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A MULTIPLE BASELINE APPROACH FOR MARINE HEATWAVES

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Abstract

Marine heatwaves and other extreme temperature events can drive biological responses including mass mortality. However, their effects depend on how they are experienced by biological systems (including human societies). We applied two different baselines (fixed and shifting) to a time series of North Sea water temperature to explore how slowly vs. quickly adapting systems would experience extreme temperatures. We tested if properties of marine heatwaves and the association with atmospheric heatwaves were robust to a change in baseline. A fixed baseline produced an increase in the frequency and duration of marine heatwaves which would be experienced as the new normal by slowly adapting systems; seven of the ten most severe heatwaves occurred between 1990 and 2018. The shifting baseline removed the trend in the frequency but not duration of heatwaves; the 1990's appeared as a period of change in the frequency of strong and severe heatwaves as compared to the 1980's. There were also common patterns among baselines: marine heatwaves were more frequent in late summer when temperatures peak; temperature variability was characterised by low frequency, large amplitude fluctuations (i.e. as red noise), known to drive extinction events. In addition, marine heatwaves occurred during or just after atmospheric heatwaves. Our work highlights the importance of identifying properties of marine heatwaves that are robust or contingent to a change in baseline.

INTRODUCTION

Increasing frequencies of heatwaves occurring over the past decades in association with global change, are currently a concern for both ecology and society (Campbell et al. 2018; Smale et al. 2019**)**. Heatwaves are extreme events characterized by a period of increased temperature, the frequency and intensity of which are associated with global warming (Fröhlicher et al. 2018; Lauffkotter et al. 2020). Heatwaves are more visible in terrestrial systems, where temperatures may change rapidly. However, also in the aquatic realm, relatively sudden changes in temperature occur. The clear definition of a heatwave is not trivial, but in recent contributions, Hobday et al. (2016) developed a workable definition for marine heatwaves, i.e. periods of time equal or longer than five days when seawater temperature exceeds a predetermined threshold (e.g. 90th quantile of a baseline temperature time series). Marine heatwaves are not small-scale phenomena but typically constitute a disturbance operating at regional scale (> 1000 km: Jacox et al. 2020; Oliver et al. 2021). Such temperature increases are important as evidenced by mass mortalities and reductions in biodiversity associated with longer period heatwaves with high intensities (Arias-Ortiz et al. 2018; Smith et al. 2023).

A critical point in the characterisation of heatwaves (either marine or atmospheric) is the definition of the baseline used to calculate threshold temperature. There are different views on whether such a baseline should be fixed or if instead it should be shifting (Amaya et al. 2023; Sen Gupta et al. 2023). The application of a fixed baseline would enable the quantification of effects of long-term temperature trends in the frequency and characteristics of marine heatwaves (Oliver et al. 2018). From the ecological standpoint, a fixed baseline is important to understand how species with limited capacity for adaptation experience thermal fluctuations in the context of warming (Oliver et al. 2021). In contrast, a shifting baseline (Jacox 2019) enables the exploration of how such fluctuations would be experienced by species able to adapt during, for example, periods of directional temperature change, such as those currently occurring as a result of global warming. The application of the shifting baseline is needed, for example to account for underlying trends in the temperature time series and for the exploration of changes in the statistical properties of extreme events at a period in the future.

Understanding the impact of the baseline choice is important for three reasons: First, we expect important interspecific variation on how marine organisms cope with extreme thermal fluctuations. Interspecific differences with regard to the ability of species to show phenotypic plasticity (i.e. the capacity of a genotype to exhibit phenotypic variation: DeWitt and Scheiner 2004) are expected, as plastic responses can occur at different time scales, within generations (e.g. acclimation, developmental plasticity) or between generations (transgenerational plasticity). Besides, the capacity to evolve (through genetic change) is favoured by high standing genetic variation, in combination with short generation time and high fecundity (Botero et al. 2015).

Secondly, the baseline affects the “threshold anomaly”, i.e. the thermal deviations from the threshold temperature defining marine heatwaves (i.e. five or more consecutive days with positive values of threshold anomalies: Hobday et al. 2016). The nature of the variability of the threshold anomalies is likely to drive the evolution of upper thermal tolerance limits, contingent on life history and generation time. For instance, for some fish, a winter marine heatwave might be irrelevant. However, for species with complex life cycles specific life phases occur at different seasons, and reproductive events require low winter temperatures; at some populations winter marine heatwaves might be important (e.g. Smith and Thatje 2013; Crickenberger and Wethey 2018). In general, life history theory predicts that environments characterized by predictable fluctuations promote phenotypic plasticity; parents may produce warm acclimated offspring through transgenerational plasticity (Donelson et al. 2018). By contrast, random fluctuations can promote bet-hedging (Joschinki and Bonte 2020) whereby parents produce offspring differing in environmental tolerance, so that at least some offspring may survive the future conditions Furthermore, time series may be noisy, but characterized as a "coloured", instead of as a "white noise". Such "colour" is assigned to a time series with analogy to light, i.e. where red colour denotes a dominance of low frequencies (= long periods) and blue-violet refers to a dominance of high frequencies (Heino and Sabadell 2003; Mustin et al. 2013). For instance, environmental time series in the marine habitat are often "pink to red" because they contain fluctuations of large amplitude (= extreme) and long periods. Importantly, environmental noise colour reflects the extinction risk (Mustin et al. 2013). However, the type of effect can depend on the life history (Heino & Sabadell 2003). Environmental red noise can promote adaptive plasticity and population persistence in species with low fecundity (Romero-Mujalli et al. 2021). The important point is that the choice of baseline could theoretically affect the noisy nature of the threshold anomalies. The threshold anomalies should be noisy because predictable temperature fluctuations (e.g. seasonal patterns) are filtered out in its computation. However, depending on the baseline, periodicities may appear if fluctuations increase in amplitude or frequency over time, beyond the (fixed) baseline, or along the shifting (or fixed) baseline.

The third point, concerns whether a change of baseline affects the *relationship* between marine heatwaves and their potential predictors. Those relationships will point towards the mechanisms driving marine heatwaves and extreme temperatures (Oliver et al. 2021). Marine heatwaves may be produced by advection in aquatic systems (Schaeffer and Roughan 2017). However, for shallow coastal systems the most likely drivers are high atmospheric temperatures in combination with reduced wind speeds, as suggested by studies of events of warm atmospheric and seawater temperature (Sparnocchia et al. 2005; Olita et al. 2007). In a system with a strong sea-air coupling marine heatwaves may be predicted, at least for short periods of time ahead, through forecast of atmospheric heatwaves. The relationships between marine and atmospheric heatwaves may be robust (or contingent) to a change in the baseline.

Here, we apply both fixed and shifting baselines using the 57-year time series of the Helgoland Roads (54.12 °N, 7.9 °E, Germany) to quantify the frequency of heatwave events in the German Bight. We evaluated if key characteristics of the heatwaves, such as intensity, duration, noise colour are either robust or contingent to a change in the baseline. Likewise, we quantify associations between marine and atmospheric heatwaves and the robustness to a change in baseline. We take the opportunity of a unique time series (de Amorim and Wiltshire et al. 2023), of in situ daily measurements of temperature to resolve and catalogue marine heatwaves occurring between 1962 and 2018. Importantly, because our time series is based on high resolution in-situ readings made with the same methods, it does not suffer from issues associated with data obtained from satellites, where e.g. frequency of measures can affect patterns, especially around the 1980's (Xu et al. 2022). Marine heatwaves are likely to be critical in the German Bight (South Eastern North Sea) which has experienced considerable rate of temperature increase especially after the 1990s (Becker et al. 1996; Huthnance et al. 2016). Projected changes in temperature for the North Sea include further increases in average temperature (1-3ºC for end of century: Schrum et al. 2016). Because of the mixing of the water column at the coast (Otto et al. 1990) marine heatwaves are likely to impact bottom habitats as well as surface waters. Decadal-scale changes have already occurred in the North Sea, in species phenology and abundance (Kirby et al. 2007; Petitgas et al. 2012; Scharfe and Wiltshire 2019), community and ecosystem (Kröncke et al. 2011; Reid et al. 2016). In particular, variability in SST has consequences for year-to-year variability in phytoplankton dynamics in the southern North Sea (McQuatters-Gollop and Vermaat 2011); important changes occurred in the plankton dynamics associated with changes in SST of the German Bight (Schlüter et al. 2008; Scharfe and Wiltshire 2019). The recent increase in the number of European atmospheric heatwaves, experienced in continental Europe (Russo et al. 2015) is likely to be reflected as fluctuations in seawater temperature, perhaps accelerating change. The association between monthly temperatures at Helgoland Roads (North Sea, German Bight) and temperatures in mainland Germany (de Amorim & Wiltshire et al. 2023) suggest a coupling between marine and atmospheric temperatures. Our paper also provides a catalogue of heatwaves to be used in the future, to study time series of plankton collected in parallel to temperature readings, since 1962.

METHODS

Data sources: The seawater, temperature time series (Fig. 1, top panel) corresponds to the daily temperature values of the Helgoland Roads time series (Amorim & Wiltshire et al. 2023) from January 1962 to December 2018 (measured at ~8:00 AM; depth < 1 m). On days when temperature data was not taken (for example, weekends or periods with bad weather), estimations were made through linear interpolation. Linear interpolation was carried out after preliminary simulations showed that such method performs equally well or better than fitting nonlinear functions. Air temperature data (daily-averages, at height = 2m) were obtained from four weather stations around the German Bight (Helgoland, List, Sankt Peter Ording and Nordeney), part of the German national grid from the Climate Data Centre of the German Weather Service (DWD 2021).

Computation of heatwaves: All analyses were carried out in R using RStudio. Heatwave events for both seawater and air temperatures were defined following Hobday et al. (2016), for the fixed baseline, with modifications for the shifting baseline, and computed using the package heatwaveR (Schegel and Smit 2021). A heatwave event was defined as a period of five or more days where the temperature was higher that the threshold 90th quantile (Q_{90}) of different baselines (see below); events of that extent separated by period of less than 48h were considered as a single heatwave event. Events that are not categorised as heatwaves, but still surpassed the Q_{90} were defined as "heat spikes". The Q_{90} was calculated using a moving window of 11 days of half width over which all values of temperature corresponding to the baseline years are pooled into a frequency distribution.

Definition of baselines: The above calculations were carried out based on a fixed and a shifting baseline of 30 years of duration for both seawater and air temperatures. The fixed baseline was set between January 1st 1962 to the 31st December 1991, and we computed the heatwave events of the full time series. The shifting baseline was then applied to years of the period 1992-2018. For this period, we defined a baseline of 30 years and computed the heatwave statistics only for the last year of that period. For instance, for the year 1992, the baseline used was the period 1963-1992; for the year 1993 the baseline was the period 1964-1993 (Fig. S1). Hence, in both approaches, the number of heatwaves was the same for the first 30 years period but was expected to vary after 1991. We adopted this specific shifting baseline because we wanted to keep a time period of 30 years in order to obtain solid estimates of the Q_{90} and be able to compare results of both baselines. We defined the target year as the last of each 30-year period because, at any given time, whether a fluctuation is experienced by organisms as "extreme", depends on the past temperatures (not on the future). Note that mathematically, it would better to have a target year towards middle of the 30-year period of the shifting baseline; however, this would mean that organisms should be responding to future conditions, which of course is not possible.

Characteristics of marine heatwaves: This analysis was carried out in three sections. First, trends in the frequency, intensity and duration of heatwaves were quantified using generalised linear and additive modelling (GAM, Woods 2017). GAMs were fitted with the package "mgcv" using thin plate spline smoothers and considering Gaussian, Poisson and negative binomial residuals. Second, temporal variation in the full set of heatwave traits (Tables S1, S2) were explored using principal components analysis (PCA) with emphasis on differentiating between pre vs post 1991 periods in order to better quantify and visualise the effects of different baselines on the results. The main traits are indicators of intensity, duration, and rate of temperature change. PCA was based on the correlation matrix in order to take into account variables measured in different units and scales (e.g. intensity in °C and time duration in days). Third, we focused on the most intense events: marine heatwaves were classified using the scheme of increasing intensity (from moderate to extreme) developed by Hobday et al. (2018) and then the distribution of the ten most intense heatwaves were studied. In addition, we searched for information on atmospheric heatwaves in order to determine whether our top 10 events were identified with critical periods of unusually high temperatures in Europe.

Variability in threshold anomalies: The daily threshold anomaly was calculated as the daily temperature minus the daily threshold temperature (here the daily Q_{90} as defined above). We studied temporal patterns in threshold anomalies because they define marine heatwaves (when positive for five or more consecutive days). We differentiate between threshold anomalies and the so-called average, maximum and cumulative "threshold intensities" (Hobday et al. 2016); threshold intensities are properties of the marine heatwaves and are calculated as the maximum, average or cumulative threshold anomalies during a marine heatwave. Temporal patterns in threshold anomalies were characterised using wavelet and spectral analyses (Cazelles et al. 2008) using the package waveletComp (Roesch and Schmidbauer 2018). For this analysis, the seasonal patterns of temperature are not present in the time series because they are filtered out when the Q_{90} is subtracted from the temperature values of each time series. In order to characterise the "colour" of the time series, we carried out spectral analysis (function *spec* in R) to time series of threshold anomalies and fitted linear statistical models to the relationship between spectral values and frequencies (both variables log-transformed). For such log-log relationship, red noise is characterised by negative slopes (e.g. slope= -1 is defined as "pink noise") while blue noise is characterised by positive slope values (white noise has 0 slope value).

Marine and Atmospheric temperatures: Associations between marine and atmospheric extreme temperatures were studied after applying the same baseline (either fixed or shifting) to both time series. Associations were studied at two different levels. First, we explored associations between threshold anomalies of each temperature time series, but transformed into binary (= 1 if threshold anomalies >Q_{90}, 0 otherwise), as representing the presence/absence of heatwaves and heat spikes. Second, we explored associations between heatwave events in paired time series (on daily time steps) also with data transformed to binary (1= heatwave, 0 otherwise). Associations were quantified with cross-correlation (Chatfield 2004) and co-occurrence analysis (Veech 2013, Griffith et al. 2016). Cross-correlation was used to determine if association peaked at specific time lags; we intended to *hypothesise* causal links between atmospheric and marine heatwaves. The use of cross-correlations for binary variables is justified because Pearson correlation transforms into the ϕ-association coefficient used in the analysis of contingency tables (definition in Sokal & Rohlf 1995, p. 741-743, see Supplement 1). For cross-correlation analysis, time series were previously detrended (by differentiation) and prewhitened (function *prewhiten* of package TSA: Chan and Ripley 2020). Co-occurrence and quantification of overlap were helpful in our case because cross-correlation analysis gave peak correlations between atmospheric and marine heatwaves at very short time lags. Co-occurrence analysis has been used in ecology to quantify and test whether patterns of species co-occurrence are random or structured. We use it here (package *cooccur* in R: Griffith et al. 2016) because it is well suited for binary data and enables for a test of whether observed co-occurrences deviate from those expected under random distribution of heatwaves. In addition, the overall overlap between marine and atmospheric heatwaves was quantified by the Schoener index of niche overlap (Broennimann et al. 2011), which ranges between 0 (no overlap) and 1 (complete overlap).

RESULTS

A fixed baseline gave more marine heatwaves (=153) than a shifting baseline (= 106; Tables S1, S2) which was due to a higher number of events for the period 1992-2018 (110 vs 63), where the calculations based on the fixed and shifting baselines differ (details in Fig S1). With the fixed baseline, the number of marine heatwaves per year increased over time, but no such increase was evident with the shifting baseline (Fig 1, Tables S3, S4). In both cases the number of days and the average duration per marine heatwave per year increased over time especially after 1990 (Fig 1, S2), although the shifting baseline led to a less pronounced increment. Trends on yearly average and maximum threshold intensities (i.e. the average and maximum threshold anomalies during the heatwave), were evaluated using the full year data, because not all years had marine heatwaves; threshold intensities increased through time (Fig S3, Tables S3, S4) although the increment was lower after application of the shifting baseline. Average threshold intensities increased at a rate twice as high for the fixed vs shifting baselines (0.32 vs 0.16 °C decade^{-1}). The shifting baseline highlighted the period between years 1990 and 2000 as dominated by marine heatwaves characterised by high threshold intensities (Fig S3); the same pattern was observed in the number of marine heatwaves per year but it was not retained in the statistical model. In addition, when taken together, heatwave components (including threshold intensities, duration and rates increase and decrease in temperature), were more variable in the latter three decades. This is shown especially after application of the fixed baseline (PCA in Fig S4: note that the cloud corresponding to the period 1992-2018 filled a larger portion of the multivariate space). Such effect reflected higher intensities and duration contributing to the first axis (>50% of total variance); rate onset and decline contributed mostly to the second component (17-22%). The majority of marine heatwaves (70%) had a duration < 30 days but some extended for > 100 days (Fig S5). The application to the shifting baseline resulted in shorter heatwaves with some of them being a fragmentation of long events detected by the fixed baseline (e.g. years 2002, 2003, 2006, 2007 and 2018: Tables S1, S2). Heatwave intensities and rates did not differ much between the fixed and shifting baselines (Figs. S6, S7) and most heatwaves were classified as moderate; however, there were more severe heatwaves after the application of the fixed than the shifting baseline (9 vs 3 events).

For the second part of the time series (years 1992-2018), where the application of the baselines differs, there were slightly different patterns of severity. The fixed baseline led to an increased number of marine heatwaves and spikes along the 30-year period (Fig. 2) and resulted in 8 out of 9 severe events (Fig S8). With the shifting baseline, there was still a change, between the 1980's and 1990's in the number of marine heatwaves and spikes (Fig 2) and in the number of strong and severe marine heatwaves (Fig. S8). With the shifting baseline, the period between 1990 and 2007 had 14 strong marine heatwaves (~7 strong events per decade) in contrast to a single event the decade of the 1980's and 3 events in the period 2008-2018.

Marine heatwaves and spikes occurred all year round (Fig 2, S8) but were concentrated March-April and July-September (Fig S9). The third quarter of the year had the highest frequency of marine heatwaves for both the fixed and shifting baselines (fixed: 35%, shifting: 42% of all heatwaves). The winters were characterised by negative threshold anomalies, except for two long mild winters (1990, 2007: Fig 2, S8) detected as very long heatwaves.

The top-10 marine heatwaves obtained by applying the fixed baseline were nine severe events (i.e. maximum threshold intensities were larger than three times the difference between the Q_{90} and climatological baseline). In addition, there was a very long event extending from Autumn 2006 to Spring 2007 (Table 1, Figs. 2, S10). In contrast, only three events were classified as severe, after applying the shifting baseline (Table S5). With both baselines, most of the top-10 events identified occurred in summer to early autumn (Fig. 2, S8, S9). The most important heatwaves identified with the fixed baseline (Fig. S9) coincided with known warm atmospheric events occurring at the continental scale. The most intense marine heatwave (duration: 84 days Summer-Autumn 2016) was associated with a long atmospheric heatwave over Europe (Zschenderlein et al. 2018). Other events that were clearly associated with atmospheric heatwaves were the mild winters of the years 1990 and 2007 (Luterbacher et al. 2004, Twardosz & Kossowska-Cezak 2016), summer heatwaves of years 2003 (Schär et al. 2004), 2006 (Russo et al 2015) and 2018 (Li et al. 2020). There were other marine heatwaves of lower intensity coinciding with known atmospheric heatwaves in Europe (Russo et al. 2015). For instance, two events detected 1976 (June and August) and two events in 1994, coincided with single atmospheric heatwaves for each year (1976: British Isles; 1994: NE Europe). Two marine heatwaves detected in Autumn 2015, followed high temperatures in northern Germany and positive August SST anomalies in the German Bight (Ionita et al. 2017). The application of the shifting baseline led to the identification of similar events post 1991, but they were detected as shorter events or as a sequence of several marine heatwaves and spikes (Fig S9: period 1991-2018).

Threshold anomalies were significantly auto-correlated, but the wavelet analysis did not reveal any periodicity, that was clear and consistent over the full time series (Fig 3). There was however a dominance of peaks of spectral density with a period of ~ 1 year, which is consistent with the increased frequency of positive threshold anomalies in autumn; peaks at longer periods (2-10 years) were intermittent. The spectral densities were robust to a change in baseline, as shown by the similarities in the period 1992-2018.

The relationship between spectral densities and frequencies for the threshold anomalies was consistent with red noise for both the fixed and shifting baselines, for the whole time series and for the period 1992-2018 (Fig 4). Values of slopes showed a linear pattern that up to frequencies corresponding to a year with the time series shifting to pink and white noise towards to lowest frequency corresponding to 8-30 years.

Cross-correlation analyses between heatwaves and threshold anomalies (Figs 5, S11-S14) of air vs. seawater temperature showed consistently significant peaks at time lags of 0-3 days irrespective of the baseline or whether the analysis was restricted to the post-1991 period (Fig. S14). Such time lags suggest that the seawater threshold anomalies responded quickly to fluctuation in atmospheric threshold anomalies, although the magnitude of oscillation in temperature was much higher in atmospheric than in marine heatwaves. The frequency of co-occurrence between marine and atmospheric heatwaves was 4-7 times higher than the expected from a null model (Fig. 5b) which was similar to that found when co-occurrence was calculated based on threshold anomalies (Fig. S13); the overlap between marine and atmospheric heatwaves ranged on 30-40% (Fig. 5c).

The co-occurrence and overlap levels found between any pair of atmospheric heatwaves (as detected in the four meteorological stations) was higher than that observed between marine and each separated atmospheric heatwave. There was a substantial number of cases were marine and atmospheric events did not fully coincide. Atmospheric threshold anomalies showed stronger oscillations than those based on seawater temperature. There were cases where a single marine heatwave occurred in association with several atmospheric heatwaves (e.g. winter-spring 1990: Fig. S15: days ~5-150) or periods when increases in seawater threshold anomalies were associated with atmospheric heatwaves without a marine heatwave event (e.g. year 2002: Fig. S16: days 1-30 and 2018: Fig. S17 days 60-150). In summary, marine heatwaves were associated with either one or more atmospheric heatwave and increments in seawater threshold anomalies were associated with atmospheric heatwaves (or spikes).

DISCUSSION

Heatwaves in aquatic systems are increasingly considered to be game changers in socio-ecosystems (Campbell et al. 2018, Smale et al. 2019, Smith et al. 2021**)**. The determination of heatwaves is however not trivial, different baselines have been discussed in order to define heatwaves (Amaya et al. 2023, Sen Gupta et al. 2023). We set the baseline to 30 years for comparison with other studies using a 30-year period (as in Hobday et al. 2016, but with a different time period) and to obtain stable estimations of Q_{90} required for the definition of heatwaves. We adopted a multiple baseline approach to study marine heatwaves based on a long-term time series of the German Bight. Our definition of shifting baseline is consistent with the fact that, at a given time of the year, a thermal fluctuation would be experienced by organisms as an extreme event, according to the past temperature conditions only, which would have shaped organismal adaptations. In addition, our definition ensures that heatwaves computed for a given year (e.g. year 2010) are not updated when the baseline is shifted to compute heatwaves for future years (e.g. year 2011). Hence both the shifting and fixed baseline share the same important characteristic that they do not re-compute old heatwaves with the addition of new data to the time series. Other types of shifting baseline may use future temperatures to re-compute past heatwaves. For example, in a scenario of warming, if heatwaves are computed for the full time series at each time the baseline is shifted (or expanded), then future researchers may erase old heatwaves from the record. However, with our definition, heatwaves computed at a given year are not modified if sometime in the future additional years of data are added to the time series.

Differences between the fixed and the shifting baselines are observed in our time series after 1991. The application of the fixed baseline suggests that, from the perspective of slow-adapting species, steady warming is experienced as progressively increasing in intensity and duration of marine heatwaves. Such a trend might continue to foster the influx and breeding success of warm species into the northern North Sea (Reise et al. 2023), while the range distribution of indigenous species might undergo poleward shifts. Under steady warming, only subtle changes in the dynamics of marine heatwaves are seen after the application of a shifting baseline. However, we found that the shifting baseline did not fully remove the temporal patterns, and instead found a shift from the 1980's (characterised by only few strong heatwaves) to the 1990's-2007, which contain two of the three severe events and twice as many strong heatwaves per decade than any other period of the time series. The end of the decade of the 1980's and the 1990s was characterised by important changes in the Northern hemisphere (Beaugrand et al. 2015), including North Sea phytoplankton (Defriez et al. 2016, Di Pane et al. 2022) and zooplankton (Kirby et al. 2007, Deschamps et al. 2023). In the German Bight the copepods assemblages shifted from a dominance of summer, long-lived herbivores to autumn, short-lived carnivores (Deschamps et al. 2023). We cannot ascribe those changes to marine heatwaves; nutrients are hypothesised to have contributed to the change at least for phytoplankton (Di Pane et al. 2022). However, our data suggest that the 1990's must have been experienced by fast adapting species, as a period of change, as compared to the 1980's. Those changes are likely to reflect a non-linear long-term temperature trend in the Helgoland Roads and the southern North Sea (Desmit et al. 2020, Amorim and Wiltshire et al. 2023).

The shifting baseline did not remove seasonal patterns in the frequency of extremely high temperatures, which are relevant in the context of species phenology. Positive threshold anomalies computed from the fixed baseline peaked in spring and late summer, while those computed from the shifting baseline peaked in late summer only. Hence, fast adapting species would still experience late summer as a critical period of marine heatwaves. In the German Bight, species differ in the timing of bloom or reproduction and in the degree of phenological shifts (e.g. Scharfe & Wiltshire 2019); hence, prediction is not straightforward. Spring marine heatwaves are likely to favour invasive species such as the exotic *Hemigrapsus sanguineus* which is adapted to warmer conditions than its native competitor *Carcinus maenas* (Espinosa-Novo et al. 2023). The timing, in terms of seasonality of heatwaves is important. Organisms who are adapted to seasons going from cold to warm (e.g. winter to spring and spring to summer) and especially in temperate systems with a high variability in weather conditions are less likely to be affected by marine heatwaves than those which are adapted to seasons with cooling trends (summer to autumn and autumn to winter). Thus, perhaps the autumn heatwaves are more critical: these may result in developmental traps (Kerr et al. 2020), as organism may not complete critical life phases before temperatures drop below the lower thermal tolerance limit. Concurrently, cold snaps due to blocking systems may be of importance in spring (see Amorim & Wiltshire, et al 2023).

A shifting baseline did not modify the noise colour of the time series of threshold anomalies; instead, the time series were red to pink noise, as in previous studies for marine habitats (Mustin et al. 2013), especially from scales of days to ~ 8 years. However, the change in baseline can be indicative of the different manner in which temperatures are experienced, because thermal fluctuations can be experienced as a scenario where rare events are characterised by suboptimal temperatures or the opposite scenario. The noise referred to here will be experienced by organisms as superimposed on the predictable pattern of seasonal temperature variation (Boersma et al. 2015). This noise is important in relation to adaptive responses of the upper thermal tolerance limits, especially because positive threshold anomalies occurred more frequently during late summer when temperatures peak. Events when temperatures matched upper thermal limits have been found in the Wadden Sea (Pörtner and Knust 2008) and even rare bad years can drive extinction in an annual species (Heino and Sabadell 2003). Biological time scales are central to how fluctuations are experienced at the population level:

short generation times (along with e.g. mutation rate and standing genetic variation) should favour rapid adaptation relative to the decade-scale changes shown here (Fig 2). Some species with short generation times (days to weeks) can undergo adaptation in response to temperature increase within a year (Dam et al. 2021, Schaum et al. 2022). Longer generation times (few years to decades) are likely to require decades or centuries for adaptation, but transgenerational acclimation (Donelson et al. 2018) might mitigate changes occurring at the scale of years to decades. The shifting baseline used here then gives an approximate representation on how those species experience thermal fluctuations, i.e. the post 1991 as a period of slight increase in the duration of marine heatwaves (Fig 1) and the decade of the 1990's as a period of slight increase in the frequency of strong and severe heatwaves. The shifting baseline is likely to be important for many marine organisms, given that microbes constitute ~70% of the total marine biomass (Ban-On et al. 2018) and that those organisms have short generation times (days to weeks). However, the rate of evolution varies among species (Raven and Beardall 2021, Barton et al. 2023) and the ability to evolve or exhibit adaptive plasticity might be limited (Stuart-Smith et al. 2017, Byrne et al. 2020). Hence, for those species with limited or slow rate of evolution, the temporal patters in threshold anomalies (Fig. 2) would point towards a shift (in the in the 1990s), from scenario of rare bad years to one of rare, good years. Hence, in principle, the fixed baseline is likely to be more important long lived organisms (generation times months to decades) such as marine invertebrates and fish, as they are less likely to adapt to changes in temperature within a year. Given that responses are species-specific and contingent on the time scales characterising the fluctuations (Schaum et al. 2022), we need a screening of thermal performance and tolerance limits under realistic heatwave scenarios in organisms with different life histories if we are to understand responses to fluctuations such as marine heatwaves.

If heatwaves become longer or more frequent, conservation and mitigation approaches will need to rely on the capacity for prediction, which require mechanistic models. In addition, the adoption of two or more baselines requires that we explore how relationships between marine heatwaves and potential predictors (e.g. atmospheric heatwaves) respond to a change in baseline. Our results suggest a link, at least for the case of long events, where atmospheric heatwaves lead to the increase of seawater temperature and may produce marine heatwaves; such a link was present after the application of both the fixed and the shifting baselines. The positive correlations between atmospheric and marine heatwaves are consistent with a previous analysis of the Helgoland Roads time series suggesting that main drivers of temperature in the shallow part of the North Sea are linked to atmospheric conditions (Amorim & Wiltshire et al. 2023). Important marine heatwaves coincided with extensive summer atmospheric heatwaves such as those of 2003 and 2015, which occurred over continental Europe and the Mediterranean, and coincided with atmospheric blocking (i.e. persistent high pressure anomalies: Ionita et al. 2017, Li et al. 2020). We know that air temperature has a strong influence on the SST of the shallower portions of North Sea, especially in the German Bight (Dippner et al 1997, Mathis et al. 2015); the atmospheric contribution is likely to dominate in enclosed shallow seas. Wind speed (in combination with air temperatures) should also be important and it is considered a driver of the formation of marine heatwaves (Holbrook et al. 2019). Advection of warmer waters might be a contributor but it should play a stronger role towards the Central and Southern North Sea, where inflow of Atlantic water has been considered a source of temperature increase (Kroncke et al. 2011, McQuatters-Gollop & Vermaat 2011).

In synthesis, a multiple baseline approach was important to identify which properties of the marine heatwaves are either contingent on (or robust to) a change in baseline. The application of the fixed baseline resulted in an increase in the duration and number of marine heatwaves over time, with nine of the ten most severe heatwaves occurring after the 1990's, most associated with large European heatwaves. The period after the 1990's might be experienced by slow adapting species as characterised by many bad years (i.e. with several heatwaves) separated by some few good years. The application of the shifting baselines removed the trend in number of marine heatwaves, resulted in shorter events of less intensity. However, the shifting baseline did not fully remove long term trends in average duration of heatwaves and still the 1990's appears as a period of change as compared to the 1980's. Irrespective of the baseline, marine heatwaves peaked in late summer and were associated with atmospheric heatwaves.

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Data Availability Statement

The data is archived in PANGAEA (Data Publisher for Earth & Environmental Science).

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FIGURE CAPTIONS

Figure 1. Time series of daily temperature, the number of marine heatwave events and number of days per year included in a marine heatwave, computed using fixed and shifting baselines. Curves were added when temperature smooths were retained after the model selection procedure (details in Table S4).

Figure 2. Heatmap of marine heatwaves and spikes after the application of a fixed (upper panel) or shifting baselines (lower panel). The scale colour is in °C above the threshold temperature. Rectangles: approximate timing of the ten most important heatwaves (details in Tables 1 and S5); note that for the fixed baseline, there was an event starting in 2006 that continued in 2007.

Figure 3. Spectrogram from wavelet analyses applied to the time series threshold anomalies calculated from the fixed or shifting baselines. Periods were computed following the geometric progression of octaves but the right and left y-axes show selected periods for ease of

interpretation. Notice the concentration of high spectral densities along the period of 365 days for most of the length of the time series.

Figure 4. Spectral analyses of daily threshold anomalies calculated from the fixed or shifting baselines (top and bottom panels respectively) for the full time series (1962-2018) and for the second period (1992-2018) reflecting the effect of the different baselines. The straight line fitting the frequencies is the linear model fit (equations in inset, all $p < 0.05$). The curve is the loess smooth of the data. In addition, a separate line for expected fit of the pink noise (slope = -1). The approximate periods corresponding to some of the frequencies (in units of 1/time) are given in the top-left panel for ease of interpretation. Note that the spectral density peaks at period ~1 year, but the peak is not clear. Recall that the seasonal variation in temperature is removed from this time series by subtraction of the threshold temperature (at the 90^{th} quantile).

Figure 5. Association between marine and atmospheric heatwaves after application of a fixed or shifting baseline (left and right panels respectively). (a) Cross-correlation of marine vs atmospheric heatwaves as detected by the meteorological station in Helgoland; plots for the remaining stations are given in Fig S8 (threshold intensities) and S9 (heatwaves). (b) Observed co-occurrence of heatwaves (outer circles) in relation to those expected based on random patterns of distribution (inner circles). (c) Overlap between heatwaves based on the Schoener index. Abbreviations in (b) and (c): MHW: marine heatwaves for Helgoland Roads, AW: atmospheric heatwaves corresponding to Helgoland (Helg), List, Nordeney (Nor) and Sankt Peter-Ording (SPO).

TABLES

Table 1. Main characteristics of the top ten heatwaves using a fixed baseline and the categorization received for both fixed (F_B) and shifting baselines (M_B). Information for the dates of start, peak and end (Day–Month), maximum temperature intensity (I_{max}: temperature above the seasonal climatology in ℃) and duration (D: in days) corresponds to calculations using a fixed baseline; (see Table S3 for similar information using the shifting baseline). The categorization of the marine heatwaves of 1975 and 1990 are the same for both windows because they shared the same 30-year baseline (1962-1991).

ID	Year	Start – Peak – End	I_{max}	D	F_B	M_B
1	1975	20.08 – 01.09 – 14.09	2.9	25	III	
2	1990	10.01 – 07.05 – 25.06	5.0	135	III	
3	1995	20.07 – 23.08 – 28.08	3.6	39	III	III
4	1997	04.08 – 19.08 – 21.09	3.2	49	III	II
5	2002	30.07 – 29.08 – 08.10	3.5	70	III	II
6	2003	08.07 – 06.08 – 06.10	3.5	90	III	II
7	2006	16.07 – 19.07 – 09.11	4.1	116	III	II
8	2007	16.11 – 11.04 – 30.05	4.7	195	II	II
9	2016	18.07 – 28.09 – 10.10	3.6	84	III	II

10	2018	19.07 – 25.07 – 25.09	3.8	68	III	II

Table S1. Timing and traits of the marine heatwave events detected at Helgoland Roads (German Bight, North Sea) between 1962 and 2018 using a fixed baseline (30 years) and setting the 90th quantile a threshold temperature (half-window of 11 days). Calculations were carried out in R (ackage *heatwaveR*). Units for variables are as follows: Duration is given in days; intensities are given in °C; rates are given in °C day^{-1}. Abbreviations for intensities give the type in the first part (Im= mean, Imax= maximum, Ivar: variance, Icum: cummulative) and the reference in the second part (with respect to: C: the climatological mean; T: the threshold intensity; A: as absolute value). Rates are: RO: onset rate; RD: decline rate.

Event	Duration	Date start	Date Peak	Date end	Im.C	Imax.C	IvarC	Icum.C	Im.T	Imax.T	Ivar.T	Icum.T	Im.A	Imax.A	Ivar.A	Icum.A	RO	RD
1	12	06/06/1966	15/06/1966	17/06/1966	2.38	3.44	0.46	28.50	0.61	1.67	0.46	7.32	14.30	15.80	0.80	171.65	0.18	0.73
2	6	12/05/1967	17/05/1967	17/05/1967	1.91	2.60	0.34	11.44	0.26	0.94	0.33	1.59	10.30	11.30	0.51	61.80	0.22	1.32
3	8	26/09/1967	28/09/1967	03/10/1967	1.42	1.54	0.13	11.33	0.30	0.43	0.13	2.37	16.36	16.60	0.23	130.90	0.17	0.07
4	9	29/07/1968	02/08/1968	06/08/1968	1.35	1.41	0.07	12.13	0.14	0.19	0.05	1.23	17.63	17.70	0.08	158.70	0.08	0.07
5	5	31/10/1968	01/11/1968	04/11/1968	1.51	1.56	0.06	7.54	0.13	0.20	0.06	0.67	13.33	13.50	0.16	66.65	0.16	0.09
6	6	12/09/1969	17/09/1969	17/09/1969	1.49	1.65	0.11	8.94	0.45	0.60	0.09	2.72	17.37	17.40	0.04	104.20	0.10	0.84
7	7	23/10/1969	29/10/1969	29/10/1969	1.37	1.53	0.08	9.56	0.09	0.21	0.07	0.63	13.96	14.20	0.20	97.70	0.04	0.89
8	6	07/06/1970	11/06/1970	12/06/1970	2.10	2.63	0.31	12.62	0.34	0.86	0.30	2.05	13.79	14.50	0.51	82.73	0.22	0.50
9	7	18/06/1970	23/06/1970	24/06/1970	3.15	3.83	0.61	22.05	1.41	2.11	0.62	9.89	16.20	17.10	0.71	113.40	0.36	1.24
10	7	13/08/1973	16/08/1973	19/08/1973	1.22	1.49	0.15	8.56	0.20	0.47	0.15	1.41	17.83	18.10	0.15	124.80	0.13	0.15
11	7	04/09/1973	07/09/1973	10/09/1973	1.40	1.58	0.17	9.77	0.41	0.60	0.17	2.90	17.61	17.80	0.17	123.30	0.18	0.14
12	5	14/09/1973	17/09/1973	18/09/1973	1.20	1.35	0.11	6.01	0.15	0.30	0.11	0.76	17.00	17.10	0.12	85.00	0.17	0.18
13	16	07/04/1974	10/04/1974	22/04/1974	1.96	2.08	0.07	31.30	0.20	0.31	0.09	3.17	7.16	7.90	0.43	114.60	0.08	0.03
14	7	25/08/1974	26/08/1974	31/08/1974	1.20	1.44	0.15	8.42	0.25	0.48	0.15	1.72	17.72	18.00	0.17	124.03	0.25	0.08
15	11	14/01/1975	21/01/1975	24/01/1975	2.10	2.26	0.14	23.13	0.30	0.49	0.15	3.34	6.46	6.70	0.20	71.02	0.08	0.10
16	9	28/01/1975	31/01/1975	05/02/1975	2.38	2.60	0.15	21.44	0.36	0.59	0.16	3.22	6.14	6.40	0.20	55.30	0.18	0.11
17	6	09/02/1975	13/02/1975	14/02/1975	2.36	2.66	0.19	14.17	0.20	0.48	0.18	1.19	5.75	6.00	0.15	34.50	0.12	0.26
18	16	27/02/1975	04/03/1975	14/03/1975	2.37	2.57	0.16	37.86	0.31	0.47	0.15	4.93	5.56	5.70	0.13	88.90	0.08	0.06
19	15	02/08/1975	05/08/1975	16/08/1975	2.21	2.80	0.41	33.20	1.10	1.66	0.42	16.48	18.70	19.30	0.44	280.50	0.43	0.14

20	25	20/08/1975	01/09/1975	13/09/1975	1.62	2.88	0.59	40.41	0.64	1.93	0.60	16.04	17.99	19.30	0.63	449.77	0.14	0.14
21	19	17/09/1975	18/09/1975	05/10/1975	1.25	1.41	0.12	23.69	0.14	0.34	0.14	2.74	16.42	17.10	0.44	312.00	0.19	0.01
22	26	26/06/1976	28/06/1976	21/07/1976	2.42	4.31	0.78	62.79	0.89	2.65	0.75	23.20	17.12	19.10	0.81	445.00	0.93	0.12
23	5	21/08/1976	24/08/1976	25/08/1976	1.26	1.51	0.20	6.32	0.29	0.55	0.20	1.46	17.86	18.10	0.18	89.30	0.14	0.25
24	5	23/11/1978	27/11/1978	27/11/1978	1.72	1.91	0.13	8.59	0.28	0.47	0.14	1.38	10.84	11.00	0.09	54.20	0.09	0.79
25	6	05/08/1981	06/08/1981	10/08/1981	1.43	1.97	0.28	8.59	0.29	0.81	0.27	1.77	17.90	18.40	0.27	107.40	0.74	0.25
26	7	30/07/1982	02/08/1982	05/08/1982	1.64	1.91	0.16	11.48	0.43	0.69	0.15	3.00	17.93	18.20	0.16	125.50	0.23	0.25
27	8	28/09/1982	04/10/1982	05/10/1982	1.56	2.29	0.41	12.50	0.43	1.14	0.40	3.46	16.36	16.90	0.36	130.90	0.19	0.76
28	8	28/10/1982	04/11/1982	04/11/1982	1.59	1.71	0.08	12.69	0.23	0.31	0.07	1.86	13.58	13.90	0.25	108.60	0.06	0.38
29	5	10/11/1982	12/11/1982	14/11/1982	1.56	1.65	0.06	7.78	0.08	0.17	0.06	0.39	12.21	12.40	0.19	61.05	0.10	0.06
30	12	23/08/1983	25/08/1983	03/09/1983	1.35	1.93	0.43	16.18	0.39	0.96	0.43	4.68	17.85	18.50	0.42	214.17	0.37	0.08
31	56	20/12/1987	02/02/1988	13/02/1988	2.16	2.68	0.27	121.18	0.41	0.76	0.22	22.74	6.82	8.10	0.80	382.05	0.03	0.04
32	64	31/01/1989	10/03/1989	04/04/1989	2.42	2.86	0.23	154.91	0.40	0.85	0.26	25.35	5.90	6.40	0.28	377.55	0.02	0.04
33	5	13/05/1989	16/05/1989	17/05/1989	1.83	2.02	0.14	9.13	0.18	0.38	0.14	0.91	10.28	10.60	0.31	51.40	0.13	0.26
34	7	16/06/1989	19/06/1989	22/06/1989	2.46	3.47	0.57	17.23	0.71	1.72	0.56	4.96	15.29	16.30	0.63	107.00	0.53	0.48
35	9	21/09/1989	25/09/1989	29/09/1989	1.38	1.64	0.16	12.39	0.28	0.55	0.16	2.53	16.63	16.90	0.25	149.70	0.13	0.10
36	8	31/10/1989	02/11/1989	07/11/1989	1.47	1.58	0.08	11.76	0.07	0.20	0.07	0.59	13.12	13.40	0.25	104.95	0.15	0.06
37	6	11/11/1989	14/11/1989	16/11/1989	1.69	1.88	0.15	10.15	0.21	0.41	0.15	1.28	12.17	12.30	0.24	73.00	0.12	0.24
38	8	21/12/1989	28/12/1989	28/12/1989	1.66	1.72	0.07	13.27	0.25	0.31	0.06	2.04	7.84	8.10	0.19	62.70	0.06	0.52
39	135	10/01/1990	07/05/1990	24/05/1990	2.85	5.00	0.65	384.08	0.97	3.35	0.70	131.18	7.68	12.50	2.02	1036.50	0.03	0.17
40	6	30/05/1990	01/06/1990	04/06/1990	3.06	4.50	0.90	18.34	1.33	2.77	0.90	7.97	13.73	15.10	0.94	82.35	1.11	0.75
41	8	28/08/1990	30/08/1990	04/09/1990	1.44	2.12	0.34	11.54	0.49	1.17	0.34	3.90	17.88	18.60	0.34	143.00	0.48	0.22
42	18	22/08/1991	04/09/1991	08/09/1991	1.38	2.07	0.37	24.82	0.41	1.10	0.37	7.46	17.82	18.40	0.38	320.70	0.07	0.24
43	9	18/09/1991	25/09/1991	26/09/1991	1.18	1.24	0.04	10.66	0.10	0.15	0.04	0.92	16.63	16.90	0.17	149.70	0.01	0.10

44	11	16/05/1992	20/05/1992	26/05/1992	2.26	2.73	0.33	24.90	0.57	1.05	0.33	6.31	11.46	12.10	0.53	126.05	0.26	0.21
45	7	25/06/1992	29/06/1992	01/07/1992	2.53	3.12	0.45	17.71	0.87	1.47	0.47	6.12	16.31	17.00	0.64	114.20	0.31	0.65
46	5	07/07/1992	09/07/1992	11/07/1992	1.89	2.22	0.33	9.46	0.38	0.71	0.33	1.91	16.67	17.00	0.33	83.37	0.57	0.36
47	7	06/08/1992	10/08/1992	12/08/1992	1.48	1.67	0.16	10.38	0.37	0.57	0.16	2.57	17.99	18.20	0.16	125.90	0.11	0.28
48	6	13/05/1993	14/05/1993	18/05/1993	1.84	1.97	0.10	11.01	0.19	0.33	0.10	1.12	10.35	10.60	0.24	62.10	0.28	0.08
49	5	01/07/1994	04/07/1994	05/07/1994	2.16	2.55	0.34	10.81	0.57	0.98	0.34	2.86	16.42	16.90	0.35	82.10	0.28	0.66
50	30	28/07/1994	04/08/1994	26/08/1994	1.78	3.23	0.65	53.46	0.69	2.05	0.58	20.69	18.25	19.60	0.59	547.60	0.20	0.10
51	8	08/12/1994	12/12/1994	15/12/1994	1.79	1.98	0.16	14.30	0.44	0.63	0.17	3.51	9.16	9.30	0.20	73.30	0.17	0.16
52	14	20/12/1994	29/12/1994	02/01/1995	1.85	2.21	0.16	25.85	0.42	0.77	0.16	5.92	7.86	8.30	0.33	110.00	0.08	0.22
53	36	18/02/1995	28/02/1995	25/03/1995	2.31	2.70	0.25	83.18	0.28	0.62	0.20	9.97	5.61	5.90	0.18	201.89	0.05	0.04
54	17	23/04/1995	24/04/1995	09/05/1995	1.81	2.12	0.16	30.73	0.13	0.41	0.16	2.26	8.65	9.60	0.53	147.00	0.30	0.03
55	39	20/07/1995	23/08/1995	27/08/1995	2.11	3.60	0.65	82.17	0.97	2.63	0.69	37.77	18.45	20.20	0.78	719.40	0.07	0.63
56	26	02/09/1995	19/09/1995	27/09/1995	1.38	1.67	0.25	35.99	0.35	0.63	0.25	9.12	17.22	17.80	0.45	447.75	0.05	0.09
57	25	08/10/1995	27/10/1995	01/11/1995	1.81	2.31	0.34	45.35	0.59	1.03	0.31	14.68	14.99	15.80	0.65	374.70	0.06	0.13
58	5	21/08/1996	23/08/1996	25/08/1996	1.40	1.90	0.32	7.02	0.43	0.93	0.32	2.16	18.00	18.50	0.32	90.00	0.39	0.35
59	7	10/07/1997	14/07/1997	16/07/1997	2.21	2.62	0.40	15.50	0.75	1.16	0.39	5.22	17.31	17.80	0.36	121.20	0.28	0.51
60	49	04/08/1997	19/08/1997	21/09/1997	2.05	3.18	0.52	100.45	1.03	2.19	0.54	50.28	18.37	19.80	0.79	900.05	0.12	0.06
61	8	28/09/1997	30/09/1997	05/10/1997	1.37	1.69	0.18	11.00	0.24	0.56	0.19	1.96	16.18	16.60	0.34	129.40	0.19	0.10
62	7	15/03/1998	16/03/1998	21/03/1998	1.99	2.08	0.07	13.90	0.11	0.18	0.06	0.76	5.48	5.50	0.05	38.33	0.10	0.05
63	18	26/03/1998	08/04/1998	12/04/1998	2.12	2.34	0.18	38.22	0.32	0.54	0.17	5.69	6.49	7.00	0.40	116.85	0.04	0.12
64	33	21/04/1998	19/05/1998	23/05/1998	2.21	3.06	0.32	73.09	0.54	1.38	0.33	17.95	9.76	12.00	1.24	322.00	0.05	0.30
65	8	28/05/1998	02/06/1998	04/06/1998	2.56	2.87	0.33	20.44	0.83	1.14	0.33	6.64	13.09	13.60	0.46	104.75	0.21	0.43
66	21	25/03/1999	09/04/1999	14/04/1999	2.02	2.26	0.11	42.43	0.22	0.46	0.12	4.54	6.43	7.20	0.48	135.05	0.03	0.09
67	15	21/04/1999	30/04/1999	05/05/1999	2.11	2.88	0.35	31.61	0.42	1.20	0.36	6.29	8.62	9.60	0.74	129.30	0.13	0.19

68	17	27/07/1999	02/08/1999	12/08/1999	2.11	2.51	0.37	35.94	0.93	1.38	0.35	15.84	18.45	19.00	0.37	313.70	0.15	0.14
69	42	03/09/1999	23/09/1999	14/10/1999	2.09	3.01	0.49	87.62	1.01	1.92	0.49	42.25	17.35	18.40	1.04	728.50	0.09	0.08
70	5	09/11/1999	12/11/1999	13/11/1999	1.76	2.25	0.30	8.81	0.29	0.77	0.29	1.43	12.53	12.90	0.22	62.67	0.22	0.41
71	20	17/03/2000	04/04/2000	05/04/2000	2.10	2.42	0.14	42.00	0.27	0.61	0.14	5.41	6.00	6.80	0.35	119.95	0.02	0.32
72	6	28/04/2000	03/05/2000	03/05/2000	2.02	2.45	0.27	12.11	0.34	0.79	0.28	2.04	8.79	9.50	0.47	52.75	0.19	0.81
73	5	12/05/2000	12/05/2000	16/05/2000	2.25	3.11	0.62	11.24	0.61	1.48	0.62	3.04	10.58	11.20	0.44	52.90	1.98	0.32
74	7	29/09/2000	02/10/2000	05/10/2000	1.46	1.73	0.17	10.20	0.32	0.60	0.17	2.27	16.22	16.50	0.21	113.55	0.19	0.18
75	15	07/12/2000	20/12/2000	21/12/2000	1.85	2.72	0.34	27.69	0.49	1.34	0.34	7.30	8.99	9.40	0.46	134.80	0.11	1.14
76	26	15/08/2001	31/08/2001	09/09/2001	1.56	2.05	0.24	40.58	0.59	1.10	0.25	15.21	18.03	18.50	0.33	468.90	0.06	0.11
77	23	11/10/2001	31/10/2001	02/11/2001	1.60	1.95	0.21	36.91	0.36	0.63	0.20	8.33	14.58	15.50	0.64	335.45	0.04	0.25
78	9	02/12/2001	10/12/2001	10/12/2001	1.83	1.98	0.20	16.46	0.46	0.64	0.21	4.13	9.76	10.00	0.17	87.80	0.07	0.90
79	12	09/02/2002	20/02/2002	20/02/2002	2.46	2.73	0.20	29.55	0.27	0.51	0.19	3.29	5.77	5.90	0.16	69.25	0.05	0.58
80	59	26/02/2002	08/04/2002	25/04/2002	2.42	2.94	0.28	142.53	0.54	1.14	0.30	31.96	6.57	8.50	0.88	387.50	0.02	0.06
81	70	30/07/2002	29/08/2002	07/10/2002	2.19	3.50	0.49	153.10	1.13	2.55	0.53	78.93	18.19	20.00	0.86	1272.95	0.07	0.05
82	13	21/06/2003	27/06/2003	03/07/2003	2.72	3.81	0.67	35.42	1.06	2.14	0.66	13.73	16.40	17.50	0.75	213.20	0.35	0.34
83	90	08/07/2003	06/08/2003	05/10/2003	2.18	3.47	0.47	196.06	1.04	2.31	0.46	93.44	18.08	19.90	0.87	1627.40	0.07	0.04
84	5	11/04/2004	13/04/2004	15/04/2004	1.96	2.14	0.14	9.79	0.19	0.37	0.13	0.95	7.02	7.20	0.15	35.10	0.12	0.17
85	6	24/04/2004	26/04/2004	29/04/2004	2.47	3.61	0.65	14.83	0.77	1.91	0.64	4.63	8.82	9.90	0.61	52.90	0.80	0.58
86	22	31/07/2004	02/08/2004	21/08/2004	1.79	2.81	0.38	39.28	0.69	1.59	0.32	15.13	18.28	19.10	0.30	402.13	0.59	0.09
87	14	03/09/2004	06/09/2004	16/09/2004	1.34	1.64	0.20	18.74	0.34	0.67	0.21	4.74	17.44	17.90	0.29	244.20	0.18	0.05
88	10	10/12/2004	13/12/2004	19/12/2004	1.58	1.77	0.11	15.81	0.22	0.43	0.11	2.25	8.67	9.00	0.33	86.70	0.13	0.06
89	6	29/06/2005	29/06/2005	04/07/2005	2.05	2.52	0.24	12.28	0.44	0.87	0.23	2.62	16.17	16.40	0.24	97.00	1.20	0.17
90	6	12/07/2005	15/07/2005	17/07/2005	2.37	2.85	0.47	14.22	0.92	1.40	0.46	5.50	17.58	18.10	0.43	105.50	0.30	0.64
91	5	26/07/2005	29/07/2005	30/07/2005	1.54	1.78	0.16	7.68	0.26	0.52	0.18	1.32	17.61	17.90	0.21	88.03	0.15	0.31

92	88	05/09/2005	22/11/2005	01/12/2005	1.86	3.23	0.54	163.43	0.61	1.78	0.42	54.11	14.85	17.70	2.09	1306.45	0.03	0.21
93	11	07/12/2005	13/12/2005	17/12/2005	1.78	2.27	0.29	19.61	0.43	0.93	0.29	4.73	9.11	9.50	0.29	100.23	0.13	0.18
94	9	09/06/2006	09/06/2006	17/06/2006	2.25	2.68	0.36	20.27	0.48	0.92	0.36	4.34	14.37	14.70	0.16	129.30	1.47	0.11
95	7	04/07/2006	10/07/2006	10/07/2006	2.26	3.23	0.58	15.82	0.73	1.73	0.60	5.08	16.87	18.10	0.74	118.10	0.28	2.68
96	116	16/07/2006	19/07/2006	08/11/2006	2.35	4.06	0.59	272.28	1.20	2.67	0.54	138.66	17.43	20.00	1.50	2022.28	0.64	0.02
97	195	16/11/2006	16/04/2007	29/05/2007	2.99	4.68	0.57	582.62	1.24	2.93	0.56	242.59	8.66	13.90	2.08	1688.70	0.03	0.06
98	16	02/06/2007	11/06/2007	17/06/2007	3.00	4.63	0.99	48.05	1.25	2.86	0.98	19.93	14.68	16.50	1.20	234.90	0.30	0.47
99	19	23/06/2007	28/06/2007	11/07/2007	1.88	2.21	0.16	35.71	0.28	0.55	0.16	5.27	16.03	16.90	0.51	304.50	0.10	0.05
100	14	18/07/2007	24/07/2007	31/07/2007	1.66	2.15	0.27	23.18	0.34	0.82	0.22	4.69	17.52	18.00	0.17	245.30	0.12	0.13
101	24	04/08/2007	15/08/2007	27/08/2007	1.52	2.00	0.33	36.57	0.48	0.97	0.32	11.49	18.08	18.60	0.32	433.80	0.07	0.07
102	25	26/02/2008	27/02/2008	21/03/2008	2.24	2.50	0.21	55.99	0.22	0.51	0.19	5.60	5.51	5.80	0.20	137.68	0.14	0.03
103	7	30/03/2008	31/03/2008	05/04/2008	1.98	2.18	0.11	13.85	0.16	0.36	0.11	1.13	6.23	6.40	0.13	43.60	0.24	0.07
104	14	25/06/2008	02/07/2008	08/07/2008	1.90	2.43	0.29	26.66	0.30	0.83	0.29	4.14	16.01	16.60	0.44	224.20	0.10	0.15
105	60	25/07/2008	01/08/2008	22/09/2008	1.40	2.25	0.32	83.89	0.33	1.02	0.26	20.09	17.67	18.50	0.48	1060.30	0.13	0.02
106	6	22/04/2009	23/04/2009	27/04/2009	2.31	2.52	0.19	13.87	0.61	0.81	0.19	3.64	8.45	8.60	0.22	50.70	0.43	0.17
107	39	03/08/2009	06/08/2009	10/09/2009	1.68	2.17	0.31	65.64	0.66	1.15	0.32	25.80	18.15	18.70	0.42	707.85	0.27	0.03
108	15	17/09/2009	23/09/2009	01/10/2009	1.33	1.61	0.18	19.94	0.24	0.52	0.17	3.56	16.64	17.00	0.29	249.65	0.09	0.07
109	12	05/12/2009	09/12/2009	16/12/2009	1.62	1.88	0.17	19.49	0.27	0.54	0.18	3.23	9.10	9.50	0.42	109.20	0.11	0.07
110	5	06/08/2010	06/08/2010	10/08/2010	1.52	1.77	0.20	7.59	0.39	0.61	0.17	1.94	18.00	18.20	0.16	90.00	0.97	0.14
111	5	20/08/2010	23/08/2010	24/08/2010	1.30	1.50	0.16	6.48	0.32	0.53	0.16	1.59	17.90	18.10	0.16	89.50	0.13	0.32
112	17	15/04/2011	27/04/2011	01/05/2011	2.86	3.90	0.47	48.68	1.15	2.20	0.47	19.58	8.86	10.30	0.70	150.70	0.16	0.56
113	7	02/06/2011	06/06/2011	08/06/2011	2.32	2.95	0.45	16.23	0.58	1.21	0.46	4.04	13.44	14.20	0.48	94.05	0.24	0.51
114	10	28/09/2011	04/10/2011	07/10/2011	1.53	1.79	0.19	15.26	0.39	0.64	0.18	3.93	16.25	16.40	0.26	162.50	0.10	0.17
115	6	23/11/2011	24/11/2011	28/11/2011	1.68	1.76	0.09	10.05	0.24	0.32	0.09	1.41	10.74	11.00	0.18	64.45	0.27	0.04

116	8	23/03/2012	29/03/2012	30/03/2012	1.97	2.30	0.17	15.72	0.15	0.48	0.17	1.18	5.84	6.30	0.25	46.70	0.07	0.35
117	7	22/05/2012	25/05/2012	28/05/2012	1.96	2.30	0.20	13.70	0.25	0.59	0.19	1.73	11.66	12.00	0.35	81.60	0.17	0.18
118	32	18/08/2012	11/09/2012	18/09/2012	1.39	1.85	0.19	44.36	0.40	0.84	0.18	12.74	17.69	18.20	0.28	565.95	0.03	0.09
119	34	20/12/2013	09/01/2014	22/01/2014	1.92	2.35	0.21	65.39	0.35	0.73	0.15	11.86	7.19	8.00	0.58	244.50	0.05	0.05
120	127	12/02/2014	23/04/2014	18/06/2014	2.64	4.12	0.46	334.65	0.80	2.41	0.51	101.30	8.93	14.50	2.89	1134.00	0.03	0.05
121	14	25/06/2014	26/06/2014	08/07/2014	2.03	2.41	0.34	28.41	0.42	0.85	0.34	5.89	16.14	17.00	0.47	225.95	0.45	0.08
122	32	16/07/2014	08/08/2014	16/08/2014	2.36	3.02	0.49	75.40	1.13	1.89	0.46	36.11	18.49	19.50	0.56	591.80	0.06	0.24
123	94	29/08/2014	13/11/2014	30/11/2014	2.21	2.97	0.50	207.65	0.99	1.59	0.37	93.05	15.50	17.80	2.09	1457.15	0.03	0.10
124	20	04/12/2014	19/12/2014	23/12/2014	1.69	2.13	0.23	33.80	0.32	0.75	0.23	6.49	8.89	9.80	0.61	177.70	0.05	0.15
125	25	08/03/2015	16/03/2015	01/04/2015	2.13	2.78	0.22	53.15	0.24	0.88	0.20	6.08	5.74	6.20	0.25	143.40	0.08	0.06
126	23	14/04/2015	27/04/2015	06/05/2015	2.29	2.90	0.28	52.72	0.59	1.20	0.27	13.57	8.51	9.60	0.71	195.70	0.06	0.14
127	11	01/10/2015	08/10/2015	11/10/2015	1.59	1.90	0.21	17.54	0.45	0.75	0.21	4.93	16.05	16.20	0.25	176.50	0.10	0.18
128	36	30/10/2015	11/11/2015	04/12/2015	1.90	2.63	0.43	68.29	0.47	1.15	0.41	16.75	12.03	13.60	1.41	432.90	0.11	0.06
129	41	09/12/2015	28/12/2015	18/01/2016	2.21	3.02	0.40	90.77	0.72	1.60	0.47	29.65	8.08	9.60	1.11	331.30	0.08	0.07
130	6	25/01/2016	28/01/2016	30/01/2016	2.15	2.28	0.10	12.93	0.19	0.31	0.10	1.17	6.10	6.20	0.11	36.60	0.10	0.12
131	6	08/02/2016	12/02/2016	13/02/2016	2.41	2.53	0.11	14.45	0.26	0.36	0.12	1.54	5.83	5.90	0.13	34.97	0.06	0.30
132	66	20/02/2016	23/02/2016	25/04/2016	2.41	2.77	0.15	158.94	0.50	0.88	0.21	32.99	6.45	8.30	0.91	425.85	0.14	0.02
133	10	09/05/2016	12/05/2016	18/05/2016	1.86	2.31	0.20	18.55	0.21	0.68	0.20	2.13	10.13	10.70	0.36	101.30	0.22	0.08
134	12	27/05/2016	03/06/2016	07/06/2016	2.32	3.44	0.53	27.80	0.59	1.71	0.53	7.05	12.98	14.30	0.86	155.80	0.24	0.44
135	84	18/07/2016	28/09/2016	09/10/2016	2.34	3.64	0.69	196.49	1.24	2.53	0.71	104.01	18.27	19.40	0.75	1534.60	0.03	0.22
136	17	18/10/2016	01/11/2016	03/11/2016	1.83	2.26	0.29	31.17	0.55	0.91	0.29	9.39	14.41	15.50	0.60	245.00	0.05	0.35
137	22	07/12/2016	28/12/2016	28/12/2016	1.86	2.42	0.35	40.94	0.49	1.00	0.33	10.70	8.68	9.20	0.38	191.00	0.05	1.42
138	5	09/01/2017	12/01/2017	13/01/2017	1.82	2.05	0.16	9.11	0.17	0.38	0.14	0.86	6.64	6.80	0.09	33.20	0.18	0.18
139	27	29/03/2017	10/04/2017	24/04/2017	2.19	3.28	0.38	59.16	0.42	1.49	0.39	11.28	7.14	8.40	0.83	192.80	0.12	0.13

140	8	16/05/2017	18/05/2017	23/05/2017	2.06	2.58	0.24	16.45	0.37	0.91	0.24	3.00	11.06	11.40	0.34	88.50	0.40	0.20
141	6	02/06/2017	06/06/2017	07/06/2017	2.48	2.75	0.34	14.88	0.74	1.01	0.34	4.45	13.53	14.00	0.33	81.20	0.17	0.79
142	9	17/06/2017	19/06/2017	25/06/2017	2.53	3.17	0.49	22.77	0.80	1.42	0.48	7.15	15.58	16.20	0.49	140.20	0.55	0.24
143	7	06/07/2017	10/07/2017	12/07/2017	2.29	2.53	0.22	16.04	0.78	1.03	0.22	5.47	17.07	17.40	0.29	119.50	0.14	0.42
144	59	08/08/2017	06/09/2017	05/10/2017	1.52	2.34	0.31	89.79	0.49	1.37	0.32	28.70	17.52	18.60	0.64	1033.90	0.04	0.04
145	15	13/10/2017	26/10/2017	27/10/2017	1.70	2.21	0.27	25.57	0.49	0.93	0.25	7.35	14.90	15.20	0.35	223.50	0.08	0.60
146	6	02/11/2017	06/11/2017	07/11/2017	1.75	2.14	0.30	10.49	0.34	0.71	0.30	2.03	13.28	13.80	0.37	79.70	0.12	0.75
147	7	24/01/2018	24/01/2018	30/01/2018	2.13	2.60	0.22	14.88	0.17	0.70	0.24	1.22	6.09	6.70	0.29	42.65	0.85	0.09
148	7	29/06/2018	04/07/2018	05/07/2018	2.31	2.95	0.38	16.14	0.70	1.38	0.39	4.92	16.47	17.30	0.51	115.30	0.25	0.92
149	68	19/07/2018	25/07/2018	24/09/2018	2.12	3.79	0.55	144.39	1.03	2.49	0.50	70.25	18.32	19.90	0.63	1245.70	0.30	0.04
150	15	12/10/2018	22/10/2018	26/10/2018	1.57	1.79	0.17	23.60	0.37	0.57	0.18	5.50	14.87	15.40	0.46	223.00	0.06	0.16
151	9	07/11/2018	15/11/2018	15/11/2018	1.79	2.00	0.14	16.10	0.32	0.53	0.13	2.88	12.56	12.80	0.20	113.05	0.07	0.98
152	12	30/11/2018	07/12/2018	11/12/2018	1.79	2.08	0.19	21.42	0.41	0.72	0.19	4.92	9.77	10.30	0.50	117.20	0.07	0.17
153	21	20/12/2018	28/12/2018	09/01/2019	1.99	2.32	0.19	41.78	0.52	0.90	0.21	10.87	7.72	8.40	0.53	162.10	0.11	0.06

Table S2. Timing and traits of the marine heatwave events detected at Helgoland Roads (German Bight, North Sea) between 1992 and 2018 using a shifting baseline (30 years) and setting the 90th quantile a threshold temperature (half-window of 11 days). The events corresponding to the first 30 years (1962-1991) are the same as the one provided in Table S1. Calculations were carried out in R (ackage *heatwaveR*). Units for variables are as follows: Duration is given in days; intensities are given in °C; rates are given in °C day^{-1}. Abbreviations for intensities give the type in the first part (Im= mean, Imax= maximum, Ivar: variance, Icum: cummulative) and the reference in the second part (with respect to: C: the climatological mean; T: the threshold intensity; A: as absolute value). Rates are: RO: onset rate; RD: decline rate. NA in rate decline: situations where the heatwave did not end at the end of the time frame used to calculate the traits.

Event	Duration	Date start	Date Peak	Date end	Im.C	Imax.C	IvarC	Icum.C	Im.T	Imax.T	Ivar.T	Icum.T	Im.A	Imax.A	Ivar.A	Icum.A	RO	RD
44	10	16/05/1992	20/05/1992	25/05/1992	2.26	2.67	0.29	22.56	0.52	0.93	0.28	5.22	11.45	12.10	0.55	114.50	0.26	0.12
45	7	25/06/1992	29/06/1992	01/07/1992	2.47	3.05	0.45	17.27	0.79	1.38	0.47	5.50	16.31	17.00	0.64	114.20	0.31	0.66
46	7	06/08/1992	10/08/1992	12/08/1992	1.42	1.60	0.16	9.91	0.33	0.54	0.16	2.32	17.99	18.20	0.16	125.90	0.11	0.28
47	20	28/07/1994	04/08/1994	16/08/1994	1.98	3.10	0.54	39.61	0.82	1.90	0.52	16.47	18.52	19.60	0.55	370.30	0.20	0.15
48	8	08/12/1994	12/12/1994	15/12/1994	1.78	1.97	0.16	14.24	0.37	0.56	0.16	2.99	9.16	9.30	0.20	73.30	0.16	0.17
49	12	20/12/1994	29/12/1994	31/12/1994	1.82	2.15	0.15	21.85	0.38	0.70	0.14	4.57	7.96	8.30	0.20	95.58	0.07	NA
50	8	24/02/1995	28/02/1995	03/03/1995	2.23	2.38	0.08	17.81	0.12	0.27	0.08	0.97	5.65	5.80	0.08	45.20	0.06	0.08
51	5	10/03/1995	13/03/1995	14/03/1995	2.15	2.25	0.09	10.77	0.19	0.30	0.09	0.95	5.78	5.90	0.09	28.90	0.06	0.46
52	12	26/07/1995	03/08/1995	06/08/1995	2.22	2.96	0.43	26.63	0.93	1.69	0.42	11.20	18.65	19.50	0.45	223.80	0.17	0.47
53	17	10/08/1995	23/08/1995	26/08/1995	2.07	3.42	0.70	35.27	1.01	2.41	0.74	17.21	18.86	20.20	0.71	320.57	0.14	0.63
54	11	03/09/1995	13/09/1995	13/09/1995	1.37	1.54	0.15	15.02	0.36	0.50	0.14	3.96	17.66	17.80	0.13	194.23	0.06	1.05
55	10	17/09/1995	19/09/1995	26/09/1995	1.40	1.58	0.11	14.00	0.30	0.50	0.11	3.02	16.96	17.30	0.21	169.62	0.18	0.05
56	24	09/10/1995	27/10/1995	01/11/1995	1.83	2.31	0.32	43.88	0.52	0.96	0.30	12.59	14.97	15.80	0.65	359.20	0.06	0.13
57	6	10/07/1997	14/07/1997	15/07/1997	2.19	2.47	0.25	13.15	0.61	0.91	0.25	3.68	17.40	17.80	0.31	104.40	0.27	0.58
58	42	05/08/1997	19/08/1997	15/09/1997	1.95	2.92	0.42	81.97	0.81	1.77	0.42	33.94	18.58	19.80	0.61	780.55	0.10	0.07
59	6	28/09/1997	30/09/1997	03/10/1997	1.37	1.62	0.17	8.22	0.18	0.43	0.18	1.07	16.31	16.60	0.27	97.84	0.20	0.12
60	10	30/03/1998	08/04/1998	08/04/1998	1.99	2.06	0.06	19.87	0.18	0.26	0.06	1.80	6.62	7.00	0.25	66.15	0.03	0.28
61	22	30/04/1998	19/05/1998	21/05/1998	2.07	2.83	0.29	45.62	0.30	1.04	0.28	6.68	10.26	12.00	0.88	225.70	0.05	0.38

62	8	28/05/1998	02/06/1998	04/06/1998	2.41	2.73	0.33	19.30	0.65	0.98	0.34	5.19	13.09	13.60	0.46	104.75	0.21	0.42
63	5	29/04/1999	30/04/1999	03/05/1999	2.11	2.50	0.28	10.54	0.35	0.74	0.28	1.73	9.32	9.60	0.23	46.60	0.43	0.21
64	16	27/07/1999	02/08/1999	11/08/1999	1.91	2.24	0.28	30.51	0.58	0.93	0.27	9.22	18.50	19.00	0.32	296.00	0.15	0.13
65	39	03/09/1999	23/09/1999	11/10/1999	2.02	2.88	0.45	78.85	0.78	1.63	0.44	30.57	17.51	18.40	0.88	683.00	0.10	0.09
66	5	09/11/1999	12/11/1999	13/11/1999	1.82	2.30	0.29	9.08	0.27	0.75	0.29	1.36	12.53	12.90	0.22	62.67	0.22	0.42
67	14	08/12/2000	20/12/2000	21/12/2000	1.79	2.60	0.33	25.08	0.40	1.23	0.33	5.66	8.97	9.40	0.48	125.60	0.09	1.15
68	5	22/08/2001	24/08/2001	26/08/2001	1.41	1.58	0.13	7.02	0.23	0.41	0.13	1.16	18.32	18.50	0.14	91.60	0.11	0.15
69	7	30/08/2001	31/08/2001	05/09/2001	1.47	1.76	0.18	10.31	0.28	0.57	0.18	1.99	18.14	18.50	0.23	127.00	0.33	0.08
70	6	12/10/2001	16/10/2001	17/10/2001	1.58	1.78	0.10	9.49	0.22	0.41	0.10	1.31	15.35	15.50	0.14	92.10	0.10	0.20
71	9	24/10/2001	31/10/2001	01/11/2001	1.78	1.97	0.21	16.04	0.33	0.50	0.20	2.97	14.14	14.40	0.30	127.25	0.08	0.35
72	7	04/12/2001	05/12/2001	10/12/2001	1.84	1.90	0.07	12.88	0.36	0.43	0.08	2.54	9.74	10.00	0.19	68.20	0.20	0.09
73	6	15/02/2002	20/02/2002	20/02/2002	2.05	2.16	0.06	12.28	0.19	0.29	0.05	1.14	5.82	5.90	0.04	34.90	0.08	0.59
74	25	10/03/2002	03/04/2002	03/04/2002	1.99	2.27	0.18	49.84	0.19	0.51	0.19	4.84	6.33	7.20	0.40	158.20	0.01	0.76
75	7	30/07/2002	01/08/2002	05/08/2002	1.63	2.04	0.19	11.39	0.20	0.61	0.18	1.40	18.23	18.60	0.20	127.60	0.35	0.13
76	55	14/08/2002	29/08/2002	07/10/2002	2.03	3.12	0.37	111.85	0.69	1.78	0.37	38.05	18.22	20.00	0.96	1002.25	0.13	0.05
77	7	26/06/2003	27/06/2003	02/07/2003	2.71	3.52	0.53	18.99	0.99	1.78	0.52	6.90	16.89	17.50	0.46	118.20	1.03	0.34
78	20	11/07/2003	16/07/2003	30/07/2003	2.19	2.98	0.40	43.74	0.60	1.37	0.40	11.94	18.10	18.80	0.48	362.00	0.22	0.09
79	26	04/08/2003	06/08/2003	29/08/2003	2.02	3.08	0.45	52.49	0.53	1.52	0.43	13.67	19.00	19.90	0.42	493.95	0.61	0.07
80	18	06/09/2003	22/09/2003	23/09/2003	1.81	2.28	0.29	32.62	0.35	0.82	0.29	6.36	17.98	18.20	0.17	323.70	0.05	0.40
81	5	12/07/2005	15/07/2005	16/07/2005	2.18	2.50	0.30	10.91	0.55	0.87	0.30	2.75	17.71	18.10	0.33	88.53	0.29	0.64
82	10	07/10/2005	14/10/2005	16/10/2005	1.69	2.16	0.20	16.88	0.25	0.71	0.19	2.52	15.86	16.10	0.23	158.60	0.10	0.27
83	41	21/10/2005	22/11/2005	30/11/2005	2.12	3.02	0.42	87.12	0.57	1.49	0.39	23.22	13.15	14.80	1.44	539.15	0.05	0.17
84	6	11/12/2005	13/12/2005	16/12/2005	1.72	2.00	0.21	10.30	0.26	0.54	0.21	1.58	9.17	9.50	0.24	55.04	0.24	0.16
85	5	09/06/2006	09/06/2006	13/06/2006	2.19	2.30	0.10	10.93	0.47	0.59	0.10	2.36	14.42	14.70	0.16	72.10	1.48	0.10

86	15	16/07/2006	19/07/2006	30/07/2006	2.31	3.69	0.61	34.72	0.72	2.07	0.60	10.74	18.48	19.60	0.58	277.23	0.64	0.19
87	5	05/08/2006	07/08/2006	09/08/2006	2.27	3.06	0.56	11.33	0.74	1.54	0.55	3.72	19.20	20.00	0.55	96.00	0.57	0.63
88	57	13/09/2006	25/10/2006	08/11/2006	2.33	3.02	0.44	132.95	0.74	1.40	0.44	42.32	16.47	18.70	1.58	939.05	0.03	0.10
89	43	19/11/2006	31/12/2006	31/12/2006	2.09	2.61	0.27	89.74	0.55	1.17	0.30	23.76	10.00	11.90	1.11	430.17	0.02	NA
90	171	19/11/2006	16/04/2007	08/05/2007	2.49	3.99	0.47	426.10	0.75	2.12	0.47	128.32	8.21	11.90	1.77	1403.70	0.02	0.08
91	18	12/05/2007	25/05/2007	29/05/2007	2.44	3.65	0.47	44.00	0.60	1.84	0.49	10.82	12.16	13.90	0.96	218.90	0.13	0.47
92	9	05/06/2007	11/06/2007	13/06/2007	3.18	4.19	0.84	28.63	1.39	2.39	0.84	12.48	15.26	16.50	1.02	137.30	0.37	0.84
93	9	20/08/2009	24/08/2009	28/08/2009	1.36	1.46	0.07	12.28	0.10	0.19	0.07	0.86	18.60	18.70	0.07	167.40	0.04	0.03
94	12	18/04/2011	27/04/2011	29/04/2011	2.14	2.96	0.28	25.73	0.37	1.17	0.28	4.40	9.13	10.30	0.54	109.60	0.12	0.46
95	12	12/03/2014	20/03/2014	23/03/2014	2.04	2.11	0.05	24.52	0.18	0.26	0.05	2.18	6.43	6.60	0.13	77.20	0.02	0.07
96	6	08/04/2014	11/04/2014	13/04/2014	1.97	2.12	0.09	11.84	0.12	0.26	0.09	0.71	7.82	8.00	0.18	46.90	0.06	0.12
97	14	18/04/2014	23/04/2014	01/05/2014	2.27	3.08	0.33	31.74	0.42	1.22	0.33	5.84	9.44	10.10	0.44	132.20	0.22	0.15
98	7	21/05/2014	21/05/2014	27/05/2014	2.21	2.54	0.23	15.50	0.45	0.76	0.23	3.15	12.63	12.70	0.11	88.40	0.78	0.14
99	21	22/07/2014	08/08/2014	11/08/2014	1.81	2.22	0.27	38.10	0.43	0.90	0.27	9.01	18.80	19.50	0.35	394.74	0.04	0.28
100	60	30/09/2014	13/11/2014	28/11/2014	2.09	2.55	0.29	125.64	0.49	0.89	0.26	29.22	14.61	17.20	1.72	876.44	0.02	0.07
101	12	06/11/2015	11/11/2015	17/11/2015	1.91	2.14	0.12	22.91	0.25	0.47	0.12	3.03	13.12	13.60	0.45	157.40	0.10	0.08
102	15	17/12/2015	28/12/2015	31/12/2015	2.03	2.40	0.23	30.48	0.47	0.85	0.24	7.04	8.87	9.10	0.25	133.04	0.08	NA
103	43	24/08/2016	28/09/2016	05/10/2016	1.99	2.88	0.60	85.58	0.70	1.42	0.50	30.07	18.61	19.40	0.55	800.40	0.06	0.20
104	7	23/07/2018	25/07/2018	29/07/2018	2.22	2.79	0.50	15.57	0.93	1.49	0.50	6.51	19.19	19.80	0.53	134.30	0.55	0.31
105	5	06/08/2018	08/08/2018	10/08/2018	1.66	2.37	0.47	8.28	0.52	1.24	0.47	2.59	19.18	19.90	0.48	95.90	0.48	0.51
106	9	02/09/2018	06/09/2018	10/09/2018	1.36	1.74	0.18	12.21	0.24	0.63	0.18	2.19	18.61	19.00	0.20	167.53	0.17	0.15

Table S3.Fixed baseline: Summary of generalised additive (GAM) and linear (GLM) models applied to the number, days per year and duration of MHW and to the average and maximum threshold intensities per year. The process of model selection is divided in three steps. Step 1: Model selection of GAM with different error distributions (=Family); NA= Family does not apply to this type of variable. Step 2: For the best GAM, the significant of the smooth terms (* in the row of EDF, ns= non-signficant) and the EDF values were checked to determine if a linear model would be more appropriate. For cases where EDF <2, GLM was carried out with the error distribution given by that of the best GAM model; otherwise the GAM model was retained. Step 3: GLM was carried out (if appropriate) and best model was retained; for the best model we present the % deviance explained and the the significance of the smooth term (or parameter estimate).

Model	Family	Number	Days per year	Average duration	Average intensity	Maximum intensity
		AIC scores				
GAM	Poisson	**212**	2140			
GAM	NegBin	220	527			
GAM	Gauss			472	108	**134**
GAM	Gamma			383		
Check on smooth terms: EDF of best GAM model						
		6.16*	1.00*	1.19*	1.00*	5.34*
Model	Variable	AIC scores				
GLM	Year		**527**	**299**	108	
GLM	None					
The model selected was:		Year	Year	Year	Year	Year
Intercept					-64.4	
Slope					0.032	
	Deviance (%)	48.1	28.0	6.4	45	16.5
	p-value	2.0×10^{-16}	1.79×10^{-8}	0.031	6.53×10^{-9}	3.22×10^{-4}

Table S4. Shifting baseline. Summary of generalised additive (GAM) and linear (GLM) models applied to the number, days per year and duration of MHW and to the average and maximum threshold intensities per year. The process of model selection is divided in three steps. Step 1: Model selection of GAM with different error distributions (=Family); NA= Family does not apply to this type of variable. Step 2: For the best GAM, the significant of the smooth terms (* in the row of EDF, ns= non-signficant) and the EDF values were checked to determine if a linear model would be more appropriate. For cases where EDF <2, GLM was carried out with the error distribution given by that of the best GAM model; otherwise the GAM model was retained. Step 3: GLM was carried out (if appropriate) and best model was retained; for the best model we present the % deviance explained and the the significance of the smooth term (or parameter estimate).

Model	Family	Number	Days per year	Average duration	Average intensity	Maximum
Step 1:		AIC scores				
GAM	Poisson	222	1970	NA	NA	NA
GAM	NegBin	**214**	444	NA	NA	NA
GAM	Gauss	NA	NA	445	106	129
GAM	Gamma	NA	NA	240	NA	NA
Step 2:		Check on smooth terms: EDF of best GAM model				
		ns	1.7	1.0	1.0	6.4*
Step 3:		AIC scores				
GLM	Year		**444**	133	**106**	
GLM	None			**132**	115	138
The model selected was:		Null	Year	Null	Year	Year
	Deviance (%)	48.1	4.2		18	32
	Intercept				-33.87	
	Slope				0.016	
	p-value	2.0×10^{-16}	0.042	0.088	0.0012	0.028

Table S5. Main characteristics of the top 10 heatwaves computed from using a shifting baseline. These were selected according to the category (all category III were included in the list) and number of days that a particular MHW spent in category II. Information for the dates (start, peak, end), maximum temperature intensity (C above the seasonal climatology) and duration (D: in days) corresponds to calculations using a shifting window.

ID	Year	Start – Peak – End	Im	D	Cat
1	1975	2.08 – 05.08 – 16.08	2.8	15	II
2	1975	20.08 – 01.09 – 14.09	2.9	25	III
3	1976	26.06 – 28.06– 21.07	4.3	26	II
4	1990	10.01 – 07.05 – 24.05	5.0	135	III
5	1994	28.07 – 4.08 – 16.08	3.1	20	II
6	1995	10.08 – 23.08 – 26.08	3.4	17	III
7	1997	05.08 – 19.08– 15.09	2.9	42	II
8	1999	03.09 – 23.09– 11.10	2.9	39	II
9	2006-2007	19.11 – 16.04 – 8.05	4.0	171	II
10	2016	24.08 – 28.09– 5.10	2.9	43	II

Supplement

Section 1: Methods: Demonstration of equality between Pearson correlation and ϕ-association.

The starting point is the contingency table of frequency of occurrence, where co-occurrence is given by n_{11} and strong associations are given by high values of n_{11} and n_{00}, as compared to n_{10} and n_{01}. By definition the expected value of X is given by $E(X) = (n_{11} + n_{10})/N = n_{1y}/N$ because the remaining frequencies of the table will be multiplied by zero. Likewise we obtain $E(Y) = n_{x1}/N$. The variances are given by $Var(X)= n_{1y}\, n_{0y}/N^2$ and $Var(Y)= n_{x1}\, n_{x0}/N^2$ and can be obtained from $Var(Z) = E(Z^2)-E^2(Z)$, e.g. for X, $Var(X) = n_{1y}/N - (n_{1y}/N)^2 = (N- n_{1y})\, n_{1y}/N^2$.

	Y=1	Y=0	Total
X=1	n_{11}	n_{10}	n_{1y}
X=0	n_{01}	n_{00}	n_{0y}
Total	n_{x1}	n_{x0}	N

The definition of the Pearson correlation coefficient is:

$$\rho = \frac{E\{[X - E(X)][Y - E(Y)]\}}{\sqrt{Var(X)Var(Y)}}$$

And the ϕ coefficient is:

$$\varphi = \frac{n_{11}n_{00} - n_{01}n_{10}}{\sqrt{n_{1y}n_{0y}n_{x1}n_{0x}}}$$

By applying the definition of variances we obtain:

$$\sqrt{Var(X)Var(Y)} = \frac{\sqrt{n_{1y}n_{0y}n_{x1}n_{0x}}}{N^2}$$

This is the denominator of the ϕ coefficient divided by N^2.

Then, by applying the definition of expected values, we obtain for the numerator:

$$E\{[X - E(X)][Y - E(Y)]\} = E(XY) - E(X)E(Y) = \frac{n_{11}}{N} - \frac{n_{1y}n_{x1}}{N^2}$$

Plugging those into the formula of Pearson correlation, we obtain the ϕ coefficient as follows:

$$\rho = \left[\frac{n_{11}}{N} - \frac{n_{1y}n_{x1}}{N^2}\right] N^2/\sqrt{n_{1y}n_{0y}n_{x1}n_{0x}}$$

$$\rho = \left[N\, n_{11} - n_{1y}n_{x1}\right]/\sqrt{n_{1y}n_{0y}n_{x1}n_{0x}}$$

$$\rho = [(n_{11} + n_{10} + n_{01} + n_{00})\, n_{11} - (n_{11} + n_{10})(n_{11} + n_{01})]/\sqrt{n_{1y}n_{0y}n_{x1}n_{0x}}$$

$$\rho = \frac{[n_{11}n_{00} - n_{10}n_{01}]}{\sqrt{n_{1y}n_{0y}n_{x1}n_{0x}}} = \varphi$$

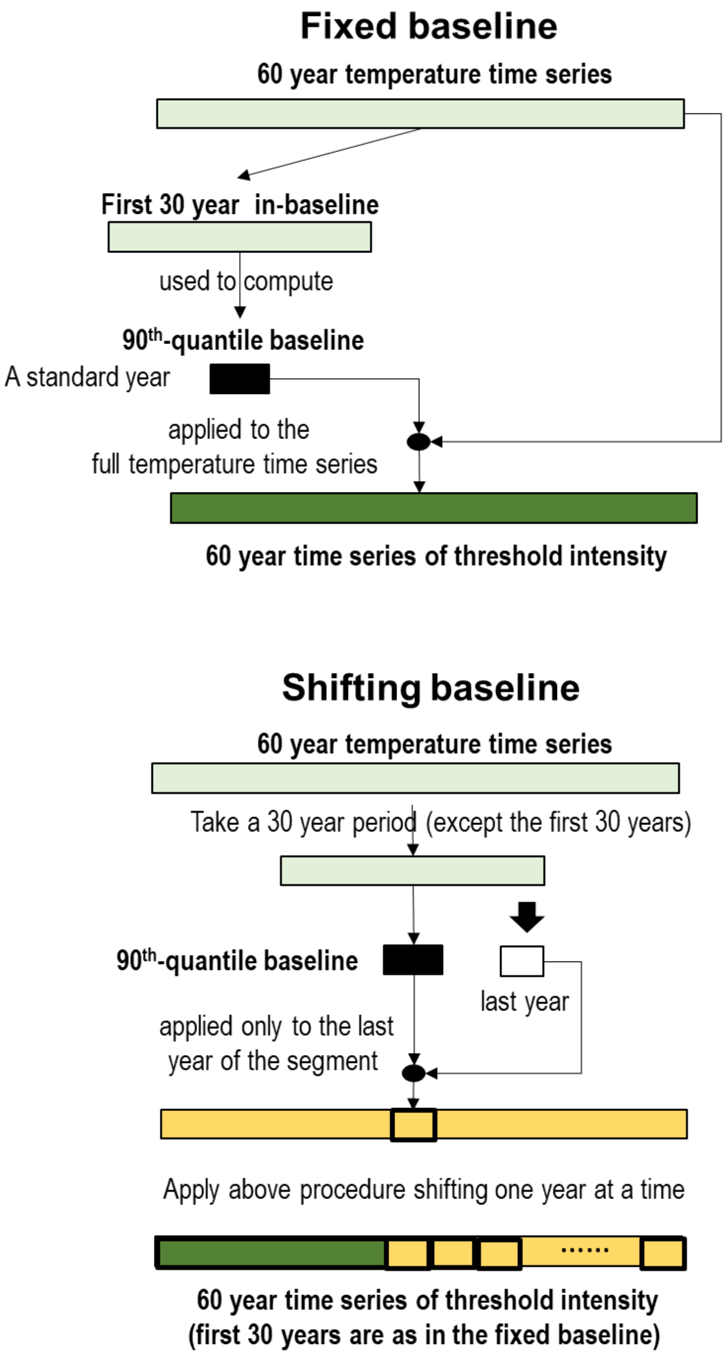


Figure S1. Calculation of baselines and threshold incidence. Fixed baseline: The first 30 years of the temperature time series (T) is used to calculate the baseline (daily 90th quantiles: q90). Then this baseline is applied to the full time series: for each day of each year, the threshold incidence (TI) is calculated as TI= T-q90. Shifting baselines: for the first 30 years, it is computed as in the fixed baseline.

For the subsequent years, a segment of 30 years is taken (e.g. from year 2 to 31) to calculate q90and then the TI is calculated for only the last year of such segment (e.g. year 31). This procedure is repeated with a new 30-year segment until TI is calculated for the remaining years. The comparison between baselines focuses on the last 30 years of the time series.

Section 2 Results

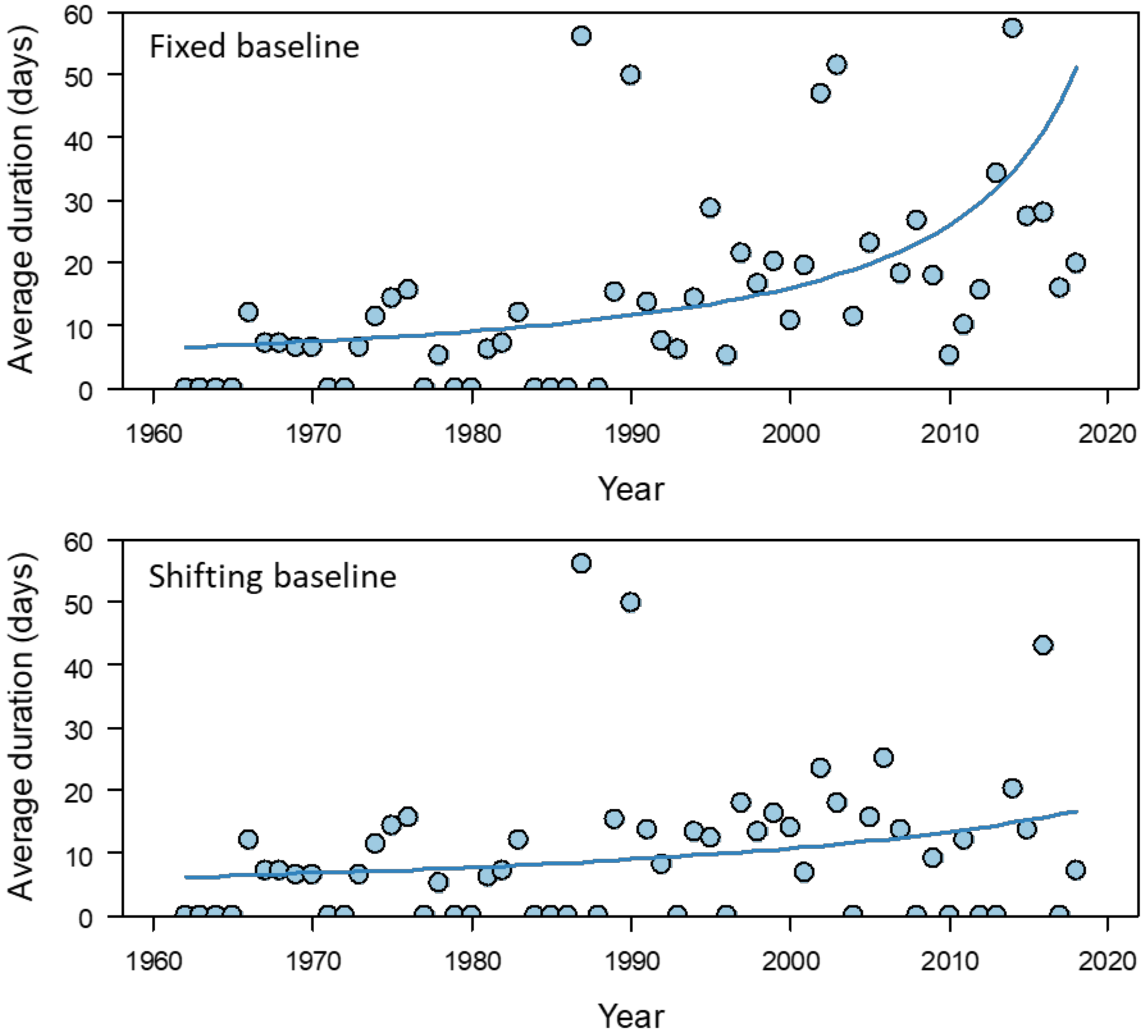


Figure S2. Temporal patterns in average duration of a MHW per year after application of a fixed and shifting baselines. Curves are best fits of generalised linear models with gamma residuals and inverse link function (details of model selection are given in Tables S3,S4).

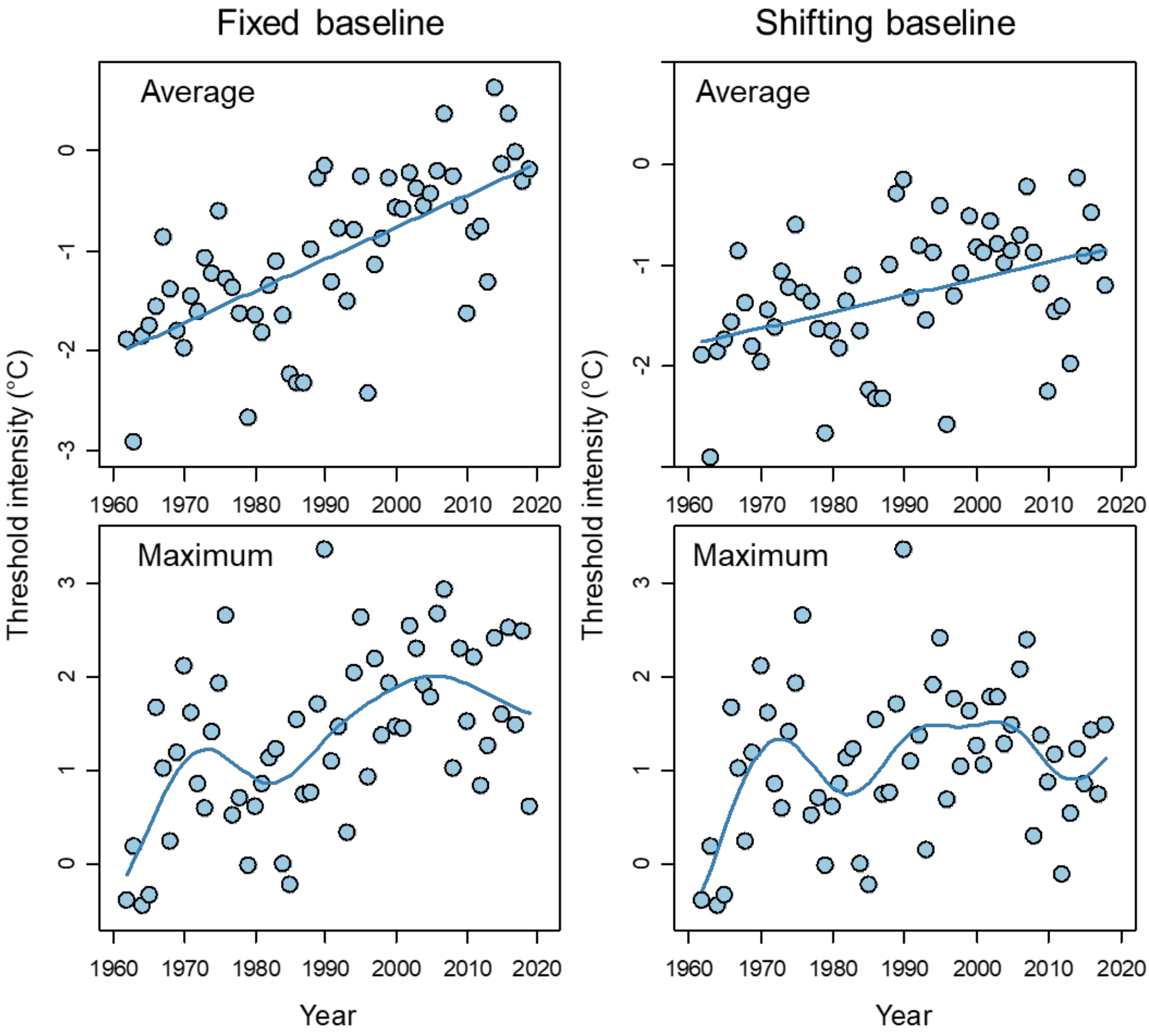
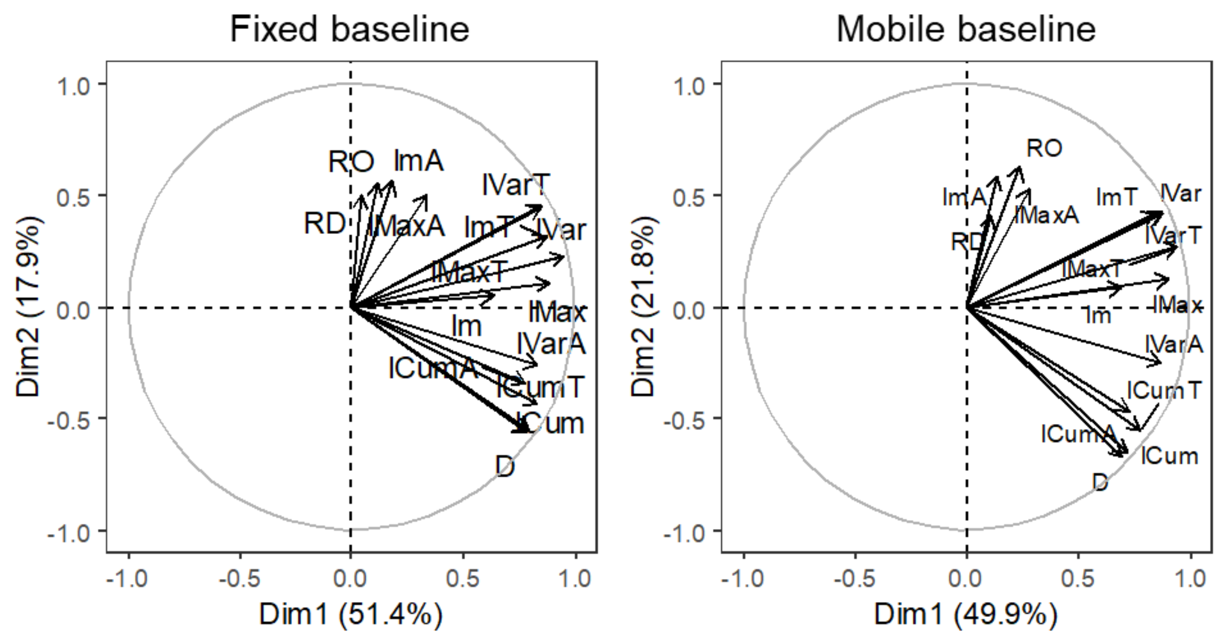


Figure S3. Temporal patterns threshold anomalies per year after application of the fixed and shifting baselines. Threshold intensity values refer to the whole year and are not restricted to those exhibited during heatwaves or spikes; hence, there is a dominance of negative values in of the data averaged by year (upper panels). Curves are best fits of generalised additive or linear models (details of model selection are given in Tables S3, S4).



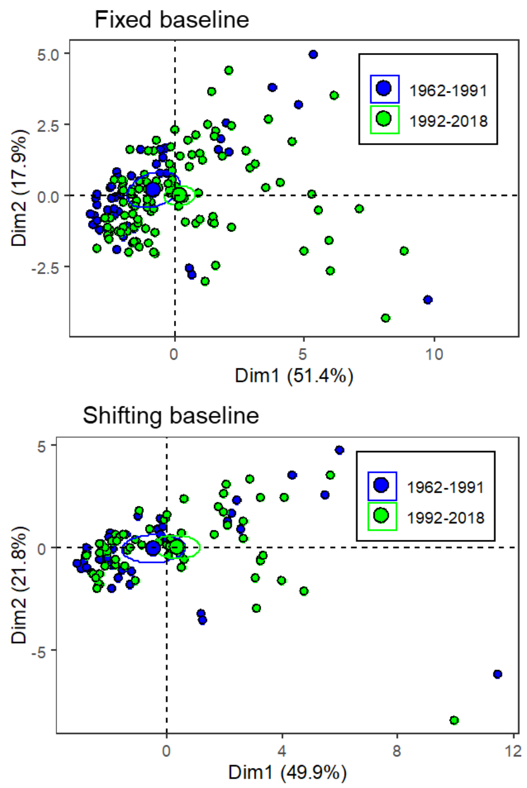


Figure S4. Principal component analyses applied to traits of the Helgoland MHW after applying a fixed or shifting baseline of 30 year. Upper panels: space of the variables; lower panel: space of the events. The PCA was applied to the correlation matrix (i.e. variables were centred and standardised). Abbreviaions: D: duration, ICum: cumulative intensity relative to the climatology, ICumA: cumulative absolute intensity; ICumT: cumulative intensity relative to the threshold. Im: average intensity relative to the climatology, ImA: average absolute intensity; ImT: average intensity relative to the threshold. IMaxA: maximum absolute intensity; IMaxT: maximum intensity relative to the threshold. IMax: Maximum intensity relative to the climatology, IMaxA: maximum absolute intensity; IMax: maximum intensity relative to the threshold, IRD inverse of the decline rate; IRO: inverse of the onset rate.

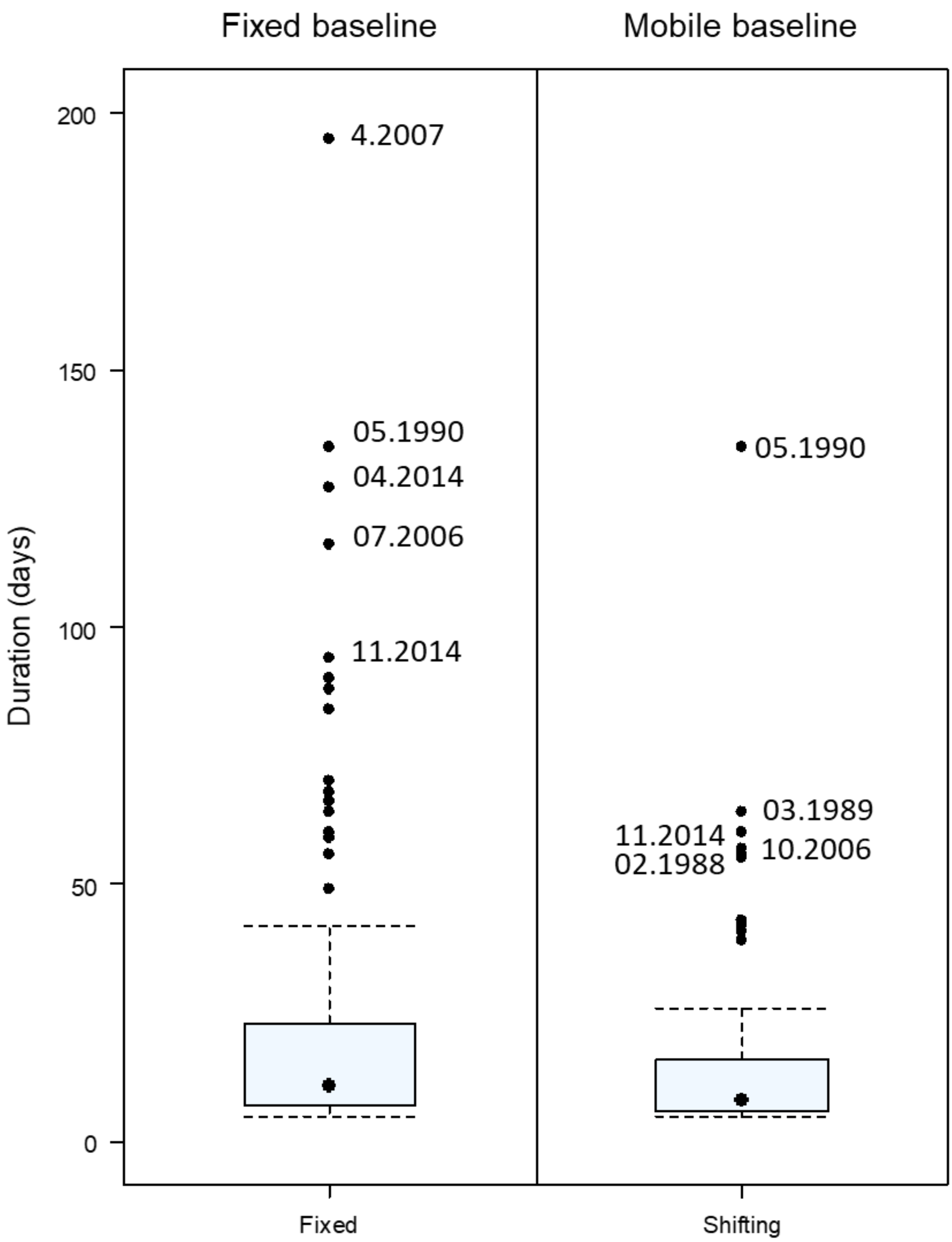


Figure S5. Box and whisker plot of duration of heatwaves computes from both the fixed and shifting baselines. The top 5 extreme heatwave events are indicated by month and year (month refers to the timing of highest intensity).

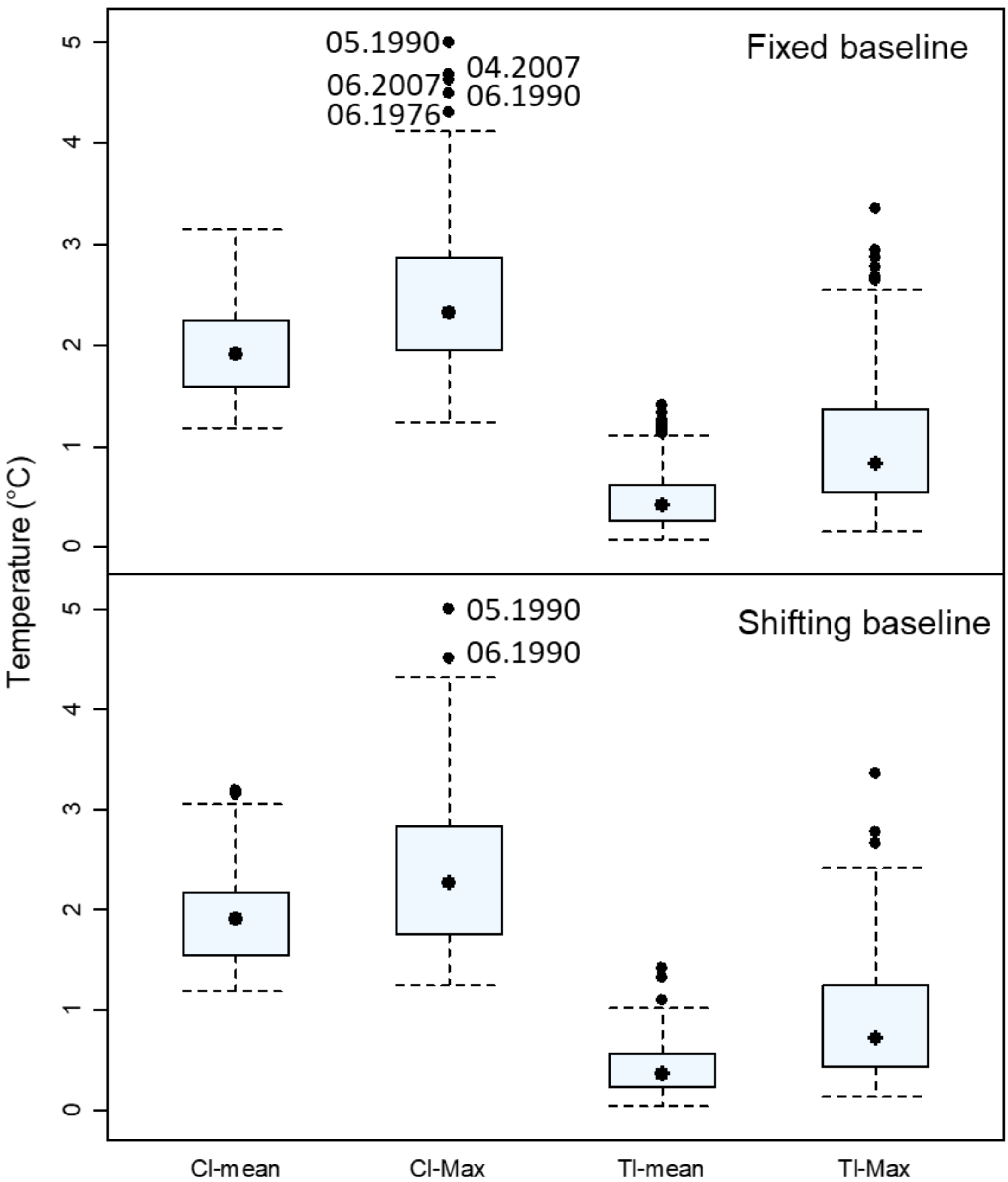


Figure S6. Summary of heatwaves mean and maximum (Max) temperature intensity with respect to the climatology (CI) or the threshold used to compute heatwave events (TI). Selected extreme heatwave events are indicated by month and year (month refers to the timing of highest intensity).

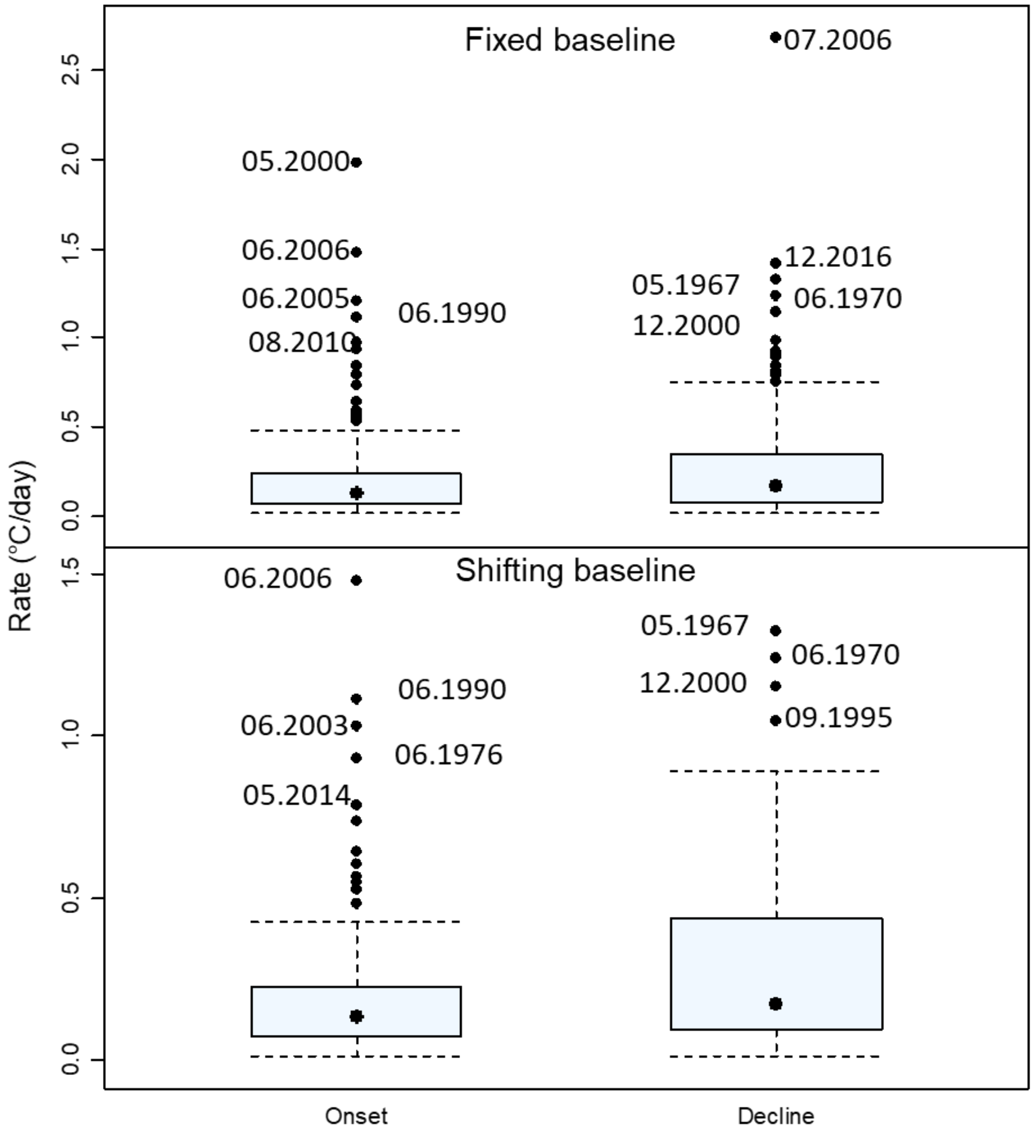


Figure S7. Summary of heatwaves rate of onset and decline. Selected extreme heatwave events are indicated by month and year (month refers to the timing of highest intensity).

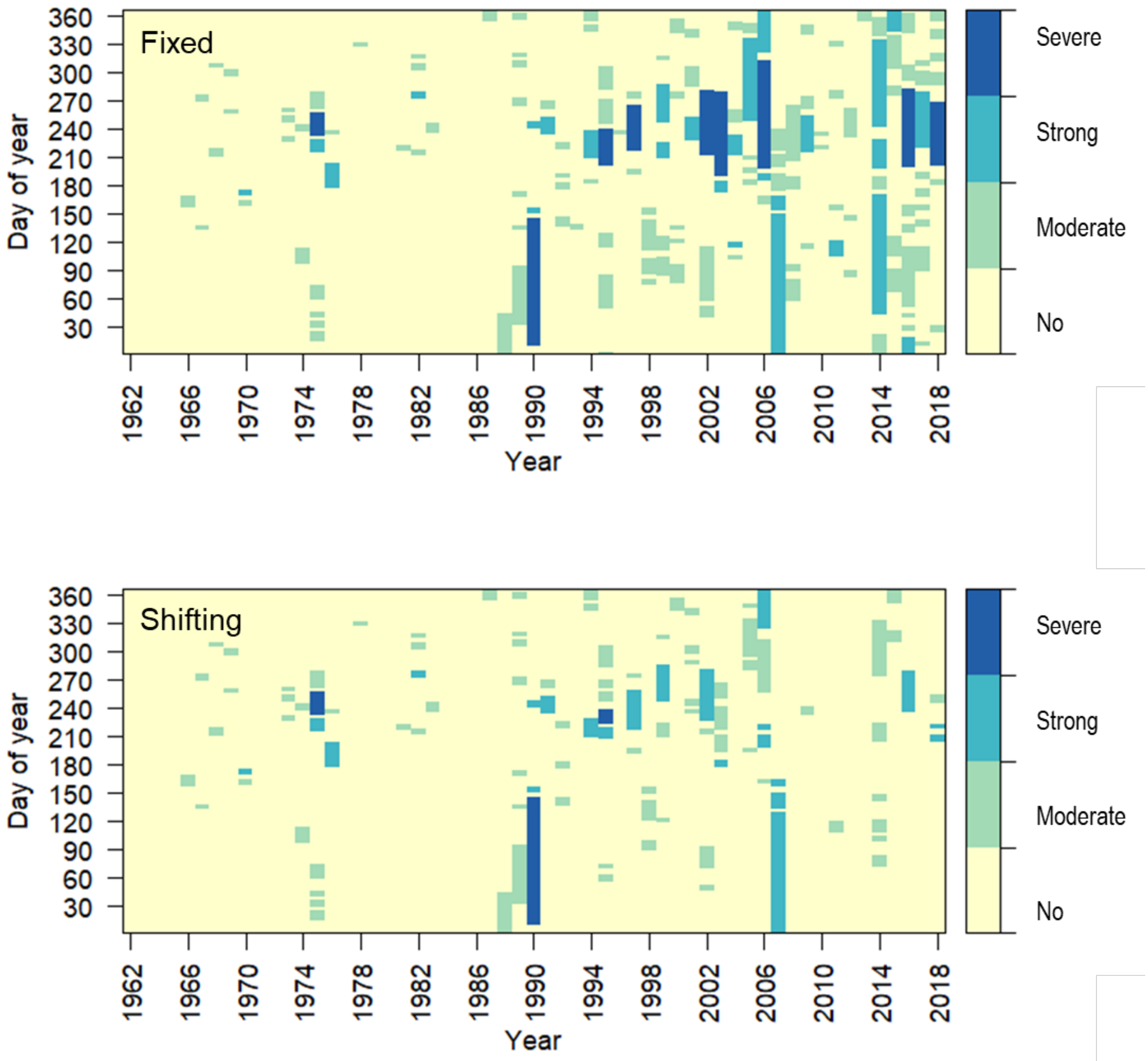


Figure S8. Heatmap of heatwaves by categories after the application of a fixed (upper panel) or shifting baselines (lower panel).

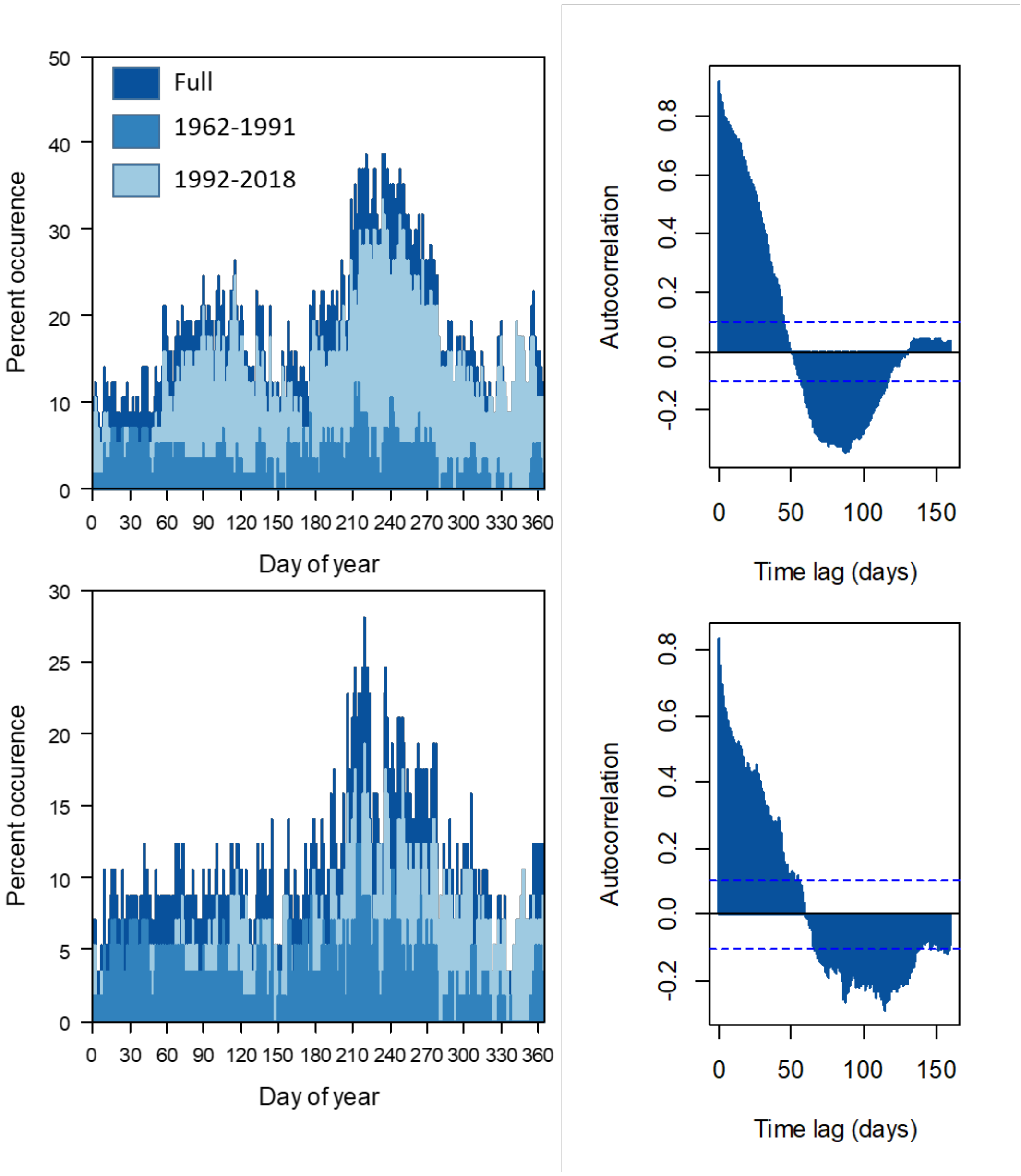


Figure S9. Seasonal patterns in positive threshold incidences: Left panels: Proportion of days with positive threshold indices for each day of the year, after application of the fixed and shifting baselines. Right panels: proportion for the full time series and discriminated by period. Right panel: autocorrelation function for the proportions based on the full time series. Notice in the left panels that proportions peak between days 150 and 300-330 consistent with a wave of 150-180 days of period, reaching a negative autocorrelation peak at ~70-100 days (as in the right panels).

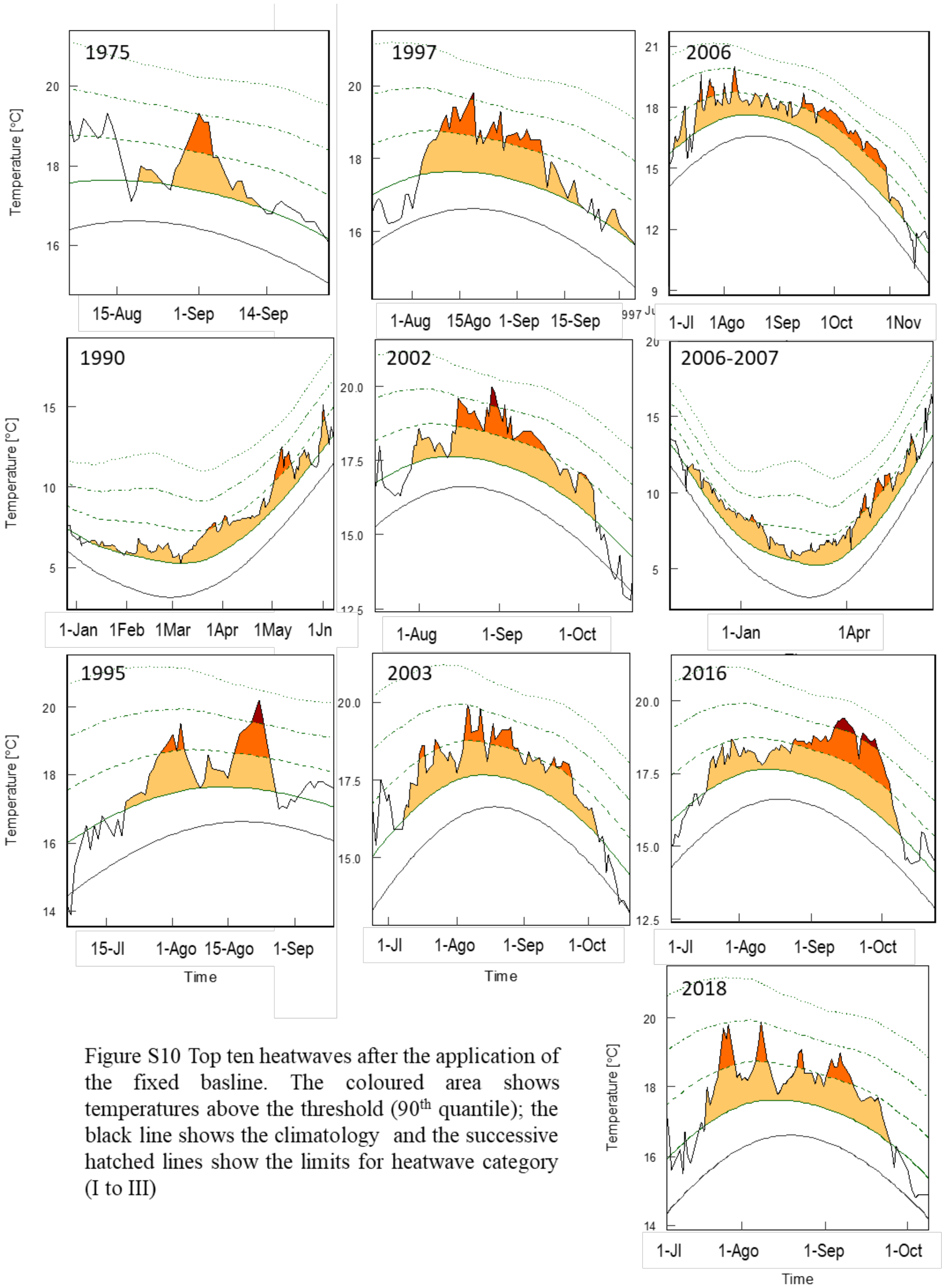


Figure S10 Top ten heatwaves after the application of the fixed basline. The coloured area shows temperatures above the threshold (90th quantile); the black line shows the climatology and the successive hatched lines show the limits for heatwave category (I to III)

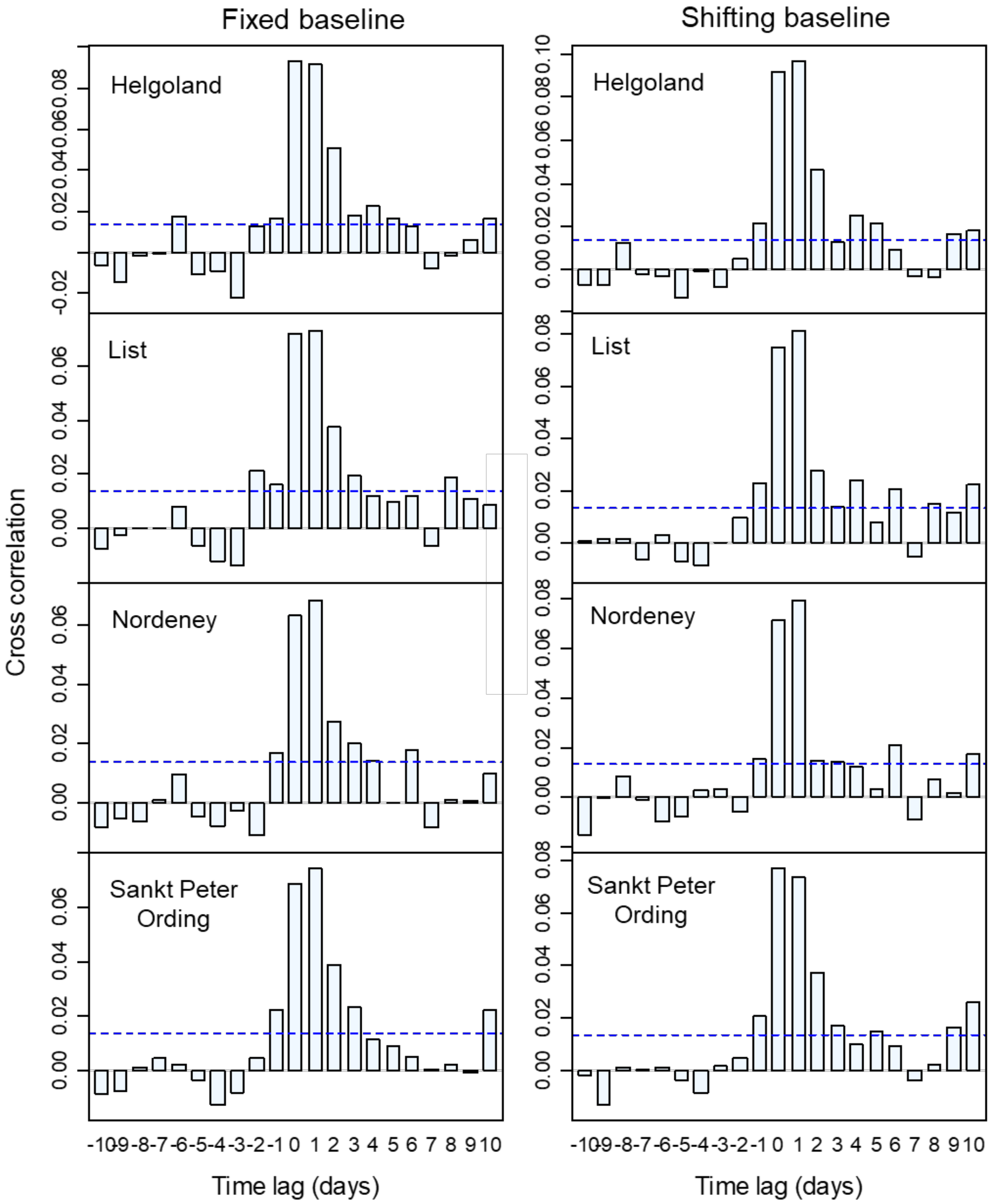


Figure S11. Cross-correlations between threshold anomalies calculated form the fixed or shifting baselines for seawater (Helgoland Roads time series) and air temperature (four meteorological stations). Data were de-trended and pre-whitened.

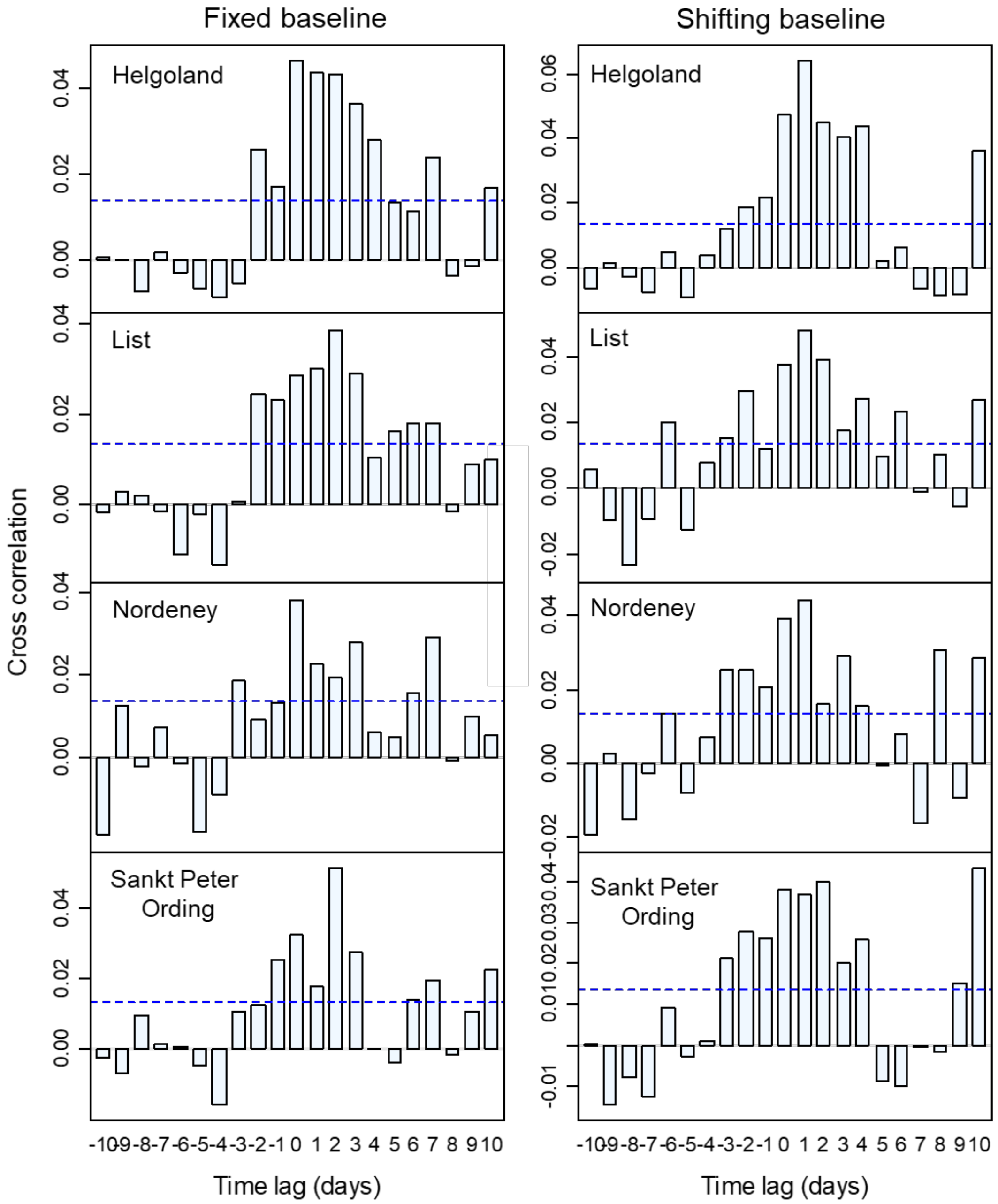


Figure S12. Cross-correlations between heatwave time series calculated from the fixed or shifting baselines for seawater (Helgoland Roads time series) and air temperature (four meteorological stations). Data were de-trended and pre-whitened.

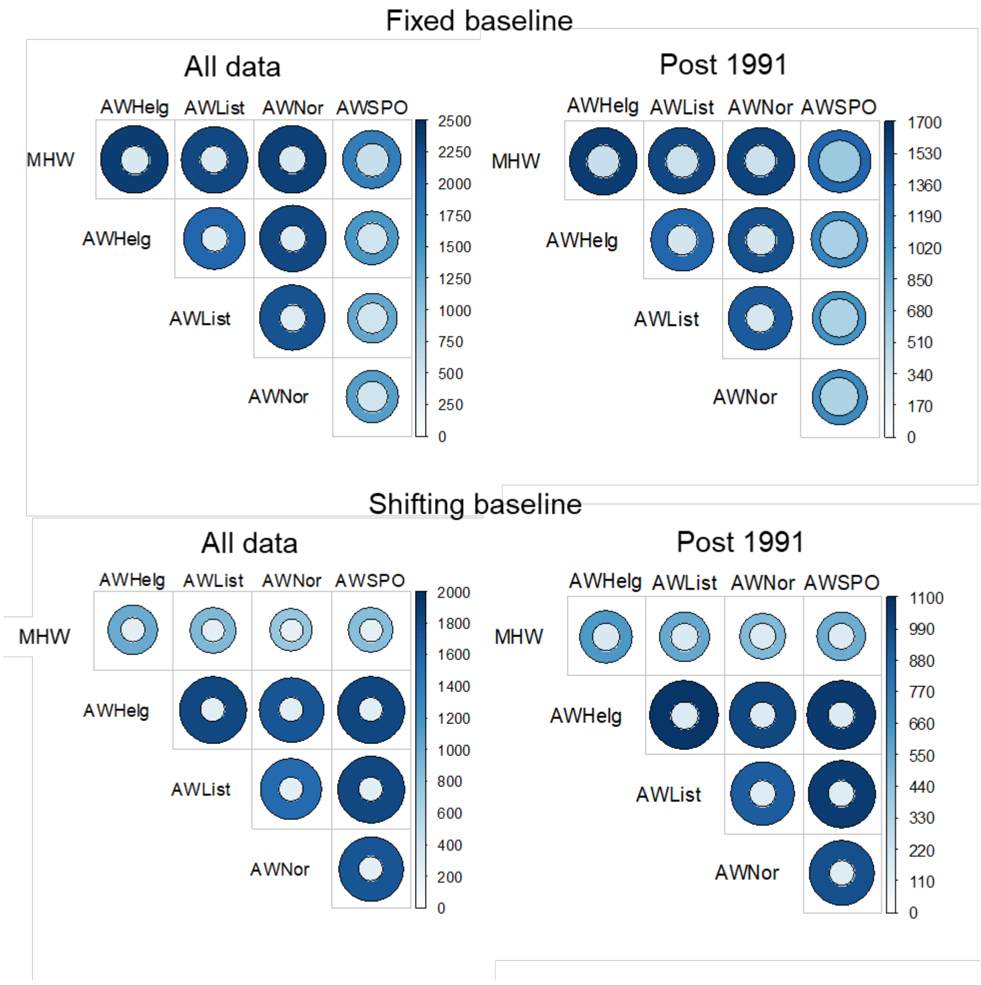


Figure S13. Observed co-occurrence of positive threshold anomalies (outer circles) in relation to those expected based on random patterns of distribution (inner circles) for time series based on the fixed or shifting baselines. Left panel: full data (1962-1991); right panels: post 1991 when effects of baselines are highlighted. Abbreviations: MHW: marine heatwaves for Helgoland Roads, AW: atmospheric heatwaves corresponding to Helgoland (Helg), List, Nordeney (Nor) and Sankt Peter-Ording (SPO).

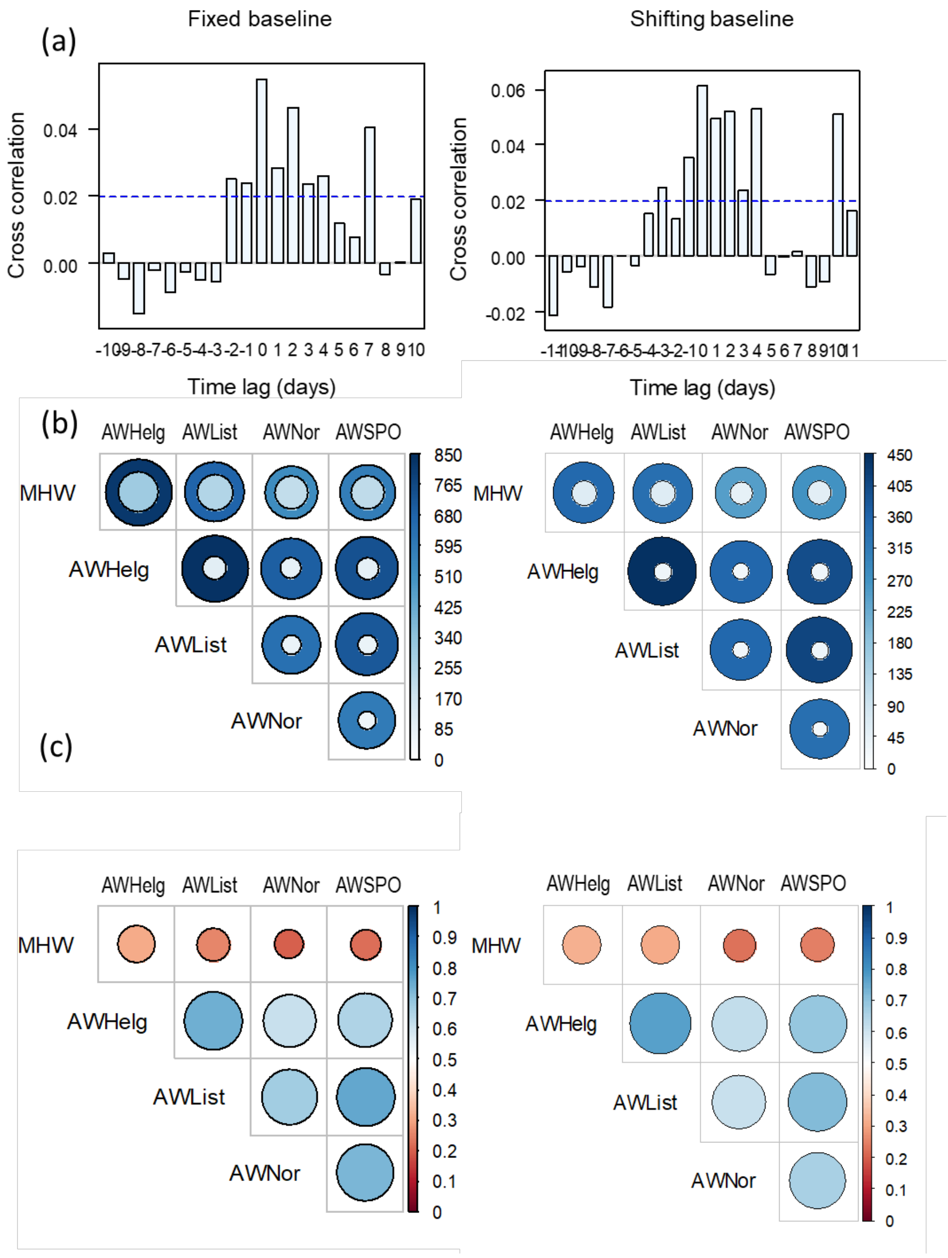


Figure S14. Association between marine and atmospheric heatwaves after application of a fixed or shifting baseline (left and right panels respectively) for the period 1992-2018, where the effect of baselines should differ. (a) Cross-correlation of marine vs atmospheric heatwaves as detected by the meteorological station in Helgoland; plots for the remaining stations are given in Fig S8 (threshold intensities) and S9 (heatwaves). (b) Observed co-occurrence of heatwaves (outer circles) in relation to those expected based on random patterns of distribution (inner circles). (c) Overlap between heatwaves based on the Schoener index. Abbreviations in (b) and (c): MHW: marine heatwaves for Helgoland Roads, AW: atmospheric heatwaves corresponding to Helgoland (Helg), List, Nordeney (Nor) and Sankt Peter-Ording (SPO).

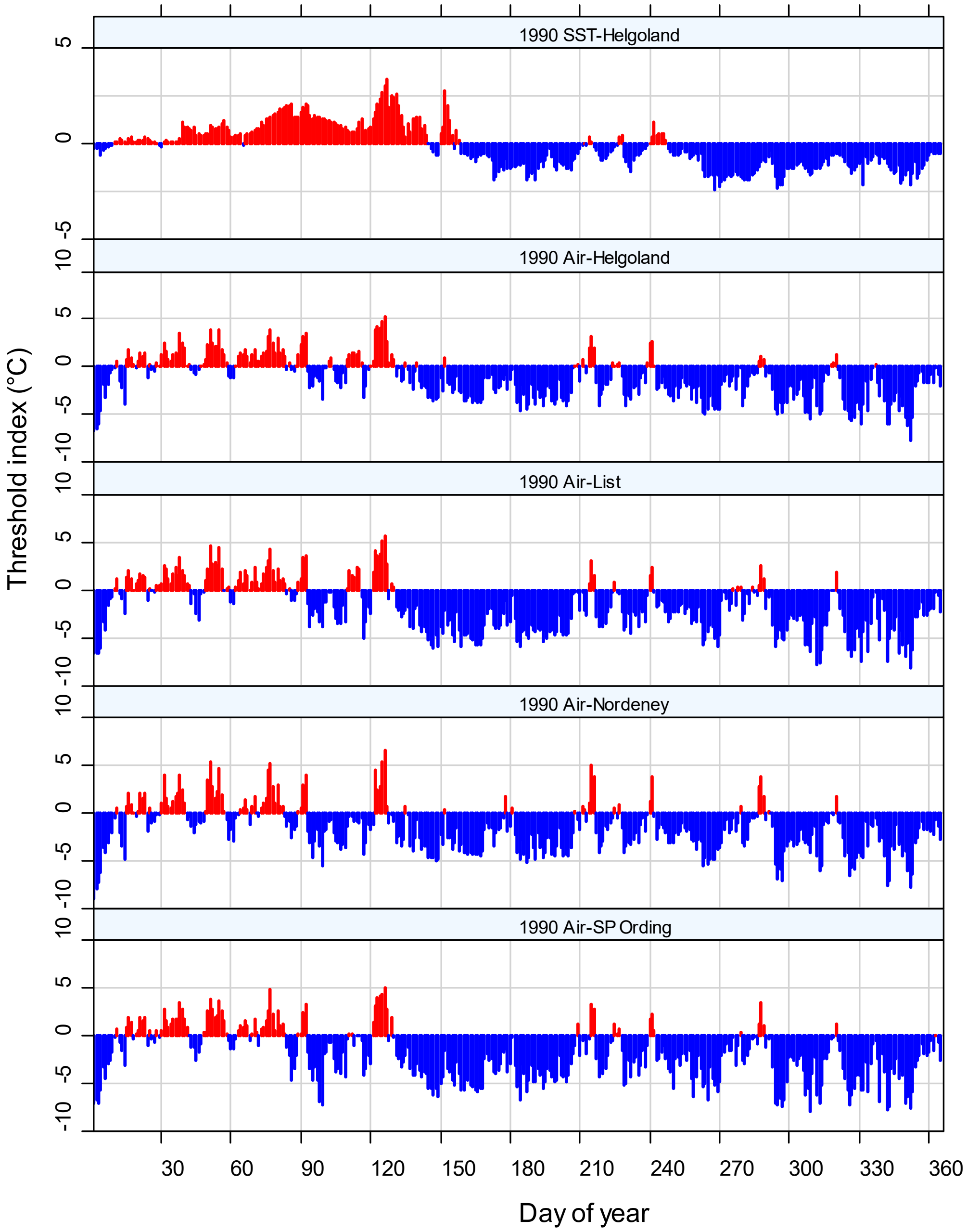


Figure S15. Time distribution of threshold incidence (year 1990) for the seawater temperature (SST) at Helgoland Roads and atmospheric temperature (Air) at four meteorological stations (Helgoland, List, Nordeney, Sankt Peter-Ording). Calculations were based on the fixed baseline.

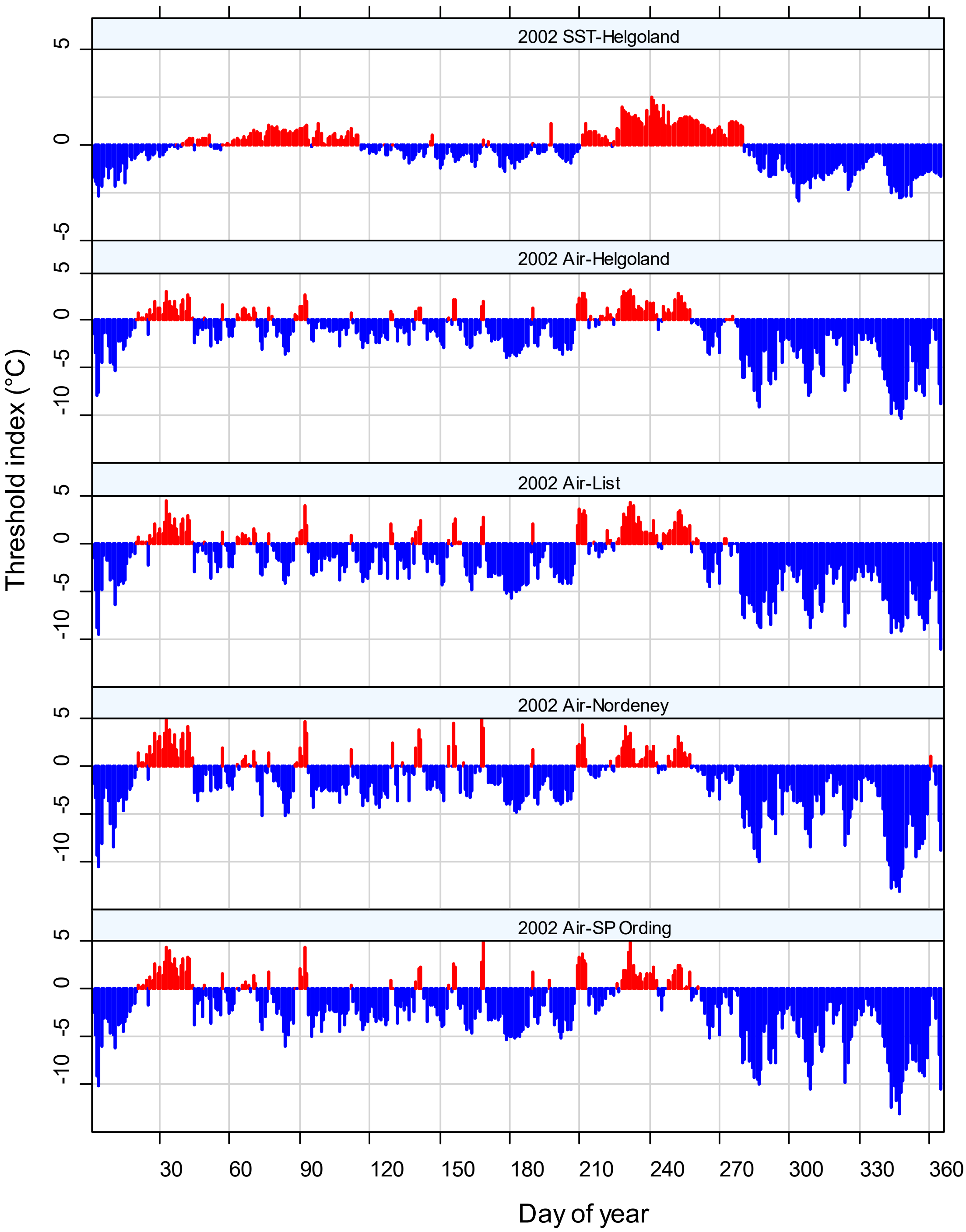


Figure S16. Time distribution of positive threshold incidence (year 2002) for the seawater temperature (SST) at Helgoland Roads and atmospheric temperature (Air) at four meteorological stations (Helgoland, List, Nordeney, Sankt Peter-Ording). Calculations were based on the fixed baseline.

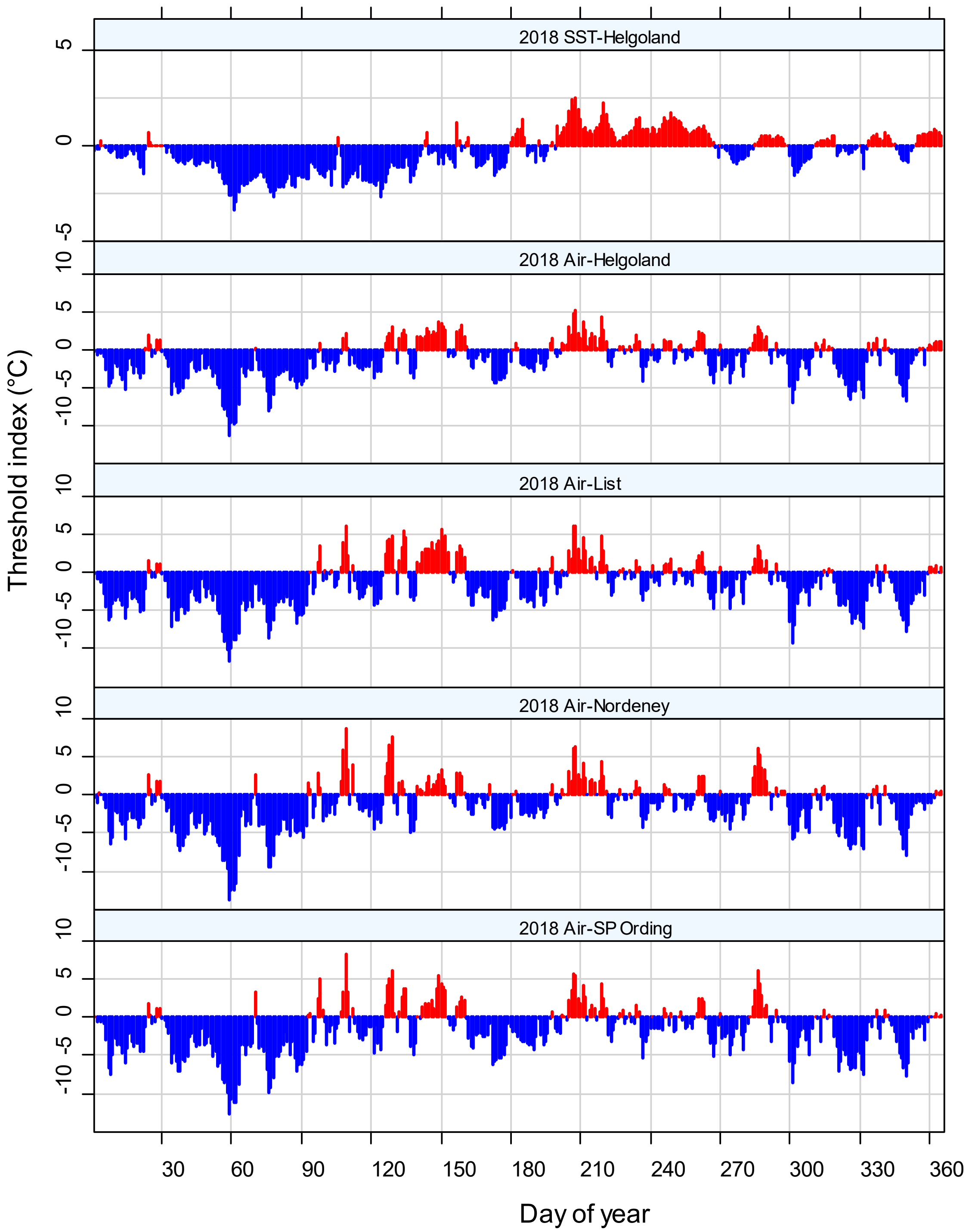


Figure S17. Time distribution of positive threshold incidence (year 2018) for the seawater temperature (SST) at Helgoland Roads and atmospheric temperature (Air) at four meteorological stations (Helgoland, List, Nordeney, Sankt Peter-Ording). Calculations were based on the fixed baseline.