The dashed lines represent the range outside which autocorrelation is statistically significant ($p < 0.05$; ± 2 standard errors). (A) 1968–1977, (B) 1978–1987, (C) 1988–1997, (D) 1998–2007, (E) 2008–2017, and (F) 1968–2017.

3.2. Spectral Characteristics

The multi-taper spectral analysis (Figure 5) identified dominant frequencies throughout the entire period of 1968–2017. SST and salinity exhibited strong periodicities centered at 7–8 years and significant subdecadal oscillations between 2 and 3 years. These periodicities relate directly to known modes of North Atlantic climate variability including the North Atlantic Oscillation and Atlantic Multidecadal Oscillation. In contrast to the physical variables, the nutrient time series were irregularly peaked but included both high frequencies (0.5–1 year) and longer cycles (3–7 years), indicating both seasonal forcing and hydroclimatic variability with predicted changes in nutrient concentrations across regimes.

The dominant diatom abundance annual cycle is predictable with the appearance of spring blooms; however, the quantity of diatom abundance diverges by repeated peaks of episodic events, sustained up to 3–5 years, attributed to changes in nutrients or hydrographic changes. *Acartia* spp. also strongly represent an annual component but their spectra bring to light interannual modes at 2–3 years, and decadal variability at 8 years. Both taxa strongly depict shifts in population dictated by shifts in environmental regime.

The wavelet power spectra (Figure 6) show all periodicity as non-stationary in time. SST and salinity show strong 7–8-year cycles from 1980 to 1990, and subsequent 2.5-year oscillation from 1993 to 1995. Nitrate and phosphate both had intermittently strong high frequency variability throughout 1970–2000, and phosphate had an additional strong 3-year mode between 2006 and 2011. Biological variables had a strongly consistent annual periodicity, while the remaining shifting multi-year variability shows a variety of periodicities. For instance, within the time window of 2014–2016, the diatom abundance periodically demonstrated a 3-year periodicity and was demonstrably periodic at 5 years from 1988 to 1992. The *Acartia* spp. had strong annual datasets during the 1980s while also reflecting multi-year variability, including perhaps, a strikingly prominent 15-year mode from 1990 to 2000. This indicates both physical and biological variability at Helgoland Roads will show distinct temporal windows of dominant periodicity, which will shift over time.

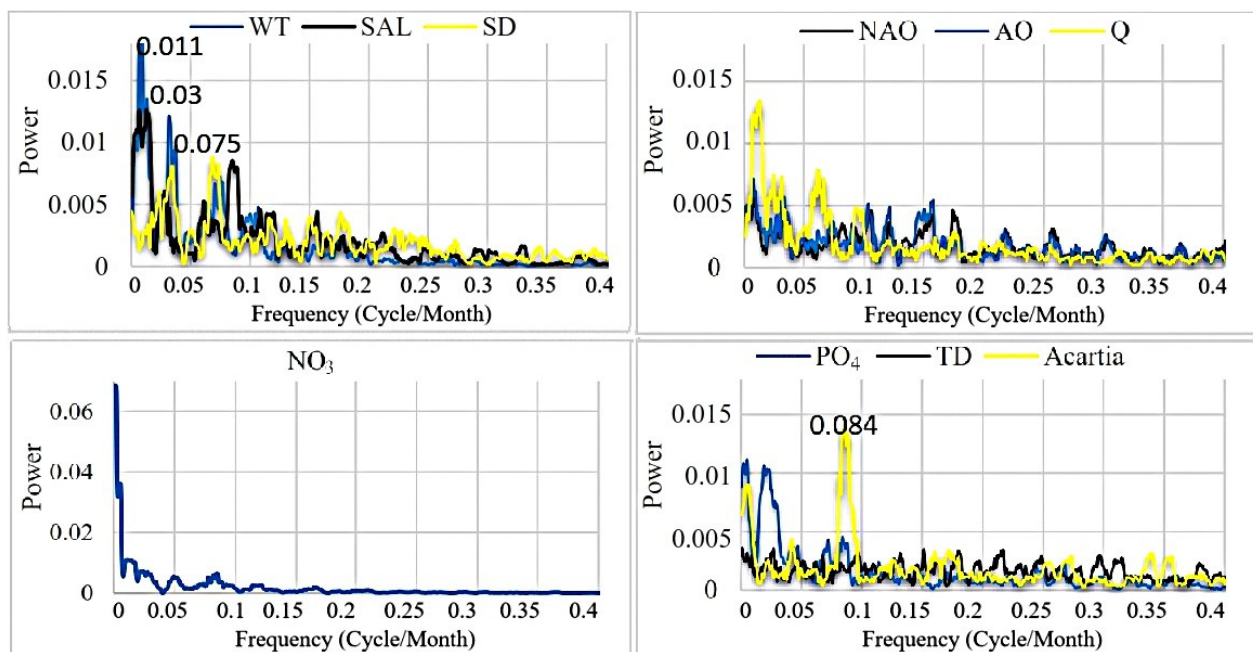


Figure 5. Multi-taper spectral analysis for the whole time series period.

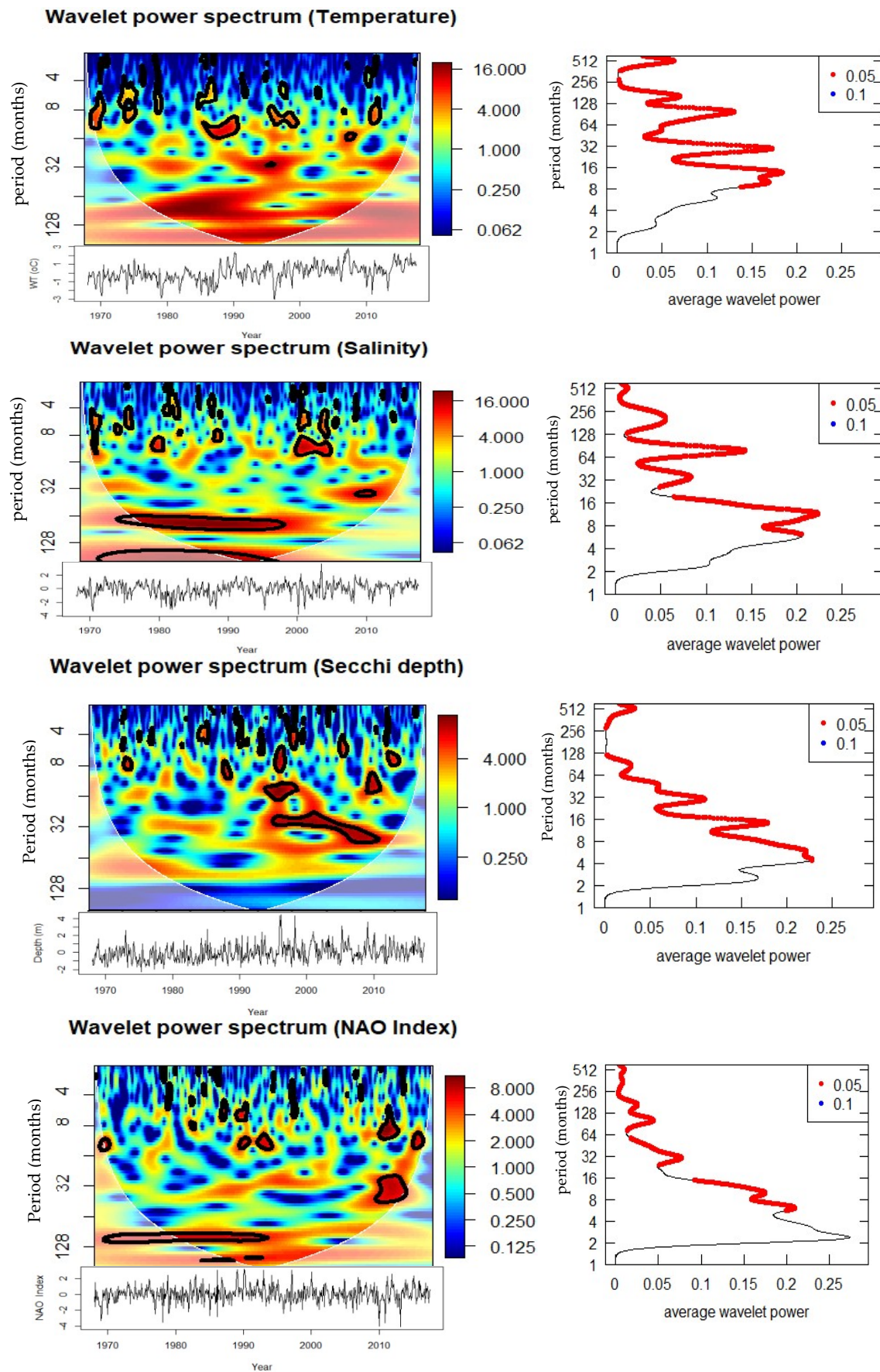


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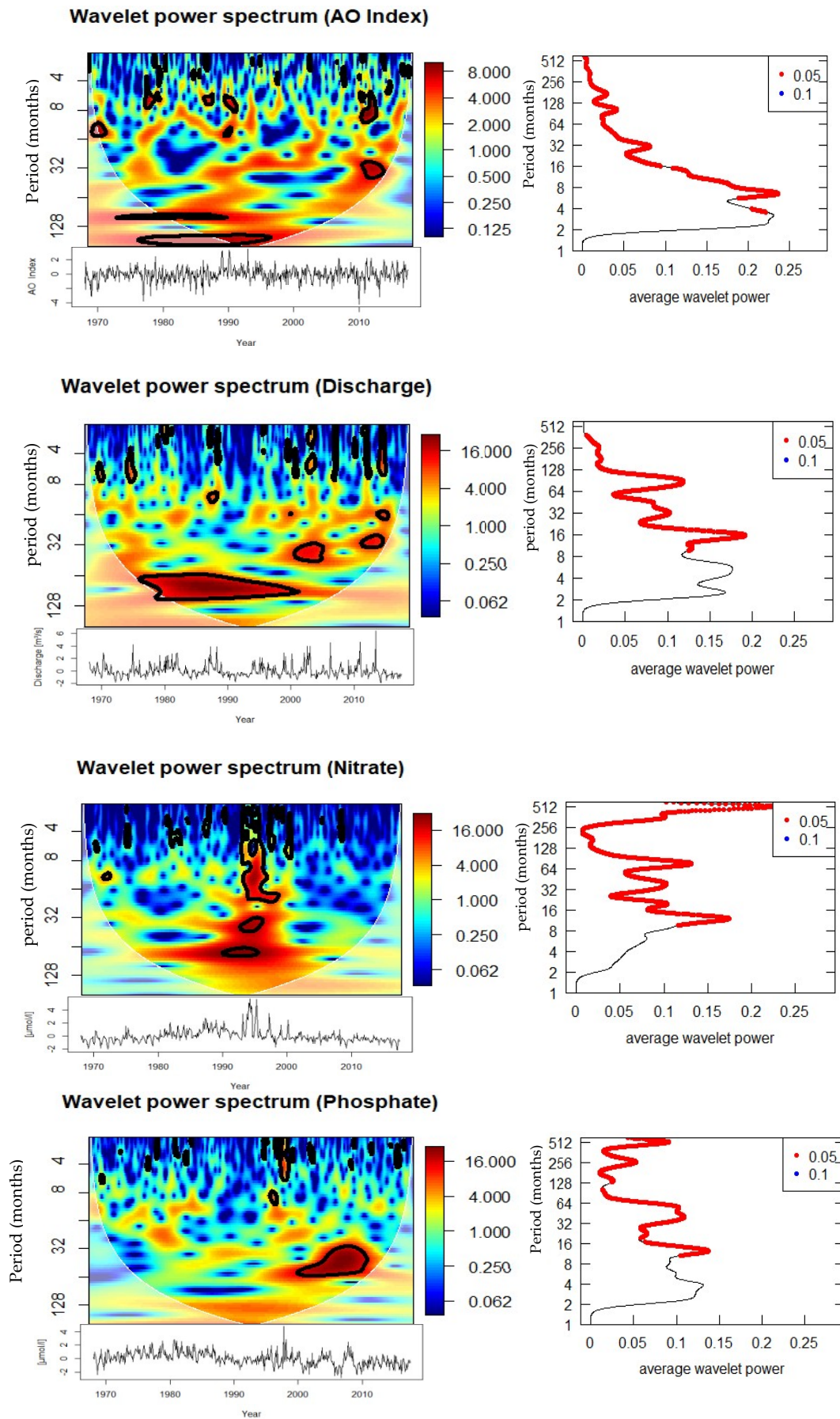


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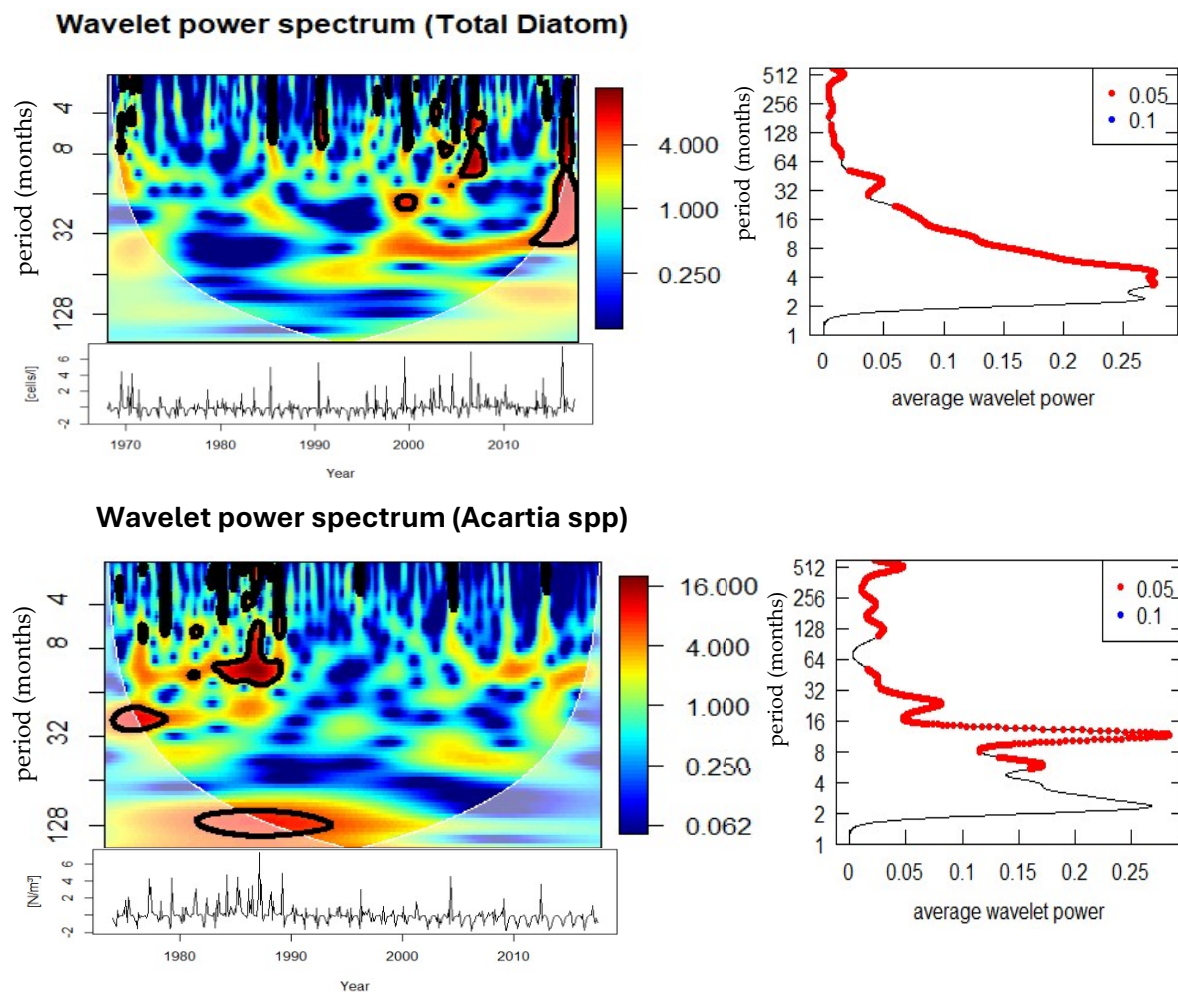


Figure 6. Wavelet-power spectrum analysis of normalized anomalies of the studied variables based on monthly mean with cone of influence (lighter shade smooth curve); black lines indicate significant power at 95% level compared to red noise.

3.3. Links Between Physical Parameters and Large-Scale Drivers

Cross-wavelet analysis provides evidence for strong relationships between local physical parameters and large-scale climatic and terrestrial drivers (Figure 7, Table 1). SST is significantly coherent with both the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) at periodicities of 2.5 years (1993–1995) and 7–8 years (1980–1990). Phase relationships indicate that these oscillations are in-phase, suggesting a direct and immediate response of SST to atmospheric forcing.

Salinity anomalies are strongly linked to Elbe River discharge, showing significant anti-phase relationships (180°) at 6–7-year cycles between 1970 and 2000. This reflects the dilution of seawater salinity by freshwater input during high discharge periods. Salinity also exhibits significant coherence with temperature at 7 years during 1980–1990 and with nitrate at both high-frequency (0.5–1 year, intermittent during 1970–2000) and multi-year (7 years, 1980–1998) scales. Phosphate also shows a 3-year anti-phase coherence with salinity between 2006 and 2011, suggesting that riverine and hydrographic processes strongly shape nutrient dynamics.

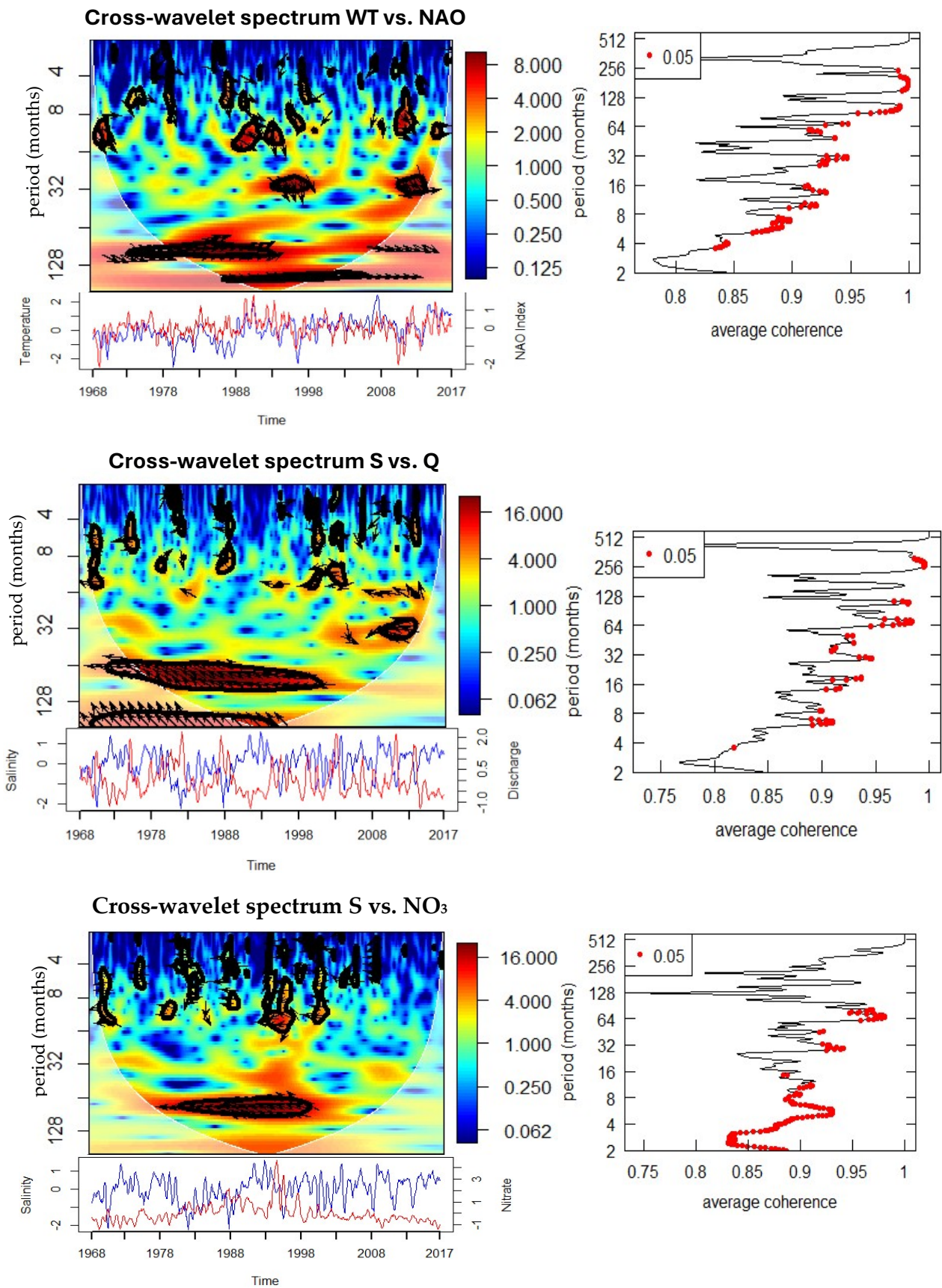


Figure 7. Cont.

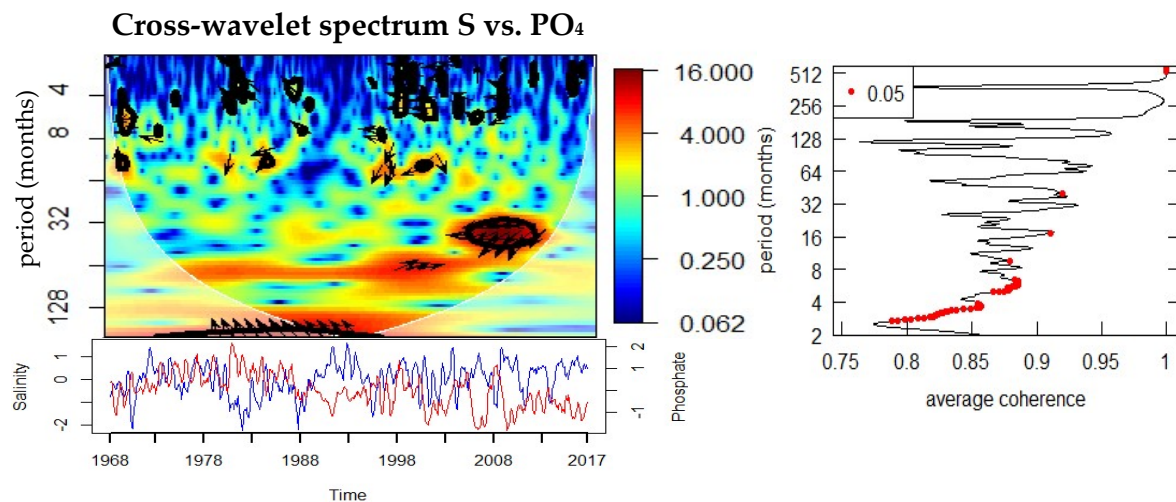


Figure 7. Cross-wavelet transform of the normalized anomaly of the time series of physical parameters with cone of influence (lighter shade smooth curve); black lines indicate significant power at 95% level compared to red noise. The relative phase relationship is shown as arrows (with in-phase pointing right, anti-phase pointing left). If the primary variable has a positive normalized anomaly, the arrow direction is in-phase and vice versa. In the time series graph (left-below), blue colour indicates primary axis and red colour indicates secondary axis.

Table 1. Summary of the drivers of T, S, and Q following cross-wavelet spectrum. Observed periodicity and associated significant time period and phase angle are also listed.

Variables	Periodicity (Years)	Time Periods	Phase Angle
For Temperature			
NAO	2.5	1993–1995	90
	7 August	1980–1990	0
AO	2.5	1993–1995	90
	7 August	1980–1990	0
For Salinity			
Temperature	7	1980–1990	90
Discharge	6 July	1970–2000	180
NO ₃	0.5–1	1970–2000	180
		(intermittent)	
PO ₄	7	1980–1998	180
	3	2006–2011	180
For Total Diatom			
Temperature	0.5–1	1970	270
	3	2014–2016	270
	5	1988–1992	
Salinity	0.5–1	1970, 2004	0
	0.5–1	2008–2012	90
NO ₃	5	1988–1995	270
	3 May	1990–1995	180
	3	2003–2010	180
For <i>Acartia</i> spp.			
Temperature	0.5–1	1984–1988,	180
	8	1985–1990	180
		1978–1988	
Salinity	1	(intermittent)	180
	8	1988–1993	90

Table 1. Cont.

Variables	Periodicity (Years)	Time Periods	Phase Angle
NO ₃	1	1977–1988 (intermittent)	0
	8	1986–1996	0
	1	1982–1987	270
PO ₄	2.5		
	15	1990–2000	0
	1	1986–1987, 2007, 2016	180
Total Diatom	3	2003–2010	180

3.4. Biological Responses to Environmental Drivers

Cross-wavelet analyses of biological and environmental parameters (Figure 8, Table 1) reveal significant multi-scale coupling. Diatom abundance shows strong coherence with SST at both annual (0.5–1-year) and multi-year (3–5-year) scales. The phase relationships suggest that diatom peaks follow temperature anomalies with a lag, indicating modulation of bloom intensity and timing by thermal conditions. Significant coherence with salinity is observed at annual (0.5–1-year) and 5-year periods, with phase shifts indicating that diatom blooms are influenced by hydrographic variability. Associations with nitrate and phosphate occur at 3–5-year cycles, particularly during 1990–1995 (nitrate) and 2003–2010 (phosphate), suggesting a strong dependence of bloom dynamics on nutrient supply.

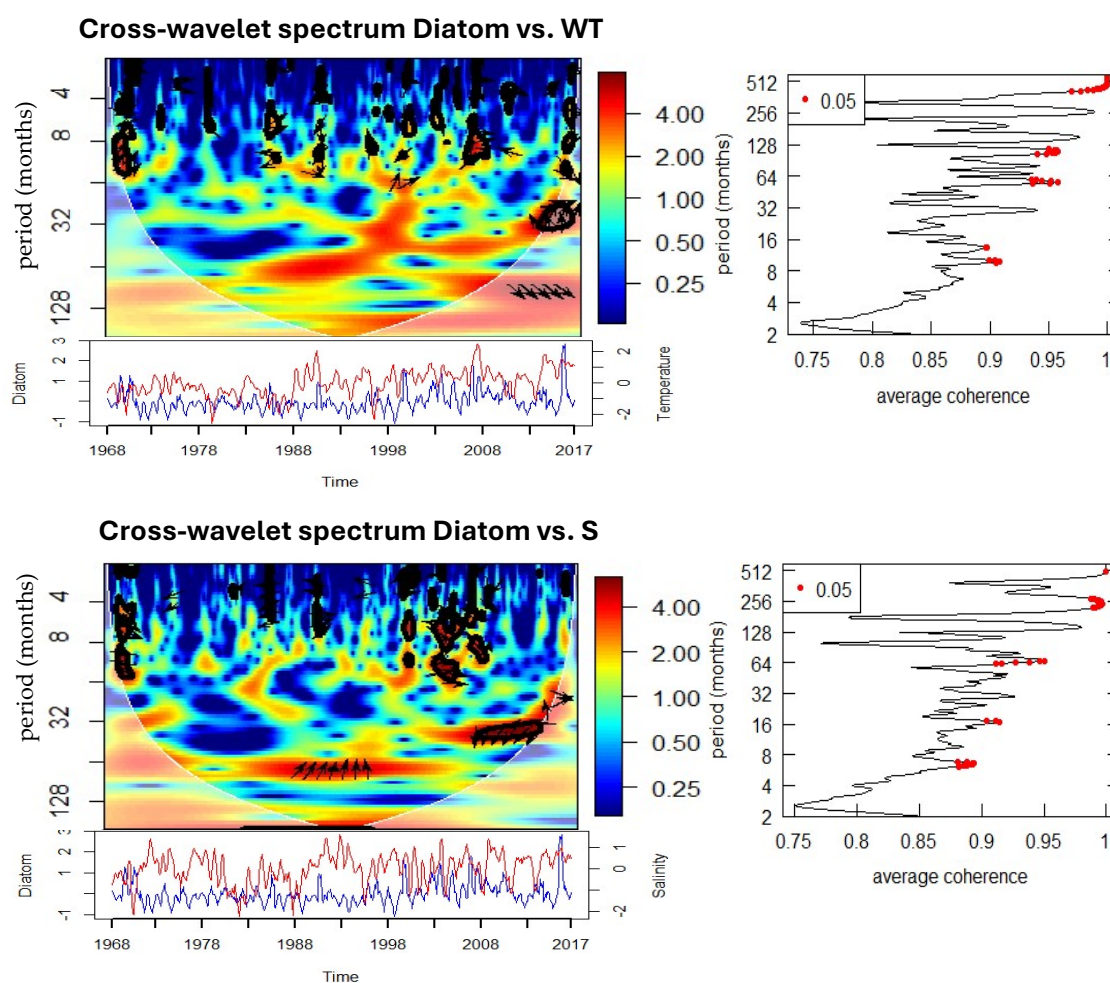
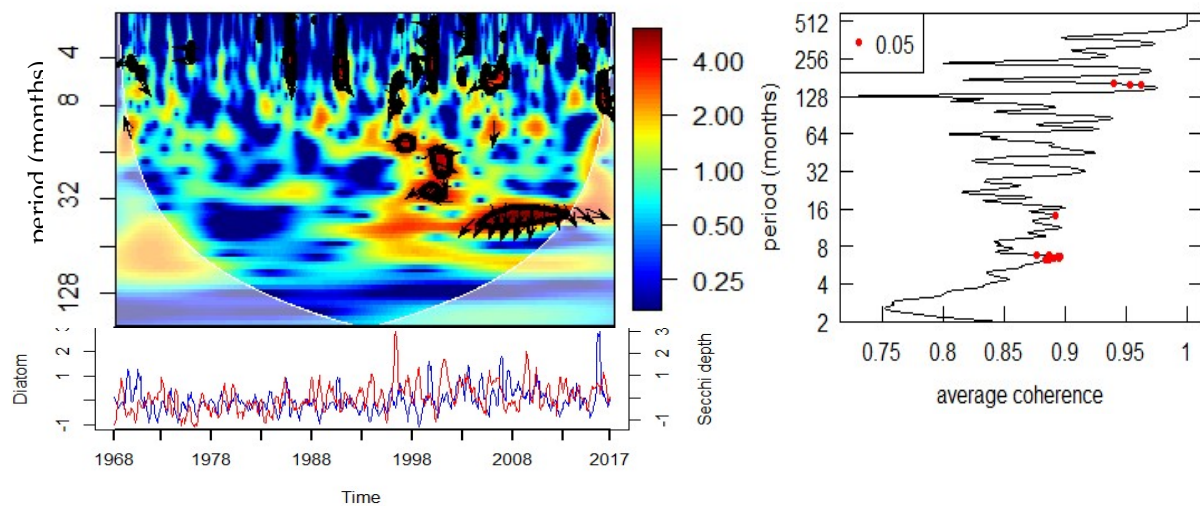
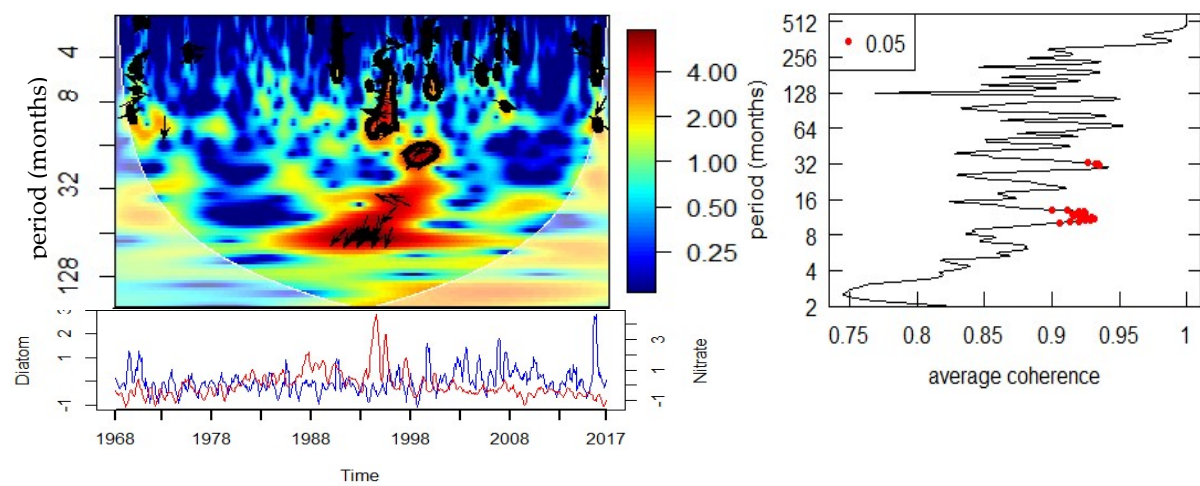


Figure 8. Cont.

Cross-wavelet spectrum Diatom vs. SD



Cross-wavelet spectrum Diatom vs. NO_3



Cross-wavelet spectrum Diatom vs. PO_4

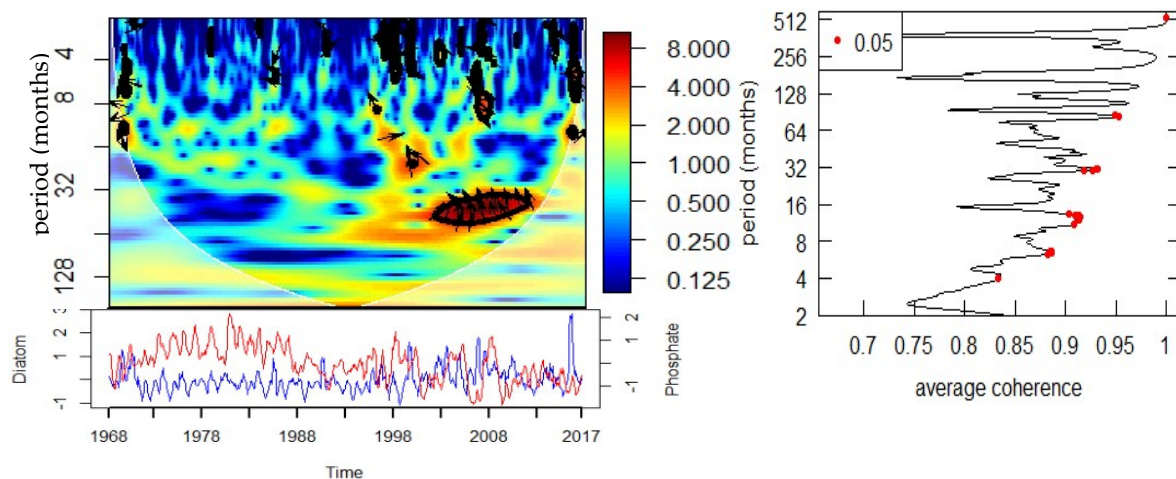
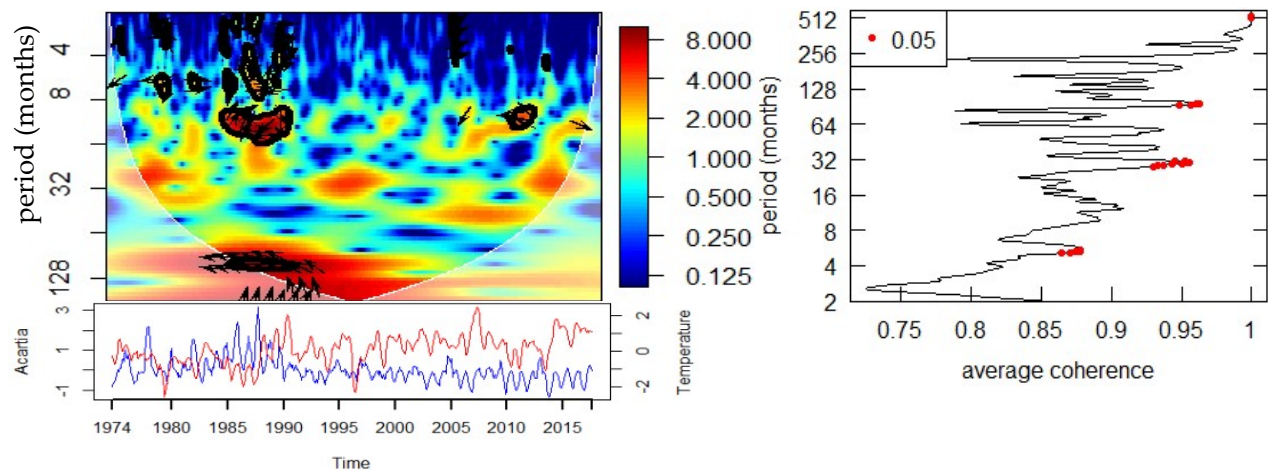
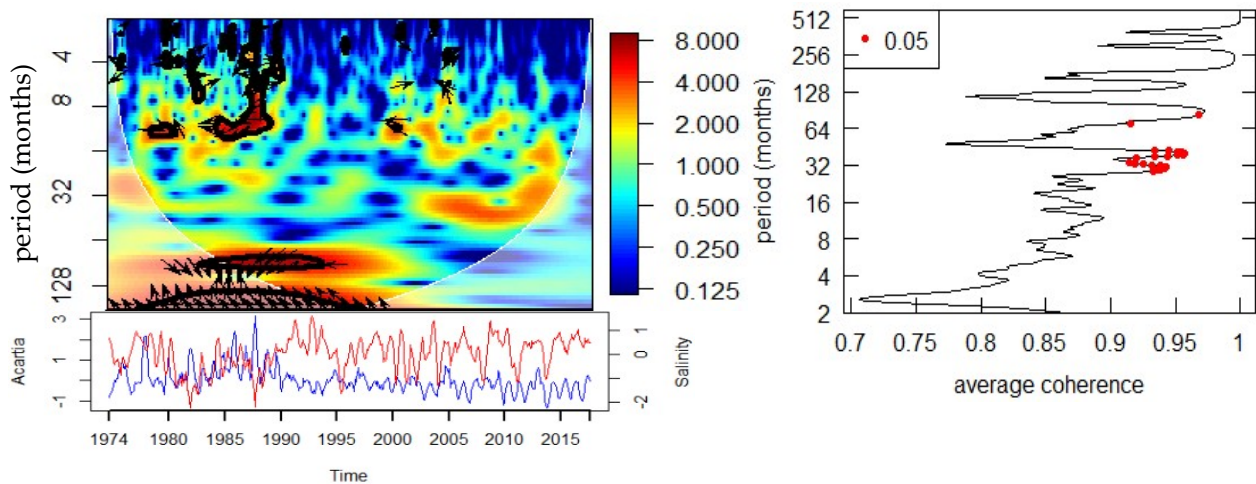


Figure 8. Cont.

Cross-wavelet spectrum Acartia vs. WT



Cross-wavelet spectrum Acartia vs. S



Cross-wavelet spectrum Acartia vs. NO₃

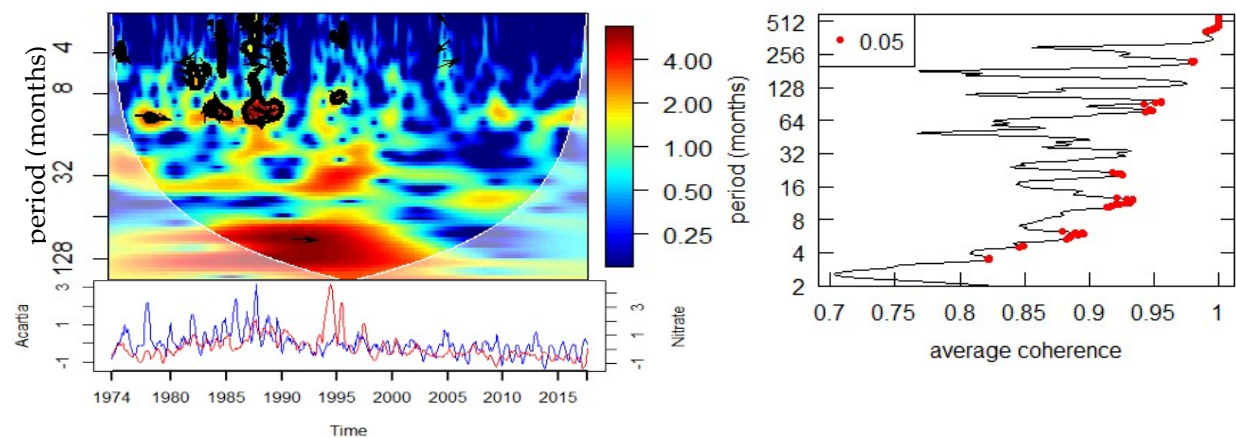


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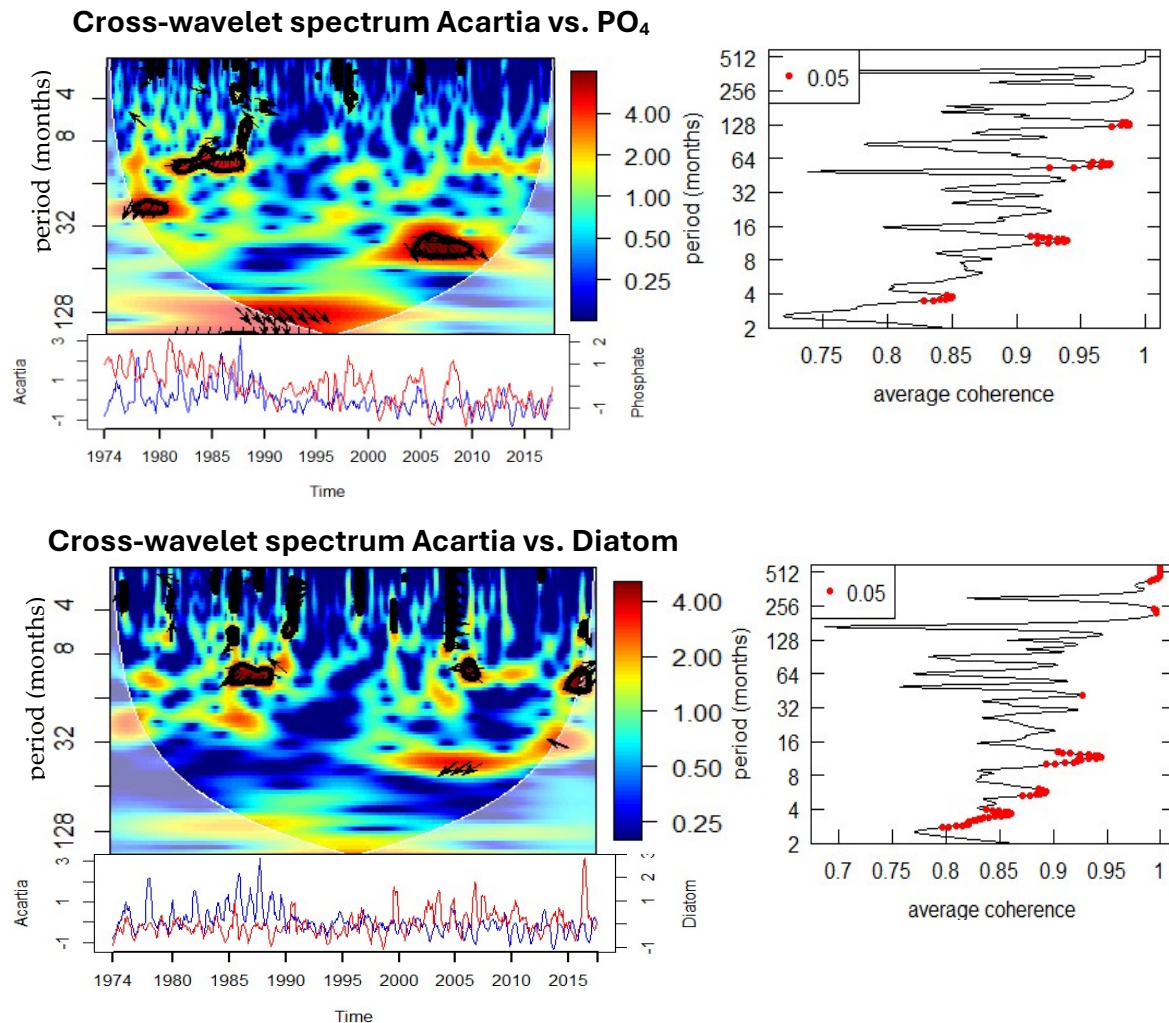


Figure 8. Cross-wavelet transform of the normalized anomaly of the time series with cone of influence (lighter shade smooth curve); black lines indicate significant power at 95% level compared to red noise. The relative phase relationship is shown as arrows (with in-phase pointing right, anti-phase pointing left). If the primary variable has a positive normalized anomaly, the arrow direction is in-phase and vice versa. In the time series graph (left-below), blue colour indicates primary axis and red colour indicates secondary axis.

Acartia spp. show a similarly complex response. Significant coherence with SST is observed at annual (0.5–1 year, 1984–1988) and decadal (~8 years, 1985–1990) scales, with phase relationships indicating alternating in-phase and anti-phase dynamics. Salinity is coherent with *Acartia* spp. abundance at annual scales (1978–1988, intermittent) and at an 8-year cycle during 1988–1993. Nutrient relationships are evident at both annual (nitrate and phosphate during the 1980s) and longer (8-year nitrate, 15-year phosphate) scales. Importantly, *Acartia* spp. abundance also shows coherence with diatom abundance at both annual (1986–1987, 2007, 2016) and 3-year (2003–2010) scales, confirming trophic coupling between primary producers and zooplankton consumers.

3.5. Synthesis of Multi-Scale Variability

Cross-wavelet coherence (Figure 7) identified substantial co-variability between SST and NAO relationships (with phase arrows indicating in-phase occurs during positive NAO periods). There was coherence between salinity and Elbe River discharge, which meant there was a fresher influence (anti-phase). The coherence was strongest for nutrients

and hydrographic parameters at the 2–4-year time scale and biological variables were intermittently coupled with both SST and nitrate. Discussions of associations made on wavelet significance testing under red-noise assumptions should be regarded as indicative correlations rather than causal connections.

Collectively, the results demonstrate that the Helgoland Roads ecosystem exhibits variability at hierarchical seasonal, interannual, and decadal time scales. Physical forcing (temperature, salinity, and discharge) drives low frequency coherence, while biological variables react to forcing with short-lived (event-driven) oscillations modulated by nutrient availability. The HR is a single coastal site, but its hydrographic setting, balancing riverine input and exchange with open-sea areas, makes it broadly representative of temperate shelf systems where terrestrial and marine drivers overlap [8,9].

4. Discussion

4.1. Variability

The robust 2–3 yr and 7–8 yr bands in SST and the significant cross-wavelet coherence with NAO/AO suggest a modulation of the thermal regimes at Helgoland Roads by large-scale atmospheric modes on subdecadal cycles, superposed on the secular warming trend seen since at least the 1980s, consistent with more recent syntheses indicating ongoing warming in the German Bight and the North Sea [24,25]. The 2–3 yr and 7–8 yr bands persisted in our data record during 1980–1990 and 1993–1995, corresponding to periods with strong NAO/AO expression in the region [26,27]. Such a modulation of subdecadal SST should be seen as one of the prime preconditions for the changes in phenology and trophodynamics seen across the North Sea planktonic community under investigation [28].

Cross-wavelet evidence demonstrating anti-phase salinity–discharge at ~6–7 years shows the overriding importance of riverine forcing at Helgoland Roads. Recent reviews have reaffirmed a river-dominated nutrient budget in the German Bight and south North Sea, with deposition from the atmosphere and inflow from the Atlantic being relatively minor and strongly seasonally driven [8,29]. The bigger picture is that river loads peaked in the 1980s and have declined (more rapidly for P than N) since, increasing the N:P ratio [8].

4.2. Ecological Response

The diatoms in Helgoland Roads demonstrate strong repeated annual (spring bloom) and secondary 3–5 yr bands that become weak and strong through time in each of the wavelets. Recent work shows that the spring bloom timing of diatoms is very resilient, while the magnitude and composition vary interannually [30], and studies of “rapid succession” also suggest that even small physical–chemical windows can cause microplankton communities to be restructured in spring [31]. This fits well with our identification of coherence between diatoms and nitrate/phosphate at multi-year scales as it relates to nutrient supply that is driven by hydrographic and climate variability. Furthermore, taxonomic and metabarcoding studies have shown that phases of diversification and turnover of diatom and dinoflagellate assemblages are still happening in Helgoland [14,32], suggesting that physical–chemical envelopes we have found in the spectral analysis may be expressed as community composition changes even as bulk bloom timing is consistent.

Cross-wavelet analysis suggests that *Acartia* spp. responded at annual, interannual (2–3 yr), and longer (~8–15 yr) scales, there is also significant coupling to SST, salinity, and nutrients—and to diatoms at annual and 3-year bands. This fits well with the multidecadal copepod studies documenting trends in copepod phenology and biomass across the North Sea; at Helgoland, studies that span decades note that temperature acts as a key variable regulating copepod reproduction and phenology [28,32]. The coherence with diatoms at both short and interannual time scales may indicate alternating bottom-up trophic control

(due to prey availability) and lags (from hydroclimate-mediated changes in food quality) that align with recent reports of reorganization in copepod communities with warming [28].

When taken together, the spatially introduced NAO/AO-driven temperature field (T), riverine-controlled salinity/nutrient loading (S), and biological periodicity (e.g., total diatoms and *Acartia* spp.) provide a picture of a non-stationary multi-scale coupled system in a highly dynamic coastal ecosystem. With river discharge at high levels (or years of high magnitude) and with a positive NAO, we generally expect a fresher, more stratified, and nutrient-rich condition in spring to promote diatom blooms and create stronger annual-band connections with *Acartia*. However, in periods dominated by lower discharge regimes and altered N:P stoichiometry, these blooms may be nutrient limited and compositional, while grazer/consumer responses appear to be of a more lagged/interannual nature, strengthening the 3–5 yr coherence bands observed here. Furthermore, regional syntheses show similar relationships to those discussed here, decreasing nutrient concentrations, mixed effects of temperature on *Chl-a*, and spatial differences in plankton response to a hydrodynamic context [24,25].

4.3. Synthesis of Temporal Patterns

The spectral and correlation analyses reveal that temperature, salinity, and nutrient variability at Helgoland Roads are dominated by seasonal and interannual cycles, with additional decadal signals linked to large-scale climatic drivers. Annual periodicities correspond to the strong seasonal stratification and mixing patterns typical of the German Bight [33], while 3–6-year oscillations coincide with variations in the North Atlantic Oscillation (NAO) and Elbe River discharge [34]. Long-term nutrient and chlorophyll trends reflect anthropogenic influences and eutrophication control measures implemented since the 1980s [8,10]. These synthesized results align with earlier time series analyses conducted in the North Sea and other temperate coastal systems [24,35,36], but the present study advances previous work by quantifying dominant periodicities through spectral methods, offering a generalized temporal model of ecosystem variability for the Helgoland Roads region.

4.4. Implications and Outlook

From a methodology perspective, the use of multi-taper spectral analysis and (cross-)wavelet analysis together creates a meaningful framework to identify the temporal scales and windows of opportunity where environmental drivers and biological responses covary, something conventional time series analysis approaches are unable to isolate in a single timeframe. From an ecological perspective, we have used the annual and interannual bands to identify risks of both short-term match–mismatch and multi-year changes in the community that are relevant to trophic transfer in the German Bight.

Future research could benefit from integrating adaptive and data-driven spectral methods that better account for non-linear and non-stationary ecological processes, such as empirical mode decomposition, Hilbert–Huang transforms, or Bayesian spectral models. These methods are increasingly applied in marine and hydrological time series to address the complex variability typical of dynamic coastal systems [37]. Combining these analytical frameworks with mechanistic ecosystem models and high-frequency monitoring will strengthen the ability to disentangle natural variability from anthropogenic influences in long-term marine observations. Moreover, incorporating Helgoland Roads monitoring with trait-based analysis of zooplankton [38] and molecular community analysis [14] will be critical for translating these spectral trends into mechanistic information of food web dynamics under climate change.

This analysis shows that time/frequency methods can detect long-term variability in coastal physical, chemical, and biological dynamics, such as wavelet and multi-taper analysis. Nevertheless, biological variables (especially abundance of plankton) are often characterized by irregular, episodic, and non-red-noise dynamics that may be related to bloom events. For this reason, the WaveletComp analysis did not assume a red-noise [AR(1)] background, which would force red-noise dynamics on time series of biological data that have a spiky nature. This kind of non-red-noise behavior is documented in ecological and biogeochemical datasets [39]; thus, detected oscillations should be seen as reflecting the dominant patterns of variability rather than the periodicity, or causal connection.

5. Conclusions

In this study, long-term spectral and correlation analyses were performed on the Helgoland Roads (HR) time series to identify the dominant temporal modes, along with their environmental drivers, of coastal variability in the southeastern North Sea. The results demonstrate that annual and semiannual cycles are mostly determined by the seasonal thermal stratification during the summer and associated tidal mixing, combined with biological production. Interannual oscillations of 3–6 years correspond to fluctuations associated with the North Atlantic Oscillation (NAO) and variability in Elbe River discharge. Longer-term (decadal) periodicities suggest gradual shifts associated with the management of eutrophication, regional warming, and large-scale hydroclimatic forcing.

In combining spectral analysis and long-term observational data, this study has resulted in a generalized conceptual model of oceanographic development in the German Bight. This model summarizes the trajectory from a nutrient-enriched, eutrophic coastal system during the 1970s and 1980s to a more regulated, climate-modulated regime in recent decades. This trajectory is a reflection of both anthropogenic mitigations associated with nutrient loads, paired with the increasing influence of atmospheric and hydrographic variability.

Overall, this study demonstrates how valuable high-resolution coastal time series are (e.g., Helgoland Roads) in detecting multi-scale patterns of ocean variability and linking local hydrographic processes to large basin-scale climatic oscillations. Future work should apply cutting-edge spectral-coherence methods and ecosystem modelling cross-correlating physical and biogeochemical parameters under different climate and management scenarios.

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