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A long-term dataset of *in-situ* temperature data reveals wind-induced up- and downwelling in the coastal waters of Nha Trang, South Central Vietnam

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ABSTRACT

In order to implement successful coastal management and protect corals, it is imperative to understand the Nha Trang Bay's coastal processes and take adequate measures to protect corals and reef structure. This paper aimed to analyze whether sudden variations in physical parameters, such as temperature, could be potentially harmful to coastal coral reefs, in addition to anthropogenic factors such as pollution and intensive fishing. In this paper, the first long-term observation (2008–2019) of temperatures, not only from SST data, but also *in situ* in coral reefs (10 and 18 m depth) at Nha Trang Bay, South Central Vietnam, was investigated. The data showed that wind-induced upwelling during summer mainly govern the coastal region. In contrast, wind-induced downwelling was found during winter, visible in all three investigated water layers (SST, 10 and 18 m). In winter, the vertical mixing is strong and there is virtually no time-lag between the layers. In summer a scattering layer was formed, the phenomenon where a layer of water with different properties (such as temperature or salinity) is formed, blocking the sinking of water. In summer, correlations with air temperature were not significant, nor were correlations with night cooling, thus having implications for the distribution of nutrients and the health of the coral reefs. However, this was only the situation near the coast. Wavelet analysis shows that the short-term variability is significantly more substantial, caused by the shallow depth of the thermocline, which is much stronger affected by tidal and weather events than in winter. As a result of the combination of large yearly temperature variations (21°C to 31°C) plus increased sediment deposition in the rainy seasons, reefs close to the shore are generally not well-developed. This paper strongly advocates for science-based monitoring of coral reef conditions and underscores the need for law enforcement within the Marine Protected Area of Nha Trang Bay.

Keywords: Coastal oceanography, temperature, sediment deposition, river runoff, corals, MPA.

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INTRODUCTION

The East Vietnam Sea (South China Sea) is influenced by the El Niño Southern Oscillation (ENSO), with coastal upwelling at the coast of Southern Vietnam [1]. Hein et al., (2013) [1] could also show that the impact of the ENSO and related nutrient dynamics is not mainly caused by wind stress [2]. According to their study, the basin-wide horizontal circulation is the reason for the inter-annual changes of the vertical nutrient uplift during the summer and not the usual regional Ekman drift currents. The SCS includes deep basins and large shelf regions and is known for internal waves along the Vietnamese coast [3].

The Vietnam Upwelling Area (VUA) (between 10.5 and 12.0 decimal degrees in South Central Vietnam) is of enormous relevance in economic development [1]. The VUA covers only one small part of the 3,000 km coastline, with more than 40 million people living there. A major part of Vietnam's rich fish and shellfish production is linked to the nutrient-rich waters of this upwelling system [4]. Recent research on the Vietnam Upwelling has demonstrated that a significant part of the variability is determined by the governing wind regime (see, e.g., [5, 6]); on the other hand, also other processes like topography or intrinsic variability are affecting the intra-seasonal upwelling [1, 7]. The latest studies have also investigated the influence of climate change on the Vietnam's upwelling [8]. They concluded that the upwelling will increase significantly under the high emission scenario.

There are two distinct seasons: the dry season (Jan–Aug) and the rainy season (Sep–Dec), with an average annual air temperature of 26°C (monthly averages of 22–32°C, overall max. 39°C and min. 14.4°C) and strong rainfall (average 1,285 mm) in Sep-Nov, contributing 70–80% of the total annual rainfall [9]. The Southwest (SW) and Northeast (NE) monsoons impact Nha Trang Bay (NTB) seasonally, found in water temperatures, circulation patterns, and plankton concentrations [10]. The most significant influence is on water temperatures, and circulation patterns. A mixed dominantly diurnal tidal regime prevails in NTB, with tides ranging from about 40 cm during neap tide to more than 2 m during spring tides. Between the islands, there is a moderate flow velocity (< 1 kn), driven by coastal winds, tides, and regional oceanography [11–13]. While NTB hosts several marine ecosystems (sandy beach, coral reefs, in lagoons, seagrass, and mangroves), there are two larger rivers (Cai in the North and Tac or Be in the South), which influence the hydrography in the bay, particularly after heavy rainfall [9].

In exceptional years with heavy annual cumulative rainfall, e.g., [9], the river sediments can easily reach distances of 10–15 km, particularly in southward direction. Sedimentation rates can reach more than 50 $g.m^{2}.d^{-1}$ in the rainy season [9]. In the ongoing cooperation program between ZMT (Germany) and ION-VAST (Vietnam) since 2008, both significant year to year variations in *in-situ* temperatures (at the surface and in 10 and 18 m depth) as well as significant year to year variations in sediment loads were detected in NTB. It is assumed that there is a strong correlation between nutrients, sedimentation, and land-based pollutants with declining coral cover and degradation of coral reefs.

NTB is well known for its rich and diverse coral reef development [14], with up to 350 species of scleractinian corals and a rich biodiversity of other reef invertebrates and fish, particularly in the MPA Hon Mun [12, 13, 15]. Latypov was the first to describe coral communities in NTB in the early 1980s [12, 13, 16–18]. High coral cover (up to 100%, [12, 13] was common for most sites in the southern part of the bay. However, growing coastal development, dredging and dumping activities, overfishing, and expansion of marine cage culture [19] since the beginning of the 2000s have resulted in a dramatic decrease in live coral cover [14]. In six of the past ten years, including 2010, 2013, and 2016 to 2019, corals in Khanh Hoa coastal area experienced heat stress [20]. In May 2010, the heat stress was stronger than in other years.

In order to implement successful coastal management and protect corals, it is of vital importance to better understand coastal processes within the Nha Trang Bay and identify not only whether sediment and accompanying land-based pollutant sources are potentially harmful to coastal coral reefs but also the sometimes rapid change of physical factors such as temperature, oxygen or salinity. One noticeable gap is that the best our knowledge available current data are from the HYCOM-Modell from the US Navy (https://www7320.nrlssc.navy.mil/GLBhycomcice1-12/schina.html). With a resolution of only 1/12^{o}, the local conditions in front of Nha Trang cannot be explained sufficiently well.

Therefore, we were interested in the long-term observation of temperatures, not only from SST data but for the first time also *in situ* in the coral reefs (10 and 18 m depth), and link these data with tides, seasons, upwelling, and potential internal waves. Research questions included: What are yearly maximum and minimum temperatures NTB's temperature-sensitive coral reefs? How profound are seasonal changes? Can major changes/trends be identified from year to year?

MATERIALS AND METHODS

Nha Trang Bay (Fig. 1) is located in the Khanh Hoa Province with an area of about 507 km^2, including 19 coastal islands. The inner NTB covers ca. 130 km^2 (greater NTB about 500 km^2) and contains nine larger islands, located about 1 km to 15 km offshore. They provide the topographic basis for many coastal and marine habitats, including coral reefs, seagrass beds, mangrove areas, sandy beaches and rocky shores [21]. NTB houses the highest coral reef diversity of any surveyed location in Vietnam [18].

Nha Trang City has more than one million inhabitants, and is flanked by two rivers, the Cái in the North and the Tac, (also called Be) in the south. These rivers carry large amounts of sediments to the coastal waters, particularly in the rainy season [22]. The plumes are visible from land, sometimes extending up to several kilometers offshore [23].

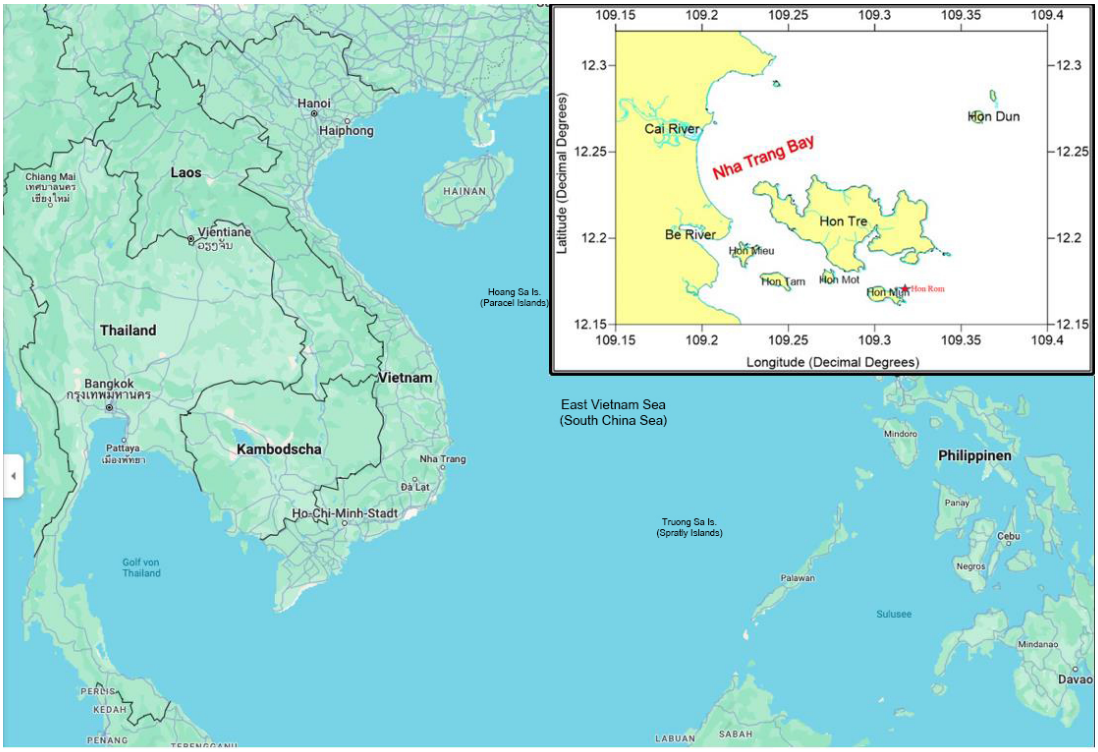

Figure 1. Overview of the East Vietnam Sea (South China Sea) with the position of Nha Trang (from nationsonline.org, modified). Inset: Map of Nha Trang Bay, Khanh Hoa Province, with the main island Hon Tre and the logger station Hon Rom (in red). The rivers Song Cái in the North and Song Bé (also called Tac) in the south are indicated

Between 2008 and 2019, two models of Hobo Loggers (Onset, USA) were deployed at Hon Rom (Position 12°10.226N/109°19.041E) in 10 m and 18 m depth (HOBO TidbiT v2 - UTBI-001 and HOBO Pendant® - UA-002-64). Hon Rom Station is located at the southern entrance of Nha Trang Bay to the south of Hon Tre Island, and it exhibits a water depth of 19 m. Although the shelf is very narrow on this area (on average only 40 km), the bathymetry shows a relatively gentle slope at Hon Rom Station.

The loggers were replaced usually once a year. Data with intervals of 30 min were secured using the Hobo Optic USB Base Station U-4 plus coupler and the software HoboWare Pro Version 374. Data files were transformed to CSV format and processed with MS Excel. Due to the theft of loggers, no data available for 2017. And for Hon Rom 18 m, additional data available are from May 2019 to May 2020. All raw data are available at https://doi.org/10.17605/OSF.IO/TAJFR [24].

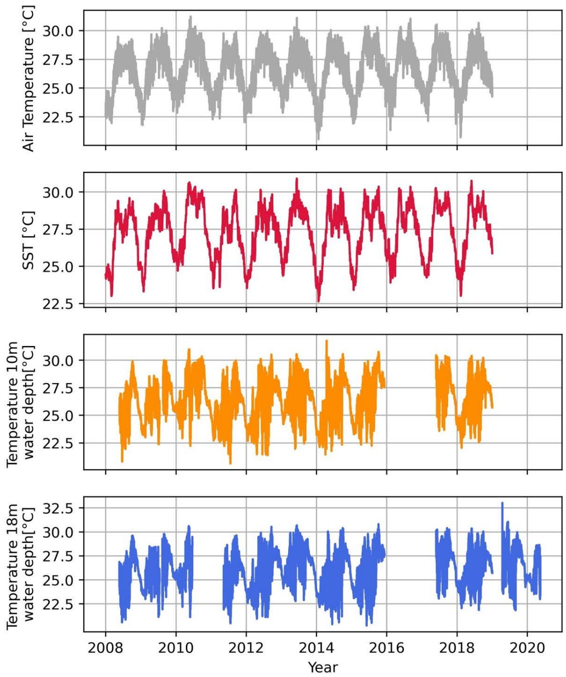

Figure 2. Comparative overview of air temperature, SST, water temperature in 10 m depth, and water temperature in 18 m depth for 2008 to 2019 at Hon Rom (gap in 2017 see Materials and Methods section)

Hourly 2 m - air temperature, SST (Fig. 2), and wind data were obtained from ERA5 model results, provided by the Copernicus Climate Change Service [25]. ERA5 data are available on a 0.25° × 0.25° grid, from which we extracted the grid point closest to Hon Rom Station. Tide data are taken from the OSU TPXO Tide Model (TPXO9-atlas-v3 dataset; [26]).

Methods such as Fast Fourier Transformation (FFT) and Heatmaps were used to explored the variability of this long-term data series. Correlations were established with publicly available modelled data such as SST, tides, monthly and yearly cycles, wind speeds and directions, and ENSO events were established. These derived correlations identified potential driving forces for the repeating temperature patterns.

Table 1 shows the periods when temperature data were collected at Hon Rom and nearby locations. For the stations C6b and Channel Mun, hourly averages of the logger data are used.

An FFT analysis of the temperature data was performed to determine the predominant periods affecting temperatures in summer (June, July, August) and winter (December, January, and February). FFT is one of the most commonly used methods for identifying periodic components in near-stationary time series in oceanographic data. Thereby, FFT separates periodic oscillations from aperiodic fluctuations and identifies regular cycle and their tendencies to appear. Therefore, this can quantify seasonal appearances [27]. The python program scipy.fft was used to calculate the FFT signal (scipy.fft expresses a function as a sum of periodic components and recovers the signal from those components). Further info at https://docs.scipy.org/doc/scipy/tutorial/fft.html, accessed 22.08.2022, and [28]. However, it is not possible to use incomplete time series with scipy.fft. The principle periods of M2, S2, K1, and S1 and their frequencies were obtained after The Open University (1999) [29]. The obtained significant frequencies are compared with principle periods of M2-, S2-, K1-, and S1-tides from The Open University (1999) [29].

Table 1. Temperature measurements between 2008 and 2018 at Hon Rom and Hon Cau

Parameter - measured	Time period	Location
Temperature at 10 m water depth (°C)	03:00:00 24/5/2008 - 23:00:00 7/12/2015	Hon Rom
	16:18:31 13/4/2014 - 23:48:31 7/12/15	C6b, 1 km West of Hon Rom
	04:00:00 28/5/2017 - 22:00:00 31/12/2018	Hon Rom
Temperature at 18 m water depth (°C)	02:00:00 23/5/2008 - 13:00:00 13/7/2009	Hon Rom
	01:00:00 12/8/2009 - 01:00:00 20/6/2010	Hon Rom
	12:00:00 11/5/2011 - 19:00:00 12/7/2015	Hon Rom
	05:00:00 28/5/2017 - 16:00:00 9/8/2018	Hon Rom
	17:45:41 9/8/2018 - 20:15:41 31/12/2018	Channel Mun, 1 km East of Hon Rom
	19:00:00 15/4/2019 - 06:00:00 15/5/2020	Hon Rom
Temperature at 13 m water depth (°C)	11:00:00 16/5/2016 - 12:00:00 11/8/2018	C16 Hon Cau, 13.6 km Northeast of Hon Rom 12.2790627, 109.3664935

Climatology data

Climatological monthly mean values of 2 m-air temperature, SST, T10, T18, and northward and eastward wind components (Figs. 3 and 4) were calculated by averaging the data for each specific month over the years 2008 to 2019, which is the period where observational data at Hon Rom Station are available. An excellent collection of the local physical characteristics of the investigation area can be found in Thao et al., (2020) (2020) [30]. This report provides precise information on the meteorological condition and the temperature, salinity, currents, waves, and climate variability of the waters in Khanh Hoa Province.

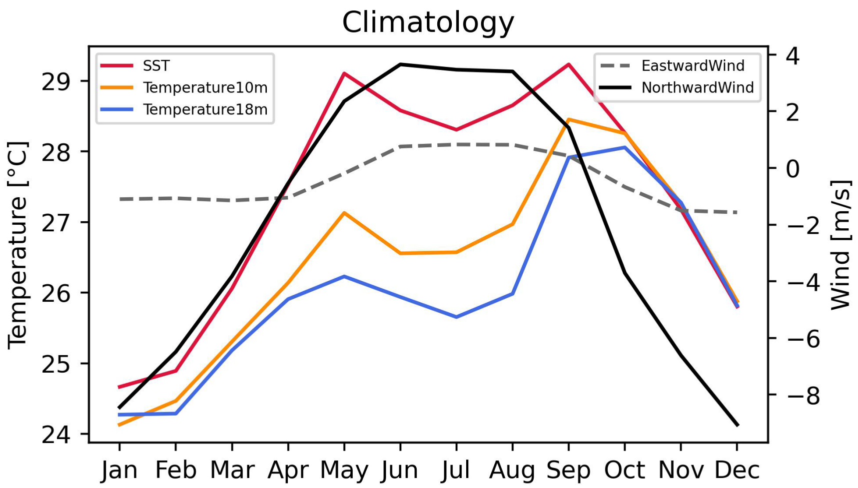

Figure 3. Average climatology data for SST, wind direction, wind strength, and water temperatures in 18 and 10 m depth for 2008 to 2019 at Hon Rom

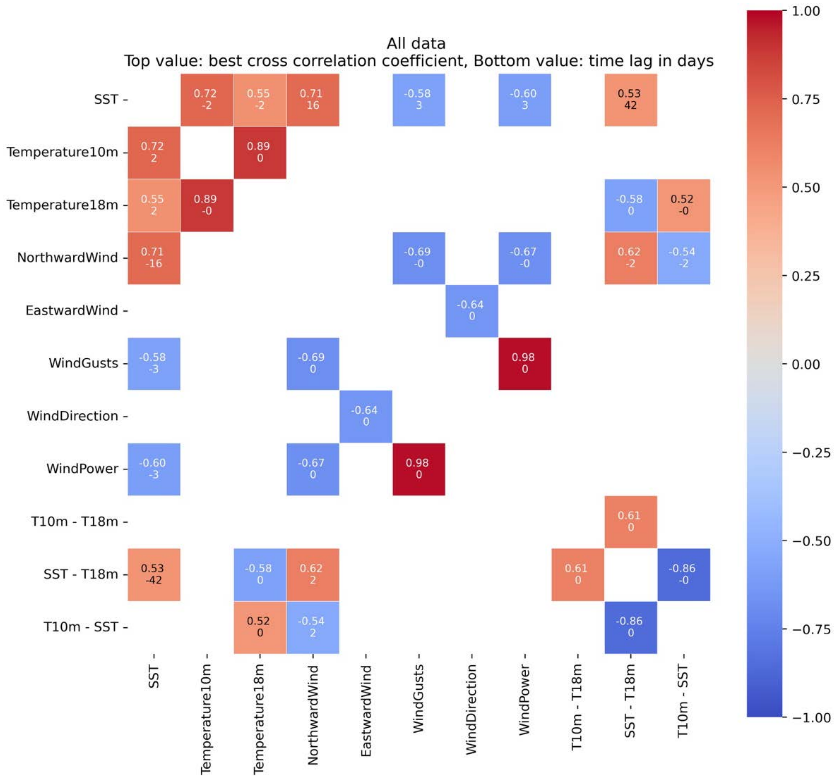

Figure 4. Heatmap cross correlations between SST, at depth temperatures and wind components (direction, power, gust) for the years 2008 to 2019 at Hon Rom. Blue represents a negative correlation, red a positive one

Correlations/Heatmaps

The correlations were calculated to determine how the measured *in situ* temperatures relate to the environmental parameters. Only SST, northward wind, eastward wind, total wind speed, direction (calculated from northward and eastward wind), and wind gusts were considered for the environmental parameters. In addition, the difference between SST and T10 and T18, as well as the difference between T10 and T18, are tested. Finally, a possible time shift is also considered to calculate the cross-correlation to determine whether the time series correlates with or without a slight time lag. The correlations are then displayed in a heat map (Fig. 5), and the time lag in days. Only significant correlations of ≥ |0.5| are shown.

The cross-correlation of the temperature data separated in summer (June, July, August) and winter (December, January, and February) is calculated with 3 h running mean to smooth the short time fluctuations. The time series with the respective correlations coefficient over the time lags are visualized.

An additional wavelet analysis with the python program PyWavelets was performed [31] to obtain more information than simple correlations, particularly to find other possible mechanisms to regulate the temperature regime.

RESULTS

The temperature data from Hon Rom between 2008 and 2019 show clear yearly cycles with average values between 24 °C and 29 °C (Fig. 2). The yearly short rises (April/May) and prolonged decreases (Sep to Jan) in temperatures are visible in air temperature, SST and water temperatures in 10 and 18 m (Fig. 3). These data show very similar yearly patterns, with steadily increasing temperatures and clear daily tidal signals from March until October when suddenly temperatures fall again without tidal signals until February. Average climatology data (SST, wind direction & strength) for the same period (Fig. 3) indicate strong north-northeast winds in summer (June, July, and August), corresponding with declining air temperatures and strongly declining water temperatures in 10 and 18 m depth. Decreasing temperatures with depth leads to strong differences in the water column. It contrasts with a prevailing southward wind in winter (December, January, February), when the wind direction shifts in October, SST, T10, and T18 drop. However, the water column shows the same temperature with depth (SST = T10 = T18).

A heat map considering all data sources about wind and temperature confirms significant relationships between SST, at-depth temperatures, and the wind components, particularly with the northward wind (Fig. 4). Data for a potential time lag in the correlations indicate up to 2 days between surface and 10 m and 18 m depth, and up to 16 days between the northward wind and the SST.

In general, temperature data correspond with the seasonal changes of monsoons and currents. Repeating long-term patterns include high daily variation from March through August, with a peak temperature of up to 31°C in September (in 2010 and 2014) and severe drops without daily variations from October to March, with minimum temperatures of 21°C (in 2008 and 2011) (Fig. 3). When comparing correlations with tides, winds and SST, results show that there is a ca. 14-day postponement of Northward Wind vs SST. Day and night (sun and moon) are the main drivers for the short frequencies and long frequencies are mainly due to lunar influence. The FFT reveals that yearly variances are influenced by sun cycles and solar radiation. Therefore, in summer, surface waters are heating intensely, but at the same time, stronger north-ward winds get upwelling. This phenomenon also explains the increased difference in in-depth water temperatures compared to SST in summer. A map (Fig. 5) shows surface and upwelling waters in different seasons.

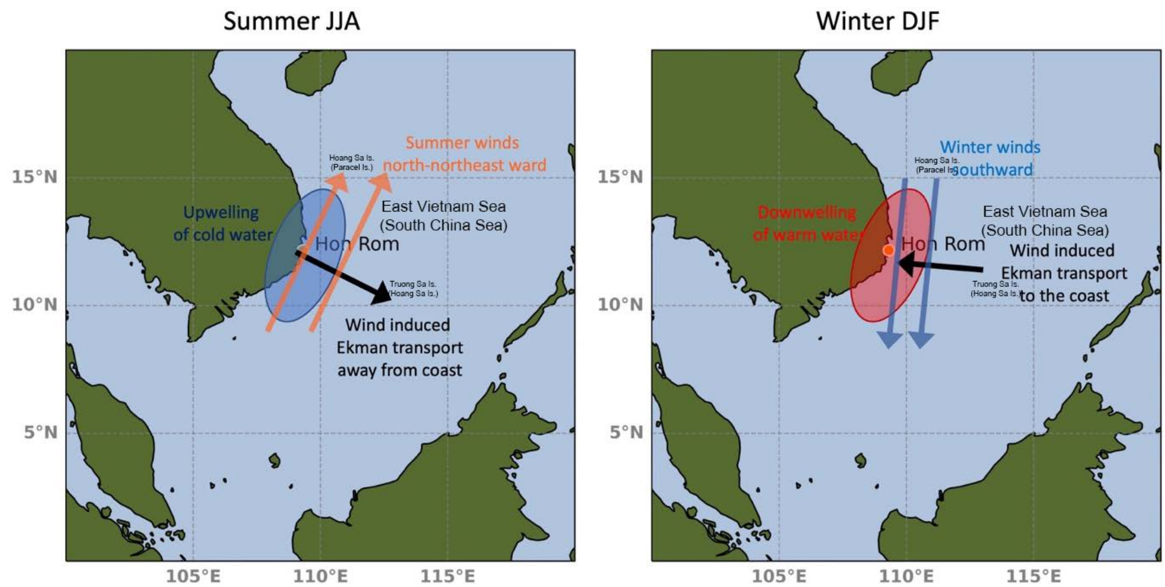

Figure 5. Map showing conditions in southern Vietnamese Waters in summer (June, July, and August; left) and winter (December, January, and February; right). black arrows: direction of surface currents; red/blue arrows: warm south-westerly/cold north-easterly monsoonal winds, blue/red shading: upwelling/downwelling area with cold/warm surface waters

Further investigations into directions of currents and main drivers involve cross-correlations in selected windows (summer, winter) (Fig. 6). During summer, the correlation is weak with a correlation coefficient of 0.37 and a time lag of 5–6 days. The positive time lag indicates that the temperature at 18 m is measured first. Then, the air temperature follows, supporting the theory on upwelling during summer (deeper water level cools down first, then also affecting air temperature due to upwelling). During winter, a high correlation coefficient is 0.74 with a time lag of - 4 days and 21 hours. The negative time lag also agrees with the downwelling during winter, with the air temperature being measured first (also due to night cooling) and then influencing the deeper water levels.

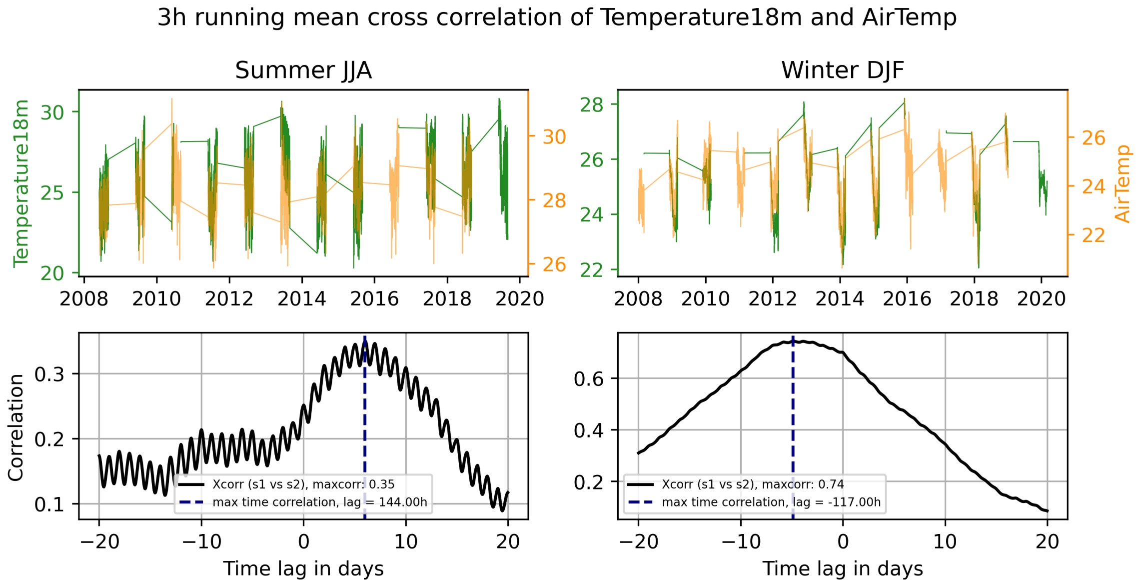

Figure 6. Cross correlation temperature at 18 m and air temperature, with a 3h running mean during summer (June, July, August JJA) and winter (December, January, February DJF)

Exceptional observations include record highs of more than 31°C lasting for several days (2009, 2010), extremely sharp drops down to 21.8 in only nine days (28.05.2010), and record low temperatures of 21°C. The range of maximum and minimum temperatures can reach more than 10°C. Intra-day variations easily cover 5°C, and, in exceptional cases, even 8°C. On several occasions, a difference of 10°C was reached over 2–3 days.

The wavelet analysis yielded interesting new insights into the energy distribution over the time series and how frequency distributions change over time. In summer, with stable and pronounced temperature stratification due to upwelling, current deviations caused by tides or large-scale weather phenomena cause distinct variability, as can be seen by the maxima of 2–6 h (tides) or monthly (weather) (see Fig. A1–A3 in Appendix). All three figures clearly show, that most energy is concentrated in summer (yellow stripes on short time scales up to 12 h (half day, maybe caused by irradiation?).

A maximum of 6 months reflects the energy caused by the monsoon. The years 2012 and 2013 were normal years, while in 2014 we have a strong El Nino year, where upwelling is reduced due to a reduced SW monsoon.

DISCUSSION

This paper investigates coastal processes within Nha Trang Bay (NTB) and whether sometimes rapid changes in physical factors such as temperature could be potentially harmful to coastal coral reefs, in addition to anthropogenic factors such as pollution and intensive fishing. It has to be noted that our investigation is limited to only one time series. However, since it is the first long-term observation (2008–2019) based on *in-situ* data from 10 m and 18 m depth, it helps to shed new light on the variability of the hydrographic regime in NTB.

The temperature data show yearly cycles with averages in winter around 24°C and in summer around 29°C (Fig. 2). Upwelling and downwelling events in winter are visible in all three investigated water layers (SST, T10, and T18). In summer, strong daily variations (up to 8°C) correlate with the tides, while these variations are absent in winter. We hypothesize that the downwelling in winter prevents (for 2–3 months) or at least mitigates the daily variations. Air temperature (cooling at night) is the driving force for the T10 and T18 temperatures in winter. When air temperatures go down, the difference in temperature between T10 and T18 is zero (Fig. 6). This means the vertical mixing is strong. There is virtually no time because cold water sinks very fast. In summer, a scattering layer is formed, blocking the sinking of water. The higher the air temperature gets, the larger the difference between T10–T18, with air temperature being ahead for 1.5 days. In summer, correlations with air temperature are much weaker, also about cooling at night.

There are a few exciting exceptions (e.g., 2013) when the difference T10 minus T18 is negative, meaning lower water is warmer. This could be an indication of reduced upwelling due to La Niña.

Looking at the FFT analyses (Fig. 7) and comparing summer and winter, summer is dominated by factor S1, which indicates cooling at night. In addition, the factors M2 and K1 also influence pointing at tides. These factors do not play a significant role in winter. However, another peak is visible in this graph (Temperature 18 m, Summer, marked with a circle (Fig. 7)), which does not fit to any tide related link, possibly suggesting a (remote) sign of a free internal wave. Those waves are well known for the South China Sea and adjacent regions [3].

When looking into directions of water (and energy/temperature) transport, processes at Hon Rom and the continental shelf margin are expected to be similar. However, a cross-correlation analysis between Hon Rom and Hon Cau, an island some 20 km in the east, revealed negative correlations. This correlation would hint at different driving forces, i.e., the shelf margin water temperature is mainly influenced by large-scale oceanographic processes of the SCS, while on the shelf air, air-cooled surface water sinks (vertical convection) in winter. The wind is an additional driving force for the downwelling. From an oceanographic point of view, this decoupling in temperate conditions over a short distance is remarkable, hinting at two different water circulation regimes in front of Nha Trang. The shelf margin is only some 20–30 km away from the coast, so the southerly oriented current of the western SCS dominates the regime and, thus, the temperature conditions. The findings of Hein et al., (2013) [1] support this theory.

Overall, the range of temperatures is much larger than expected, potentially limiting optimal coral growth. We have prolonged phases in summer with extremely high temperatures, sometimes even exceeding 31°C. In winter, there are cold episodes with temperatures as low as 20°C, while corals prefer stable conditions. We were able to show these daily large fluctuations down to 19/20 m (the 18 m station plus the effect of tides of 1.7 m).

As a result of the combination of large yearly temperature variations (21°C to 31°C) plus increased sediment deposition in the rainy seasons [9], reefs close to the shore are generally not well developed [14, 20]. On the other hand, coral surveys in 2011/2012 [10] and 2018/2019 [15] revealed selected locations further offshore where coral cover is high and diverse, indicating potential stress resistance and discrete resilience patterns. In exceptional cases (in non-polluted waters) corals can tolerate heat waves for up to two months [32].

In general, wind and temperature patterns are stable over the years. However, the Vietnam Upwelling is known to be influenced by the ENSO regime (see, e.g., [33]). Accordingly, we detected exceptional alterations, particularly under extreme ENSO events. During La Nina, an intensification of the SW monsoon is observed, which leads to an enhanced upwelling in NTB area. In contrast, an El Nino leads to weaker SW monsoonal winds and, thus, to a reduced upwelling. Since Hon

Rom Station is located at the edge of the Vietnam Upwelling Center, only extreme ENSO events are reflected in our temperature data, i.e., during La Nina in 2010 and El Nino in 2014.

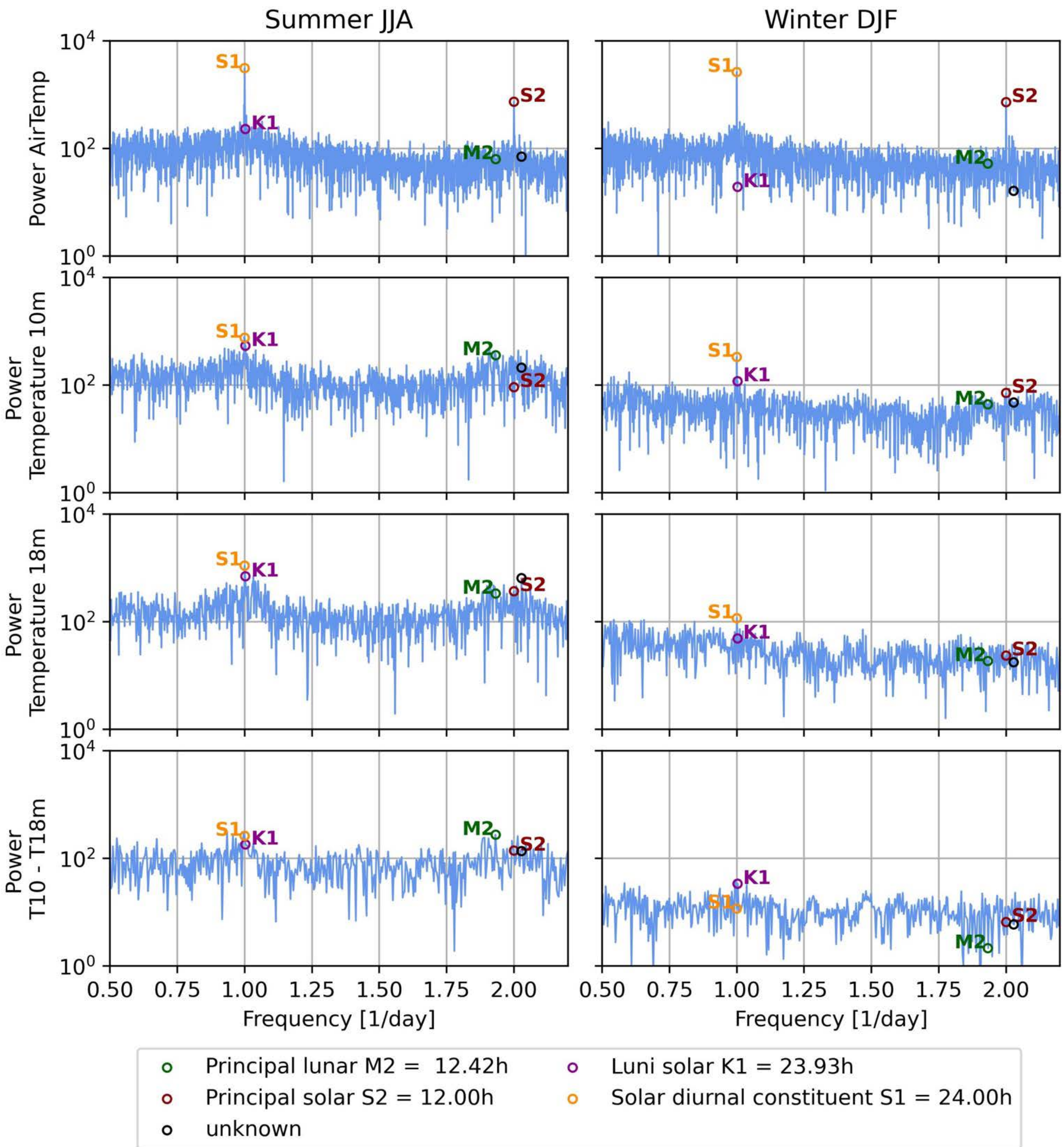

Figure 7. Power Spectrum of temperature components, comparing the summer (June, July, August) JJA and the winter (December, January, February) DJF situation

In addition, several anthropogenic stressors (sediment loads, intensive fishing, dense cage aquaculture of fish and rock lobsters [19, 34] have increased over the last decade, imposing multiple stress on marine life, particularly coral reefs. In a recent study, Van et al., (2022) [20] showed that corals in the province of Khanh Hoa (which includes NTB), experienced severe heat stress in the past ten years, particularly in summer, starting in May. In 2010, this led to substantial coral bleaching, and Van et al., (2022) [20] attributed this to an increase in SST plus the suppression of upwelling (ENSO related). It must be stated that Van et al., (2022) [20] "only" used monthly averaged SST data.

For coastal managers in regions with conflicting interests, such as in NTB, it is vital to understand coastal processes better and identify the main drivers. With this study, we want to contribute valuable data and background information about the hydrographic and oceanographic situation in NTB and its surroundings. This study supports science-based monitoring of marine ecosystems such as coral reefs or seagrass areas. it is an essential step for a successful Coastal Zone Management of NTB. This study also justifies law enforcement within the Marine Protected Areas (e.g., MPA Hon Mun). It can help to understand why coral reefs, suffering from increased pressure through anthropogenic activities, have a hard time recovering. It is highly recommended that regular medium-scale monitoring of corals is established and that all activities not be restricted only to the area of the MPA Hon Mun.

Data availability: all raw data are freely (GNU General Public Licence 3.0) available for download at Kunzmann (2023). https://doi.org/10.17605/OSF.IO/TAJFR

CONCLUSIONS

Nha Trang Bay (NTB) is influenced by two monsoon seasons. Water temperatures display yearly cycles between averages of 24°C in winter and 29°C in summer. Extreme values easily reach 31°C and 20°C, with daily fluctuations up to 8°C difference correlated with the tides.

Upwelling events in summer and downwelling events in winter are visible in all three investigated water layers (SST, T10, and T18).

In winter the vertical mixing is strong and there is virtually no time lag between the layers. In summer a scattering layer is formed, blocking the sinking of water. In summer correlations with air temperature are much weaker, as in case with cooling at night.

Wavelet analysis shows that the short-term variability is significantly stronger, caused by the shallow depth of the thermocline, which is much stronger affected by tidal and weather events than in winter.

Wavelet analysis demonstrates the existence of pronounced inter-annual differences. In the El Nino Year 2014 a weakened variability of summer stratification can be observed due to a decreased upwelling.

As a result of large yearly temperature variations (21°C to 31°C) and increased sediment deposition in the rainy seasons, reefs near shore are generally underdeveloped.

This paper supports science-based monitoring of coral reef conditions by providing arguments and justifications for law enforcement within the MPA of NTB.

Author contributions: AK collected the data, started data processing, wrote the first draft and submitted the manuscript, HTD collected the data, managed the necessary permits and helped with graphs, DB and SP processed the data, performed statistical treatments, prepared individual graphs, TP supported interpretation of data, suggested individual graphs. All authors read and corrected the final manuscript.

The authors declare no competing interests. The paper has not been submitted to any other journal.

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APPENDIX

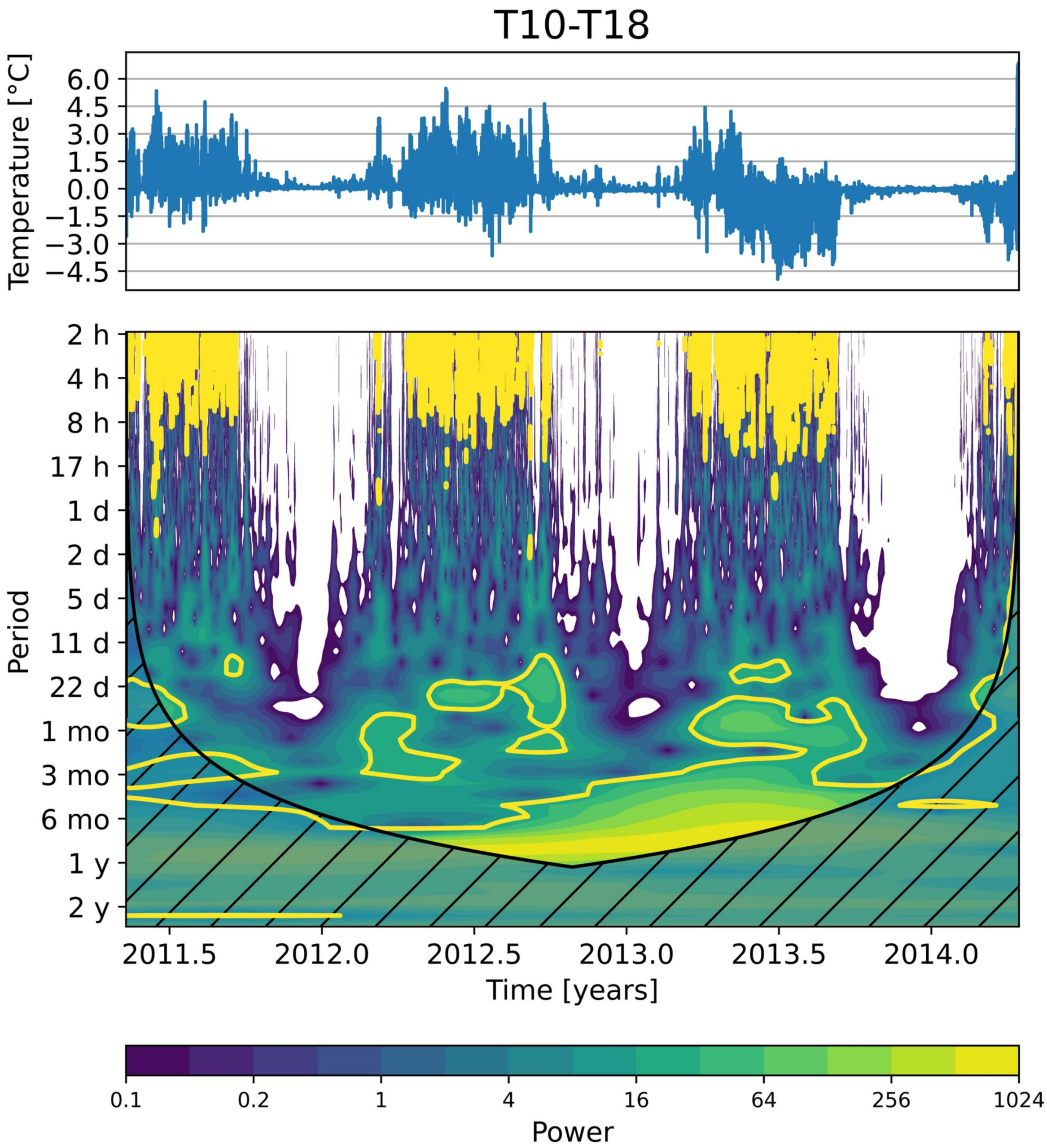

Figure A1. T10–T18 wavelet

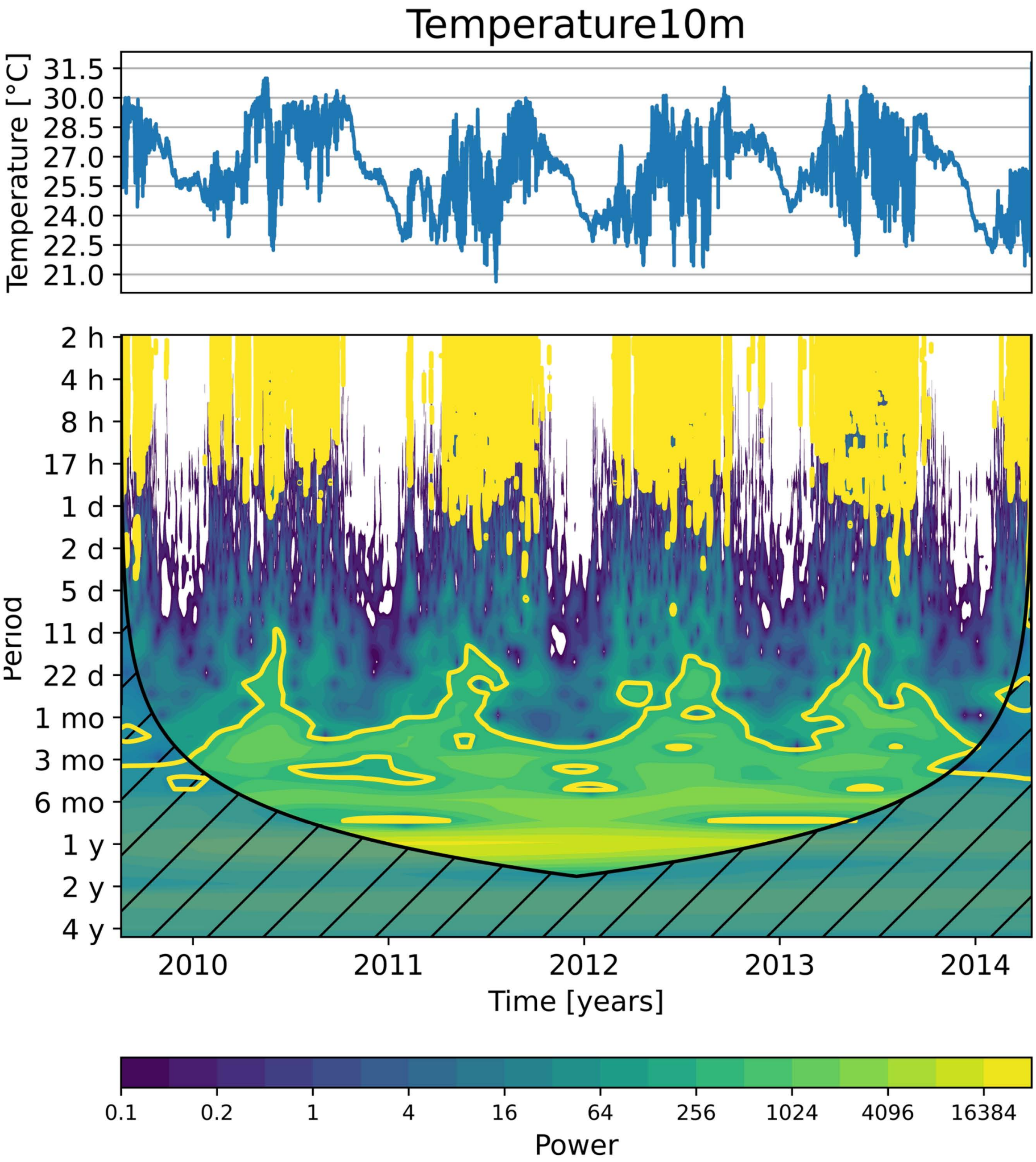

Figure A2. Temperature 10 m wavelet

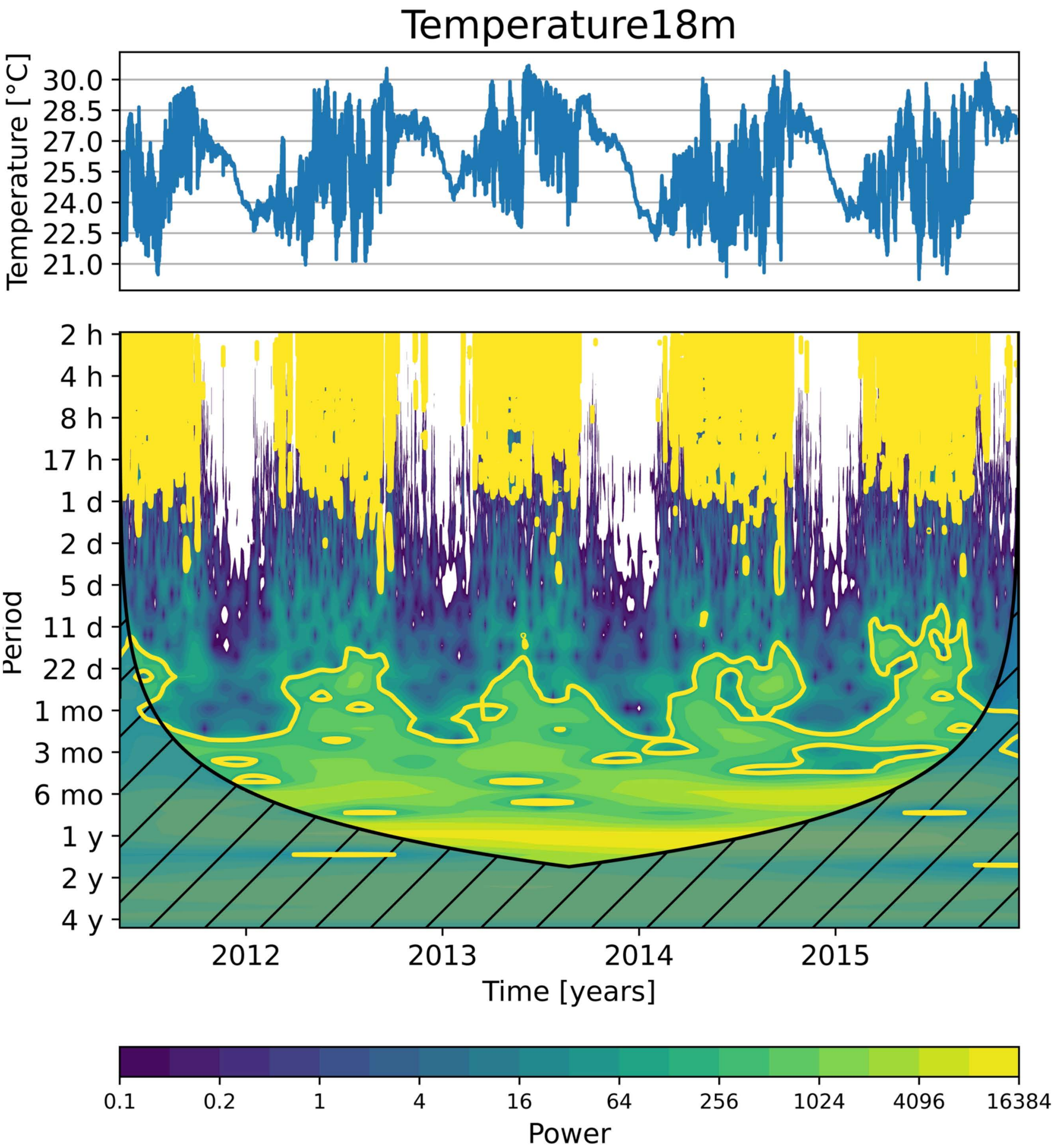

Figure A3. Temperature 18 m wavelet